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and

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Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees
Volume 2: Site-Specific Technical Report

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EXECUTIVE SUMMARY

REPORT STRUCTURE

This report is structured in two volumes. Volume 1 (Research Report) covers background information on indigenous trees and forests, project details, research methods, economic and financial viability assessments, market and product potential information, rapid screening techniques for estimating water use efficiencies, and general conclusions and recommendations. Volume 2 (Site-Specific Technical Report) provides details on the respective field measurement sites/species, specific measurement methods employed, results and conclusions/recommendations.

MOTIVATION

South Africa is very reliant on its plantations of introduced tree species to meet its pulp and timber needs, and the benefits of this industry in terms of production, income generation and job provision are undisputed (Chamberlain *et al*. 2005). The downside is that these benefits come at some environmental cost, not least the impact of the industry on water resources (Dye & Versfeld, 2007; Dye, 2012). Many catchment areas are consequently now closed to further afforestation, but economic growth and development continue unabated. Imports and improved productivity are potential solutions to continue meeting the demand for timber and forest products, but further consideration of the feasibility of expanding indigenous tree resources is also warranted. 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 perceptions that indigenous tree species use less water than introduced tree plantations. While data from previous studies are available on the water-use efficiency (WUE) of common introduced plantation species in South Africa (Olbrich *et al*. 1996; Dye *et al*. 2001), information on the water-use of indigenous trees and forests is scarce and indirect, and relationships between growth and water-use within indigenous forests have only started to be investigated in South Africa within the last 10 years (Dye *et al*. 2008).

Information on the water-use, growth and economic value of indigenous trees is required in order to facilitate sustainable land-use planning from hydrological, ecological and socio-economic perspectives. New and innovative techniques to quantify the water-use (transpiration and total evaporation) of a range of tree species and forest types are available

(Jarmain *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. 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.

PROJECT OBJECTIVE AND AIMS

The overall objective of this project was:
To measure and model the water use and growth of indigenous trees in different types of tree systems, and to quantify the economic benefits and costs of the biomass production under a range of bio-climatic conditions in South Africa.

The specific aims of this project were:
1. To screen, shortlist and select indigenous tree species that are most promising for natural forest and indigenous plantation tree production systems with particular attention to single species/even aged and mixed species/mixed aged tree systems.
2. To improve knowledge of the water use efficiency (WUE) of indigenous trees under natural forest and indigenous plantation systems through growth and water use measurements and modelling, using proven methods and techniques.
3. To analyse the economic viability and market potential of biomass products from natural indigenous forests and indigenous plantation tree systems (in different social contexts) and in comparison with exotic commercial plantations.
4. To develop and test a rapid screening technique to identify indigenous tree species-site combinations based on water use, economic viability and eco-system adaptability, thereby optimizing WUE and socio-economic potential.

METHODS

The project conducted intensive measurements of tree and forest water use, stem growth, weather variables, soil water dynamics and tree attributes, as well as economic and financial assessments within indigenous and introduced tree systems. Research work focussed on priority individual indigenous tree species and forest types, through 6 phases of field measurements and data collection exercises. The studies started on indigenous *Podocarpus henkelii* (Henkel's Yellowwood) trees, growing in a single species/even aged stand in the KZN midlands, and compared growth, water-use and a financial analysis for a comparative Yellowwood plantation against an introduced *Pinus patula* plantation. Phase 2 measurements were conducted over a year in an indigenous Scarp (Transkei Coastal) forest at Manubi (Eastern Cape), and included sap flow and stem growth monitoring on indigenous *Millettia grandis* (Umzimbeet) and *Ptaeroxylon obliquum* (Sneezewood) trees, as well as on a commercially grown coppicing Eucalyptus species in the area, for comparative purposes. Additional water use measurements in the mixed species/mixed age indigenous Scarp forest at Manubi were collected by means of eddy covariance measurements of total evaporation above the forest canopy. This site also formed the basis for an economic assessment of the resource use of selected indigenous species occurring in that forest. Data collected through a field survey of approximately 120 surveys/questionnaires conducted amongst rural inhabitants in the Manubi area, was analysed and interpreted.

Phase 3 measurements consisted of the collection of primary data on tree and forest water-use and growth rates in indigenous *Prunus africana* (Red Stinkwood), *Celtis africana* (White Stinkwood) and *Rapanea melanophloeos* (Cape Beech) trees growing within Southern Mistbelt forest at Ingeli State Forest in southern KZN. Additional water use measurements in the mixed species/mixed age indigenous Southern Mistbelt forest at Ingeli were collected by means of eddy covariance measurements of Total evaporation above the forest canopy. A subsequent modelling exercise to calibrate models against seasonally observed ET rates, and extrapolate to a full year of ET estimates was carried out. A phase 4 study site (Richards Bay Minerals) was then established in northern KZN, where measurements took place on indigenous *Vachellia kosiensis* (Dune Sweet Thorn, previously *Acacia karroo*) trees growing on rehabilitated dunes, as well as on introduced *Casuarina equisetifolia* and *Eucalyptus grandis* species for comparative purposes.

Phase 5 measurements consisted of the establishment of a research site in the southern Cape, where water use and growth data were collected and compared between indigenous *Ocotea bullata* (Black Stinkwood), *Ilex mitis* (Cape Holly) and *Podocarpus latifolius* (Real Yellowwood) trees, in contrast to simultaneous measurements on introduced *Pinus radiata* trees growing in a plantation environment in the same area. A test of the ability of the MAESPA tree water use model to replicate the transpiration trends and volumes observed in the *Ilex mitis* tree at this site was carried out. Finally, Phase 6 water use and growth measurements on additional *Millettia grandis* (Umzimbeet) and *Ptaeroxylon obliquum* (Sneezewood) trees were taken at a site in Pietermaritzburg.

Research was also conducted on the more formal/recognised markets where indigenous timber products are traded, and information on potential products, processes and values associated with those markets was collected.

RESULTS

Results showed that the range and average of observed 1-year water-use totals (transpiration component) was noticeably less for indigenous tree species compared to introduced plantation tree species. Maximum water-use was also 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 8100 L tree^{-1} year^{-1}, irrespective of tree size, whereas sap flows in the more productive introduced plantation trees exceeded 20 000 L tree^{-1} year^{-1} in some cases. 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.

Evidence suggests that indigenous forests cannot compete with plantations of introduced tree species for wood production, and this was confirmed through a comparison of the growth rates observed in respective indigenous and introduced tree species in this study. Certain instances of relatively high 1-year stem growth rates in indigenous species were observed in the study, with *Millettia grandis* (Umzimbeet), *Prunus africana* (Red Stnkwood) and *Celtis african*a (White Stinkwood) being the best performing species. However, it should be borne in mind that the conditions under which these particular indigenous trees were growing were more favourable than the average plantation environment. These trees were free-standing, unshaded trees with little competition for resources, growing in riparian zones with readily available water.

In terms of growth and water-use it was found that while biomass production was much lower for the indigenous tree species, they also used much less water than introduced plantation species. Resultant WUE estimates showed substantial variation, even within a particular species, but on average results indicated that indigenous tree species appear to exhibit similar water use efficiencies to introduced plantation tree species. This supports the argument of a general correlation between growth and water use.

The MAESPA model was found to be well suited to predict long-term water use of individual indigenous trees with well-defined canopies. An important application of this finding is the rapid screening of WUE of trees, where growth increments measured on the stems of sample trees can be matched to water use over the same period. In this way, a wide range of sample trees of varying species, of different ages and growing on different sites can be assessed with relative ease, and ranked according to their WUE.

The economic viability of specific indigenous tree species could not be judged in a fully inclusive fashion in this project due to the number of unknown variables. Additional field trial data is required to account for this limitation. However, the value of indigenous forests in the upkeep and maintenance of rural livelihoods appeared to be substantial, particularly if the opportunity cost of this function was accounted for. Regarding the financial viability of a Yellowwood plantation, it was noted that the direct production costs were comparatively small relative to the opportunity cost of the extremely long rotation cycle when compared to an introduced plantation. However, the extremely long rotation period required rendered it uncompetitive against introduced species such as pine, unless it was possible to shorten growing periods (via breeding and selection programmes). Additional challenges associated with the more formal indigenous wood market were found to be numerous. These included unpredictable and variable supply, widely ranging shape, size and quality of logs, high harvesting and extraction costs, and unpredictable market demand. Consequently, this study represents an important descriptive presentation of the dynamics associated with the formal and informal indigenous tree product markets.

CONCLUSIONS

The relatively low water-use characteristics of indigenous tree species suggests that they are promising for expanding natural and plantation tree production systems in South Africa, maximising benefits (goods and services) while minimising resource impacts (water-use). Apart from the importance of accurate site/species matching, appropriate species for establishment need to be considered from environmental, social and economic perspectives. Potential benefits include suppression of alien invasive plants, biodiversity conservation, provision of ecosystem services, supporting rural livelihoods, ecotourism and urban greening. Given the increasing pressure on water resources and a growing demand for timber and non-timber forest products, further exploration of the numerous multiple-use indigenous tree species that are found in this country, matched to the wide range of existing climatic and site conditions, is merited. There is surely potential for managed, productive and sustainable indigenous forest and woodland systems. Considering that further afforestation with commercial forest species is now restricted due to limitations in available land and concerns about reductions in catchment water yields, the possibility of expanding low water-use forms of forestry with indigenous trees deserves to be explored further.

From a wood production point of view, it appears unlikely that indigenous species will be competitive in terms of volume production, and their economic viability appears to be limited, apart from certain scenarios. However, much depends upon the growth or demand of markets for indigenous timber products, and whether supply can be enhanced to meet that demand. Furthermore, with appropriate recognition of the “non-tangible” benefits (eco-system services) of indigenous trees, their value could be increasingly recognized. By virtue of their low water-use impacts, this study has confirmed the important role of indigenous trees from an ecohydrological perspective, and the findings have wider scale applicability in fields such as forest restoration, erosion control, replacement of invasive alien species and multiple-use indigenous tree wood-lots, particularly where water-conservation is a priority.

The link between growth rates and water use suggests that easily obtained growth rates of trees (e.g. 1-yr stem biomass increments) may be used to provide a rough estimate of corresponding water use, without the need for expensive and technically demanding water use monitoring equipment. Alternatively, modelling approaches, particularly with the MAESPA model were shown to have promise in predicting water use of trees and forests, and combined with less technically demanding growth measurements, could provide useful estimates of water-use efficiency.

EXTENT TO WHICH CONTRACT OBJECTIVES HAVE BEEN MET

The terms of reference for this project were similar to the aim and objectives stated above. The general requirement was “*To measure and model the water use and growth of indigenous trees in different types of tree systems, and to quantify the economic benefits and costs of the biomass production under a range of bio-climatic conditions in South Africa.”* The extent to which contract objectives have been met may be assessed in relation to the specific objectives of the project:

1. *To screen, shortlist and select indigenous tree species that are most promising for natural and plantation tree production systems with particular attention to single species/even aged and mixed species/mixed aged tree systems.*

This objective was addressed through the stakeholder workshop and subsequent short-listing and selection of priority indigenous tree species and forest types for measurement in the project. The main findings that illustrate how this objective was met include:

a) The drafting of a short-list of indigenous tree species considered to be the most promising for natural and plantation tree production systems, and the subsequent identification of the top 10 indigenous tree species considered to be the most beneficial from environmental, social and economic perspectives.
b) The compilation of a database of planted indigenous tree stands in South Africa, based on data collected during an awareness campaign and appeals for relevant information, conducted through a range of media and publicity channels. These incorporated television, internet, publications and presentations.
c) The identification of appropriate tree species and suitable sites for water use measurements and modeling with particular attention to single species/even aged and mixed species/mixed aged tree systems.

2. *To improve knowledge of the water use efficiency (WUE) of indigenous trees under natural and plantation systems through growth and water use measurements and modeling, using proven methods and techniques.*

This objective was addressed by means of six phases of field work, conducted for a minimum duration of 12-months each, and located in a diverse range of bio-climatic environments. At each of these sites, detailed measurements were taken of tree/forest water-use, above-ground stem biomass increments, weather variables, soil water fluctuations and tree/forest attributes. The data facilitated the calculation of Water Use Efficiency (WUE) for the respective indigenous tree species and forest types, as well as an understanding of the driving variables (weather, water availability, tree/forest attributes). Parameterisation and testing of the MAESPA and Penman-Monteith ("Big-Leaf"-type) models at a selection of these sites, investigated their ability to replicate the field observations of tree and forest water-use. The main findings that illustrate how this objective was met include:

a) The generation of detailed and quality-checked data on tree water use (transpiration), utilizable stem growth (biomass increment) and resultant water use efficiency (g wood produced per Litre water transpired) for a wide range of priority indigenous tree species, observed in different bio-climatic regions, over a minimum time period of one year for each species.
b) A growing body of evidence that suggests that indigenous tree species tend to use less water than similarly-sized introduced tree species, but also grow substantially slower than they do, with the net result of similar biophysical water use efficiency tendencies.

c) The resultant conclusion that there appears to be a trade-off between growth rates and water use of trees.
d) Confirmation of the important role of indigenous trees from an ecohydrological perspective, and their wider scale applicability in fields such as forest restoration, erosion control, replacement of invasive alien species and multiple-use indigenous tree wood-lots, particularly where water-conservation is a priority.

3. *To analyse the economic viability and market potential of biomass products from indigenous natural and plantation tree systems (in different social contexts) and in comparison with exotic commercial plantations.*

This objective was addressed by means of economic and financial assessments conducted on informal indigenous tree product markets (resource use in Manubi forest), as well as more formal/recognised indigenous wood markets (indigenous tree plantations, SANParks auctions, indigenous wood sales and potential products). Information on potential products, supply and demand processes, trading and values associated with those markets was collected. The main findings that illustrate how this objective was met include:

a) Improved understanding of the economic viability and market potential of biomass products from indigenous natural and plantation tree systems (in different social contexts) and in comparison with exotic commercial plantations.
b) The conclusion that the informal indigenous tree product industry is heterogeneous, amorphous and unregulated; yet economically significant at local scales, and the quantification of the economic value of some products in this industry through a case study.
c) The conclusion that the more formal indigenous tree product industry is currently a small, high-value, niche market, with potential for growth, but with considerable challenges in terms of sourcing, availability and reliability of supply, quality variation, transportation and milling.
d) Indications that the financial viability of Yellowwood plantations may be favourable over a 45-yr rotation period, given certain assumptions and a long-term perspective.

4. *To develop and test a rapid screening technique to identify indigenous tree species-site combinations based on water use, economic viability and eco-system adaptability, thereby optimizing WUE and socio-economic potential.*"

This objective was addressed through consideration of the necessary data and information required to assess WUE and site-species optimality, taking into account the economic/financial value of preferred indigenous tree species. Based on experience gained from field measurements it took into account practicalities associated with obtaining the requisite data, compared to a modelling approach. The main findings that illustrate how this objective was met include:

a) The impression, gained from a review of literature and information, that there is not yet the necessary understanding to identify complex attributes like cumulative growth and transpiration from one or more easily measured attributes.
b) The conclusion that growth increments, using a series of measurements of stem and branch diameters of various sizes, taken at the start and end of a 12-month period can yield accurate annual growth rates to compare among different species.
c) The identification of the MAESPA model as a potentially suitable model for transpiration simulation and subsequent WUE ranking.
d) Recommendations on a procedure for ranking tree species in terms of their water use efficiency, which is practical and avoids the difficulties of measuring transpiration.

Additional over-arching objectives of the project, including capacity building, timely progress reporting and production of project-related conference papers/posters, popular articles and scientific articles, were met, as detailed in the following integrated final report.

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman Symbols

c_p	specific heat capacity of air at constant pressure (approximately 1040 J kg^{-1} K^{-1})
D	deep drainage (mm)
E_s	soil evaporation (mm day^{-1})
ET	total evaporation (mm)
ET_{EC}	total evaporation (mm) from eddy covariance measurements
ET_o	FAO-56 reference total evaporation (mm)
ET_{sz}	ASCE-EWRI short grass (0.12 m) reference evaporation (mm)
g_c	canopy conductance (m s^{-1}) = ($1/r_s$)
g_{cmax}	maximum conductance (m s^{-1})
G	soil heat flux (W m^{-2})
H	sensible heat flux (W m^{-2})
LE	latent heat flux (W m^{-2})
P	precipitation (mm)
Q	streamflow (mm)
r_b	leaf boundary layer resistance (s m^{-1})
r_s	stomatal resistance (s m^{-1})
R	surface runoff (mm)
R_n	net irradiance (W m^{-2})
spha	stems per hectare
T	transpiration (mm or L)
T_a	temperature of the air (°C)
T_{sonic}	air temperature using sonic temperature (°C)
V_h	Heat Pulse Velocity (cm hr^{-1})
w	vertical wind velocity (m s^{-1})
W	contribution from water table upward (mm)

Greek symbols

Δ	slope of saturated vapour pressure vs air ($kPa\ ^oC^{-1}$)
ΔS	change in soil water storage (mm)
γ	psychrometric constant ($kPa\ ^oC^{-1}$)
θ	actual volumetric water content (m^3 m^{-3})
ρ_a	density of air (approximately 1.12 kg m^{-3})
ρ_s	bulk density of soil (kg m^{-3})
ρ_w	density of water (kg m^{-3})
λ	latent heat of vaporisation of water (J kg^{-1})

Abbreviations

ASCE	American Society of Civil engineers
AWS	Automatic weather station
CSIR	Council for Scientific and Industrial Research
DAFF/DOA	Department of Agriculture, Forestry and Fisheries
DWS/DWAF	Department of Water Affairs & Sanitation
FAO-56	Food and Agriculture Organisation, paper no. 56
GDP	Gross Domestic Product
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
LAI	Leaf Area Index
MAP	Mean Annual Precipitation
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
SWB	Soil Water Balance
TDR	Time Domain Reflectometry
VPD	Vapour Pressure Deficit
WUE	Water Use Efficiency

1 INTRODUCTION

South Africa is very reliant on its plantations of introduced tree species to meet its pulp and timber needs, and the benefits of this industry in terms of production, income generation and job provision are undisputed (Chamberlain *et al*., 2005). The downside is that these benefits come at some environmental cost, not least the impact of the industry on water resources (Dye & Versfeld, 2007). Many catchment areas are consequently now closed to further afforestation, but economic growth and development continue unabated. Imports and improved productivity are potential solutions to continue meeting the demand for timber and forest products, but further consideration of the feasibility of expanding indigenous tree resources is also warranted. 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 perceptions that indigenous tree species use less water than introduced tree plantations, however up to now these have been unsubstantiated. While data from previous studies are available on the water-use efficiency (WUE) of common introduced plantation species in South Africa (Olbrich *et al*., 1996; Dye *et al*., 2001), information on the water-use of indigenous trees and forests is scarce and indirect, and relationships between growth and water-use within indigenous forests have until now not been investigated in South Africa.

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. This information is required in order to facilitate sustainable land-use planning from a hydrological perspective (Dye *et al*., 2008). New and innovative techniques to quantify the water-use (transpiration and total evaporation) of a range of tree species and forest types are available (Jarmain *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. Evidence of low and efficient water-use in indigenous tree species would make them 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 also 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. This 6-year research project (2009-2015) was commissioned to study the water-use, growth rates and economic value of the biomass of indigenous trees and forests under a wide range of bio-climatic conditions in South Africa. It follows on from an earlier pioneering WRC study, which conducted preliminary investigations of water-use and growth rates in various indigenous tree systems in South Africa (Dye *et al*., 2008). Research questions posed by this study included:

1. Do indigenous tree species use less water than introduced plantation tree species?
2. Do indigenous tree species use water more efficiently than introduced plantation tree species?
3. Is there scope for the expansion of indigenous tree systems in South Africa from economic, financial, social and environmental perspectives?

2 *PODOCARPUS HENKELII* AND *PINUS PATULA* PLANTATIONS AT KARKLOOF[1]

2.1 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 considerable 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

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[1] When making reference to this section, please cite as follows:

Gush, M.B., Bulcock, H.H. and Naiken, V., 2015. *Podocarpus henkelii* and *Pinus patula* plantations at Karkloof. In: Gush, M.B. and Dye, P.J. (Eds). 2015. Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees: Volume 2 (Site-Specific Technical Report). Water Research Commission, Pretoria, RSA, WRC Report 1876/2/15, Section 2.

of introduced species (FSA, 2014)[2]. 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 disproportionally 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. 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. This evidence was largely anecdotal (Wilson, 1982; Cooper, 1985; Cawe and McKenzie, 1989) before the first process-based measurements of indigenous tree water use were initiated in South Africa (Dye *et al*., 2008). Studies of water use by plantations of South African indigenous tree species are still rare, and the work reported on in this section sought to expand these observations.

2.2 Materials and Methods

2.2.1 Site description

A suitable monitoring site was sought which exhibited certain characteristics, namely accessibility, security, appropriate indigenous tree species of adequate size to measure, and the presence of a suitable control site for simultaneous measurements on an introduced tree species. Two study sites (-29.356463° S; 30.197488° E', alt. 1148 m.a.s.l) situated 50 m apart from each other were subsequently selected on the Mondi owned Tetworth estate in Karkloof, near Howick in the KwaZulu-Natal Midlands (**Figure 1**). The site has a mean annual precipitation of 1271 mm (Lynch and Schulze, 2006), most of which falls during the summer months between October and April. The mean annual potential evaporation of the area is high at between 1600-1800 mm (Schulze, 1997), but the FAO-56 short grass reference evaporation (Allen *et al*., 1998) was 1518 mm for the period of the study. Mucina and Rutherford (2006) describe the area as southern mistbelt forest. A characteristic of the local rainfall regime is a strong orographic effect, caused

[2] Details on a comparative financial analysis between a Yellowwood plantation and a Pine plantation are reported on in Volume 1.

by the lifting and convective cooling of the summer south-east winds over the Karkloof mountain range (Dye *et al*., 2008).

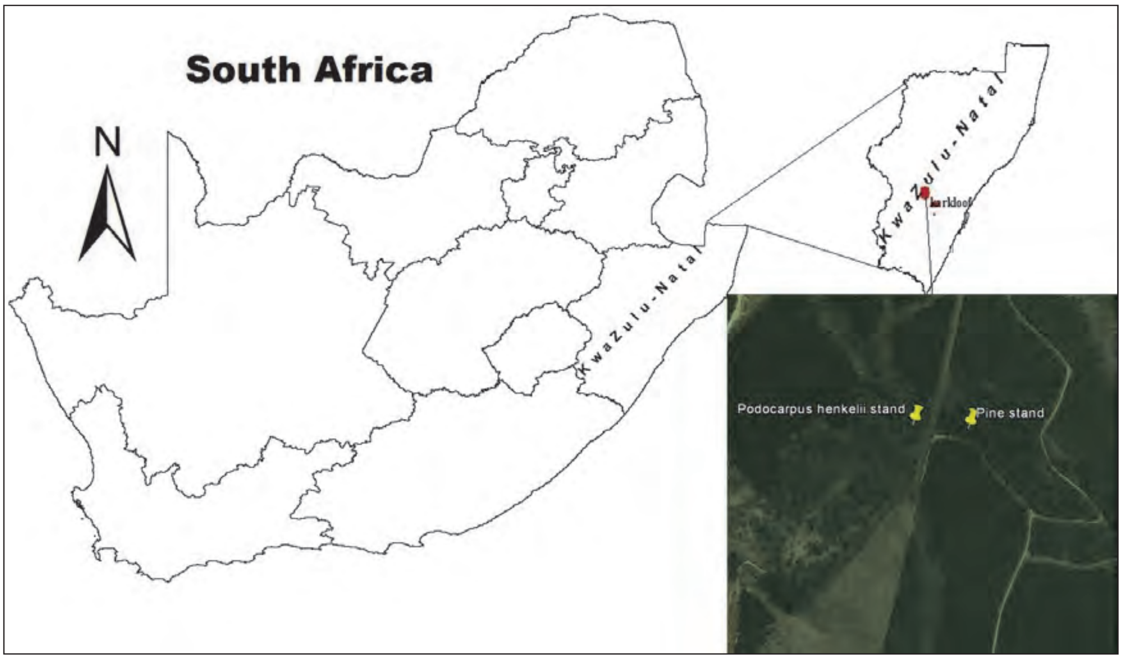

Figure 1. Location of the Karkloof study site.

Water-use, tree growth and resultant WUE determination, as well as canopy and litter interception studies, were carried out on a small (1 ha) *Podocarpus henkelii* Stapf ex Dallim. & Jacks. (Henkel's Yellowwood) plantation and an adjacent *Pinus patula* Schlechtd. & Cham. (Mexican Weeping Pine) plantation between July 2009 and August 2010. The Yellowwood plantation was located close to a riparian area, but at an elevation above which the soil would be classified as truly riparian. Information on past stand management is limited due to changes in ownership of this particular farm, and the trees are of an unknown age. However, by virtue of their size (average tree height of 8 m) and stem diameters (DBH: 15-30 cm) the trees were estimated to be roughly 40 years old. The trees were hand-planted, but had not been pruned. The planting spacing was somewhat irregular but an average distance between trees (3 m x 3 m) translated into a planting density of approximately 1111 trees per hectare. The study trees were selected after first conducting a survey (n=40) of the range of stem sizes present in the plantation, and trees were subsequently assigned to one of 3 stem circumference size classes, with each size class being represented by a sample (HPV) tree on which sap flow measurements were conducted. This was done to facilitate eventual scaling up of single-tree transpiration measurements to the plantation scale in a representative manner. The annual transpiration totals for the 3 study trees were weighted according to the number of trees in the size class that they represented, and a single transpiration rate for the plantation was determined, accounting for variations in stem circumference and water-use, within the plantation. The trees needed to be in close proximity to each other due to the constraints of the thermocouple wire lengths that were connected to the multiplexer and logger.

The Pine stand provided mid-slope plantation trees of an introduced species which were of similar size to the indigenous trees; so that comparative measurements could be taken under the same site quality, aspect and weather conditions. It consisted of a commercially planted 3 ha stand of *P. patula* grown for saw timber with a planting density of 816 trees per hectare (3.5 m x 3.5 m) and was not situated in a riparian zone. The trees were planted in September 2002, making them approximately 9 years old at the beginning of the study. They were subjected to limited thinning and pruning since 2003. The soils at both sites were classified as Clovelly, characterised by an orthic A-horizon and a yellow-brown apedal B-horizon with a sandy-clay-loam texture and a depth of more than 1.2 m. Both sites had a similar slope of 23% (1:4.1) and 26% (1:3.8) for the *P. patula* and *P. henkelii* stands respectively. The *P. patula* stand was on a south-west (SW) facing slope and the *P. henkelii* was on a south-south-west (SSW) facing slope.

2.2.2 Field measurements

The measurement methodology aimed primarily to determine the water use efficiency of the measured trees by means of accurate measurements of water-use and growth for a minimum period of one year. Measurements of additional variables and processes useful for future modelling exercises were also conducted. The following components were included overall:

1. Hourly measurements of a full suite of climatic variables using Automatic Weather Station (AWS) sensors (solar radiation, temperature, relative humidity, wind speed and rainfall),
2. Sap flow (transpiration/water-use) monitoring on an hourly basis using Heat Pulse Velocity (HPV) systems,
3. Soil water content measurements in the A-horizon (hourly),
4. Tree growth measurements (stem biomass increments) – annual,
5. Interception (foliage and litter) studies (minute/rainfall event-based),
6. Regular monthly site visits to check and maintain systems, change batteries, download data, and record physiological changes in the trees.

Weather

Monitoring of weather variables at this site commenced in July 2009, and data collection continued mostly uninterrupted throughout the monitoring period apart from brief interruptions due to battery failure. Missing data for these periods were sourced from the closest South African Sugar research Institute (SASRI) weather station, namely Crammond. Hourly data were aggregated into daily and monthly totals or averages.

Sap flow (transpiration) and soil water

The Heat Pulse Velocity (HPV) technique is an internationally accepted method for the measurement of sap flow (water-use) in woody plants and has been extensively applied in South Africa (Dye & Olbrich, 1993; Dye, 1996; Dye, Soko & Poulter, 1996; Dye *et al*., 1996; Gush, 2008; Gush & Dye, 2009). The heat ratio method (HRM) of the HPV technique (Burgess *et al*., 2001) was selected for sap flow measurements at this site because of its ability to accurately measure low rates of sap flow, expected to be the case in indigenous tree species. The HRM requires a line-heater to be inserted in the xylem at the vertical 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 (TCs), following the release of a pulse of heat by the line heater. For these measurements 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 to determine radial variations in sap flow. Insertion depths of the TC's were calculated after first determining the total sapwood depth for each species, and then spacing the probes evenly throughout. 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. CR1000 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 & 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 (determined by below-bark individual probe 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. Individual-tree sap-flow volumes (L yr^{-1}) were scaled up to a hectare using the planting density to also derive sap flow (transpiration) totals in mm-equivalent volumes for the year. Three Yellow-wood trees and two Pine trees (Table 1).were instrumented at the site, using separate HPV systems (Figure 2 and Figure 3).

Table 1. Details of the *Podocarpus henkelii* and *Pinus patula* trees selected for sap flow measurements.

Species	Diameter at breast height (cm)	Tree height (m)	Sapwood depth (cm)	Wound width (mm)	Bark width (mm)	Wood density ($g.cm^{-3}$)
P.henkelii 1	14.0	6.3	5.5	3.0	7.0	0.47
P.henkelii 2	23.0	7.3	9.5	3.0	7.0	0.47
P.henkelii 3	18.0	7.0	7.5	3.0	7.0	0.47
P. patula 1	20.0	8.8	8.5	4.0	10.0	0.38
P. patula 2	24.0	10.8	10.0	4.0	10.0	0.38

Figure 2. Heat Pulse Velocity system measuring sap flow in indigenous *Podocarpus henkelii* (Yellow-wood) trees (Photo: M. Gush).

Figure 3. Heat Pulse Velocity system measuring sap flow in *Pinus patula* trees (Photo: M. Gush).

A CS615 TDR-type soil water content sensor was installed in the top 20 cm of the A-horizon, in proximity to the sample trees in order to measure changes in volumetric soil water content over time.

<u>Stem biomass increments and water use efficiency</u>

In addition to sap flow measurements, stem biomass increments surveys were undertaken for both *P. henkelii* and *P. patula* in order to calculate water use efficiency (WUE). Stem volume increment measurements were carried out at the inception of the study on 13 August 2009 and subsequently a year later on 12 August 2010 in order to include all seasons in one year. Stem circumferences were measured at 1 m intervals up the tree, and subsequently converted into volume by assuming that the stem consists of a series of truncated cones with a complete cone on the top (Gush *et al*. 2011). The volume (V; m³) of the individual cones was calculated using Equation 1:

$$V = (\pi r^2 h)/3 \qquad \text{(Eq. 1.)}$$

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. 2):

$$V = (\pi h (r_1^2 + r_1 r_2 + r_2^2))/3 \qquad \text{(Eq. 2.)}$$

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 were totalled for each tree, which allowed for the calculation of stem volume increase in the year. The stem volume increments were converted to dry mass using the wood densities determined from samples collected for each species in this study as shown in Table 1. In conjunction with the sap flow (water-use) results this allowed the calculation of WUE, defined as mass of woody biomass produced (g) per unit of water transpired (L), and results were compared against existing data for indigenous and introduced tree species available from previous studies (Olbrich *et al*., 1996; Dye *et al*., 2001; Gush & Dye, 2009).

Interception studies

Canopy interception rates were determined by means of throughfall measurements undertaken at the *P. henkelii* site using a nest of three "V" shaped troughs based on the design of Cuartus *et al*. (2007) constructed from galvanised sheeting (Bulcock and Jewitt, 2012). The dimensions of each trough were 0.1 m wide x 2.0 m long. Conventional "U" or "V" shaped troughs were susceptible to blockage by fallen debris and water loss from splash. However, this system minimized splash out by using steep "V" shaped sides. The troughs were covered with mosquito netting to minimize the entry of debris, which reduced the demand of cleaning and maintaining the system. A correction factor for each trough was derived from laboratory measurements to account for the "initial abstraction" from the netting. The troughs were then connected to a tipping bucket gauge and an event data logger. Because the trough represents a linear and continuous sampling surface, the linear variation of leaves, branches, and tree crown is assumed to provide a representative integral of the throughfall caught (Cuartus *et al*. (2007). The three troughs were arranged in a radial pattern with an equal spacing of 120°, and extended from the tree trunk towards the edged of the canopy.

Litter interception and water that drains to the soil were measured at the *P. henkelii* site using two round galvanized iron basins that fit into each other. The upper basin which has a diameter of 500 mm is filled with litter and has a geotextile lining on top of a wire mesh base, so water can percolate into the lower basin. The water that is collected in the lower basin drains into a tipping bucket and records the water that would have drained to the soil. The litter interception is then calculated as the difference between throughfall and the water that drained to the soil. Further details of the design can be found in Bulcock and Jewitt (2012).

2.3 Results and Discussion

2.3.1 Weather

The start of the rainy season in this area is usually in October; however the rains commenced early in the monitoring year (Figure 4), with substantial amounts falling in August (51 mm) and September (75 mm). The rainfall season was also prolonged, with rainfall of 53 mm as late as April. A high percentage of rain-days were recorded during the year (there were 197 rain days, or 54% of the days, with rainfall). No drought periods were experienced; however the total precipitation for the year was only 1061 mm, which is approximately 200 mm below the long-term mean. The high percentage of rain days influenced the other weather variables, so while daily maximum temperatures regularly peaked above 30°C (with the highest recorded temperature being 41.1°C on 17 December 2009), monthly means of maximum temperature were mild initially, peaking in February and March (Figure 5). The frequent overcast conditions also limited the extent to which temperatures cooled at night, with the lowest recorded temperature being a mere 0.8°C on 12 July 2010. Daily average solar radiation values increased gradually to 22.3 MJ m^{-2} day^{-1} in February 2010, but dropped noticeably in June and July 2010 to daily averages of approximately 7.7 MJ m^{-2} day^{-1}. Wind speeds were generally low (±0.5 m s^{-1}) peaking at a daily average of 1.4 m s^{-1} in August (Table 2).

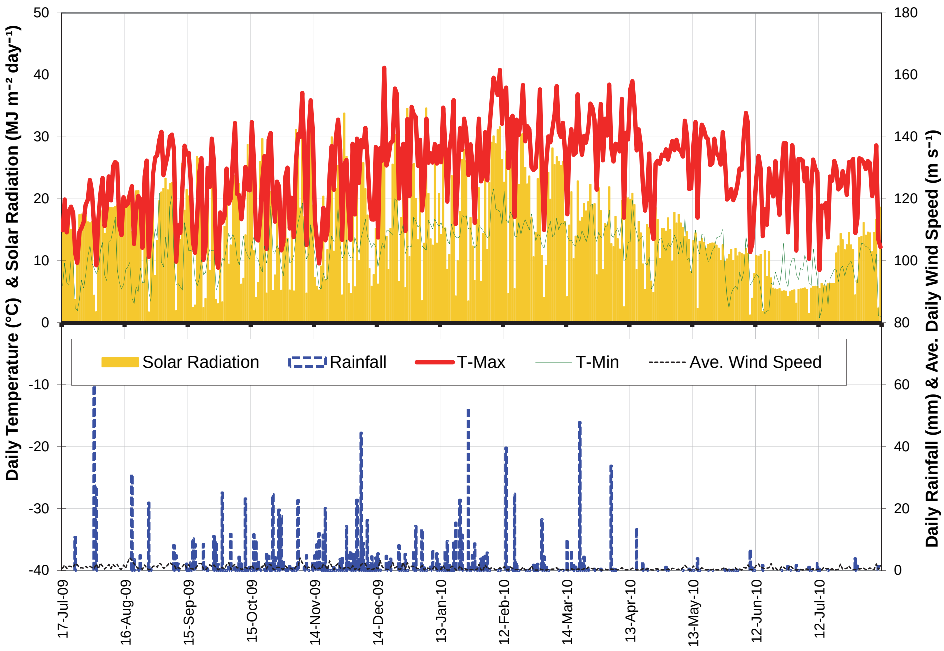

Figure 4. Daily values of maximum and minimum temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), rainfall (mm) and windspeed (m s^{-1}) measured at the Karkloof site.

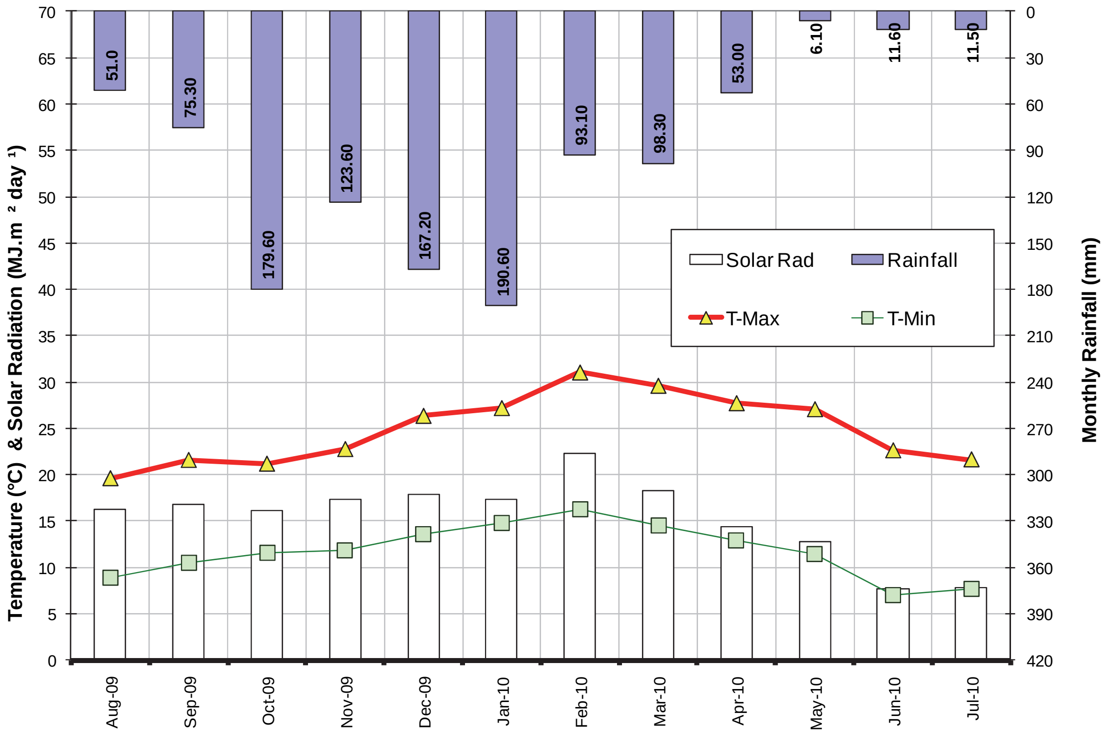

Figure 5. Average daily maximum and minimum temperatures (°C) and solar radiation totals (MJ m⁻² day⁻¹) per month, with rainfall totals (mm) measured at the Karkloof site.

Table 2. Aggregated monthly values of selected daily weather variables as measured at the Karkloof site.

Month/Variable	Aug '09	Sep '09	Oct '09	Nov '09	Dec '09	Jan '10	Feb '10	Mar '10	Apr '10	May '10	Jun '10	Jul '10
Rainfall Totals (mm)	51.0	75.3	179.6	123.6	167.2	190.6	93.1	98.3	53.0	6.1	11.6	11.5
Ave. Daily Max T (°C)	19.6	21.6	21.2	22.7	26.3	27.2	31.0	29.6	27.7	27.1	22.6	21.6
Ave. Daily Min T (°C)	8.9	10.5	11.5	11.8	13.6	14.8	16.2	14.5	12.9	11.5	7.1	7.6
Ave. Daily Solar. Rad. (MJ m^{-2} day^{-1})	16.3	16.7	16.2	17.4	17.9	17.4	22.3	18.2	14.4	12.8	7.7	7.8
Ave. Daily Wind Speed (m s^{-1})	1.4	1.3	1.0	1.2	1.1	0.7	0.6	0.4	0.4	0.5	0.8	0.5

2.3.2 Soil water

Soil water content levels climbed from 17% in late winter to a maximum of approximately 37% in the middle of the summer rainy season (Dec/Jan) in response to individual rainfall events. The summer average soil water content was in the region of 30%, and started to decline in February, reaching minimum values of around 15% by August (Figure 6). No responses to declines in soil water levels were observed in the sap flow velocities of the sample trees indicating that they were able to access water from deeper soil levels.

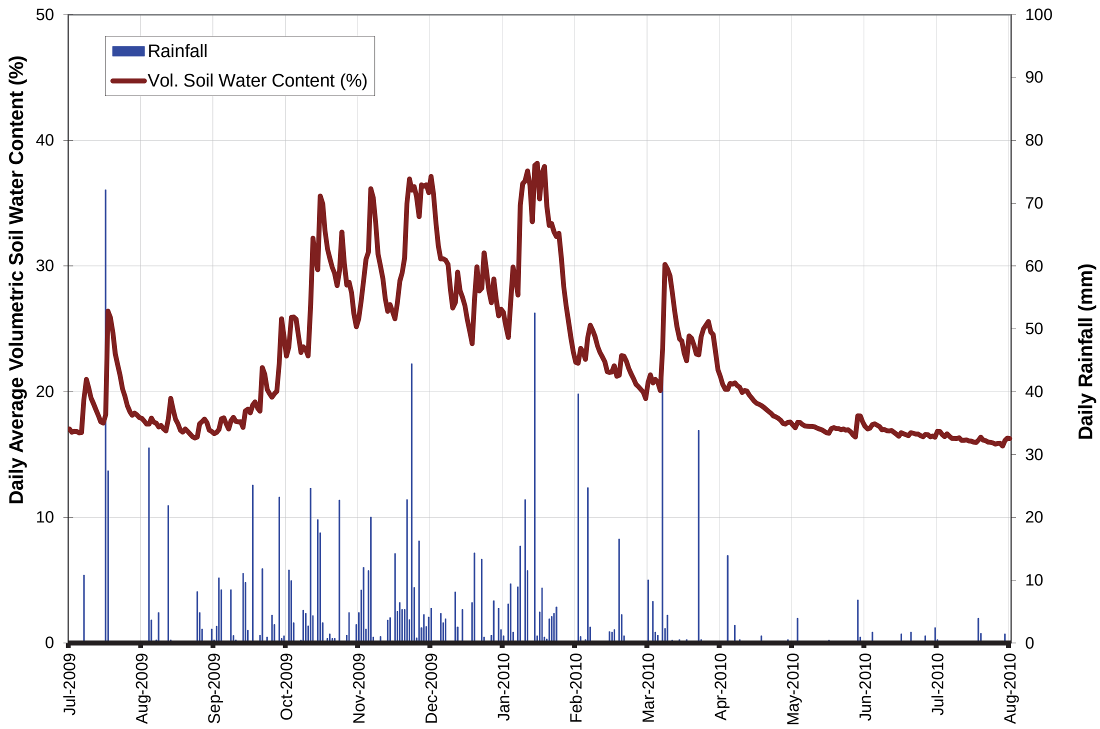

Figure 6. Fluctuations in volumetric soil water content measured beneath *P. henkelii* trees between July 2009 and August 2010.

2.3.3 Tree water use

Sap flow (water-use) volumes recorded in the Yellowwood trees illustrate consistent transpiration rates year-round (Figure 7). This is attributable to the evergreen nature of this species and the lack of seasonal water stress due to the riparian location. A slight decline in sap flow rates is evident during the dry season, particularly around September when leaf exchange takes place. Thereafter, sap flow rates increase towards mid-summer, as leaf areas, temperatures and available water from rainfall increase. Towards the end of March sap flow rates gradually decline once more and the cycle is repeated. Individual days of wet, overcast weather in the summer (when available energy from solar radiation is limited) are characterised by very low sap flow rates. Daily volumes of water-use in these trees peaked at between 10 and 20 L day^{-1} during the summer, declining marginally to between 5 and 15 L day^{-1} in winter. Annual transpiration totals for the 3 study trees were weighted according to the number of trees in the size class that they represented, and a single transpiration rate for the plantation was determined, accounting for variations in stem circumference and water-use, within the Yellowwood plantation (Table 3). Individual tree water-use volumes (L yr^{-1}) were also scaled up to weighted plantation equivalent depths of water-use (mm) using planting density in the stand.

Table 3. Weighting of observed transpiration volumes in 3 *Podocarpus henkelii* trees relative to stem circumference variation within the plantation, to determine a representative total water-use

Stem circ. size classes (cm)	No. of trees in sub-sample	HPV tree no.	HPV tree stem circ. (cm)	1-yr Water-use (L $tree^{-1}$)	1-yr Water-use (mm)	Weighting
≤45 cm	10	1	44.2	1 755	195.0	29.4%
45-65 cm	10	3	60.0	3 554	394.9	29.4%
≥65 cm	14	2	73.5	5 033	559.2	41.2%
Weighted Total for Plantation				**3 634**	**403.7**	**100.0%**

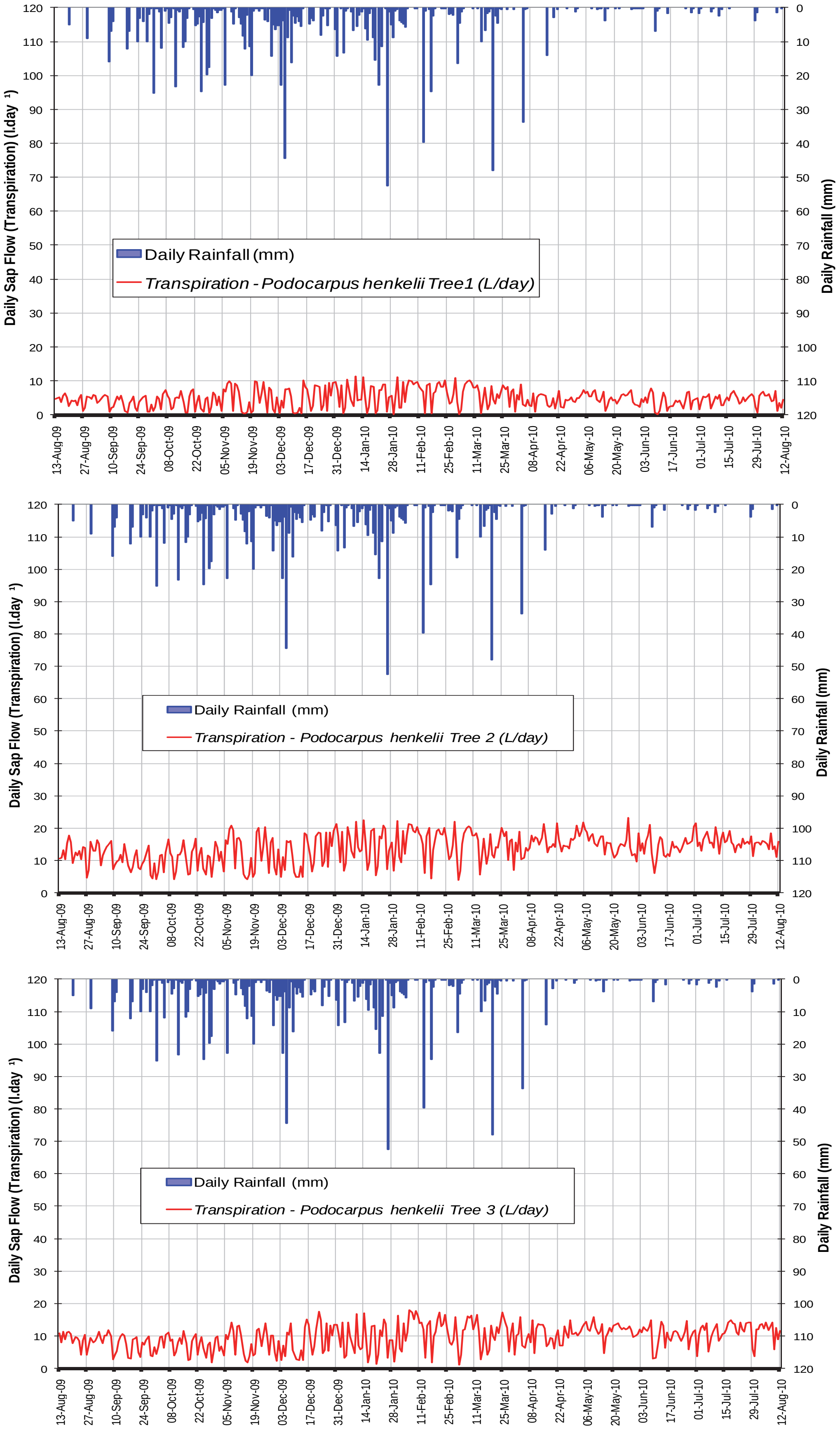

Figure 7. Daily sap flow (water-use) volumes (L day^{-1}) recorded in 3 indigenous *Podocarpus henkelii* trees

Sap flow (water-use) volumes recorded in the *P. patula* trees illustrate a more distinct seasonal transpiration pattern (Figure 8). The trees are evergreen and clearly transpire throughout the year, however peak flow rates were recorded in February and March. These are the warmest months of the year, towards the end of the rainy season when water availability is good. In the middle of the growing season peak sap flow volumes of 50-100 L day^{-1} were recorded in these trees, which is five times greater than the volumes recorded in the yellowwood trees. These dropped to approximately 30 L day^{-1} in the late winter months. Annual transpiration totals for the 2 study trees were averaged to determine a single transpiration rate for the *Pinus patula* plantation (Table 4).

Table 4. Weighting of observed transpiration volumes in 2 *Pinus patula* trees, to determine a representative total water-use

HPV tree no.	DBH (cm)	1-yr Water-use (L $tree^{-1}$)	1-yr Water-use (mm)	Weighting
Pinus patula 1	20.0	9 849	804	50%
Pinus patula 2	25.6	16 067	1 312	50%
Weighted Total for plantation		**12 958**	**1 058**	**100.0%**

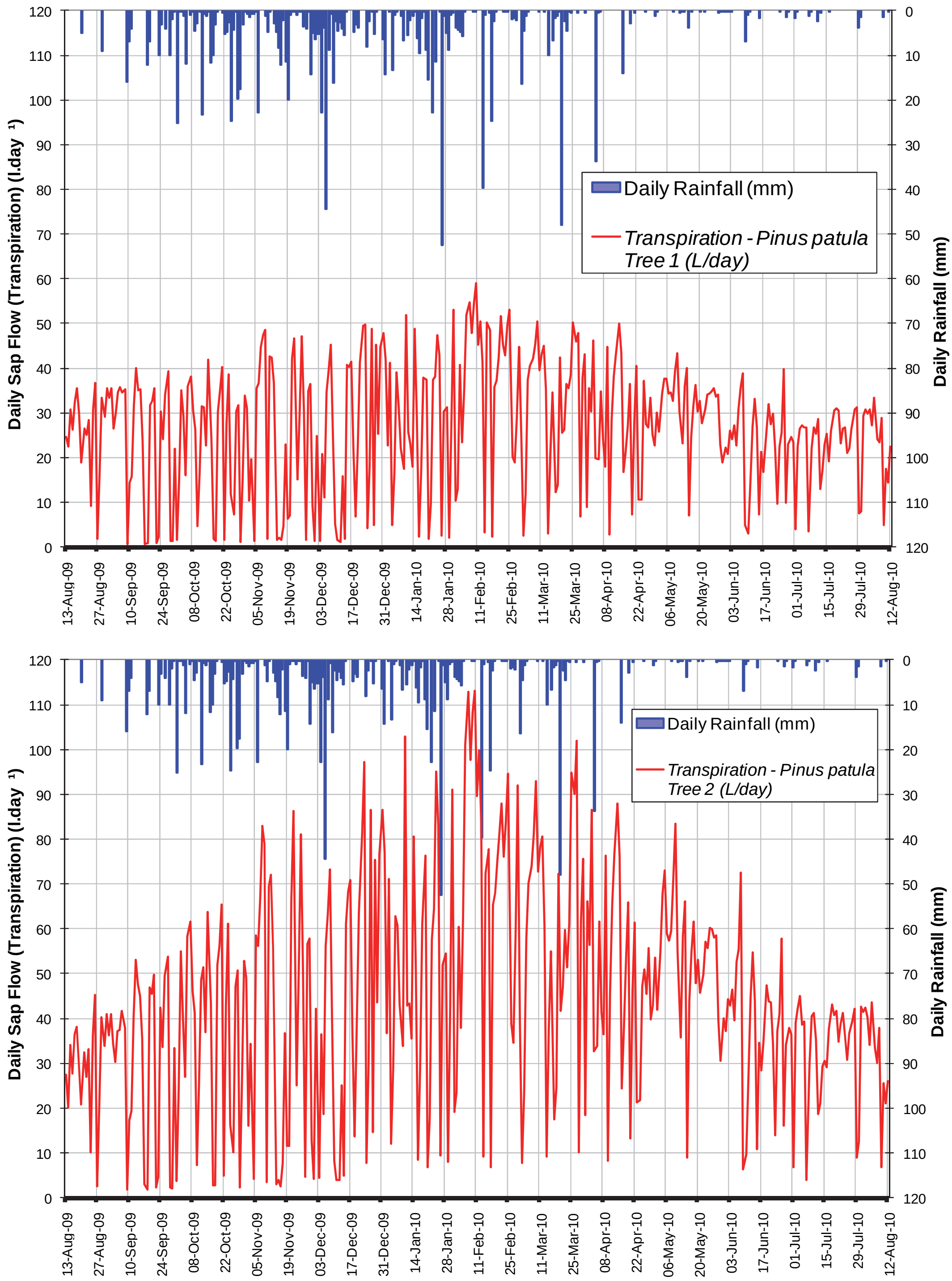

Figure 8. Daily sap flow (water-use) volumes (L day^{-1}) recorded in 2 *Pinus patula* trees

2.3.4 Stem biomass increments and water use efficiency

Using observed stem growth increments from the respective sample trees, water-use efficiency (defined as amount of stem biomass produced (g) per unit of water transpired (L)) was calculated for the respective study trees (Table 5).

Table 5. Summary of WUE data for indigenous *Podocarpus henkelii* trees and introduced *Pinus patula* trees, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use

Tree	1-yr Water-use (L)	Stem Volume Increment (m^3)	Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
P. henkelii 1	1 755	0.0022	0.47	1 006.2	0.57
P. henkelii 2	5 033	0.0109	0.47	5 091.8	1.01
P. henkelii 3	3 554	0.0052	0.47	2 452.3	0.69
P. patula 1	9 849	0.0516	0.38	19 596.6	1.99
P. patula 2	16 067	0.0904	0.38	34 333.0	2.14

2.3.5 Interception studies

Canopy interception accounted for 29.8% and 22.1% of gross precipitation for *P. henkelii* and *P. patula*, respectively. The highest absolute monthly canopy interception loss for both *P. henkelii* and *P. patula* was recorded in December 2009 at 50.4 mm and 37.2 mm, respectively. The highest canopy interception losses are expected during the summer months when there is the highest rainfall, as well as highest evaporation potential due to the higher temperatures. Conversely, the lowest absolute canopy interception losses were recorded during the winter months when there is very little rainfall, with as little as 3.7 mm and 2.7 mm being lost to canopy interception in May 2010 for P. henkelii and P. patula, respectively. Litter interception is the lowest evaporative loss, accounting for only 6.2% and 10.7% of gross precipitation for *P. henkelii* and *P. patula*, respectively. The small litter interception amount can be attributed to the large number of consecutive rain days, during the rainy summer months, thereby not allowing time for much evaporation to take place. The study site is also situated in a mistbelt and the presence of mist suppresses evaporation. The trees also have a dense canopy with a Plant Area Index (PAI) of between 3.5 and 4.0 for *P. henkelii* and between 2.3 and 2.5 for *P. patula*, and therefore little solar radiation reaches the litter to aid in evaporation. During the winter months there is little rainfall and, after canopy interception losses have been accounted for, there is little throughfall to be intercepted by the litter (Bulcock *et al*. 2014).

2.4 Discussion

Objectives of this study included testing whether an indigenous tree plantation uses less water than an introduced tree plantation, and also 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 *Afrocarpus 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^{-1}) than similarly sized (DBH 19.3 cm) *A. falcatus* trees (6 L day^{-1}) 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). One previous study on the transpiration, stem growth and subsequent WUE of *Afrocarpus falcatus* (Thunb.) R.Br. ex Mirb. (Outeniqua Yellowwood) plantation, situated on the Woodbush-De Hoek Forest Plantation in the Limpopo Province of South Africa, was reported by Dye *et al*. (2008).

Observed daily transpiration rates from the *P. henkelii* trees in this study (5 to 20 L day^{-1}) were similar to those reported by Fetene and Beck (2004), and considerably less than those recorded in the adjacent *Pinus patula* stand (10 to 110 L day^{-1}). Annual transpiration totals for this indigenous tree stand (3634 L/404 mm) were consequently substantially less than *Pinus patula* transpiration data reported by Olbrich *et al.* (1996) and Dye *et al.* (2001), illustrating that their water-use was less than that of most introduced trees sampled, but so was their growth (Figure 9). Of the data reported by Olbrich *et al*. (1996) and Dye *et al.* (2001), 72% of the trees studied had annual water-use values exceeding those of the *A. falcatus* trees in this study, some using as much as 22 900 L $tree^{-1}$ $year^{-1}$. 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 $tree^{-1}$ day^{-1} to 150 L $tree^{-1}$ day^{-1}, substantially more than the average 10 L $tree^{-1}$ day^{-1} for these *P. henkelii* trees.

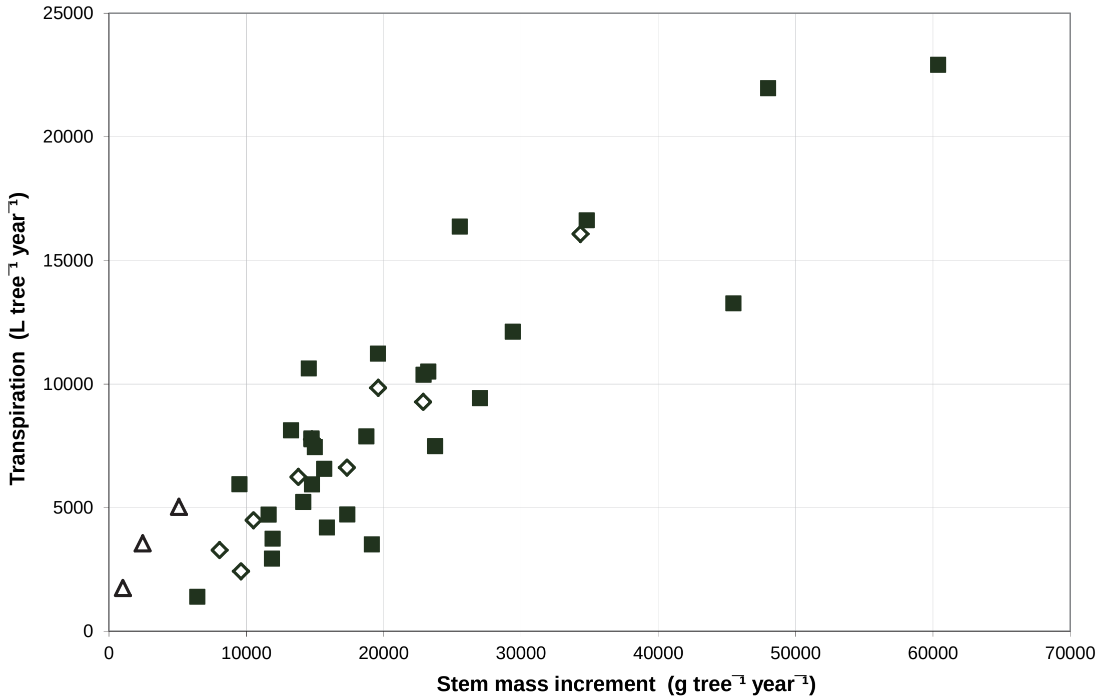

Figure 9. 1-year transpiration totals (L tree^{-1} year^{-1}) and stem mass increments (g tree^{-1} year^{-1}) for plantation-grown Eucalypts (■) (after Dye *et al.*, 2001), Pines (◊) (Olbrich *et al.*, 1996) and *P. henkelii* trees (Δ – this study).

The data from Olbrich *et al.* (1996) and Dye *et al.* (2001) may also be compared to the field observations in this study in terms of WUE. The calculated WUE of the *P. henkelii* plantation (0.76 g stem wood per L water transpired) was low compared to the results for the adjacent *Pinus patula* plantation in this study (2.06 g stem wood per L water transpired), and also below that of more widely measured introduced tree plantations (Ave = 2.48 g stem wood per L water transpired). In conclusion, the water-use of the plantation-grown *P. henkelii* trees in this study were less than those of adjacent *Pinus patula* trees of similar size, and more widely grown introduced tree species in general (Pines or Eucalypts). However, indigenous *P. henkelii* trees did not use water as efficiently as the introduced tree species because, while their water-use was less, their growth rates were proportionally even lower.

3 MIXED SPECIES/MIXED AGE TRANSKEI COASTAL SCARP FOREST AND EUCALYPTUS PLANTATION AT MANUBI[3]

3.1 Introduction

Products and services from indigenous tree species and forests are sought after in South Africa, due to their quality, durability, economic value, cultural significance and aesthetic appeal. However, their slow growth rates and limited extent render 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. Consequently, after more than a century during which timber supplies in South Africa came from the natural forests, the emphasis then switched to plantation forestry. 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 1.27 million hectares in 2014 (FSA, 2014). The projected decline in the production of structural timber from the commercial timber plantations stimulated an evaluation of the potential to produce more timber from the South African natural forests (Ham *et al*., 2010). Timber harvesting from natural forests continues on a small scale[4], either through a controlled but rather passive system of mortality retrieval in a few areas, or through uncontrolled tree and bark use, with both negative and positive effects on the forests. So while South Africa timber is sourced mainly from plantations, natural forests and woodlands also contribute. The latter have the potential to provide some timber to the primary and secondary forestry industries but the yields are small and the resource base limited.

Sixteen long-term Permanent Sample Plots (PSPs) were established since 1987 in the natural forests of South Africa from the Cape Peninsula to the

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[3] When making reference to this section, please cite as follows:

Gush, M.B., Dye, P.J., Naiken, V. and Geldenhuys, C.J. 2015. Mixed species/mixed age Transkei Coastal Scarp Forest and Eucalyptus Plantation at Manubi. In: Gush, M.B. and Dye, P.J. (Eds). 2015. Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees: Volume 2 (Site-Specific Technical Report). Water Research Commission, Pretoria, RSA, WRC Report 1876/2/15, Section 3.

[4] Details on an economic study of *Millettia grandis* (Umzimbeet), *Ptaeroxylon obliquum* (Sneezewood) and *Vachellia karroo* (Sweet Thorn) carried out at Manubi are reported on in Volume 1.

Soutpansberg to obtain information on growth, recruitment and mortality of indigenous forests (Geldenhuys & Golding, 2008). The plot sites were selected to represent the latitudinal gradient of natural forests in South Africa, and local altitudinal gradients. They represent major forests within the main national forest groups and types (von Maltitz *et al*., 2003; Mucina & Geldenhuys, 2006), i.e. in Afrotemperate forest (Cape Peninsula and southern Cape), Mistbelt forest (Amathole, Ingeli/Weza, Magoebaskloof, Soutpansberg) and Scarp forest (Manubi and Ngome). The data are being used to assess the potential for sustainable timber supply levels from South African natural forests.

As one of the forests containing a PSP, where measurements of growth, recruitment and mortality patterns in indigenous forests are periodically carried out, the Manubi State Forest was deemed suitable for measurements in this study. It represented a good example of the Scarp Forest group (identified as a priority Forest type to study in this project), and it contained a number of the individual priority species present. The PSP growth data was also consequently available to complement the water use measurements and WUE calculations carried out in the study.

3.2 Materials and Methods

3.2.1 Site and species description

The Manubi forest (-32.451° S; 28.596° E) is a state-owned mixed-species, mixed-age evergreen indigenous forest, located in the coastal region of the Eastern Cape Province of South Africa (Figure 10). It is approximately 760 ha in extent, and ranges in elevation from 150 to 230 m.a.s.l. It is characterised primarily by very rich doleritic soil, with approximately 30% of the forest underlain by soil derived from Beaufort shales (King, 1940) and the mean annual rainfall is approximately 1070 mm (Schulze and Lynch, 2007). The Manubi Forest is classified as a Transkei Coastal Scarp Forest type, within the broader Scarp Forest Group (Mucina and Rutherford, 2006) and it is dominated by *Chionanthus peglerae, Strychnos mitis, Drypetes gerrardii, Olea capensis* subsp. *macrocarpa, Vepris lanceolata* and *Syzygium gerrardii* in the canopy. The sub-canopy is dominated by *Englerophytum natalense, Allophylus dregeana*, *Diospyros natalensis* and *Tricalysia lanceolata*. *Trichocladus crinitus* and *Buxus natalensis* form the major component of the sparse to dense shrub understorey. The Manubi forest has belts of introduced Euclayptus species ringing certain perimeter areas, which provide supplies of timber to adjacent rural communities (Figure 11).

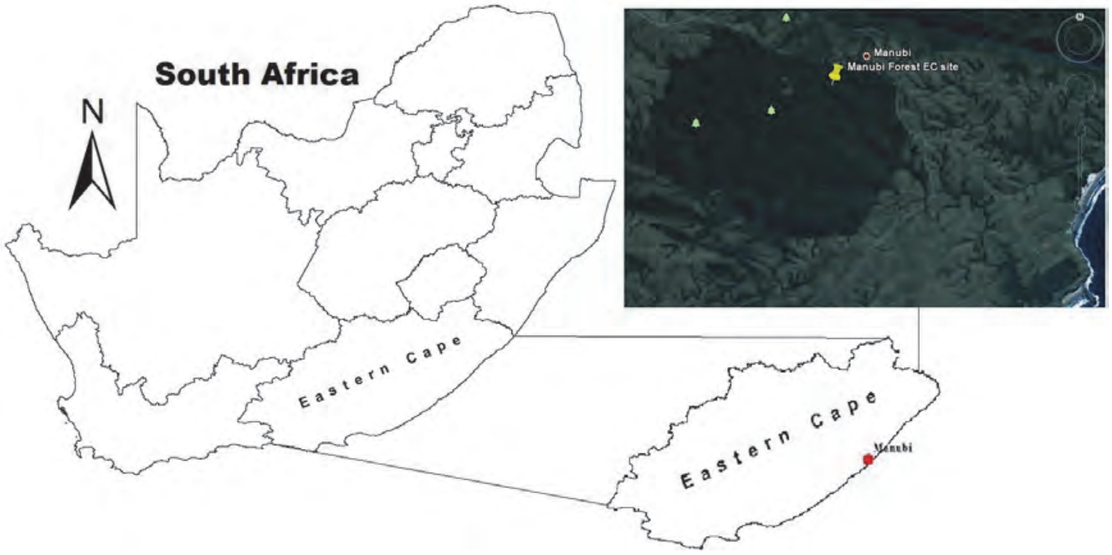

Figure 10. Aerial view and geographical position of the Manubi State Forest

Figure 11. Traditional settlement on the edge of the Manubi State Forest. Note the introduced Eucalyptus belt, with the indigenous forest behind (Photo: M. Gush).

The indigenous forest as a whole was assessed in terms of growth (PSP plots) and total evaporation, while additional tree species targeted for water-use (transpiration) and growth measurements at Manubi comprised the indigenous species *Millettia grandis* (Umzimbeet) and *Ptaeroxylon obliquum*

(Sneezewood), as well as the introduced species *Eucalyptus grandis*. These species were monitored individually, at three separate sites.

The *Ptaeroxylon obliquum* (Sneezewood) is a commonly occurring and well utilized species in this region, and with the assistance of local residents a cluster of suitable trees was found for monitoring (Figure 12). The Sneezewood site is a riparian strip of indigenous forest on a rocky bank near an ephemeral stream channel. *Millettia grandis* (Umzimbeet) trees were prevalent and pioneering on the edge of the indigenous forest. The selected Umzimbeet site was a riparian open area, previously under tall eucalyptus trees, ring-barked and long dead but still standing. The area was heavily infested with lantana and other invasive plants but there was some regeneration of indigenous species, particularly Umzimbeet. Sunlight and water were not limiting at this site. The sample tree was multi-stemmed with stems of different sizes (Figure 13). The Eucalyptus site, selected for comparative measurements of an introduced species, was situated within a belt of Eucalyptus trees providing timber to the local community). Four stems of different sizes that had coppiced from large stumps were monitored (Figure 14).

Figure 12. View of the instrumentation and trees at the Sneezewood site (Photo: M. Gush).

Figure 13. View of instrumentation that was installed, and the stems that were monitored, at the Umzimbeet site (Photo: M. Gush).

Figure 14. View of the coppiced eucalyptus stems that were monitored (Photo: M. Gush).

3.2.2 Field measurements

As part of this study a number of different measurements were conducted at Manubi, and the installation of these systems took place in September 2010. These consisted of continuous (hourly) monitoring of a full suite of weather variables at an appropriate open location beside the forest; continuous (hourly) sap flow (transpiration) measurements on individual indigenous and introduced tree species within the forest; and short-term (5-10 days) seasonal measurements of total evaporation (ET_{EC}) above the indigenous forest canopy. It was imperative that growth rates in the forests or individual tree species were obtainable in order to derive WUE. For trees yielding sap flow measurements this was achieved by conducting simultaneous measurements of stem growth increment over a year. For the indigenous forest measurements this necessitated the availability of long-term growth plots in the forest. Manubi Forest is one of a limited number of indigenous forests in South Africa that has such PSPs. In addition to the measurements, a modelling exercise was conducted in order to extrapolate the short-term ET_{EC} measurements to a full year of daily values.

Weather

Weather data (solar radiation, maximum and minimum temperature and relative humidity, wind speed, wind direction and rainfall) were recorded on an hourly basis from 2 Sep. 2010 to 5 Sep. 2011 using an automatic Weather station (Campbell Scientific Inc., Logan, Utah, USA) positioned in an open grassed area at 32.441°S and 28.611°E, at an elevation of 180 m.a.s.l.

Sap flow (transpiration) and soil water

The heat ratio method (HRM) of the HPV technique (Burgess *et al.*, 2001), as described in Chapter 2, was utilised for sap flow measurements in this study. Average tree density within the Manubi forest (all indigenous species) was estimated by Geldenhuys and Rathogwa (1995) to be 1248 spha (all trees with DBH >50 mm). Using this value to scale individual tree sap flow volumes (L yr^{-1}) up to a hectare, sap flow (transpiration) totals in mm-equivalent volumes for the year were also estimated. Two Sneezewood trees, three Umzimbeet stems and two coppiced Eucalyptus stems (Table 6) were instrumented at the respective sites, using separate HPV systems.

Table 6. Details of the individual trees selected for sap flow measurements at Manubi.

Species	Diameter at breast height (cm)	Tree height (m)	Sapwood depth (cm)	Wound width (mm)	Bark width (mm)	Wood density ($g.cm^{-3}$)
P. obliquum 1	8.2	10.3	2.0	3.5	6.0	0.73
P. obliquum 2	14.5	10.7	2.2	3.5	6.0	0.73
M .grandis stem 1	4.8	4.8	1.8	4.0	6.0	0.79
M .grandis stem 2	6.9	6.1	2.9	4.0	5.0	0.79
M .grandis stem 3	6.5	5.9	2.6	4.0	5.0	0.79
Eucalyptus stem 1	5.7	7.2	1.5	4.0	4.0	0.50
Eucalyptus stem 2	11.5	11.2	3.4	4.0	4.0	0.50

Volumetric soil water content within the forest, and at the respective sap flow study sites, was recorded hourly in the top 100 mm of the soil profile from 1 Sep 2010 to 5 Sep 2011, using CS616 soil water content probes (Campbell Scientific Inc., Logan, Utah, USA). Soil samples taken in the vicinity of the probes were assessed for gravimetric water content, and assisted in calibration of the soil water data which was adjusted accordingly.

Stem biomass increments and water use efficiency

Stem biomass increments surveys, according to the method described in Chapter 2, were undertaken for all sample trees in order to calculate WUE. Stem volume increment measurements were carried out at the inception of the study in September 2010 and subsequently a year later in September 2011 in order to incorporate a full year. The stem volume increments were converted to dry mass using the wood densities determined from samples collected for each species in this study. In conjunction with the sap flow (water-use) results this allowed the calculation of WUE, defined as mass of woody biomass produced (g) per unit of water transpired (L), and results were compared against existing data for indigenous and introduced tree species available from previous studies (Olbrich *et al*., 1996; Dye *et al*., 2001; Gush & Dye, 2009).

Total evaporation (ET)

Total evaporation (ET) of the forest was measured using the eddy covariance technique (ET_{EC}) over three short field campaigns representing spring (3 to 7 Sep. 2010), summer (24 Feb. to 2 Mar. 2011) and winter (11 to 18 May 2011). Sensors were mounted on a Clark WT8 pneumatic telescopic mast (Figure 15) positioned approximately 250 m from the northern boundary of the forest and 2.75 km from the southern boundary of the forest (32.443°S; 28.609°E) at an elevation of 172 m.a.s.l. Due to fetch limitations associated with the predominantly north/south wind direction, sensors were mounted at 18 m above ground (2.5 m above maximum canopy height). This allowed for a maximum upwind measurement footprint of 250 m.

Figure 15. Fully installed telescopic mast projecting above forest canopy, with supporting guy ropes and mounted eddy covariance instrumentation (Photo: M. Gush).

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. 3):

$$R_n - G - LE - H = 0 \qquad \text{Equation 3}$$

where R_n (W m^{-2}) is the net (incoming minus reflected) radiation above the canopy surface, G (W m^{-2}) the energy required to heat the soil (soil heat flux), LE (W m^{-2}) the energy required to evaporate water (latent energy flux) and H (W m^{-2}) the energy required to heat the atmosphere above the soil (sensible heat flux). R_n was measured using a net radiometer (Model 240-110 NR-Lite, Kipp & Zonen, Delft, Netherlands). G was measured in the forest floor using soil heat flux plates (model HFT-S, REBS) buried 80 mm below the soil surface, together with soil temperature averaging probes 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 CSAT3 three-dimensional ultrasonic anemometer (CSAT3, Campbell Scientific Inc., Logan, Utah, USA). *LE* was measured with a LiCor LI-7500 open path infrared gas analyser (IRGA). Measurements conducted at 20Hz and averaged every 30 minutes were stored on a CR5000 data logger (Campbell Scientific Inc., Logan, Utah, USA). The installation procedure, position of the mast and sensor mounting heights were kept consistent in all campaigns. The Leaf Area Index (LAI) of the forest was recorded during each field campaign using a LAI2000 plant canopy analyzer (LiCor, Lincoln, Nebraska).

3.2.3 Modelling

Observed weather, soil water and seasonal ET_{EC} data were used to estimate daily actual ET data for the year (Sep. 2010 to Oct. 2011). The approach followed was to calculate reference ET_o using version 3.1.07 of the software REF-ET (http://www.kimberly.uidaho.edu/ref-et/index.html) and to express daily measured ET from the EC field campaigns as a fraction of ET_o. Reference total evaporation, as defined in the software, is the ET that occurs from a 'reference' crop such as clipped grass or alfalfa and is consistent with internationally accepted methods (Allen *et al*., 1998). Measurements taken during each field campaign showed LAI in this evergreen forest to be relatively constant, ranging from 3.5 to 3.6. Seasonal variations in ET could therefore not be attributed to changes in leaf area. However, soil water content did vary markedly through the year and was considered to be the most likely cause of variations in ET. Consequently, the ratio ET_{EC}/ET_o was plotted against volumetric soil water content in the topsoil to derive a two-component relationship between soil water content and the ET_{EC}/ET_o ratio. The two lines were regressed against two groups of points describing each segment of the relation, and the regression equations were used to estimate ET from soil water content and ET_o over the entire year.

3.3 Results and Discussion

3.3.1 Weather

The weather station collected uninterrupted data from time of installation (2 September 2010) to time of dismantling (5 September 2011). The monitoring year exhibited fairly typical patterns of a coastal summer/all year rainfall region, showing only moderate seasonal change, and a mild wet climate. The 1-year rainfall total recorded at the site was 1311 mm, reflecting conditions that were wetter than average. The cooling influence of coastal breezes is evident in the relatively mild maximum temperatures, with a once-off daily maximum of 35.8°C, and an average daily maximum of 23.7°C. Average daily minimum temperature was 14.3°C. The influence of individual rainfall events on solar radiation values is evident, and the high percentage of rain days has often resulted in relatively low solar radiation values at the site, with a daily average of 13.7 MJ m^{-2} day^{-1}. Wind speeds have generally been low and very consistent, averaging 1 m s^{-1}, with gusts of up to 10.6 m s^{-1}, without much seasonal change. All data collected from the weather station were of good quality, and hourly values were collated into daily (Figure 16) and monthly (Figure 17) totals or averages.

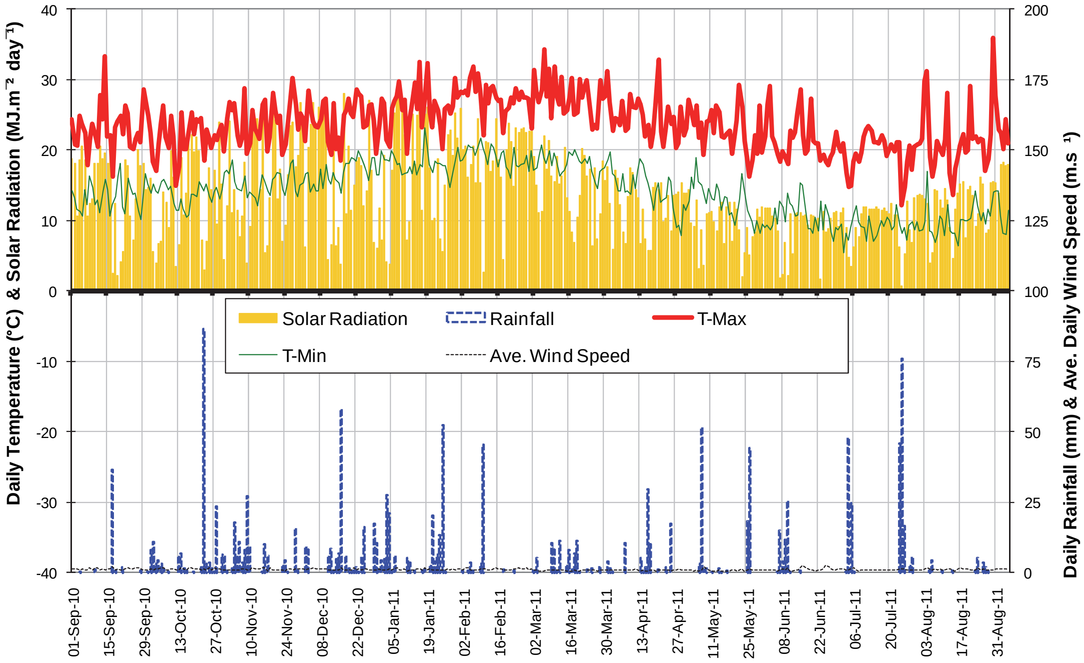

Figure 16. Daily maximum and minimum temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), average daily wind speed (m s^{-1}) and rainfall (mm) at the Manubi site from 2 September 2010 to 5 September 2011.

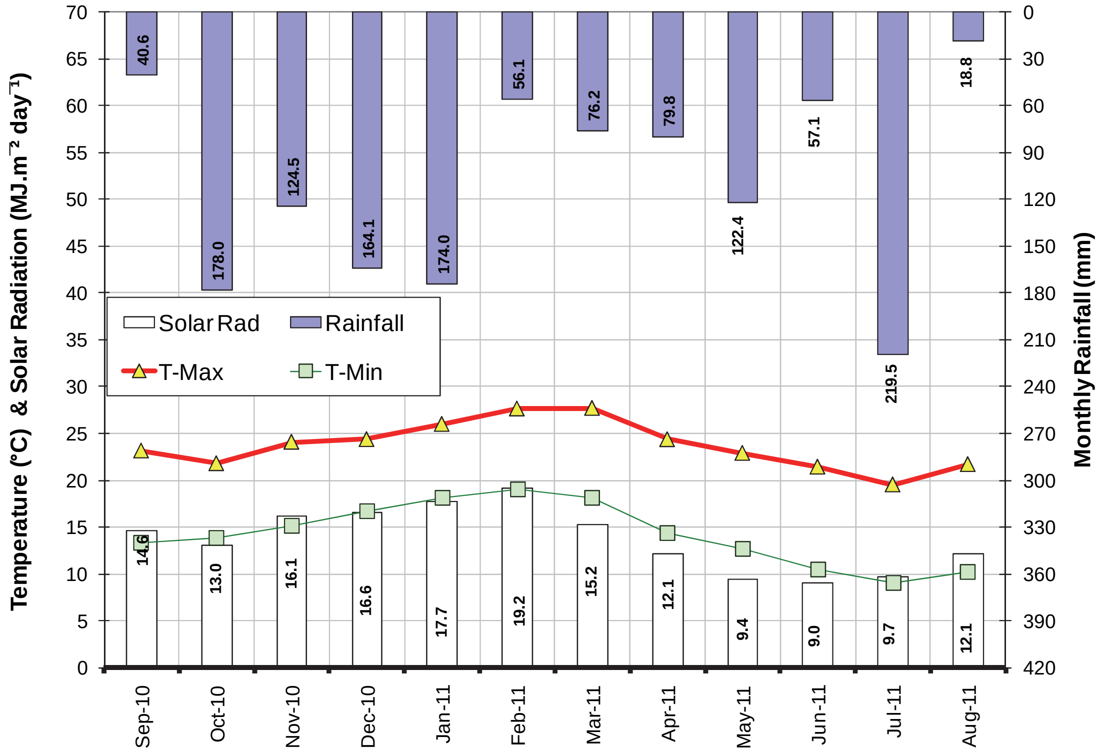

Figure 17. Average daily maximum and minimum temperatures (°C) and solar radiation totals (MJ m^{-2} day^{-1}) per month, with rainfall totals (mm) measured at the Manubi site from September 2010 to August 2011.

3.3.2 Soil water

The dry conditions experienced at the Sneezewood site initially (6-7% volumetric water content) are evident from the time series of soil water data recorded in the upper soil layer. However, subsequent rainfall events raised overall soil water levels to above 40% at times, providing adequate water for transpiration. From the relatively steep slope of the drainage curve following rainfall events (Figure 18), the soil appears to lose water rapidly and dry out quickly, potentially accounting for strong links between water availability and transpiration. Similar patterns of soil water were observed at the riparian Umzimbeet site (Figure 19).

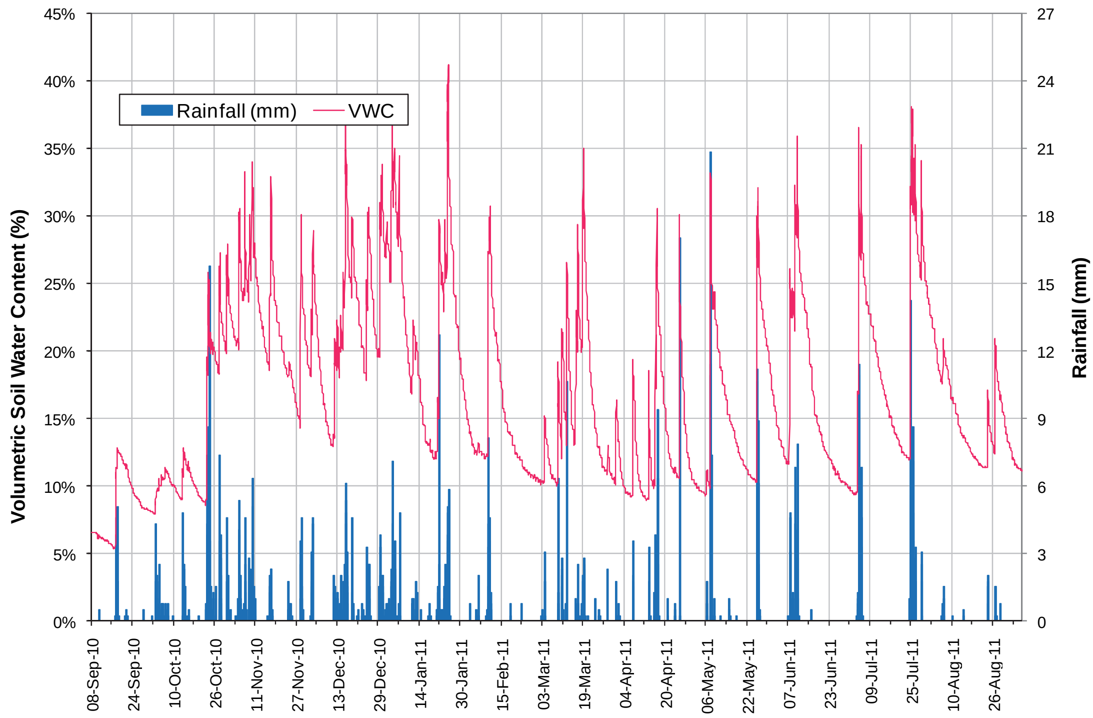

Figure 18. Fluctuations in volumetric soil water content at the Sneezewood site between 8 September 2010 and 5 September 2011.

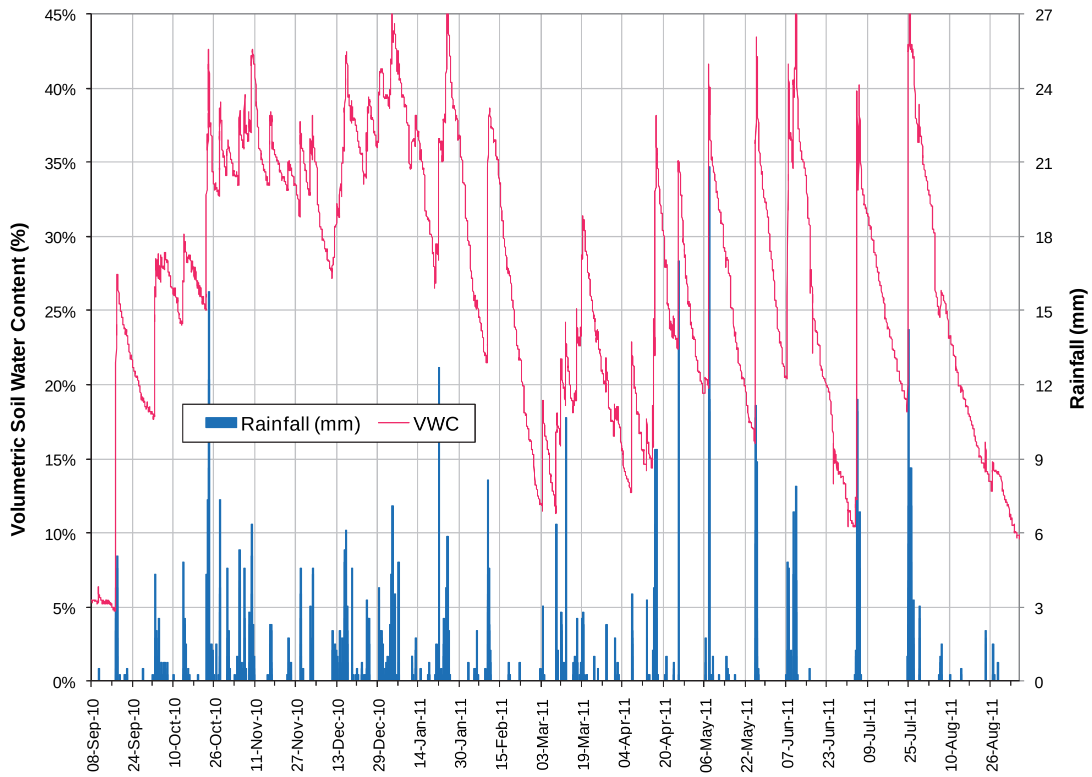

Figure 19. Fluctuations in volumetric soil water content at the Umzimbeet site between 8 September 2010 and 5 September 2011.

3.3.3 Tree water use

Daily sap flow (transpiration) volumes (L day⁻¹), measured in two *Ptaeroxylon obliquum* (Sneezewood) trees are illustrated in Figure 20 and Figure 21.

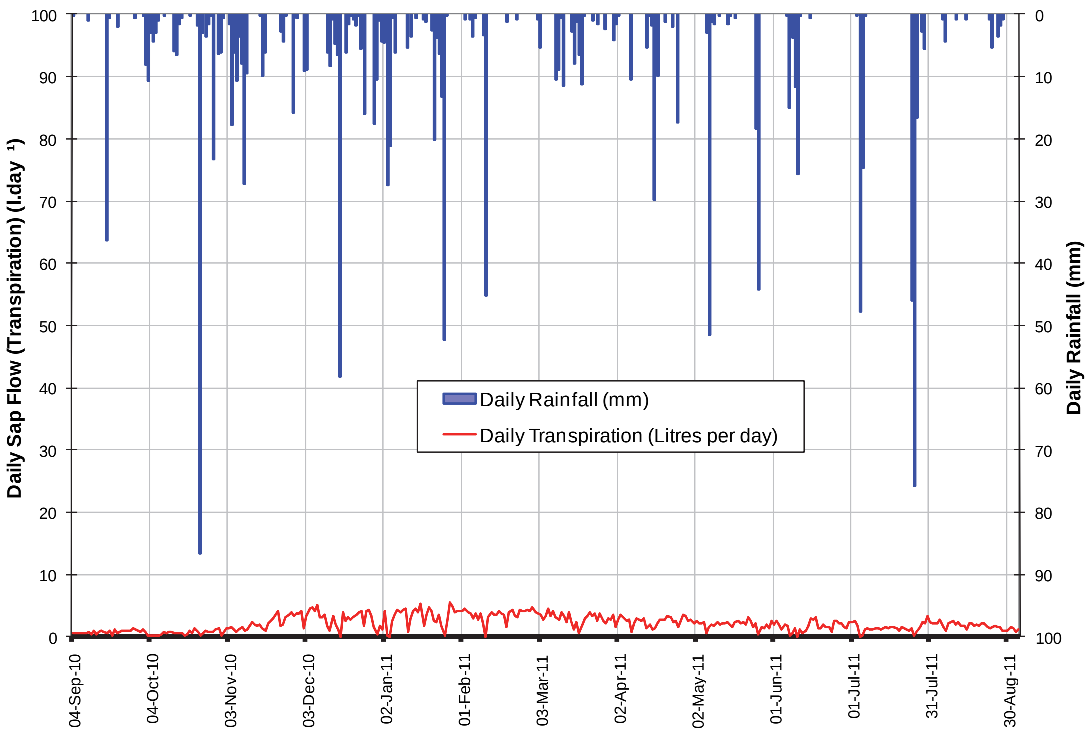

Figure 20. Daily sap flow (transpiration) volumes (L day⁻¹) for *Ptaeroxylon obliquum* tree 1 from 6 September 2010 to 5 September 2011.

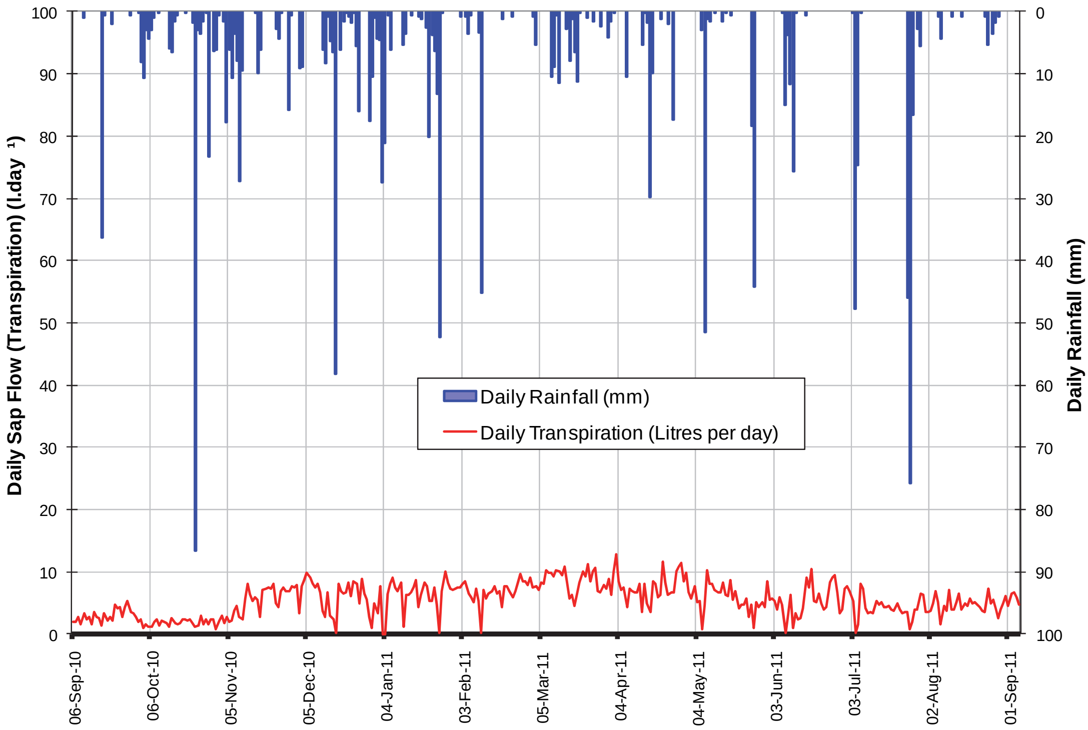

Figure 21. Daily sap flow (transpiration) volumes (L day⁻¹) for *Ptaeroxylon obliquum* tree 2 from 6 September 2010 to 5 September 2011.

The annual transpiration totals for the *Ptaeroxylon obliquum* study trees were averaged to determine a single average transpiration rate (**Table 7**). These were scaled up to a hectare (mm-equivalent) using the Manubi forest tree density estimate by Geldenhuys and Rathogwa (1995) of 1248 spha.

Table 7. Observed transpiration volumes in two *Ptaeroxylon obliquum* trees growing in Manubi State Forest.

HPV tree no.	DBH (cm)	1-yr Water-use (L tree⁻¹)	1-yr Water-use (mm)	Weighting
P. obliquum 1	8.2	786	98	50%
P. obliquum 2	14.5	2 005	250	50%
Weighted Total		**1 396**	**174**	**100.0%**

Daily sap flow (transpiration) volumes (L day⁻¹), measured in three *Millettia grandis* (Umzimbeet) stems are illustrated in Figure 22, Figure 23 and Figure 24.

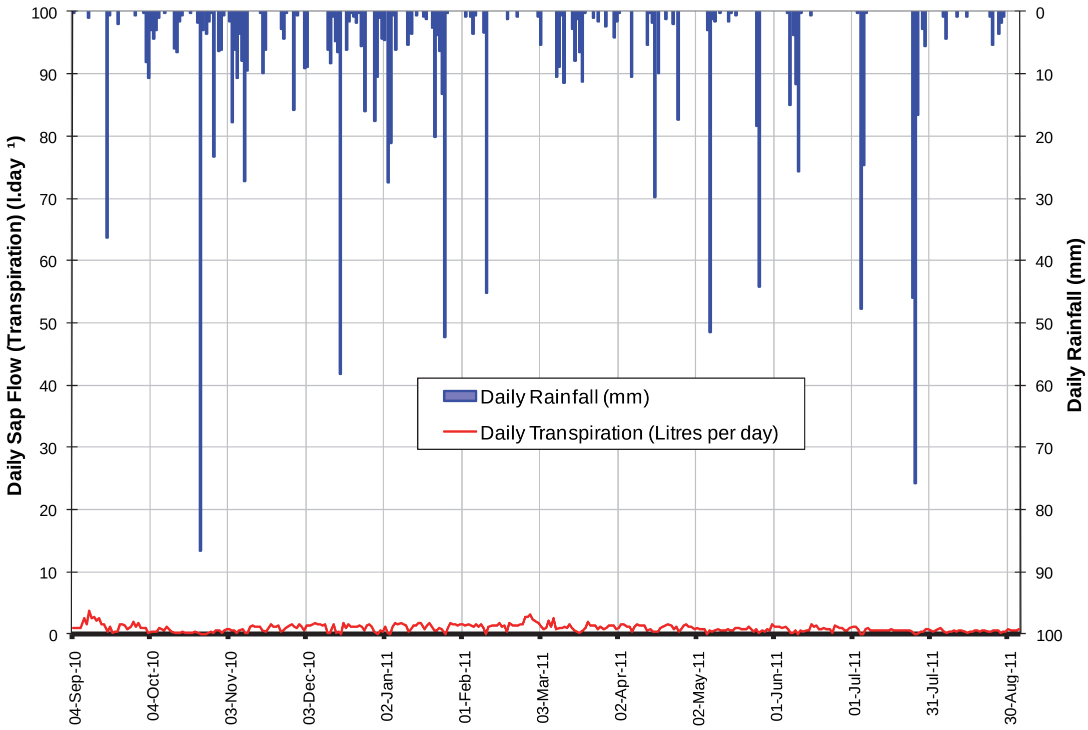

Figure 22. Daily sap flow (transpiration) volumes (L day^{-1}) for *Milletia grandis* stem 1 from 6 September 2010 to 5 September 2011.

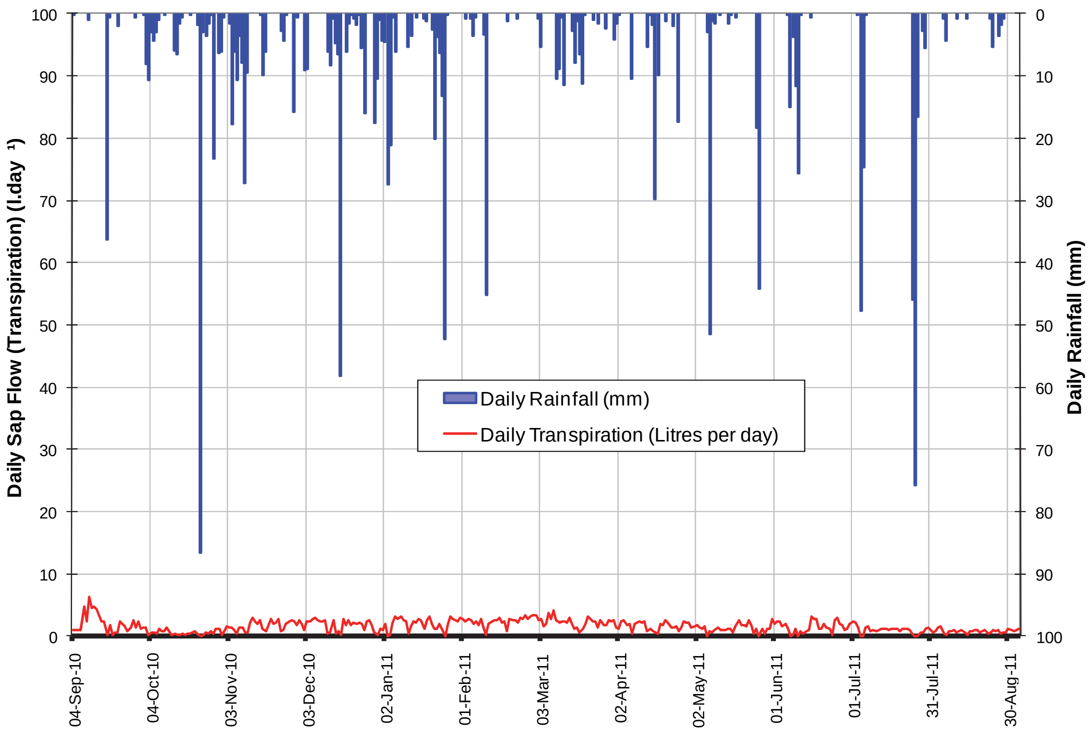

Figure 23. Daily sap flow (transpiration) volumes (L day^{-1}) for *Milletia grandis* stem 2 from 6 September 2010 to 5 September 2011.

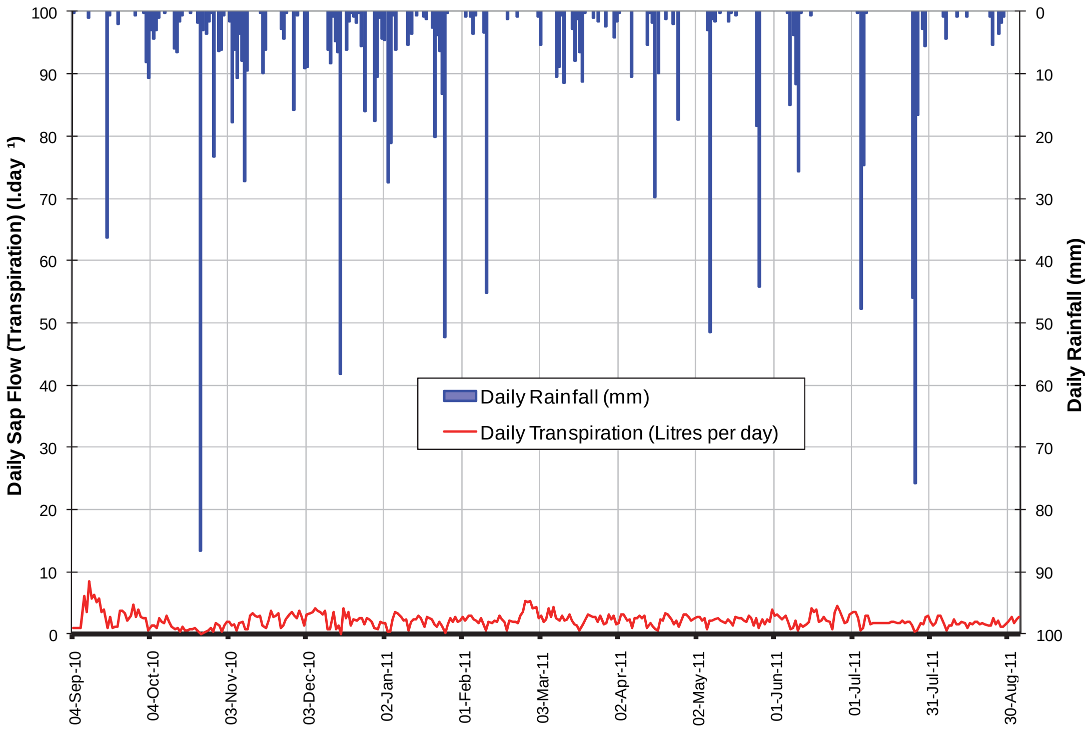

Figure 24. Daily sap flow (transpiration) volumes (L day^{-1}) for *Milletia grandis* stem 3 from 6 September 2010 to 5 September 2011.

The annual transpiration totals for the three *Millettia grandis* stems were summed and multiplied by 2 (as there were six stems of similar size on this tree, of which three were measured) to determine a single transpiration rate (L yr^{-1}) for the tree (Table 8). These were scaled up to a hectare (mm-equivalent) using the Manubi forest tree density estimate by Geldenhuys and Rathogwa (1995) of 1248 spha.

Table 8. Observed transpiration volumes in 3 *Millettia grandis* stems growing in Manubi State Forest.

HPV stem no.	DBH (cm)	1-yr Water-use (L stem^{-1})	1-yr Water-use (mm)
M. grandis 1	4.8	343	43
M. grandis 2	6.9	576	72
M. grandis 3	6.5	806	101
Total		**1 725**	**216**
Tree Total (6 stems)		**3 450**	**432**

Daily sap flow (transpiration) volumes (L day^{-1}), measured in 2 *Eucalyptus* stems are illustrated in Figure 25 and Figure 26.

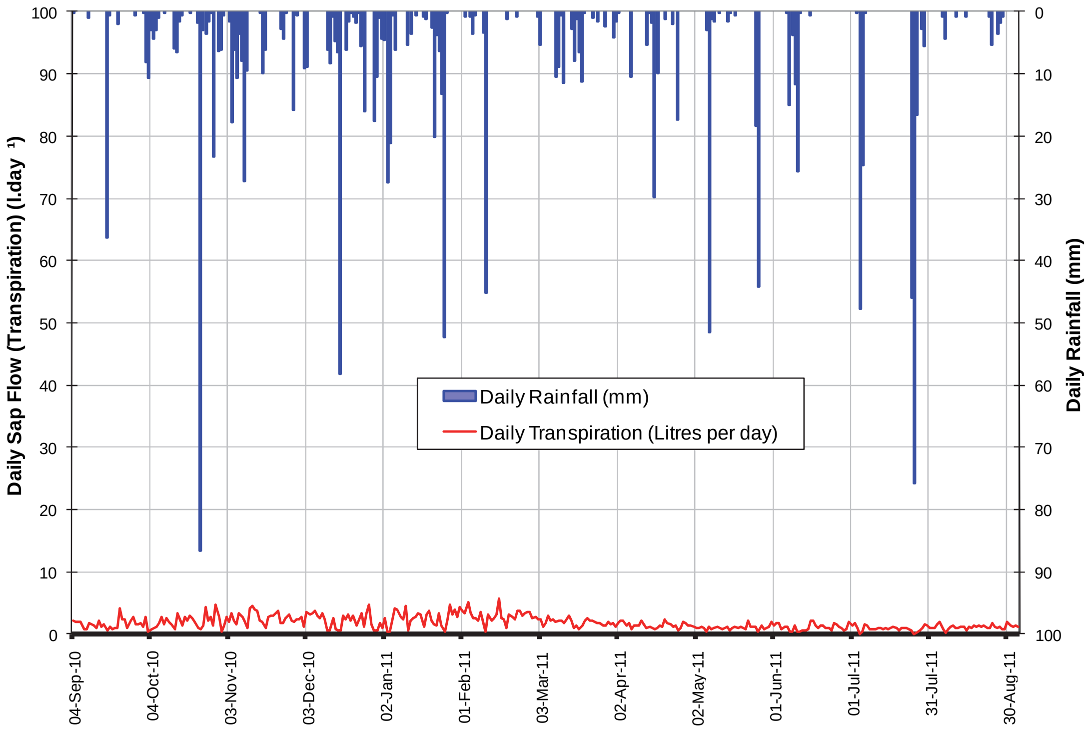

Figure 25. Daily sap flow (transpiration) volumes (L day^{-1}) for *Eucalyptus* stem 3 from 4 September 2010 to 3 September 2011.

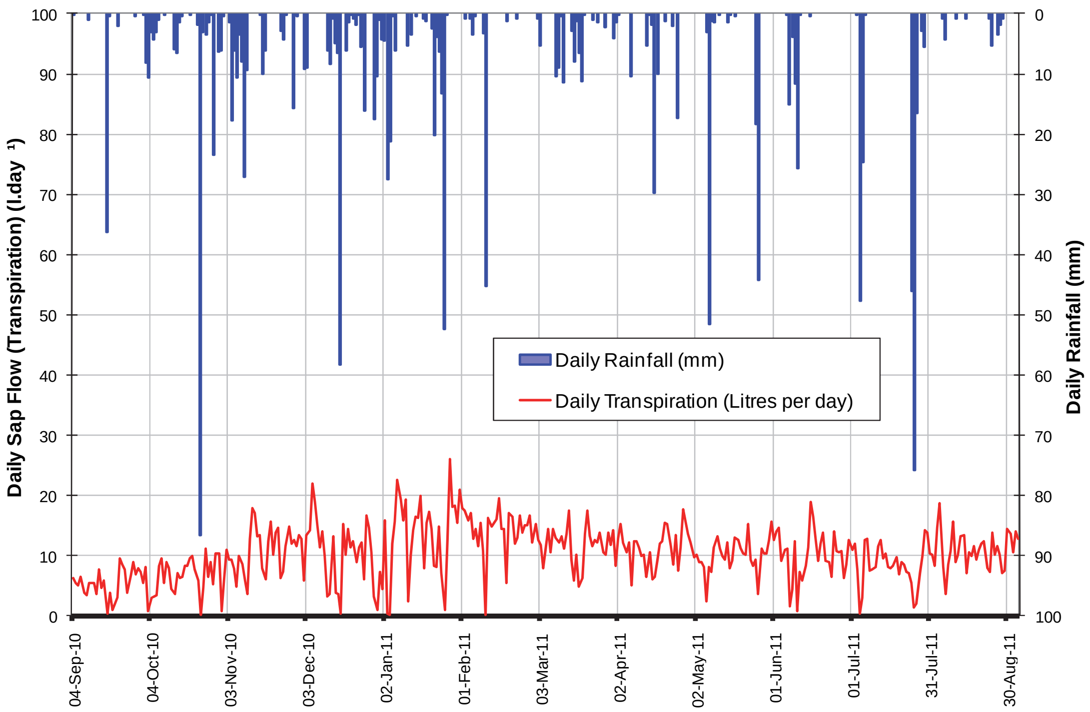

Figure 26. Daily sap flow (transpiration) volumes (L day^{-1}) for *Eucalyptus* stem 4 from 4 September 2010 to 3 September 2011.

Within the eucalyptus belt, trees were spaced at 2.5 m X 2.5 m apart, which corresponds to an original planting density of 1600 spha. However, due to the coppicing that took place in subsequent rotations, there was an average of 3 stems per stump. Consequently the coppice stem density was estimated to be 1600*3 = 4800 spha in the plantation. A stem size survey was conducted in the plantation and a range of coppice stem sizes were observed, from small stems of <3 cm in diameter to larger stems in excess of 10 cm diameter. However the average stem diameter was found to be 6.8 cm. Of the stems surveyed, approximately 48.5% were smaller than 6.8 cm DBH (represented by stem 3), and 51.5% were larger (represented by stem 4). This stem size distribution was used to weight and scale individual tree sap flow volumes (L yr^{-1}) to transpiration totals in mm-equivalent volumes for the year at a plantation scale (Table 9).

Table 9. Observed transpiration volumes in 2 coppicing *Eucalyptus* stems growing in a plantation near Manubi State Forest.

HPV stem no.	DBH (cm)	1-yr Water-use (L $stem^{-1}$)	1-yr Water-use (mm)	Weighting
Eucalyptus 3	5.7	653	313	48.5%
Eucalyptus 4	11.5	3 767	1 808	51.5%
Weighted Total		**2 210**	**1 061**	**100.0%**

3.3.4 Total Evaporation (ET)

A spring field campaign measured total evaporation (ET_{EC}) above the Manubi forest from 2 to 7 September 2010, a summer field campaign from 24 February to 2 March, and a winter campaign from 11 to 18 May 2011. Relatively consistent weather patterns were experienced over the spring campaign, with no rain, moderate temperatures (11-24°C), high humidity (50-90%) and consistent wind speeds of around 1 m s^{-1}. Consequently total evaporation rates measured above the forest were also within a narrow range from 0.97 to 1.37 mm day^{-1} (Figure 27).

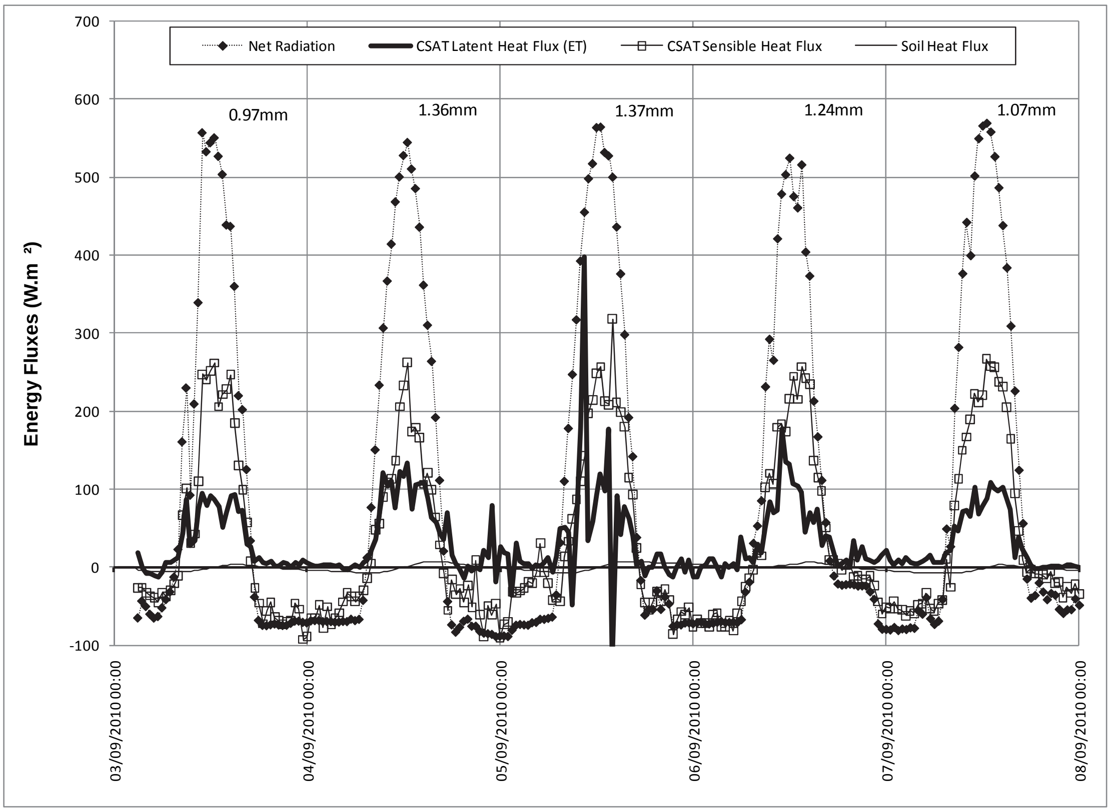

Figure 27. Half-hourly energy fluxes and resultant daily total evaporation totals (mm) measured above the indigenous Manubi State Forest near Butterworth, using the CSAT 3D eddy covariance system, from 3 to 7 September 2010.

Extremely consistent weather patterns were experienced over the summer monitoring period, with moderate temperatures (18-31°C), high humidity's (45-95%) and consistent wind speeds of around 1.3 m s^{-1}. There was no substantial rainfall over this period, apart from just 0.7 mm on the evening of 2 March 2011. Resultant total evaporation rates measured above the forest ranged from 2.42 to 3.41 mm day^{-1} (Figure 28). These were approximately three times higher than those measured in the spring campaign, and reflect the influence of higher solar radiation levels, increased temperatures and readily available soil water after the summer rainfall season.

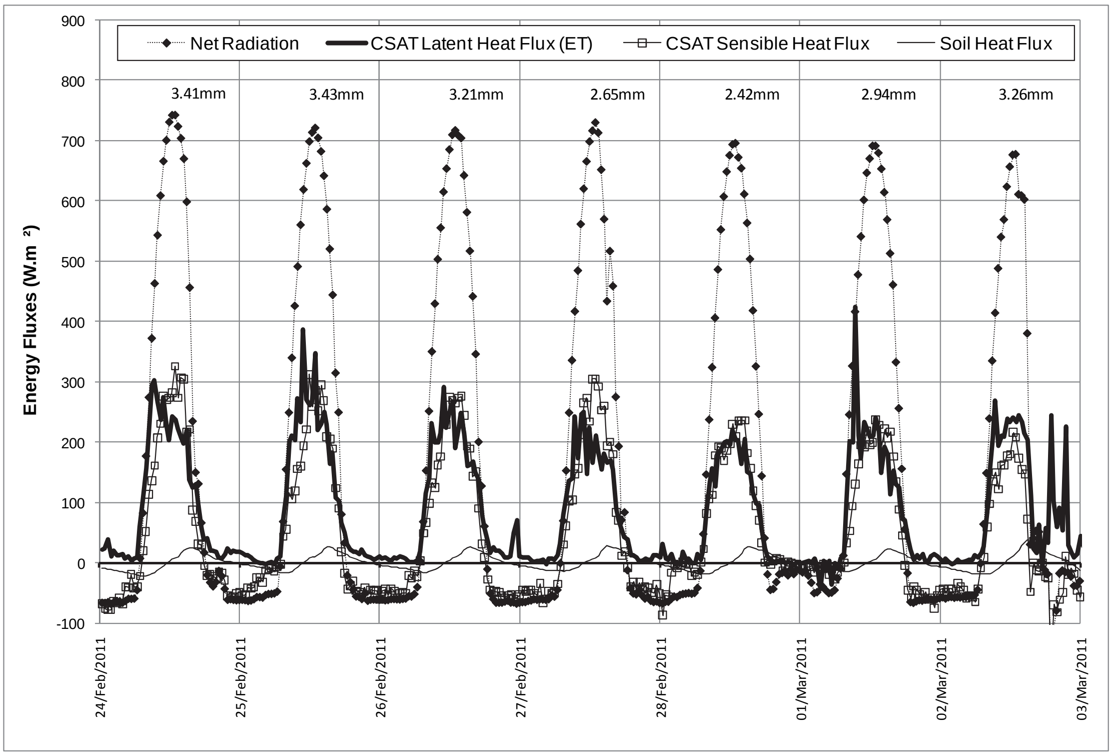

Figure 28. Half-hourly energy fluxes and resultant daily total evaporation totals (mm) measured above the indigenous Manubi State Forest near Butterworth, using the CSAT 3D eddy covariance system, from 24 February to 2 March 2011.

Cool and dry weather conditions were experienced during the winter campaign, with mild temperatures (11-26°C), low humidity's (average 55%) and consistent low wind speeds (average 0.5 m s^{-1}). There was no substantial rainfall over this period. Resultant total evaporation rates measured above the forest ranged from 1.1 to 2.1 mm day^{-1} (Figure 29). These were approximately half of those measured in the earlier summer campaign (2.4 to 3.4 mm day^{-1}), and reflected the cooler, drier winter conditions.

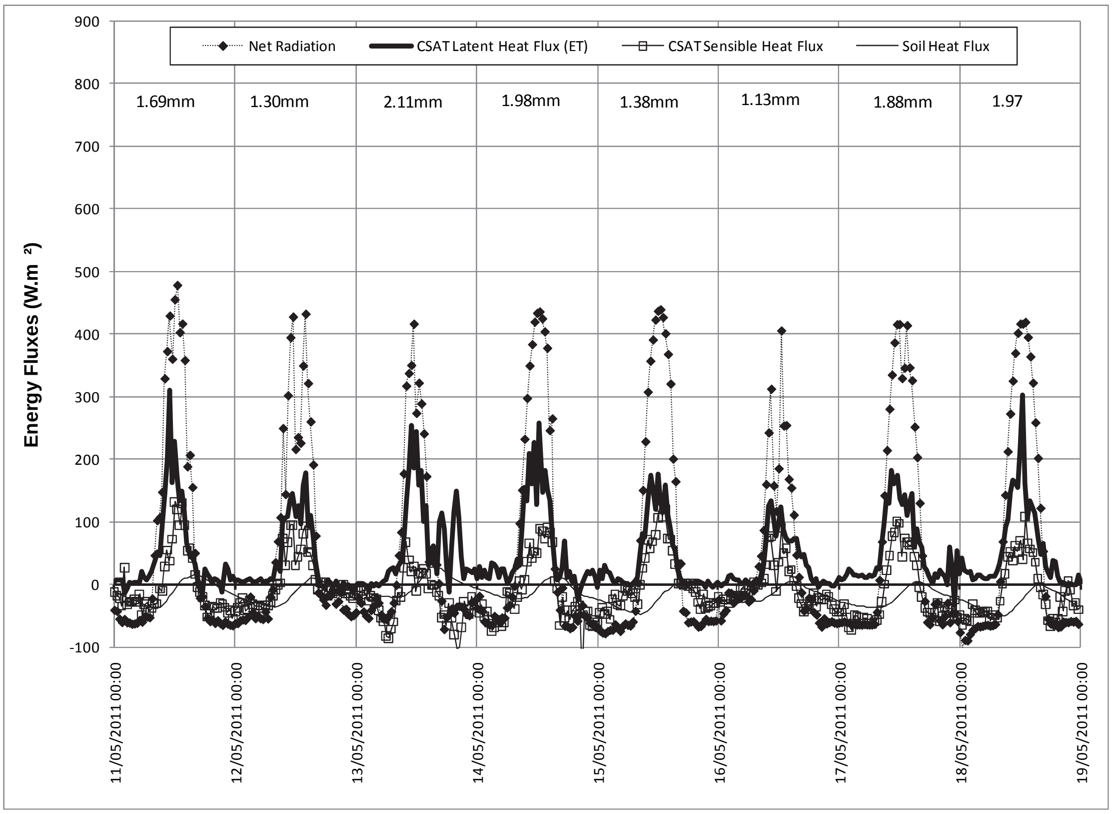

Figure 29. Half-hourly energy fluxes and resultant daily total evaporation totals (mm) measured above the indigenous Manubi State Forest near Butterworth, using the CSAT 3D eddy covariance system, from 11 to 18 May 2011.

Readings of the Leaf Area Index of the forest were also taken and were found to average 3.6 m^2 m^{-2} in May 2011, similar to previous seasonal measurements in September 2010 (3.5) and February 2011 (3.6). The Albedo of the forest was also measured over the course of the field campaigns and was consistently found to be 0.1 during the mid-day hours.

3.3.5 Stem biomass increments and water use efficiency

Following a year of monitoring at the sites, final surveys were carried out on 6 September 2011 to assess stem biomass increment over the year. Biomass increments were converted from volume to mass (Table 10) using wood densities determined for the tree species.

Table 10. 1-year stem volume increments observed in the sample trees at Manubi between September 2010 and September 2011.

Tree No.	Initial Height (m)	Final Height (m)	Initial DBH (cm)	Final DBH (cm)	Initial Stem Volume (m^3)	Final Stem Volume (m^3)	Stem Volume Increment (m^3)	Stem Mass Increment (kg)
Sneezewood 1	10.2	10.3	7.9	8.2	0.0263	0.0293	0.00295	2.15
Sneezewood 2	10.6	10.7	13.7	14.5	0.1041	0.1126	0.00848	6.17
Umzimbeet 1	4.7	4.8	4.2	4.9	0.0046	0.0058	0.00114	0.91
Umzimbeet 2	6.0	6.1	5.1	6.0	0.0081	0.0113	0.00320	2.54
Umzimbeet 3	5.6	5.9	5.6	6.5	0.0089	0.0124	0.00355	2.81
Eucalyptus 3	5.8	7.2	4.6	5.7	0.0055	0.0096	0.00414	2.07
Eucalyptus 4	8.3	11.2	9.2	11.5	0.0227	0.0457	0.02298	11.49

In conjunction with the sap flow (water-use) results, it was then possible to calculate WUE, defined as amount of stem biomass produced (g) per unit of water transpired (L) (Table 11, Table 12 and Table 13).

Table 11. Summary of WUE data for indigenous *Ptaeroxylon obliquum* trees, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use between September 2010 and September 2011.

Tree no.	1-yr Water-use (L)	Stem Volume Increment (m^3)	Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
1	786	0.00295	0.73	2 145.9	2.73
2	2 005	0.00848	0.73	6 168.2	3.08

Table 12. Summary of WUE data for indigenous *Millettia grandis* trees, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use between September 2010 and September 2011.

Tree no.	1-yr Water-use (L)	Stem Volume Increment (m^3)	Wood Density ($g\ cm^{-3}$)	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
1	343	0.00114	0.79	905.3	2.64
2	576	0.00320	0.79	2 536.8	4.40
3	806	0.00355	0.79	2 811.6	3.49
Totals (3 stems)	**1 725**	**0.00790**	**0.79**	**6 253.632**	**3.63**
Totals (6 stems)	**3 450**	**0.01579**	**0.79**	**1 2507.3**	**3.63**

Table 13. Summary of WUE data for introduced *Eucalyptus* tree stems, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use between September 2010 and September 2011.

Stem no.	1-yr Water-use (L)	Stem Volume Increment (m^3)	Wood Density ($g\ cm^{-3}$)	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
3	653	0.00414	0.50	2 068.1	3.17
4	3 767	0.02298	0.50	11 488.0	3.05
Weighted Average	**2 210**	**0.01384**	**0.50**	**6 919.3**	**3.13**

3.3.6 Modelling

The daily ratios ET_{EC}/ET_o were plotted against volumetric soil water content in the topsoil to derive a two-component relationship between soil water content and the ET_{EC}/ET_o ratio (Figure 30). There are some ratios of ET_{EC}/ET_o that exceed 1, and these were attributed to the greater total evaporation potential of forests compared to a reference grass cover caused by the higher leaf areas, aerodynamic roughness, rooting depths and soil water availability associated with forests (Le Maitre *et al*., 2015). These higher ratios were noted during the winter months when the available energy was relatively low (i.e. lower ET_o) but when the evergreen trees would have access to deeper soil water reserves (i.e. higher ET). There are clearly a number of uncertainties associated with this approach (related to the estimates of ET_o, the limited depth of the soil water data, as well as the observations of ET_{EC})

but Figure 31 indicates that the estimated daily ET data are good approximations of the measured ET_{EC} values from the three EC field campaigns, the slope estimate (1.03) having a standard error of 0.035.

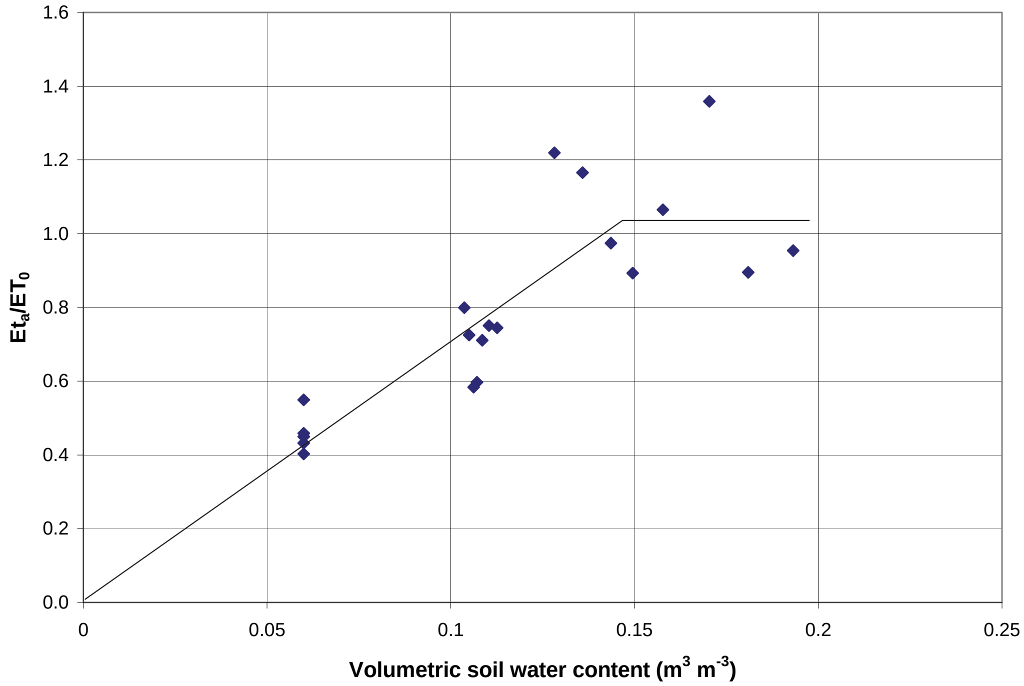

Figure 30. The relation between volumetric soil water content of the topsoil and the ratio of ET_{EC}/ET_0 at Manubi forest. Line segments define the model used to estimate ET over the entire year.

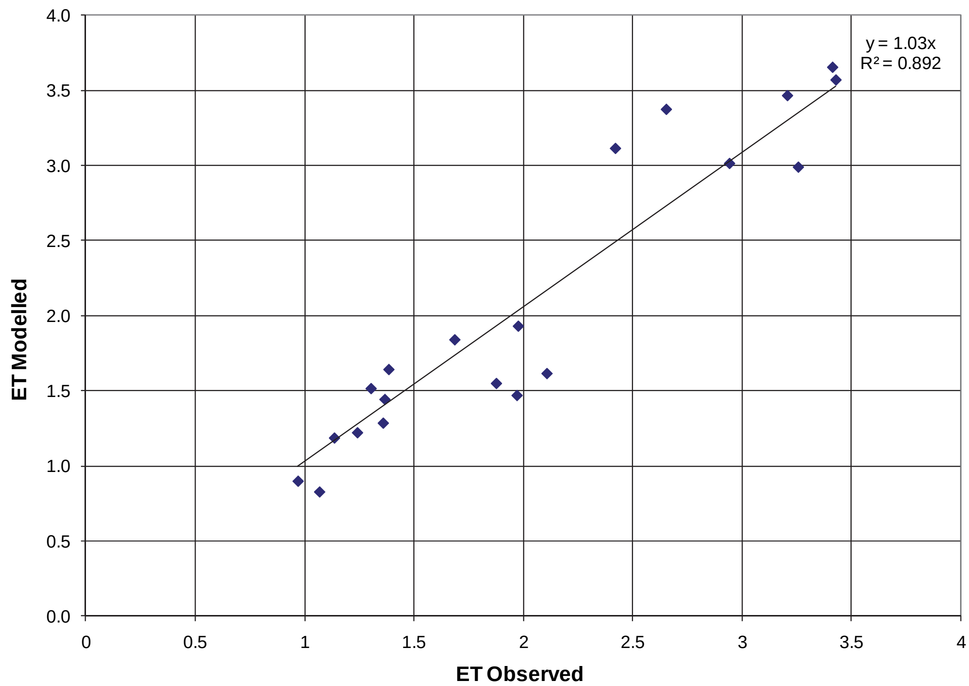

Figure 31. Simulated Daily ET compared against observed values from three seasonal field campaigns.

The full year cumulative ET estimated in this way equalled 891 mm (Figure 32). In an additional modelling exercise, utilising the same field data but this time applying a version of the Pitman model modified to run at a daily temporal scale, Hughes *et al.* (2014) acquired a similar result, with ET estimated at 813 mm (Table 14).

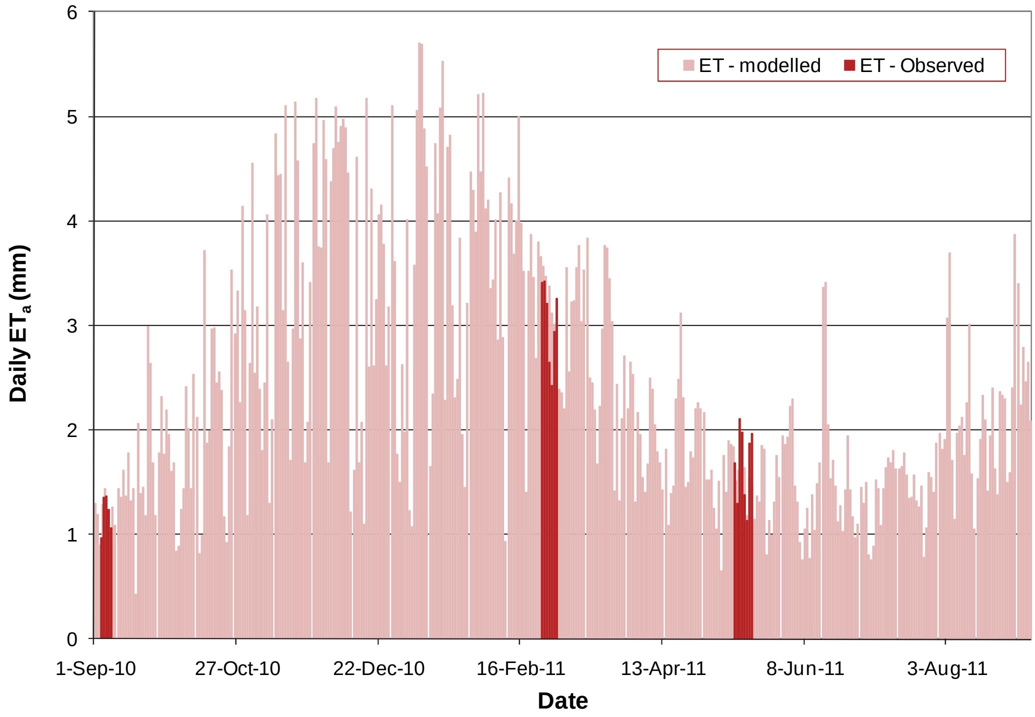

Figure 32. Daily ET estimated for the entire year at Manubi forest, with observed data from seasonal campaigns highlighted.

Table 14. Manubi Forest Pitman model water balance results (Hughes *et al.*, 2014).

Component	Field data	Pitman model simulations	
		Daily (2 soil layer)	Daily (1 soil layer)
Potential or reference evap. (ET_0 mm)	966	1 250	1 250
Rainfall (mm)	1 297	1 297	1 297
Interception loss (mm)	n/a	262	262
ET from upper soil layer (mm)	n/a	198	n/a
ET from lower soil layer (mm)	n/a	353	525
Total actual evap. (mm)	891	(813)	(787)
Surface runoff (mm)	n/a	0	0
Interflow runoff (mm)	n/a	123	129
GW recharge (mm)	n/a	274	272
Change in soil storage (mm)	19	87	109

3.3.7 Whole forest WUE

Data from the PSPs were used to obtain estimates of forest stand volume growth. Stem length was not measured in the long-term forest growth plots, so data for utilizable stem volume (up to the main branches) for the southern Cape forests were pooled across all canopy and subcanopy species to develop a DBH-Volume relationship. This was subsequently applied to the DBH data for the Manubi PSP site in order to calculate stand volume growth. A power function gave the best fit for the DBH-Volume relationship:

$$\text{Stem volume} = 0.000137 * \text{DBH}^{2.13}$$

Using this equation, the stem volume of each tree in the forest growth plot, for the first and second measurement (19 years apart at the Manubi plot), were calculated. The difference between the second and first measurement gave the following mean volume growth rate at Manubi:

1988: 89.267 m^3 ha^{-1}; 2006: 83.909 m^3 ha^{-1}; Growth: -0.298 m^3 ha^{-1} yr^{-1}

The fact that the PSP reflected negative growth at Manubi (due to stem mortality) meant that it was not possible to calculate whole forest WUE for this site.

3.4 Discussion

At Manubi, low water-use volumes within indigenous trees species (compared to introduced Eucalypts) were observed. This was particularly evident when scaling up individual tree water-use volumes (Litres $tree^{-1}$ yr^{-1}) to spatial estimates of water-use (mm yr^{-1}). This was due to the cumulative water-use total of high stem densities in the Eucalyptus plantation compared to relatively lower tree densities within the indigenous forest. One surprising result from the Manubi measurements was the very high water-use efficiency trend observed in most of the indigenous trees. WUE values for the indigenous tree species were generally higher than those observed in the Eucalypts, mainly as a result of good stem growth in the indigenous trees during the year. This is contrary to what has been observed at other sites. Again, allometric relationships within the trees may be the reason for this observation, particularly given the fact that the Eucalyptus trees were coppicing from large 2^{nd} rotation stumps, and ageing root systems. Consequently the stems may have had to allocate more resources to the large root system to keep it going.

Daily ET from the Manubi forest as a whole was shown to be governed primarily by weather conditions and soil water availability. In contrast to a moist southern Cape forest (Groenkop, George, Dye *et al*., 2008), ET/ET_0 varied markedly from season to season. A near-constant LAI showed that this seasonal change is not caused by variation in canopy leaf area. Soil water content in the topsoil fluctuated widely through the year. Despite these measurements not representing the deeper soil horizons which are exploited by tree roots, there was a strong correlation between soil water content and ET/ET_0 that conforms to the general relationship reported for many other forest sites (Dunin *et al*., 1985; Landsberg and Gower, 1997; Granier *et al*., 2000) and crops (Denmead and Shaw, 1961; Gardner, 1983). This result suggests that the forest is sensitive to the water content in the topsoil. This may reflect the evolution of a cautious strategy towards soil water utilization in an environment characterised by relatively low rainfall, limited soil water storage and regular dry spells, some of which can be extreme in duration and intensity. It may also be attributed to the relatively shallow fine root systems often characteristic of indigenous forests, where there are high levels of nutrient cycling in the topsoil, with resultant high root densities and dependencies on water in these shallow soil levels.

From an economic perspective, relevant data were collected and analysed, useful contacts in the indigenous wood industry were made, and the resulting findings provide perspectives on the economic potential of indigenous tree resources in this particular social context.

4 SOUTHERN MISTBELT FOREST AND ASSOCIATED INDIGENOUS TREE SPECIES AT INGELI[5]

4.1 Introduction

The Ingeli Forest forms part of the larger Weza Forest complex and is classified as an Eastern Mistbelt Forest type, within the broader Southern Mistbelt Forest Group. This is one of the priority Forest Groups identified by the reference group and workshop participants, earlier in the project. Eastern Mistbelt Forests are high and multi-layered forests (approximately 15-30 m tall), comprising two layers of trees, a full, dense understorey and a very well developed herb layer. They occur in an extensive band at middle altitudes (850-1600 m above sea level) often on steep eastern to western slopes of the mountains or escarpments (fire refugia) from the Kokstad-Mount Ayliff-Bizana area in the Eastern Cape to the midlands of KwaZulu-Natal. They range from small (<1 ha) to large (>1500 ha) forests. Detailed floristic and structural descriptions of this forest type are found in Geldenhuys (1999) and von Maltitz *et al*. (2003). They are dominated by a range of species that vary in importance in different parts of the forest: *Xymalos monospora, Podocarpus henkelii, Afrocarpus falcatus, Podocarpus latifolius, Ocotea bullata, Celtis africana, Calodendrum capense, Apodytes dimidiata, Curtisia dentata, Cussonia spicata* complex, *Kiggelaria africana, Prunus africana* (nowhere common), *Ptaeroxylon obliquum, Rapanea melanophloeos, Rhus chirindensis, Vepris lanceolata* and *Zanthoxylum davyi*. The strangler fig, *Ficus craterostoma*, occurs in many of the forests. Important sub-canopy trees and shrubs include *Allophylus dregeanus, Calpurnia aurea, Clausena anisata, Cryptocarya woodii, Diospyros whyteana, Eugenia zuluensis, Halleria lucida, Maytenus mossambicensis, Pterocelastrus rostratus, Rothmannia capensis, Trichocladus ellipticus* and *Trimeria grandifolia*. A fern layer is well developed in many parts of the forests, and include a variety of species. Tree species are predominantly single stemmed, but *Xymalos monospora* is typically multi-stemmed. The majority of trees are evergreen, but many deciduous trees are

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[5] When making reference to this section, please cite as follows:

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present that gives the impression of an open forest canopy during the winter (dry) months (von Maltitz *et al*., 2003).

4.2 Materials and Methods

4.2.1 Site description

The Ingeli State Forest (-30.532044° S; 29.700827° E, Alt = 1232 m.a.s.l.) is located between Kokstad and Port Shepstone in southern KZN (Figure 33).

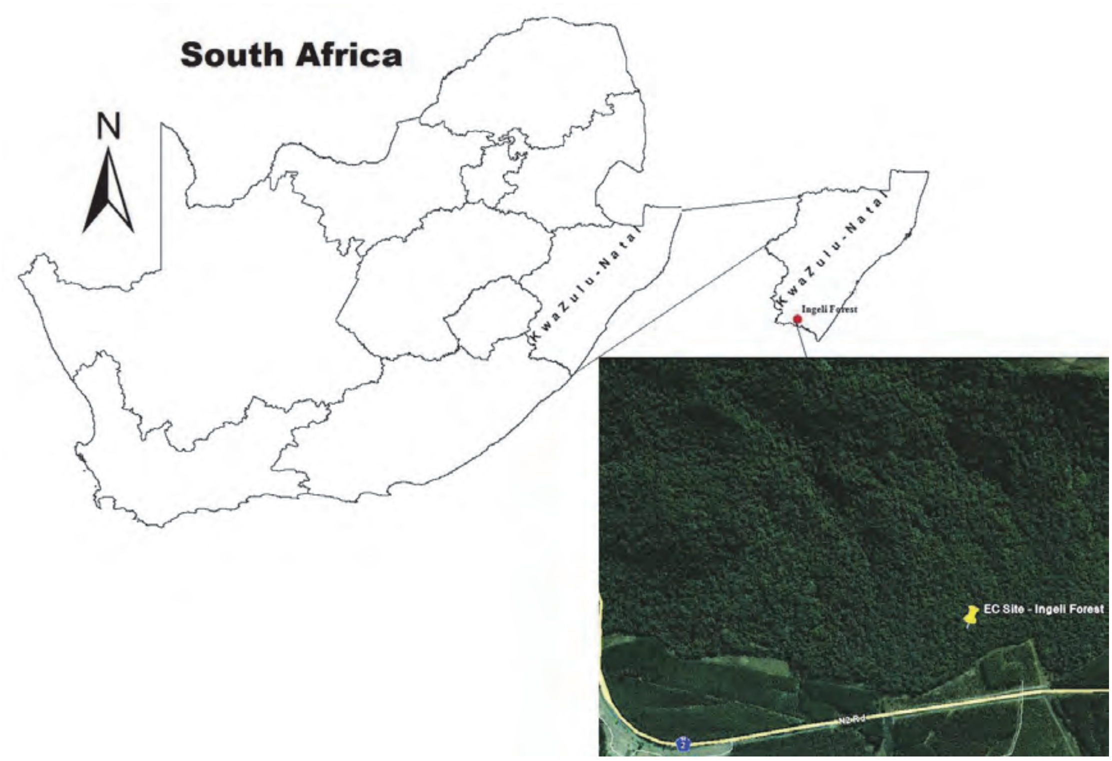

Figure 33. Aerial view and geographical position of the Ingeli State Forest.

These forests frequently experience heavy summer mist, and are generally moist. The mean annual rainfall in the area varies between 804 and 1123 mm, with the wet season (mean rainfall 91 to 197 mm per month) from October to March, and the dry season (7 to 24 mm per month) between June-July (Cawe 1986). The soils are generally doleritic, highly weathered and iron-rich, but relatively nutrient rich and loamy. The area is underlain by the Ecca Group (black shales, mudstones and sandstones and the Beaufort Group (mudstones, sandstones, dolerite and shales) (Cawe 1986). Historically these forests were surrounded by grassland, but in many areas are now surrounded by commercial timber plantations. A long-term growth plot in the Ingeli area

(Geldenhuys 1999) gives an average tree density of 1112 spha (for stem with DBH >50 mm), mean DBH of 24.3 cm, and mean basal area of 40 $m^2.ha^{-1}$.

4.2.2 Field measurements

The inaugural field campaign to install instrumentation and take measurements within the Ingeli forest was carried out from 4 to 14 October 2011. During this trip sap flow (water-use/transpiration) monitoring systems were installed in various indigenous and introduced tree species, a complete automatic weather station was set up in the vicinity of the forest, short-term total evaporation measurements were taken above the forest canopy using micrometeorological instrumentation (eddy covariance system) mounted on a telescopic mast, and accurate above-ground stem biomass measurements on all the HPV trees, as well as additional pertinent information from the forest (tree heights, species and leaf area index), were recorded. Three independent HPV sites were installed in various locations, namely a Stinkwood site, and two Cape Beech sites.

Weather

Weather data (solar radiation, maximum and minimum temperature and relative humidity, wind speed, wind direction and rainfall) were recorded on an hourly basis from 6 October 2011 to 20 November 2013 using an automatic weather station (Campbell Scientific Inc., Logan, Utah, USA) positioned in an open grassed area (-30.540772° S; 29.675638° E) within the DAFF Wesa office grounds, at an elevation of 1223 m.a.s.l.

Sap flow (transpiration) and soil water

The heat ratio method (HRM) of the HPV technique (Burgess *et al.*, 2001), as described in Chapter 2 was utilised for sap flow measurements. A *Celtis africana* (White Stinkwood), a *Prunus africana* (Red Stinkwood) and a *Rapanea melanophloeos* (Cape Beech) tree1 (Table 15) were instrumented at the respective sites, using separate sap flow monitoring systems (Figure 34 and Figure 35). The Thermal Dissipation Probe (TDP) technique (Granier, 1985, 1987) was applied on an additional *Rapanea melanophloeos* (Cape Beech) tree2.

Table 15. Details of the individual trees selected for sap flow measurements at Ingeli.

Species	Diameter at breast height (cm)	Tree height (m)	Sapwood depth (cm)	Wound width (mm)	Bark width (mm)	Wood density ($g.cm^{-3}$)
C. africana	21.1	11.5	5.5	3.0	4	0.69
P .africana	18.9	12.4	5.5.	3.5	5	0.61
R. melanophloeos 1	13.3	11.0	4.5	4.0	7	0.59
R. melanophloeos 2	11.5	10.5	4.5	4.0	7	0.59

Figure 34. Heat Pulse Velocity system measuring sap flow in indigenous *Celtis africana* (White Stink-wood) *and Prunus africana* (Red Stink-wood) trees at Ingeli (Photo: M. Gush).

Figure 35. Heat Pulse Velocity system measuring sap flow in *Rapanea melanophloeos* (Cape Beech) trees at Ingeli (Photo: M. Gush).

The Thermal Dissipation Probe (TDP) method measures temperature changes in a heated probe implanted in the sapwood and an unheated reference probe below the heated probe (Figure 36). These sensors are spaced 40 mm apart and measure changes in heat dissipation caused by the movement of sap up the stem of the plant. Increases in sap flow result in the heated probe been cooled causing the temperature difference (dT) to be small. While when the sap flow velocity is low the temperature difference (dT) between the two sensors is the greatest. This approach enables the measurement of sap flow velocity. The Thermal TDP technique uses a constant heating method where the heating element of the probe stays on and permits continuous and frequent measurements allowing a continuous signal to the logger. This allows the difference in temperature between the probes (dT) to be continuously recorded and automatically converted to sap velocity.

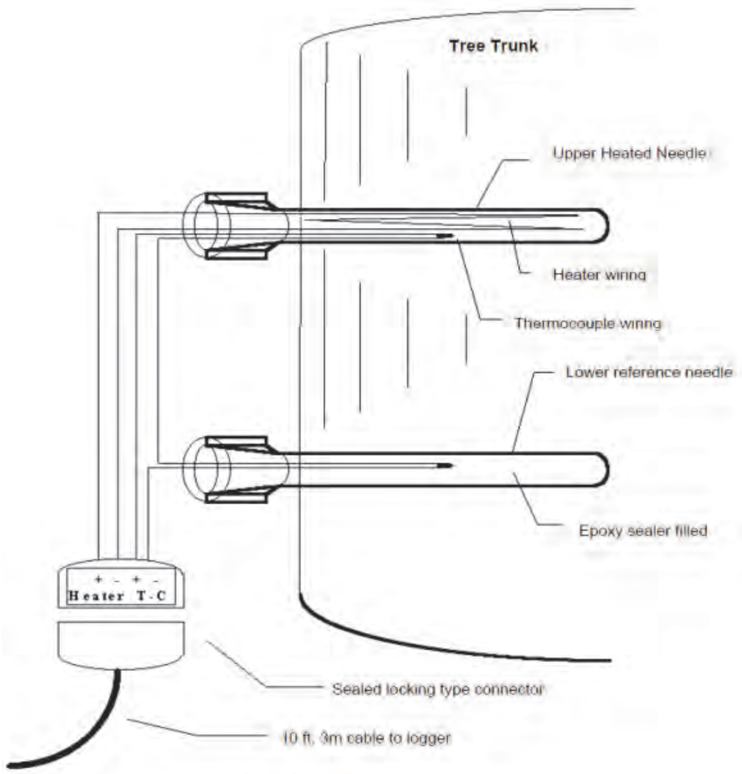

Figure 36. Illustration of installed TDP system.

From Granier (1985, 1987) average sap flow velocity V (cm/s) may be empirically determined by the exponential expression:

$$V = 0.0119 * K^{1.231} \quad \text{Eq. 5.1}$$

where the parameter K is defined as:

$$K = (dTM - dT)/dT \quad \text{Eq. 5.2}$$

where dT is the measured difference in temperature between that of the heated needle relative to the lower non-heated needle. The value of dT is determined from the differential voltage measured between the upper and lower thermocouples. The parameter dTM is the maximum value of dT when there is no sap flow (zero set value) (Dynamax, 1997). The TDP method requires that the physical dimensions of the sapwood be known in order to convert velocity to a sap flow rate as follows:

$$Fs = As * V * 3600 \quad \text{Eq. 5.3}$$

where Fs is the sap flux density ($cm^3 \ h^{-1}$), As is the cross-sectional area of sapwood, V is sap flow velocity, and the multiplier of 3600 is used to convert to hourly values (Dynamax, 1997). The system was wired to accommodate a

CR1000 logger which was programmed using CR basic programming language within the LoggerNet software supplied by Campbell Scientific.

Volumetric soil water content within the forest, and at the respective sap flow study sites, was recorded hourly in the top 100 mm of the soil profile throughout the monitoring period using CS616 Soil water content probes (Campbell Scientific Inc., Logan, Utah, USA). Soil samples taken in the vicinity of the probes were assessed for gravimetric water content, and assisted in calibration of the soil water data which was adjusted accordingly.

Stem biomass increments and water use efficiency

Stem biomass increments surveys, according to the method described in Chapter 2, were undertaken for all sample trees in order to calculate WUE. An initial survey was conducted on the trees on 11 October 2011, after they had been instrumented with the HPV systems. Subsequent stem volume surveys were carried out on 23 May 2012, 5 December 2012, 13 February 2013, 17 July 2013, 21 August 2013 and 31 October 2013. Stem biomass increments over 12 months of monitoring were converted from volume to mass using wood densities determined for the trees (Table 15). In conjunction with the sap flow (water-use) results, this allowed the calculation of WUE, defined as mass of above-ground woody stem biomass produced (g) per unit of water transpired (L).

Total evaporation (ET)

Total evaporation of the forest was measured using the eddy covariance technique (ET_{EC}), as described in chapter 3. Measurements were conducted over three field campaigns representing spring (6 to 12 Oct 2011), winter (23 to 31 May 2012) and a 69-day summer period (5 December 2012 to 11 February 2013). Sensors were mounted on a Clark WT8 pneumatic telescopic mast (Figure 37). As no immediate vehicle access to the forest was possible measurements were conducted at a point within the Ingeli forest to which the telescopic mast batteries and instrumentation could be carried by hand from the southern boundary of the forest. A suitable location for the installation of the mast (-30.532492° S; 29.700068° E, elevation = 1230 m) was identified approximately 150 m from the southern boundary and 1.1km from the northern boundary of the forest. From this point northwards the forest begins to climb dramatically in altitude, rising 300 m to the grassland plateau above. The predominant wind direction is down the slope from the North, providing adequate “fetch” for the EC technique

Figure 37. Telescopic mast and eddy covariance system projecting above the Ingeli forest canopy, and measuring ET_{EC} (Photo: M. Gush).

4.2.3 Modelling

The purpose of this task was to model the water use of Ingeli forest to improve our understanding of the water use efficiency (WUE) of indigenous forests. Growth data are available from fixed plots in the Ingeli forest, but we required an assessment of water use that covered at least one full year to describe the typical pattern of total evaporation (ET) in different seasons of the year. Water use was defined here as total ET from the forest, and included wet canopy evaporation, and the total transpiration from the trees. Modelling of ET from the forest was undertaken for three main reasons:

- To estimate ET over the full AWS data record, extrapolating between periods of field measurements, to provide a continuous and complete estimate of cumulative water use.
- to further our understanding of the controls on the ET process from indigenous forests of this type.
- to estimate the magnitude of wet canopy evaporation which, under wet and misty conditions and low flux rates, may not be accurately measured with EC systems.

An eddy covariance (EC) micrometeorological system was deployed to measure 30-minute ET_{EC} during three separate field campaigns in different seasons. Total evaporation (ET_{EC}) data collected over a total of 84 days during the three field campaigns, together with estimates of ET_o derived from the weather data, were used to parameterise the model. The method was the same as that described in Chapter 2.

Modelling daily ET

Measured ET_{EC} was recorded over the three field campaigns. Thirty-minute readings were totalled over each 24-hour period. These daily ET_{EC} totals were used to determine 1) if soil water availability is an important factor governing ET in the dry winter months, and 2) if a useful relationship to calculated reference evaporation exists, by which daily ET from the Ingeli forest can be predicted.

Modelling hourly ET

Rainfall interception by forest canopies can be relatively large, especially at high altitude forest sites in South Africa with high rainfall and frequent misty conditions (Bulcock, 2011; Bulcock and Jewitt, 2012). Evaporation from wet canopies can therefore be a substantial component of ET. There is some doubt as to how accurately EC systems can measure this loss under these conditions. Evaporation from wet canopies is not specifically considered in the ET_0 formula but needs particular attention in forests due to high leaf areas and high aerodynamic roughness of the canopy. A full ET estimation from Ingeli forest therefore requires an evaluation of canopy rainfall storage, evaporation of free water and the frequency and duration of rainfall and drying conditions at hourly intervals.

An additional reason for examining hourly patterns of ET and weather variables is to reveal more about controls on ET which are not captured at a daily time step.

The MAESPA model

The MAESPA tree/forest model was used to model hourly ET from Ingeli forest. The MAESPA model (Duursma and Medlyn, 2012; Medlyn *et al.*, 2005) is a quantitative tool that calculates forest canopy radiation absorption, photosynthesis, energy balance and water balance (Duursma, 2014). The model integrates two Process Based Models (PBMs), namely the MAESTRA (Medlyn *et al.*, 2005) and SPA (Williams *et al.*, 2001) models. The MAESTRA model is a tree array model that uses radiation transfer calculations and leaf physiology to calculate radiation absorption, photosynthesis and transpiration of individual trees or stands (Medlyn *et al.*, 2005). MAESTRA, however, does not include dynamic water balance so feedbacks to plant performance from soil water cannot be simulated (Duursma, 2014). On the other hand, the SPA model simulates the impacts of soil water availability on the water use of forest canopies. It however assumes a horizontally homogenous canopy, rendering it impractical for individual trees (Duursma and Medlyn, 2012). The detailed soil water balance routines of the SPA model were added to the MAESTRA model, resulting in the MAESPA model (Figure 38). A very comprehensive description of MAESPA is available on the internet (http://maespa.github.io/manual.html) and further details are available in Duursma and Medlyn (2012).

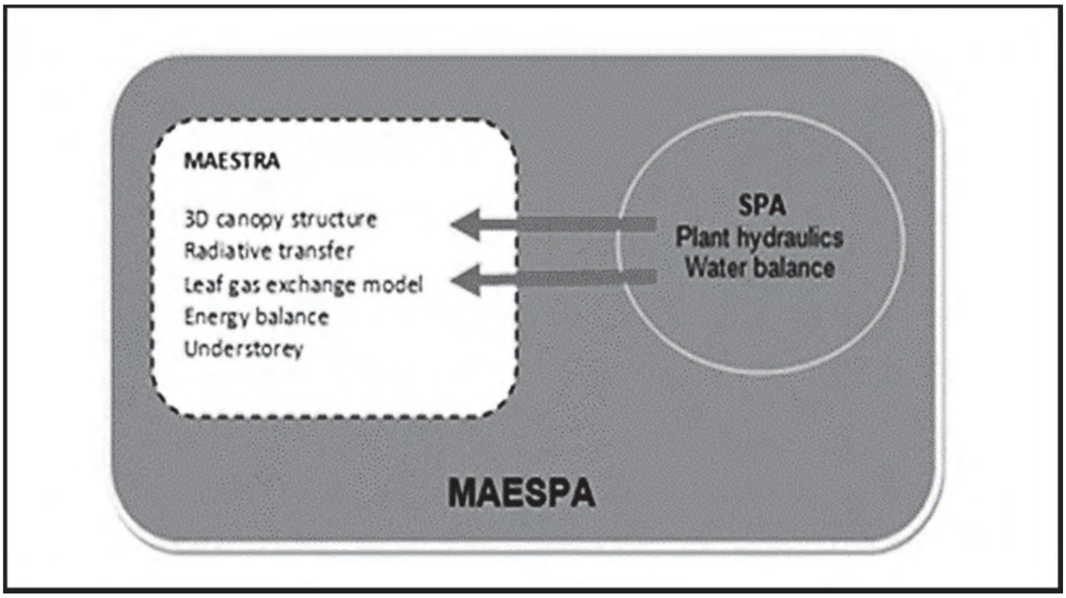

Figure 38. The MAESPA model, a result of integrated components of the MAESTRA and SPA models adapted from (Duursma, 2014).

MAESPA is a tree array model that uses detailed radiative transfer calculations and leaf physiology to calculate radiation absorption, photosynthesis, transpiration and total water use of individual trees growing singly, or as a group of trees in a stand. It has been shown to successfully scale up from leaf-level to canopy-level processes (Medlyn *et al*., 2005). MAESPA appears to have sufficient detail to describe a wide range of indigenous species of South African trees. For example, it is able to account for different canopy shapes, leaf inclination and leaf distribution within the canopy, leaf flushes and senescence in older leaf cohorts, seasonal changes in LAI, differences in photosynthesis and transpiration rates in different leaf cohorts, varying stomatal presence on abaxial and adaxial leaf surfaces, shading effects from own leaves and neighbouring trees, rainfall interception and evaporation, understorey transpiration, soil evaporation, boundary layer resistances, etc. Our present state of knowledge of the physiology of indigenous trees is poor and much further study is required to improve model parameterization. Nevertheless, MAESPA can be run with limited parameterization, using default values for many parameters. The MAESPA model structure is applicable to modelling indigenous tree species in natural stands as it simulates individual trees using explicit spatial coordinates (Duursma, 2014). Some of the model applications include; calculating the soil water balance for a small subplot surrounded by rows of other trees, simulating an entire stand using a subset of trees to derive the water balance, simulating a single tree for individual water use and soil water balance, and simulating canopy sapflow using the Penman Monteith equation (Duursma, 2014; Duursma and Medlyn, 2012). Essential features of the transpiration module of MAESPA are:

- MAESPA models growth and water-use of tree stands, forest patches or individual trees.
- A forest canopy is represented in the model as an array of tree crowns, whose positions and dimensions are specified. Single trees are easily handled, and understory water-use can also be simulated.
- Calculations are performed for just one tree crown at a time, the 'target tree', but there can be multiple target trees in a plot, representing the same or different species, and different size classes.
- The distribution of leaf area within the target crown is specified, as is the leaf angle distribution.
- The main meteorological driving variables are incident solar radiation, air temperature and humidity.
- The target crown is divided by the model into a number of grid points, and the radiation penetrating to each grid point is calculated for three wavebands (PAR, near infra-red and longwave). Direct, diffuse, and scattered radiation are considered separately.
- The absorbed PAR at each grid point drives the photosynthesis and transpiration routines.
- Photosynthesis is calculated from the Farquhar-von Caemmerer model.
- Stomatal conductance can be calculated from either of the Jarvis, Ball-Berry, Ball-Berry-Leuning or Ball-Berry-Opti models.
- Transpiration is calculated by applying the Penman-Monteith equation at each gridpoint, and summing over the gridpoints.
- Evaporation of water intercepted by leaf surfaces is also calculated.
- Time steps are generally 30 min, 60 min or daily.
- The model is implemented in Fortran with simple text input and output files, and is freely available on the internet.
- Output files can be read into Excel for easier interpretation and graphing.
- MAESTRA/MAESPA are thoroughly validated on many tree species, and more than 100 papers have been published in the scientific literature.

MAESPA inputs and outputs
The FORTRAN executable file requires seven main input files that are edited using any text editor. They are:

- CONFILE, Simulation and control file
- MET, Meteorological drivers, site location
- PHY, Leaf physiology file
- STR, Stand structure file
- TREES, Tree size and location file
- WATPARS, Water balance, soil and plant hydraulics file
- USTOREY, Understory file (optional)

These files (but not an understory file), with their parameter values for the Ingeli forest, are shown in Appendix A. A one-hour time step was chosen as appropriate for this study. Several output files provide a comprehensive summary view of the hourly and daily radiation balance, growth and water balance of the site.

MAESPA undertakes the following calculation steps:

- Site geographical coordinates and day of year are used to calculate day length and the geometry of sun's movement across the sky.
- Light interception by one or more representative target trees is calculated according to canopy dimensions and leaf characteristics. MAESPA takes shading into account, both self-shading and also by neighbouring trees.
- Photosynthesis is calculated in different parts of the canopy, using the Farquhar/Caemmerer/Berry model (Farquhar *et al*., 1989). Calculated net photosynthesis is used to estimate stomatal conductance for different parts of the canopy. The Tuzet model of stomatal conductance (Tuzet *et al*., 2003) was selected for use in this study.
- The Penman-Monteith equation is then solved for each canopy section to calculate transpiration.
- MAESPA takes boundary layer conductance and wind speed into account to simulate effect of wind on transpiration process.
- The Rutter model (Rutter *et al*., 1972; Rutter *et al*., 1975; Rutter and Morton, 1977) is used to estimate canopy rainfall storage capacity and calculate drainage from the canopy, rainfall throughfall and evaporation of intercepted rainfall. Free water on leaf surfaces is evaporated according to weather conditions, assuming an infinitely high stomatal conductance while the leaves remain wet.
- The option to model water use by understorey plants was not adopted in this study, due to insufficient data on this stratum of the forest. Also, the understorey plants were heavily shaded by the tree and shrub

canopies, and so their contribution towards the total forest ET is expected to be small.

Stand Structure

The forest site was conceptually defined as a 50 by 50 m stand. The forest canopy was found to be structurally very heterogeneous and therefore unsuited to precisely describing individual canopies on the basis of their canopy shape, total leaf area and leaf distribution within the canopy volume. The approach adopted therefore was to assume a continuous canopy of one species with average properties. The forest leaf area index was measured as 3.2 in June 2014. This was reduced to 2.5 to adjust for estimated light interception by non-leaf material such as branches and stems. The canopy was simulated by adding 5 by 5 rows of large identical trees with canopies stretching from 1 to 20 m in height, each canopy being oval in shape, with canopies at maximum width touching each other. A random arrangement of leaves within canopies was assumed with a leaf area of 250 m^2 assigned to each tree. The model thus describes a continuous canopy in which there is no distinction between tree species. Taller plants in the understory were included in the generic forest canopy, while shorter plants and soil evaporation was assumed to contribute a negligible amount towards whole-stand ET owing to the high forest LAI.

Site Conditions and Tree Attributes

A southerly aspect (180^o) and a 4% slope were specified for the site. The soil was assumed, based on published reports and field auguring, to be 1.5 m deep, with a 60 cm deep sandy clay A horizon, and an underlying 90 cm deep sandy clay B horizon. It is classified as a Humic, Rhodic, thick haplic Inanda form (Fey, 2010). Physical properties of different soil textures are described by Cosby *et al*. (1984). Total fine root mass was estimated as 1000 g m^{-2}, with 0.5 of this apportioned to the A horizon and 0.5 to the B horizon. Additional soil parameter values are shown in appendix 1 (WATPARS). Modelled rainfall interception is sensitive to the canopy storage capacity. No estimates of this could be found pertaining to South African temperate evergreen indigenous forests. Estimation is made more difficult by the fact that maximum canopy storage capacity is not a fixed quantity, but depends on rainfall intensity. A review of literature relating to evergreen indigenous forests suggested that a value of 0.8 mm may be a realistic value to adopt for the Ingeli study site. Several leaf photosynthetic parameter values are defined in appendix 1 (PHY) and are used in the calculation of stomatal conductance using the Tuzet model. Parameters for boundary layer conductance are shown in the STR file.

4.3 Results and Discussion

4.3.1 Weather

Good quality weather data was collected at this site between when the station was installed on 7 October 2011 and when it was removed on 20 November 2013. Data collection during this period was unbroken apart from 11 days (14-24 March 2012), when recording stopped due to battery failure. A faulty pyranometer also led to the loss of some solar radiation data from the station between August and November 2013. Data for these instances was sourced from weather stations operated by the South African Sugar Research Institute (SASRI http://www.sasa.org.za/sasri.aspx). The SASRI Paddock AWS provided daily weather data from the same region, which was tested and found to correlate closely with previously collected data from Ingeli, and was subsequently used to patch missing data. Hourly values were collated into daily and monthly summaries (Figure 39 and Figure 40).

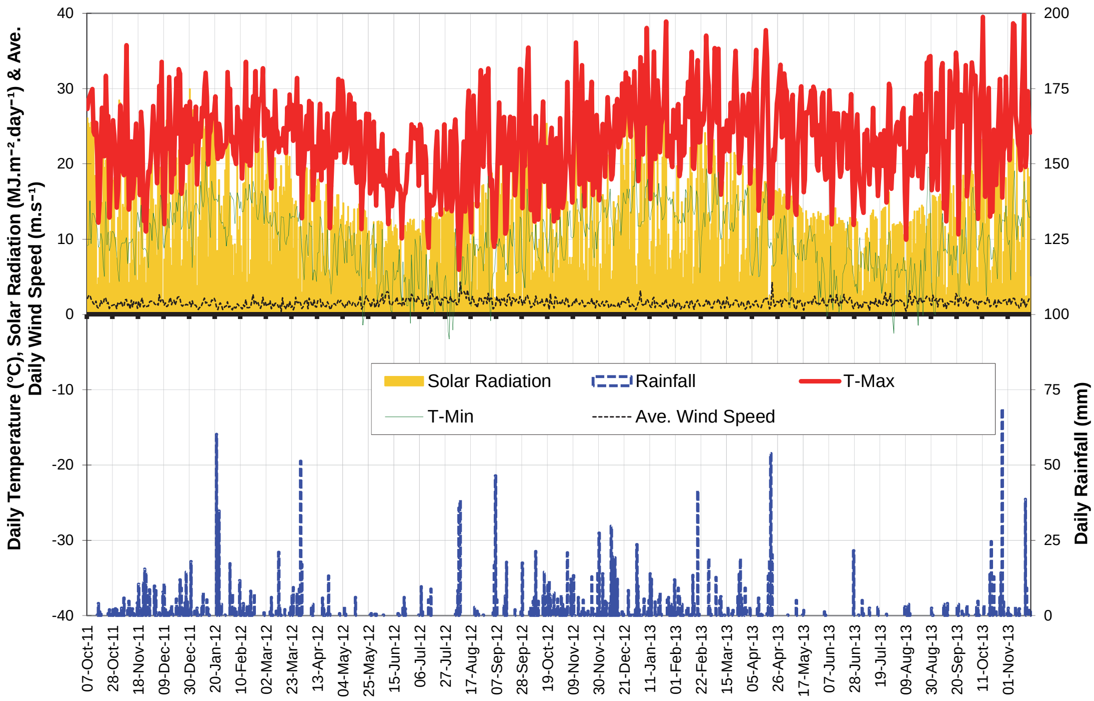

Figure 39. Daily maximum and minimum temperatures (°C), solar radiation (MJ m⁻² day⁻¹), average daily wind speed (m s⁻¹) and rainfall (mm) at the Ingeli site from 7 October 2011 to 19 November 2013.

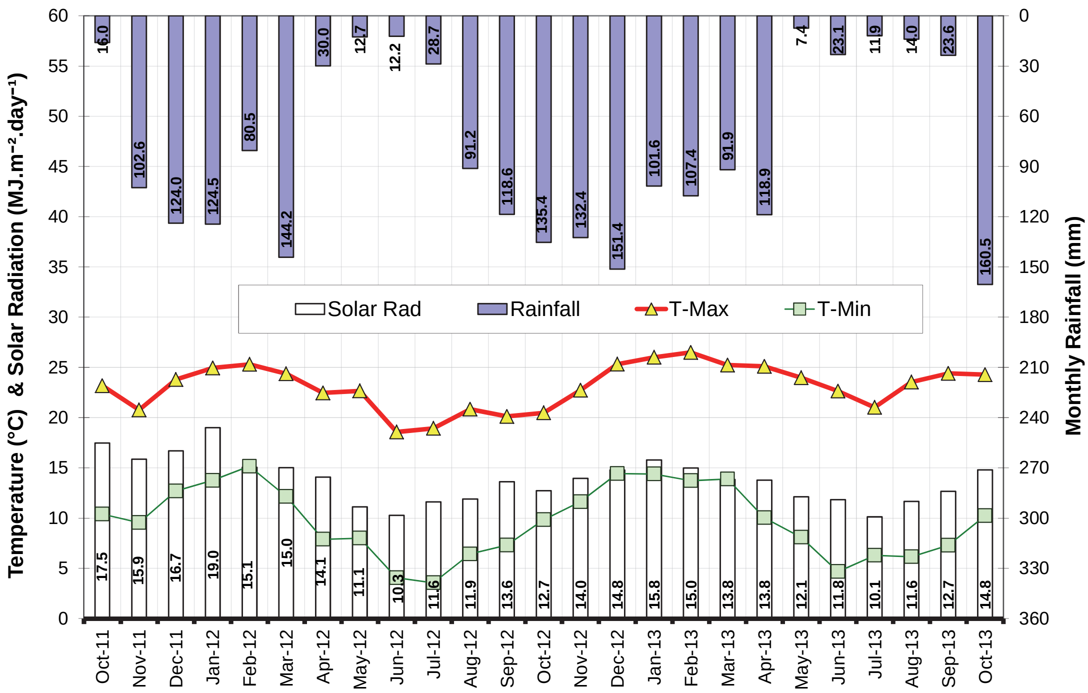

Figure 40. Monthly values of mean daily maximum/minimum temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), and rainfall totals (mm) at the Ingeli site from October 2011 to October 2013.

Monitoring yielded two years of weather data from this summer rainfall site. Warm and wet summers contrasted with cool and relatively dry winters, although some rainfall was recorded in every month. The coldest temperature recorded at the site was -3°C on 30 July 2012, while the warmest was 38.9°C on 24 January 2013. Total annual rainfall recorded at the site over the first hydrological year (Oct 2011 to Sep 2012) was 885 mm, which is remarkably similar to the Mean Annual Precipitation for the site of 888 mm (Schulze and Lynch, 2007). The rainfall total in the subsequent hydrological year (Oct 2012 to Sep 2013) was a very similar 919 mm. Seasonal variation in solar radiation was evident but not pronounced, due to the moderating influence of frequent summer mists on peak values. Daily average solar radiation peaked at a mere 19 MJ m^{-2} day^{-1} in summer (January 2012), and did not fall below 10 MJ m^{-2} day^{-1} in winter (June 2012). Daily wind-speed was also relatively consistent, averaging 1.6 m s^{-1} and ranging between 1.2 m s^{-1} (February 2012) and 2 m s^{-1} (August 2012).

4.3.2 Soil water

Figure 41 shows the pattern of daily rainfall, volumetric soil water in the top 20 cm of soil (note the reversed axis), and reference evaporation (ET_0) over the period in which good quality AWS data were recorded (7 October 2011 to 19

November 2013). Measured 30-minute ET over the three field campaigns is also shown (refer to the next section).

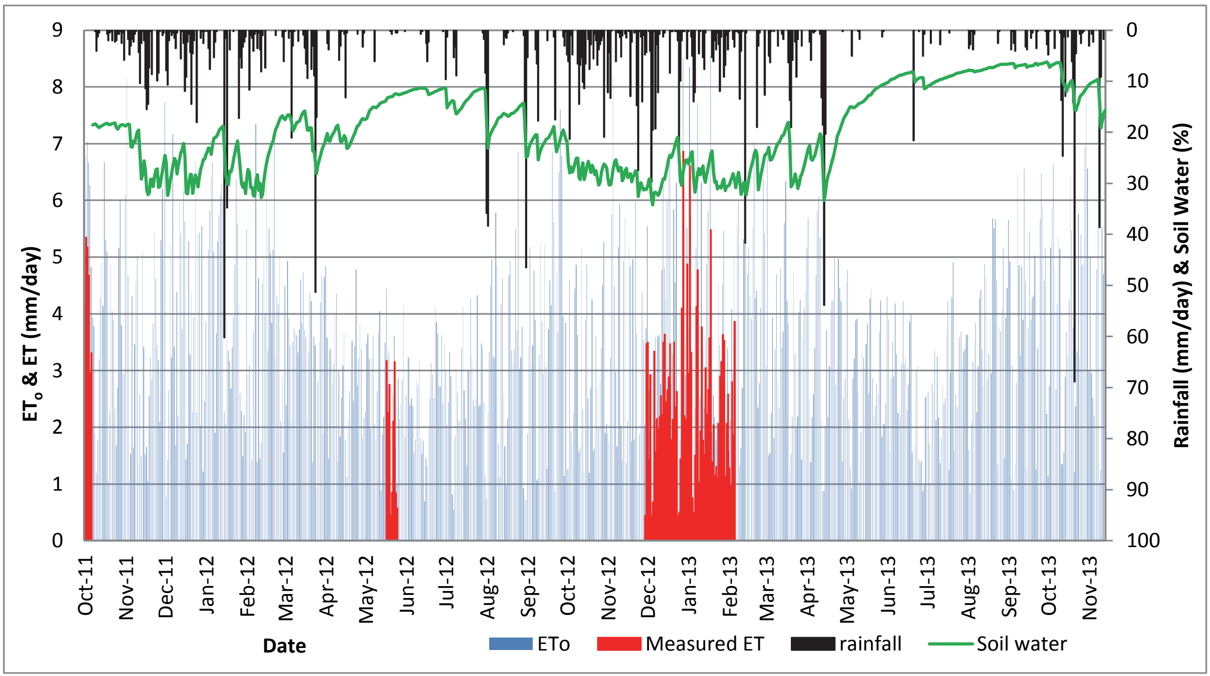

Figure 41. Seasonal patterns of daily rainfall, soil water content, reference evaporation (ET_o) and measured total evaporation (ET) recorded in the Ingeli forest.

4.3.3 Tree water use

Heat pulse (i.e. sap flow) velocities observed in the Red Stinkwood (*Prunus africana*) were fairly consistent and generally low (10-15 $cm.hr^{-1}$) for the duration of the monitoring period. A slight decline in sap flow velocities was evident at certain times in the year (e.g. October/November), during periods of frequent rain. In the White Stinkwood (*Celtis africana*) a far more pronounced seasonal fluctuation in heat pulse velocities (sap flow) was evident due to the deciduous nature of this species. Peak heat pulse velocity rates ranging from 20-30 $cm.hr^{-1}$ were observed in this tree in mid-summer (Dec). Thereafter sap flow declined consistently before stopping around mid-July as its leaves were shed towards winter. Clear reductions in transpiration during days of rain were also observed. Despite individual rainfall-related fluctuations and longer-term seasonal changes in observed soil water at shallower levels in the forest soil profile through the year (Figure 41) there was no limitation in terms of available water for these trees as they had roots which extended into the stream channel. Changes in sap flow were thus more directly linked to physiological changes (e.g. leaf area) and other micrometeorological drivers (e.g. solar radiation and temperature).

Monitoring of sap flow rates in the *Rapanea melanophloeos* (Cape Beech) trees commenced on 11 October 2011, and was terminated on 20 November 2013, when the equipment was removed. The heat pulse velocities observed in these trees have been low (<10 cm hr^{-1}), with slight seasonal trends evident. It appears that the trees maintain relatively consistent transpiration rates throughout the summer rainfall season from October to May. Thereafter sap flow velocities decline as soil water levels dry out, and temperatures/solar radiation values are lower. Sap flow rates in the trees increase slowly again from September onwards. This species appears to be sensitive to soil water availability in the upper soil horizon, suggesting a predominance of shallow roots.

Wood samples from the sample trees were excised to determine additional information necessary for the final tree water use calculations (e.g. bark thickness; wound width; sapwood depth; sapwood water content, air-dry density and basic density). Daily transpiration volumes calculated for the *Prunus africana* (Red Stinkwood), *Celtis africana* (White Stinkwood) and *Rapanea melanophloeos* (Cape Beech) trees are illustrated in Figure 42, Figure 43 and Figure 44.

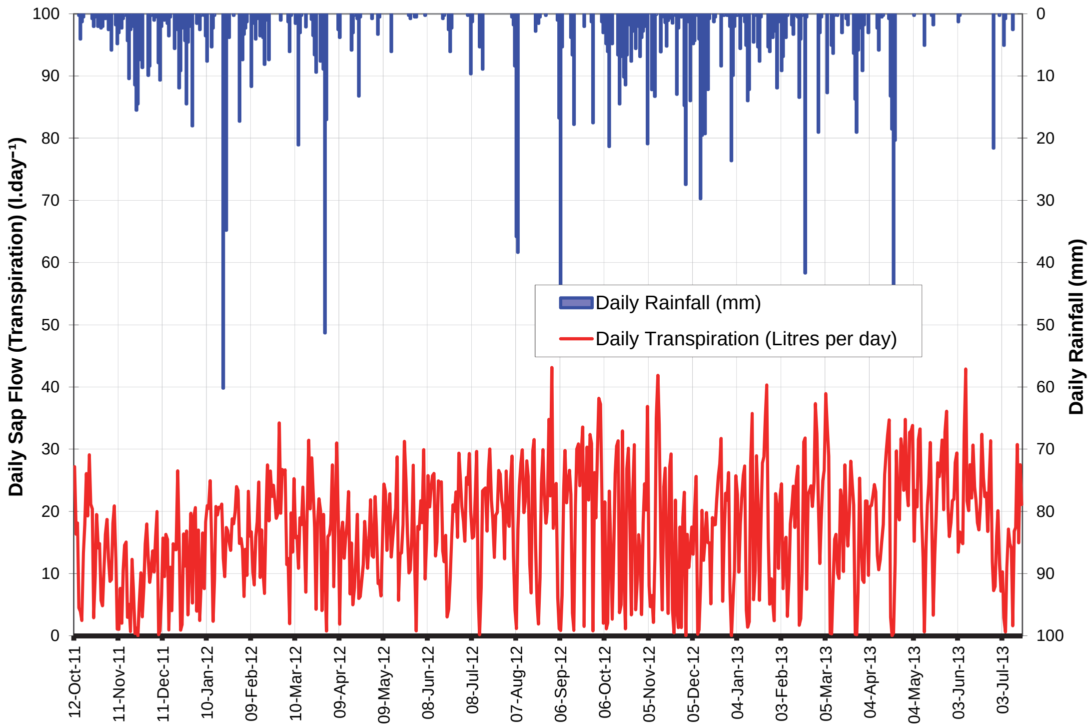

Figure 42. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Prunus africana* (Red Stinkwood) tree from 12 October 2011 to 16 July 2013.

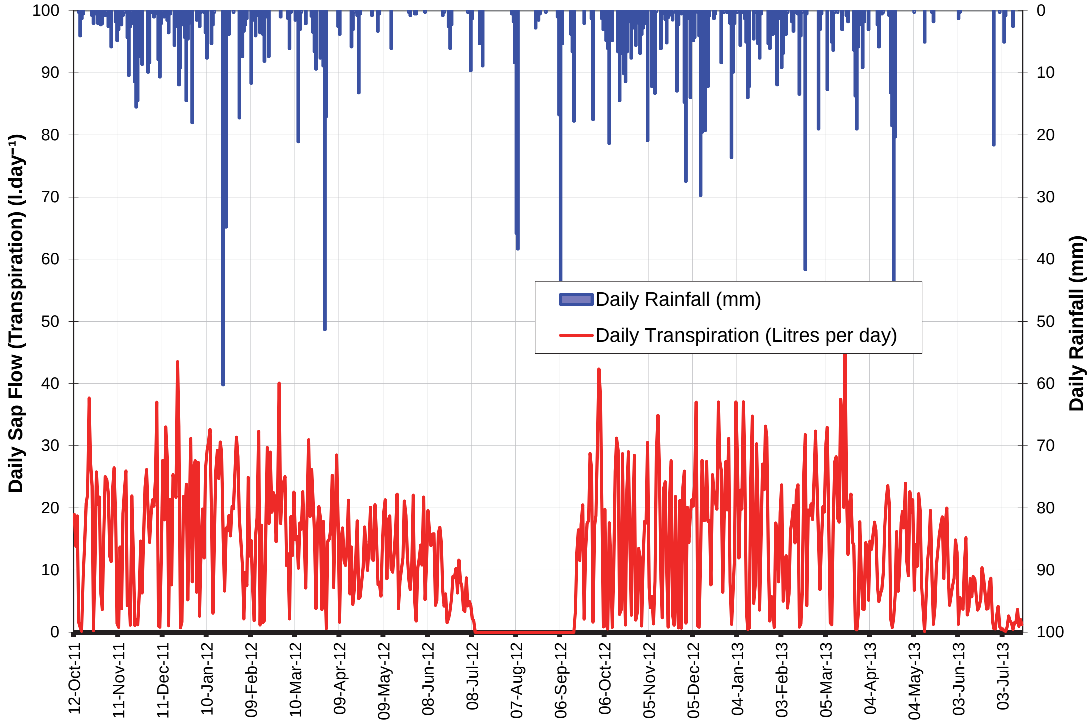

Figure 43. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Celtis africana* (White Stinkwood) tree from 12 October 2011 to 16 July 2013.

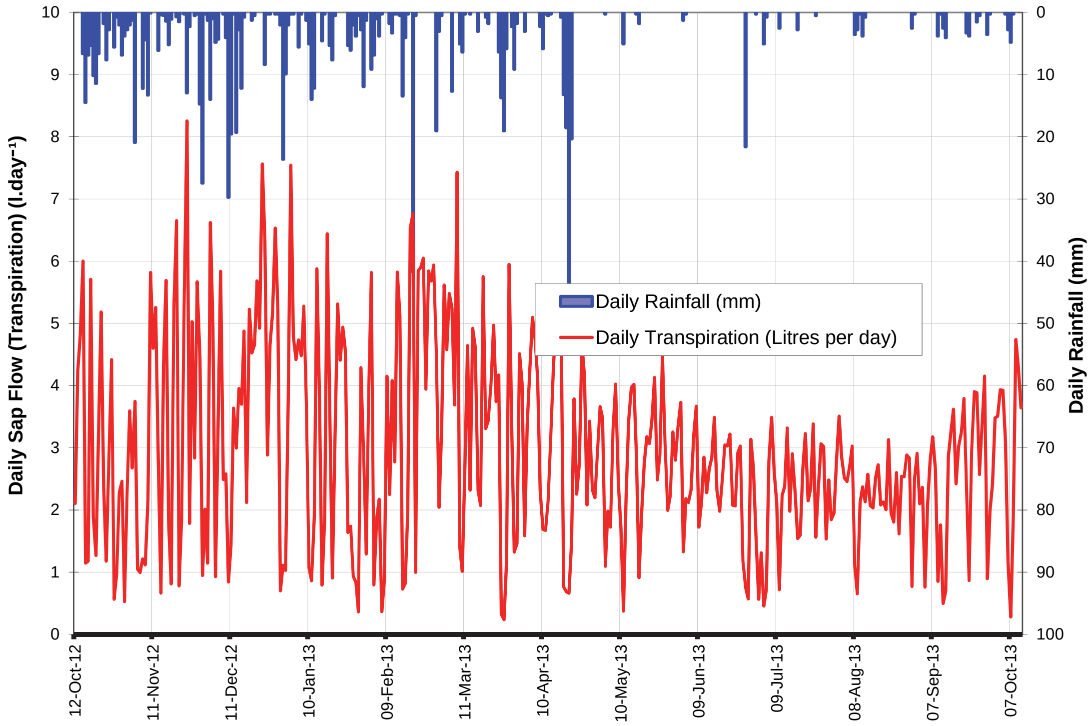

Figure 44. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Rapanea melanophloeos* (Cape Beech) tree from 12 Oct 2012 to 11 Oct 2013.

4.3.4 *Total Evaporation (ET)*

A spring field campaign measured total evaporation (ET_{EC}) above the Ingeli forest from 6 to 12 October 2011, a winter campaign from 23 to 31 May 2012, and a 69-day summer campaign (5 December 2012 to 11 February 2013). Periods of warm and dry weather, with clear skies, were experienced over the spring monitoring period, with daily temperatures generally ranging between 11-28°C, daily solar radiation totals of around 25 MJ m^{-2} day^{-1} and relatively high daily average wind speeds of around 2 m s^{-1}. Consequently total evaporation rates measured above the forest during these days were high, peaking at 5.34 mm. However, some cooler days (e.g. 6 & 12 October) combined with misty conditions during the night and early morning, reduced daily ET_{EC} totals on these days to approximately 3 mm (Figure 45). No rain was recorded over the monitoring period, although heavy mists were evident during the night of 11 October through to the early morning of 12 October, and again that evening. The effects of mist on the energy balance variables are evident in the data.

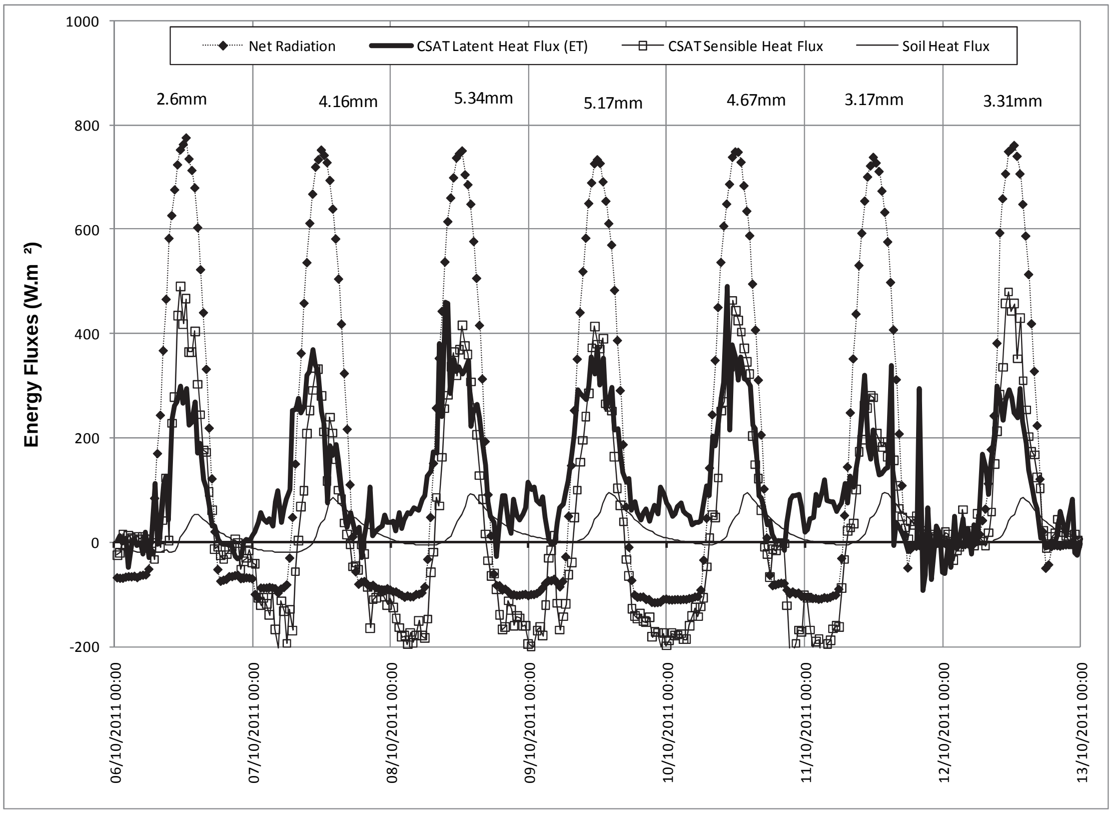

Figure 45. Half-hourly energy fluxes and resultant daily total evaporation totals (mm) measured above the indigenous Ingeli forest, using the CSAT 3D eddy covariance system, from 6-12 Oct 2011.

For the most part, typical winter weather conditions were experienced during the winter campaign, with temperatures ranging from 5-27°C, low wind speeds (average 1.6 m s^{-1}) and wide-ranging humidity (9-97.6%). Clear skies were experienced on some days, resulting in high ET_{EC} values, but there were also some minor rainfall events over this period (26/27 May and 30/31 May), during which the overcast and misty conditions limited available energy with resultant low ET_{EC} values being recorded. Solar Radiation ranged from 4 MJ m^{-2} day^{-1} on rainy days to 13 MJ m^{-2} day^{-1} on sunny clear days. Consequently, total evaporation rates measured above the forest exhibited a wide range from 0.44 to 3.17 mm day^{-1} (Figure 46).

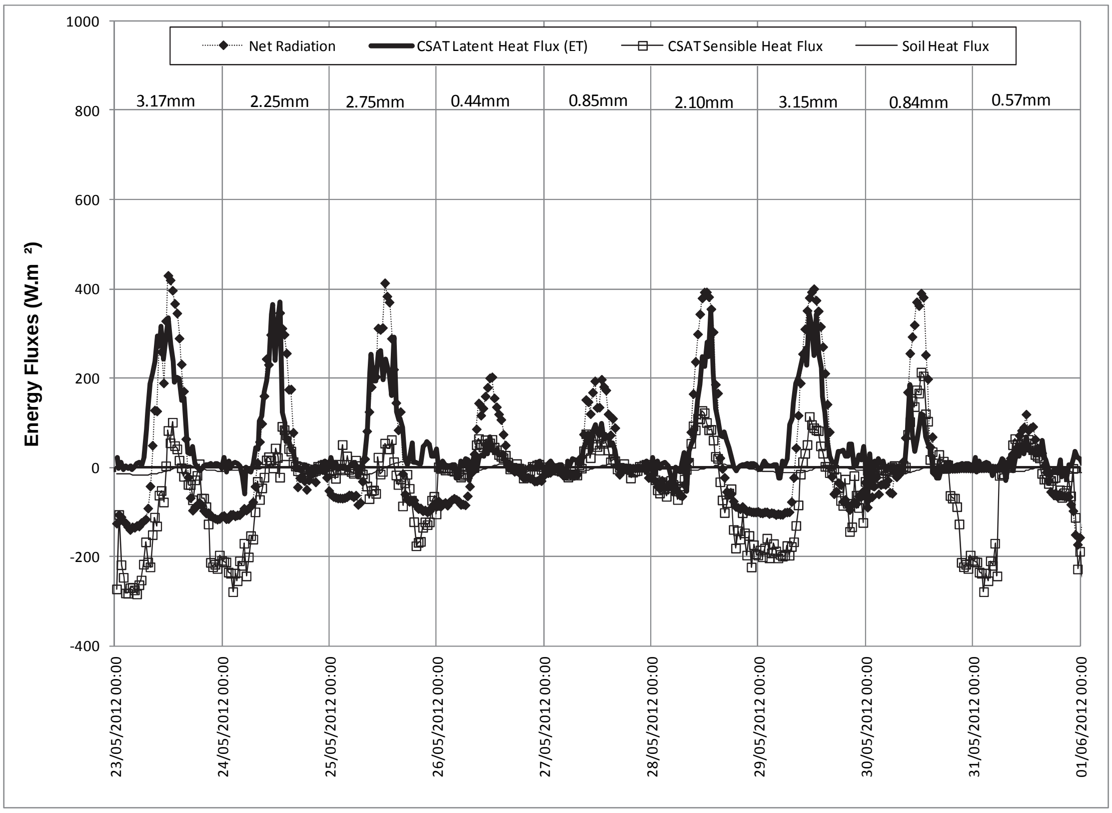

Figure 46. Half-hourly energy fluxes and resultant daily total evaporation totals (mm) measured above the indigenous Ingeli forest, using the CSAT 3D eddy covariance system, from 23-31 May 2012.

A prolonged final campaign conducted over a 69-day period in mid-summer was made possible through the assistance of the local DAFF staff (forest guards), who assisted in regular exchange and charging of the batteries used to power the system. Typical summer weather conditions were experienced during this campaign, with numerous rainfall events and periods of mist and drizzle, interspersed with extremely hot and humid conditions. Daily maximum temperatures ranged from 15 to 39°C, wind speeds were generally low (maximum 3.2 m s^{-1}, average 1.3 m s^{-1}) and humidity was high. Clear skies were experienced regularly, resulting in high ET_{EC} values, but there was also substantial rainfall over this period (261 mm), and daily rainfall exceeding 1 mm was recorded on 34 out of the 69 days. Consequently, solar radiation ranged widely from 4 MJ m^{-2} day^{-1} on rainy days to 28 MJ m^{-2} day^{-1} on sunny clear days. The observed hourly ET_{EC} data were thoroughly checked for data spikes (caused by mist/water on the sensors), and missing data (caused by inadequate power due to low battery voltages). These periods were patched using reliable data collected under conditions of similar weather at other times in the campaign. Resultant total evaporation rates measured above the forest exhibited a wide range from 0.44 to 6.86 mm day^{-1} (Figure 47). In previous campaigns, spring (October 2011) ET_{EC} rates peaked at 5.34 mm and winter (May 2012) ET_{EC} rates only reached 3.2 mm day^{-1}.

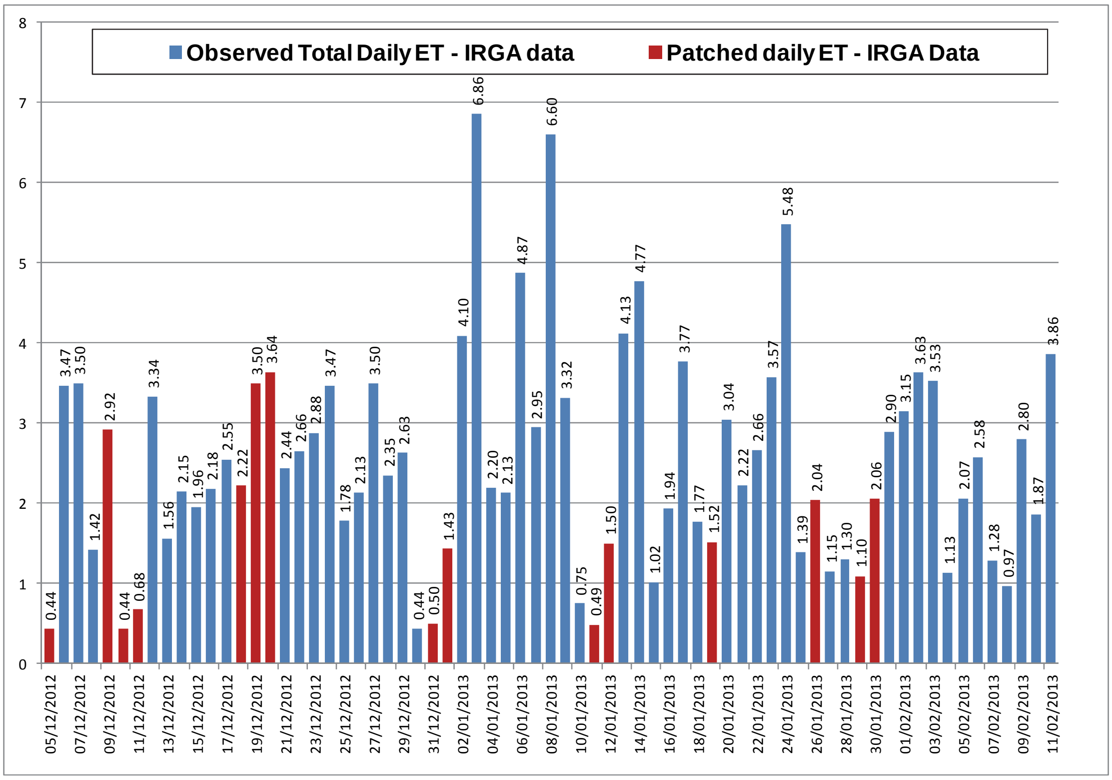

Figure 47. Daily total evaporation (ET_{EC}) totals (mm) measured above the indigenous Ingeli forest, using the CSAT 3D eddy covariance system, between 5 December 2012 and 11 February 2013.

4.3.5 Stem biomass increments and water use efficiency

Stem biomass increments over 12 months of monitoring were converted from volume to mass (Table 16) using wood densities determined for the trees.

Table 16. 1-year stem volume increments observed in a *Prunus africana* (Red Stinkwood), a *Celtis africana* (White Stinkwood) and a Rapanea melanophloeos (Cape Beech) at Ingeli.

Tree Species	Tree Height (m)	Initial DBH (cm)	Final DBH (cm)	Initial Stem Volume (m^3)	Final Stem Volume (m^3)	Stem Volume Increment (m^3)	Wood density (g cm^{-3})	Stem Mass Increment (kg)
P. africana	11.5	18.9	20.3	0.1588	0.1842	0.0254	0.69	17.5
C. africana	12.4	21.1	21.9	0.2179	0.2366	0.0187	0.61	11.3
R. melanophloeos	11.0	13.8	14.2	0.0797	0.0860	0.0063	0.59	3.7

In conjunction with the sap flow (water-use) results, it was then possible to calculate WUE, defined as amount of stem biomass produced (g) per unit of water transpired (L) (Table 17).

Table 17. Summary of WUE data for indigenous *Prunus africana* (Red Stinkwood), a *Celtis africana* (White Stinkwood) and a *Rapanea melanophloeos* (Cape Beech) at Ingeli, as calculated from a mass-based ratio of 1-year biomass increment (stem wood) over water-use.

Tree Species	1-yr Water-use (L)	Stem Volume Increment (m^3)	Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
P. africana	6 803	0.0254	0.69	17 540	2.73
C. africana	4 156	0.0187	0.61	11 291	2.58
R. melanophloeos	1 242	0.0063	0.59	3 679	2.98

4.3.6 Modelling

Modelled Daily ET

Figure 48 shows a comparison of ET_{EC} to ET_0 using daily data from all three field campaigns. The first and third field campaigns occurred during periods of rainfall and relatively high soil water content, whereas the second field campaign coincided with dry conditions. The brown data points in Figure 48 represent the data collected during the second field campaign and show that there was no indication of reduced ET_{EC} during this time. The trees are believed to have sourced water from deeper levels in the soil after the topsoil dried out. ET_0 combines the influence of solar irradiance, vapour pressure deficit and wind (FAO-56) and accounts for 74% of the total variance. A straight line fit to these data shows ET_{EC} to be 0.63 of ET_0.

Figure 49 shows a strong correlation between daily ET_{EC} and solar irradiance. Again, there is no indication of reduced daily ET_{EC} during the second, driest field campaign. The influence of VPD is clearly an additional factor in determining daily ET (Figure 50). Daily ET was estimated for the entire two-year period assuming ET to be 0.63 of ET_0 (Figure 51). Total ET equaled 1689 mm over 775 days, and approximated 795 mm per year. Annual rainfall over the same period was 2026 mm, and so ET equaled 83% of rainfall, with the remainder either stored in the soil profile, draining below the soil profile, or lost as wet canopy evaporation. Maximum modelled daily ET equaled 5.4 mm day^{-1}.

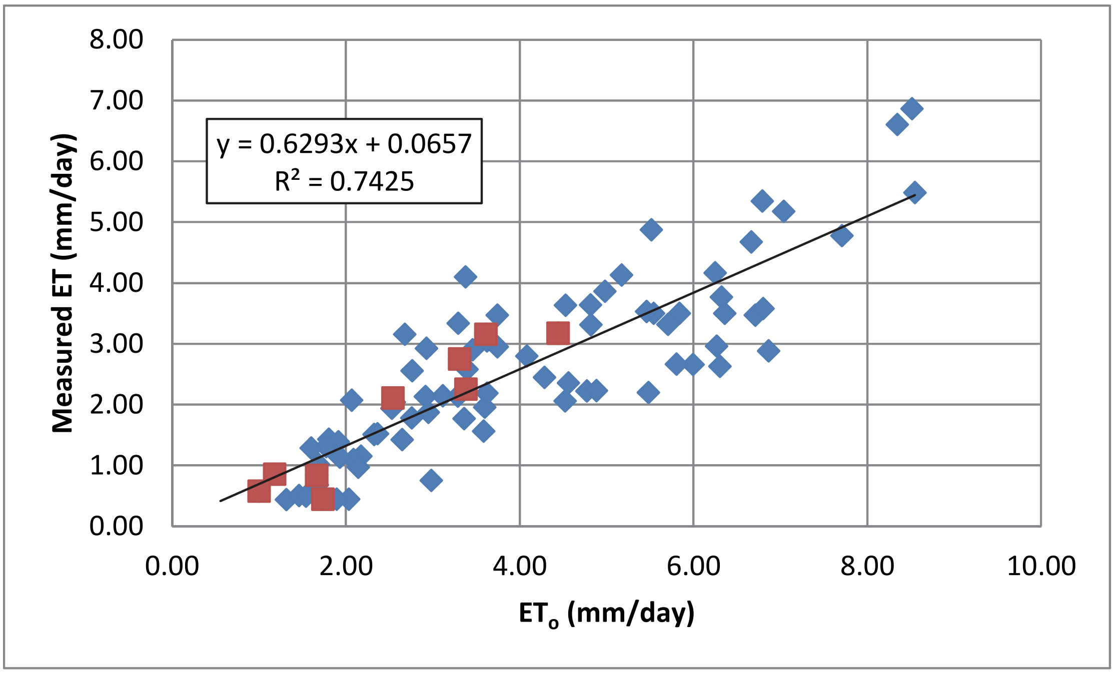

Figure 48. The relation between ET_o and measured ET_{EC} (mm day^{-1}). The brown squares represent data recorded in the second field campaign.

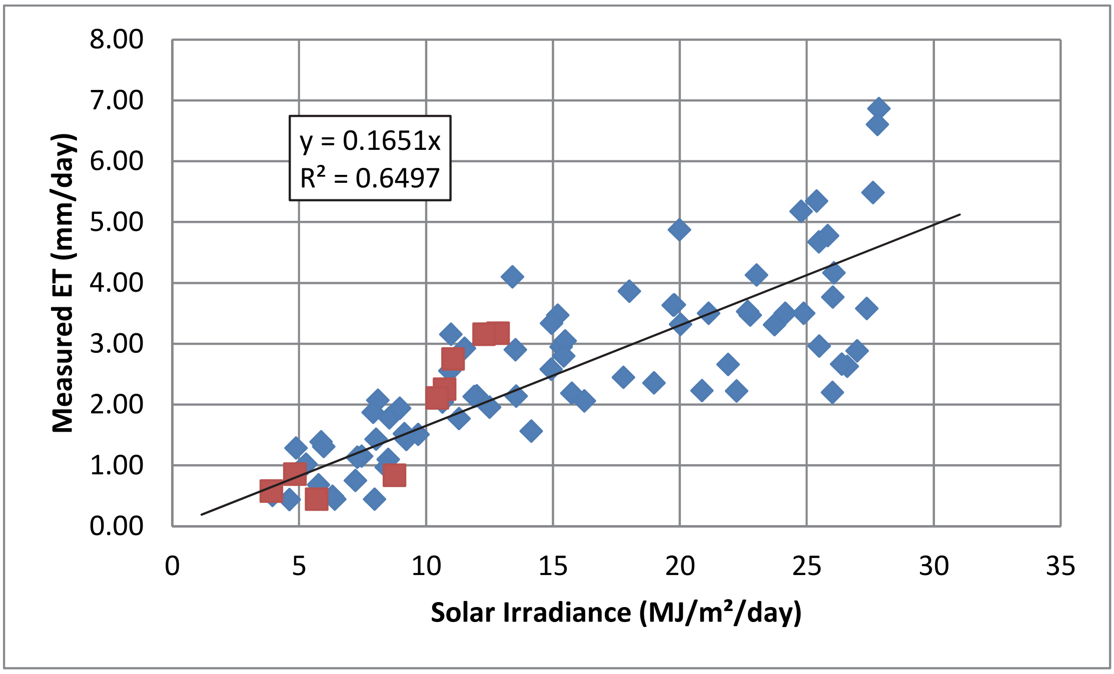

Figure 49. The relation between solar irradiance (MJ m^{-2} day^{-1}) and measured ET_{EC} (mm day^{-1}). The brown symbols represent data recorded in the second field campaign.

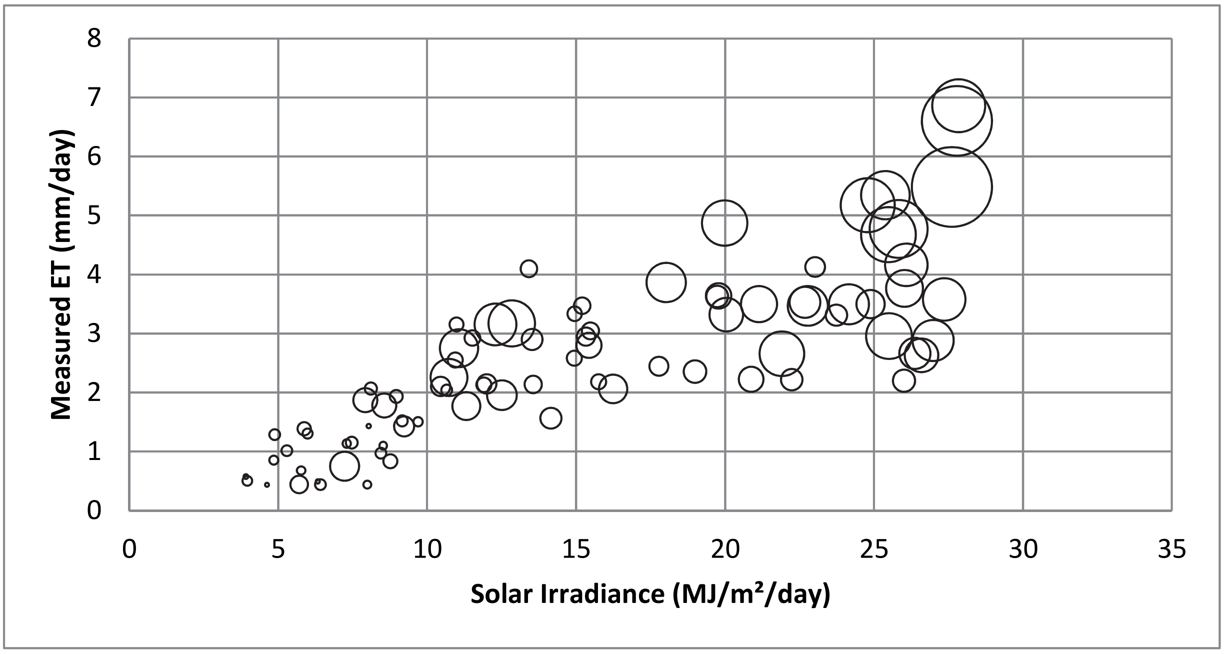

Figure 50. A plot of solar irradiance (MJ m^{-2} day^{-1}) versus measured daily ET_{EC} (mm day^{-1}). The diameter of symbols varies in proportion to daily mean VPD (KPa).

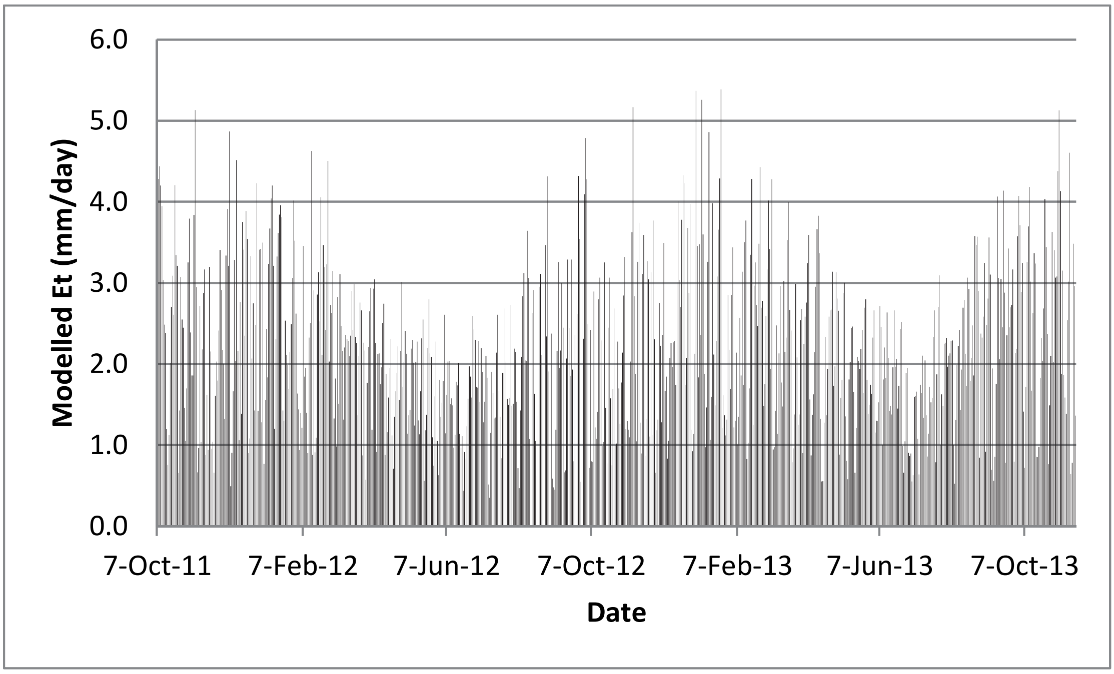

Figure 51. Daily ET estimated as a fraction (0.63) of ET_0 over the full simulation period.

<u>Modelled Hourly ET (One-month Simulation)</u>

Only one month of data (15 December 2012 to 15 January 2012) were used to parameterize the model to keep the data size to manageable proportions. Figure 52 shows the pattern of hourly ET over the month, while Figure 53 illustrates a scatter plot of measured versus modelled hourly ET. The modelled values include transpiration from dry leaves and evaporation from wet leaves.

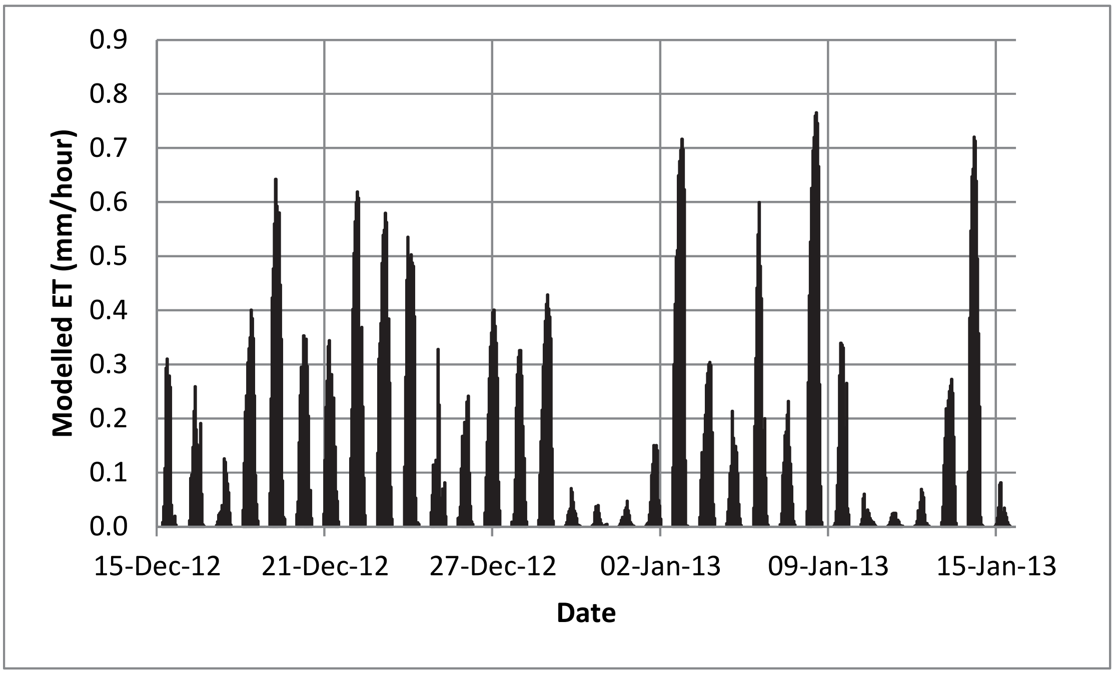

Figure 52. Simulated hourly ET over the one-month period from 15 December 2012 to 15 January 2013.

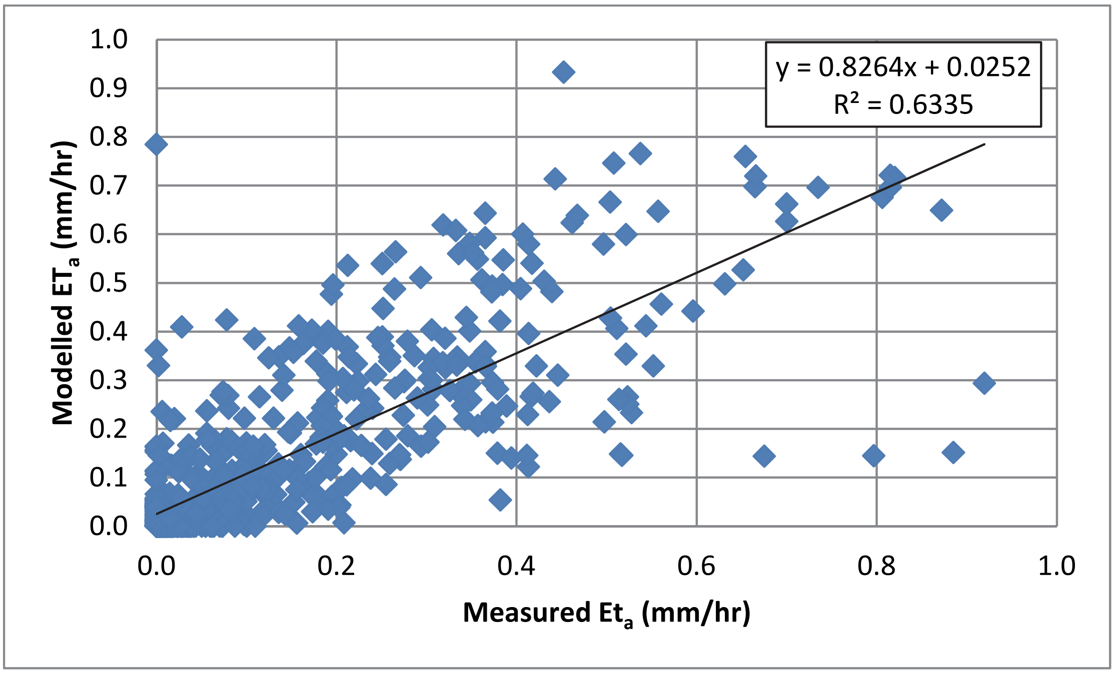

Figure 53. A comparison of measured and modelled hourly ET over a one-month period from 15 December 2012 to 15 January 2013.

Several outlying data points indicate high values of modelled ET associated with much lower measured values. These are shown in Figure 54 to be associated with wet conditions when evaporation of free water is taking place from the leaves. The diameter of symbols is in proportion to the modelled hourly free water evaporation rate from the leaves, with highest rates (maximum of 0.93 mm hr^{-1}) associated with periods when the canopy storage capacity is full, and when net radiation is sufficient to permit high evaporation rates. All but two of the hourly periods are associated with ET rates below 0.45 mm hr^{-1}, which is commonly reported in forest evaporation studies (Klaassen *et al*., 1998). The two highest readings of 0.93 and 0.78 mm hr^{-1} are exceptionally high, and assumed to coincide with conditions of very high evaporative demand and energy availability, and full canopy storage. Since EC systems are known to incur error in estimating ET during wet and misty conditions, these modelled evaporation rates are expected to be the more realistic estimates of hourly ET.

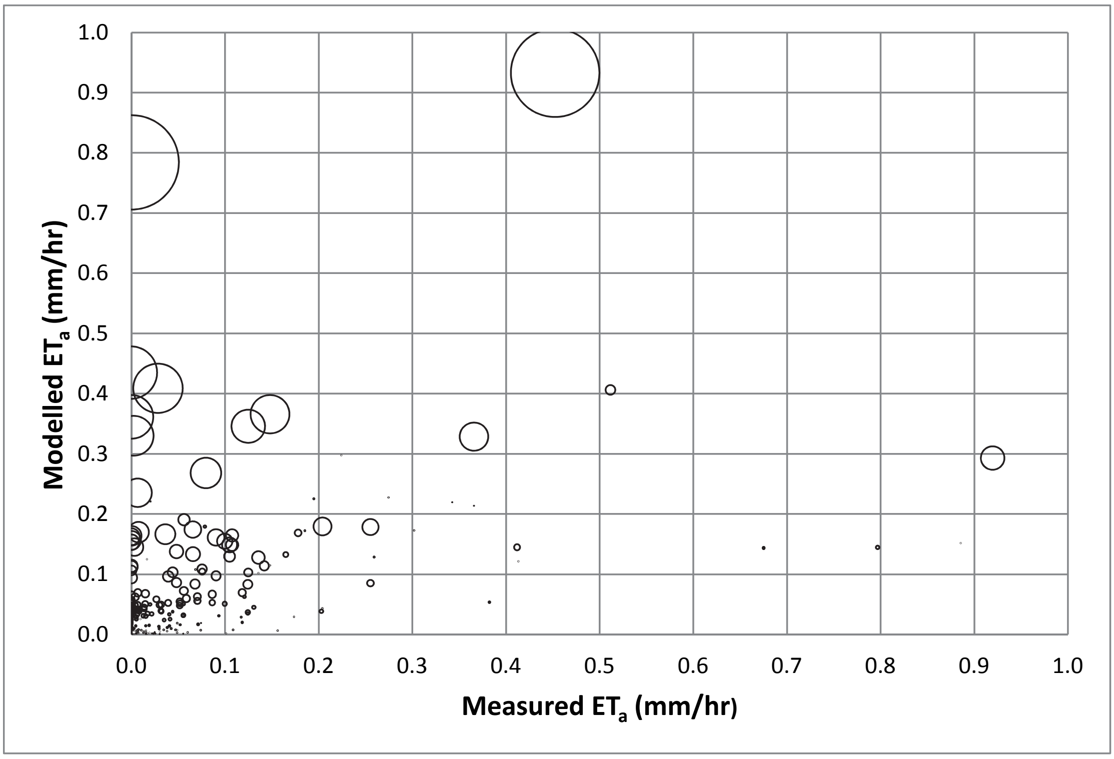

Figure 54. Comparison of measured and modelled hourly ET during wet canopy conditions. The diameter of the symbols varies according to the amount of evaporation of free water.

Some further outliers are seen below the main cluster of points in Figure 53, where measured ET greatly exceeds modelled ET. These were examined in relation to meteorological conditions at the time they were recorded. Most were found to be associated with hours characterized by high PAR within wet leaf periods. One explanation may be that the model does not accurately simulate the combination of free water evaporation and transpiration from partially wet canopies under conditions of high solar irradiance and evaporative demand. Another possibility is that the leaves dry more slowly than is simulated, leading to underestimation of ET towards the end of wet canopy periods. These hypotheses need to be tested in the field by evaluating the Rutter rainfall interception model and recording leaf wetness sensors.

A sub-set of data were extracted to include only hours when the leaves were completely dry, to examine the model performance in predicting stomatal conductance and transpiration from fully dry leaves. Figure 55 compares measured to modelled values and reveals a more satisfactory slope, intercept and R^2.

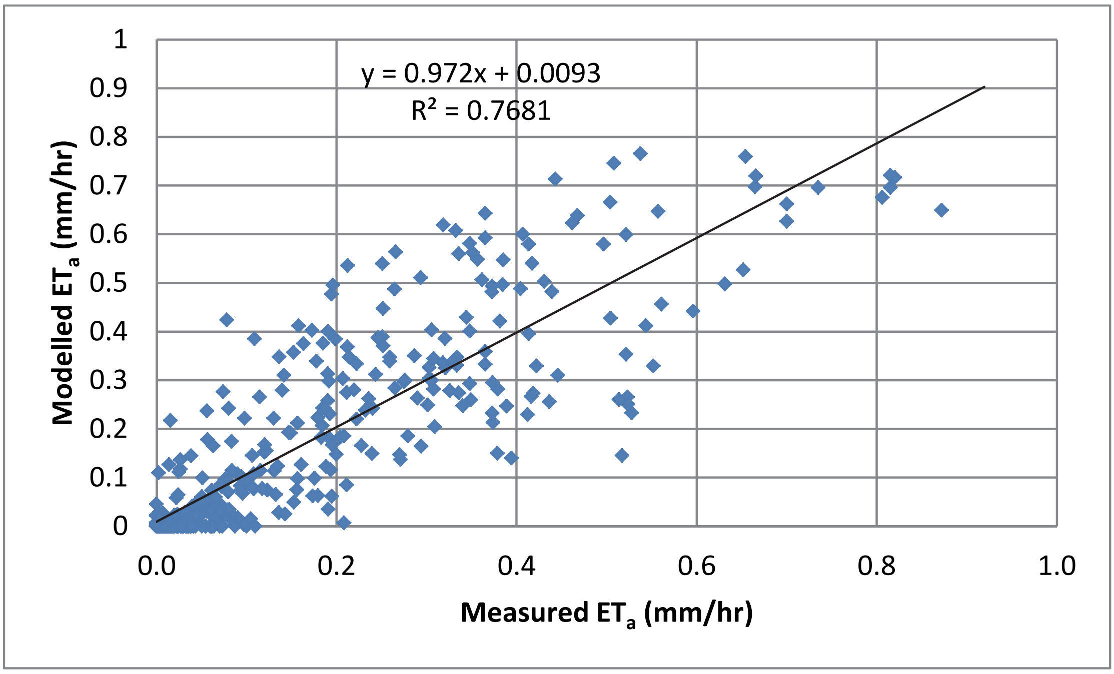

Figure 55. A comparison of measured to modelled ET for hours when the leaves were fully dry.

The major water balance components for the one-month period are shown (Table 18).

Table 18. Simulated rainfall partitioning for the period from 15 December 2012 to 15 January 2013.

Hydrological process	Total quantity (mm)	% of precipitation
Precipitation	105.4	100.0
Total measured ET	87.0	82.5
Total modelled transpiration	77.6	73.6
Total modelled wet canopy evaporation	13.6	12.9
Total modelled ET	91.2	86.5

Modelled Hourly ET (21-month Simulation)

The parameterized MAESPA model used in the one-month hourly simulation was then run for hourly time-steps over the total period of available hourly AWS data, from 7 October 2011 to 24 July 2013. Problems were encountered in simulating the last month of this period, when the model reported frequent failed convergence in calculating canopy photosynthesis and transpiration. Since the cause of this problem could not be identified, the last 37 days were omitted from the water balance analysis. The simulation period thus spanned 21 months (619 days, 14856 hours), from 7 October 2011 to 16 June 2013. It still included two full summer seasons when most of the annual rainfall occurs. Table 19 summarizes the water balance over this period.

Table 19. Simulated rainfall partitioning for the period from 7 October 2011 to 16 June 2013.

Hydrological process	Total (mm)	% of precipitation
Total precipitation	1 733.1	100.0
Total transpiration	1 488.9	85.9
Total wet canopy evaporation	240.6	13.9
Total ET	1 729.5	100.0
Total throughfall	1 492.4	86.1
Total soil deep drainage	187.6	10.8
Total soil surface evaporation	84.5	4.9

Based on the fact that these results indicated that forest ET was equivalent to rainfall, the estimated ET of the forest for the first 12-month period (Oct 2011 to Sep 2012) was 885 mm and for the second (Oct 2012 to Sep 2013) was 991 mm. This is somewhat higher than the ET of 795 mm estimated using the observed ET/ET_o relationship described above.

4.3.7 Whole forest WUE

Data from the PSPs were used to obtain estimates of forest stand volume growth. Stem length was not measured in the long-term forest growth plots, so data for utilizable stem volume (up to the main branches) for the southern Cape forests were pooled across all canopy and subcanopy species to develop a DBH-Volume relationship. This was subsequently applied to the DBH data for the Manubi PSP site in order to calculate stand volume growth. A power function gave the best fit for the DBH-Volume relationship:

Stem volume = $0.000137*DBH^{2.13}$

Using this equation, the stem volume of each tree in the forest growth plot, for the first and second measurement (5 years apart at the Ingeli plot), were calculated. The difference between the second and first measurement gave the following mean volume growth rate at Ingeli:

1998: 88.316 m^3 ha^{-1}; 2003: 88.719 m^3 ha^{-1}; Growth: 0.140 m^3 ha^{-1} $year^{-1}$

Based on the forest water use modelling exercise undertaken for this site, annual ET for the forest was estimated at 795 mm (7950 m^3 ha^{-1}). Converting the annual forest growth estimate of 0.140 m^3 ha^{-1} to a mass-based estimate using an average wood density of 0.565 g cm^{-3} resulted in utilizable stem biomass increment of 79100 g ha^{-1} $year^{-1}$. Combining this with the above ET estimate (7959000 L) yielded a whole forest WUE estimate of 0.0099 g stem wood per L water transpired.

4.4 Discussion

Based on PSP data, DBH-Stem volume equations were developed for certain species at this site and in the southern Cape, using the southern Cape tree volume data. However, data were not available for two of the study species, and *Olea capensis macrocarpa* data were used to develop the equations for *Prunus africana* and *Ptaeroxylon obliquum*. The DBH-Stem volume equations were as follows:

Afrocarpus falcatus: Stem volume = $0.000142*DBH^{2.27}$
Ocotea bullata: Stem volume = $0.000217*DBH^{2.09}$
Ilex mitis: Stem volume = $0.000212*DBH^{2.02}$
Rapanea melanophloeos: Stem volume = $0.000152*DBH^{2.16}$
Olea capensis macrocarpa (for *P. africana* and *P. obliquum*):
Stem volume = $0.000178*DBH^{2.02}$

The growth data of all trees of a species in all 16 long-term growth plots were used to calculate a DBH-Volume growth relationship for the species. Only a few trees of the following species were present in the growth plots: *Ilex mitis* (3), *Prunus africana* (1) and *Ptareroxylon obliquum* (4). The curves for the DBH-Volume growth relationships are shown in Figure 56.

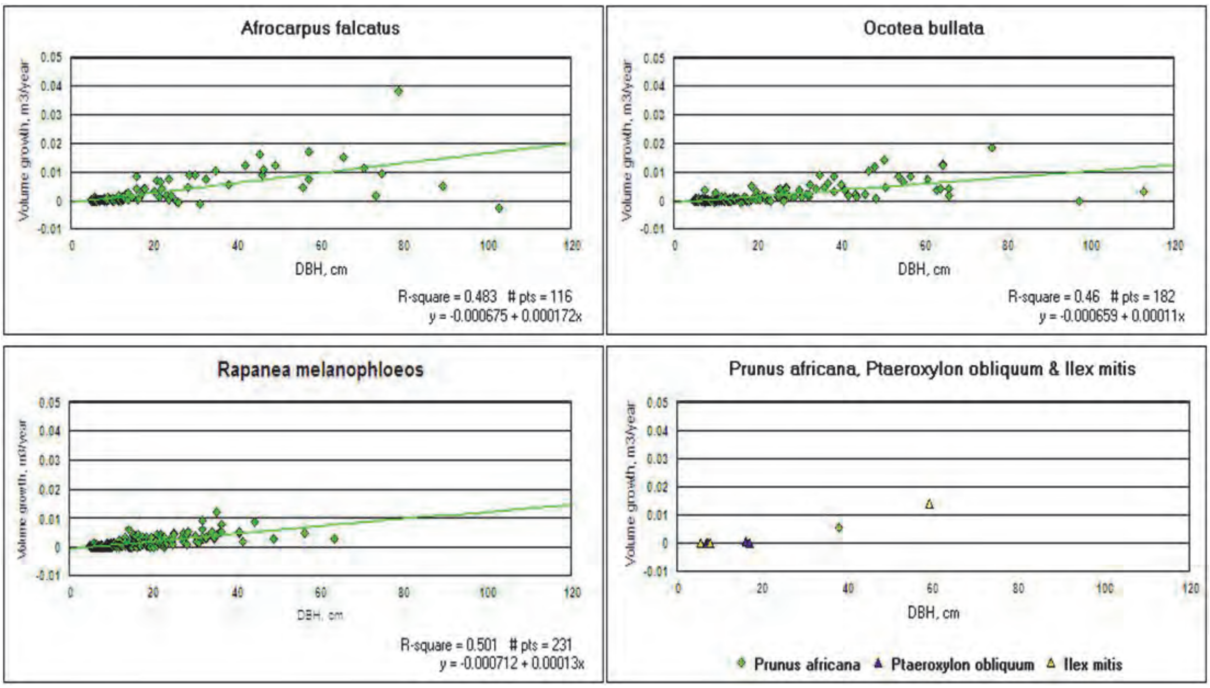

Figure 56. Dbh-Volume growth relationships for the studied species.

All these species are relatively more light-demanding then the general forest species for successful establishment of their regeneration and fast growth, and would therefore grow better in large gaps and relatively open planted stands.

The purpose of the forest modelling exercise was to generate an estimate of total evapotranspiration from the Ingeli forest site over a period of nearly two years. Periods of measured ET comprised only 13.6% of the final total simulation period and were too limited to provide a total estimate of the full period. The MAESPA model was parameterized using available data, and comparison of measured to modelled hourly ET over a month-long calibration period showed that the model accounted for 77% of the variance of the data. Considering that spikes and noise in EC measurements are known to cause up to 15% error in flux measurements (Burba, 2013), the calibration exercise is considered to have been successful.

MAESPA yielded an ET estimate of 1730 mm. This is very close to the measured precipitation over the same period (1733 mm), suggesting that the forest is efficient in utilizing the available rainfall at this site. Both years during which the study took place were years of average annual precipitation, and so the water balance results shown are likely to be close to the average over longer time periods. MAESPA can also be run for longer periods using weather data from nearby weather stations with longer records to examine the year-to-year variation in ET. Long-term water use at Ingeli forest may therefore be estimated, and compared to tree growth increments to establish the water use efficiency of the forest.

The model estimated total deep drainage below the soil profile as 188 mm, but much of this represented drainage immediately following the start of the simulation, suggesting that the soil water content specified at the start needs to be revised.

In view of the perception that EC systems may not provide accurate ET measurements during wet and misty weather, the MAESPA estimate of rainfall interception and evaporation under wet canopy conditions may be a more credible quantification of this process. Rainfall interception loss equaled 241 mm (14% of gross rainfall) over the entire simulation period. This falls within the range reported for a variety of closed-canopy tropical and sub-tropical forests elsewhere (Table 20). However, these modelled predictions need experimental verification, with field estimates of four parameters (RUTTERB, RUTTERD, MAXSTORAGE and THROUGHFALL) required from typical indigenous forest sites.

Table 20. A summary of interception and throughfall estimates reported for a variety of closed-canopy forests.

Forest type	Country	Interception as % of precipitation	Throughfall as % of precipitation	Reference
Ingeli indigenous evergreen forest	South Africa	14	86.1	This report
Eucalyptus grandis	South Africa	15	85.1	Bulcock & Jewitt, 2012
Acacia mearnsii	South Africa	28	72.3	Bulcock & Jewitt, 2012
Pinus patula	South Africa	21	78.6	Bulcock & Jewitt, 2012
Rain forest	Colombia	12-17	87.2	Marin *et al*., 2000
Catinga	Venezuela	-	91	Herrera, 1979
Rain forest	Brazil	20	80.2	Franken *et al*., 1992
Rain forest	Brazil	9	87-91	Lloyd & Marques, 1988
Rain forest	Brazil	12-13	86-87	Ubarana, 1996
Mixed broadleaved forest	Chile	19-37	60-80	Huber & Iroume, 2001
Evergreen broadleaf forest	China	16	77.3	Cui *et al*., 2006
Evergreen broadleaf forest	China	28	69.3	Huang *et al*., 2000
Evergreen broadleaf forest	China	19	77.7	Li *et al*., 1997
Evergreen broadleaf forest	China	11	87.0	Liu *et al*., 2003
Evergreen broadleaf forest	Japan	14	67.9	Masukata *et al*., 1990
Mature montane rainforest	Indonesia	18	81.9	Dietz *et al*., 2006

There was no discernible reduction of ET during the dry winter campaign, so the trees appear to have access to sufficient soil water to continue ET at potential rates through the year. This is a similar result to what was obtained at Groenkop forest outside George (Dye *et al*., 2008).

MAESPA has extrapolated from the relatively short measurement windows to cover a continuous period of nearly two years. The simulated water balance looks realistic, supporting the view that the EC measurements are accurate. MAESPA provides a very effective means of “gap filling” ET between periods of measurement. Instrumentation such as the EC system is expensive and scarce, requiring systems to be used across multiple research sites. MAESPA provides a detailed series of output files which allow comprehensive validations against a range of field measurements.

5 *VACHELLIA (ACACIA) KOSIENSIS*, *CASUARINA EQUISETIFOLIA* AND *EUCALYPTUS GRANDIS* PLANTATIONS AT RICHARDS BAY[6]

5.1 Introduction

Barnes (2001) lists numerous benefits of indigenous *Vachellia (Acacia)*[7] species, including that they provide firewood, fodder for domestic animals and honey bees, poles for fencing and construction, wood for carving and furniture, medicines, gum and brushwood for fencing; they seed naturally into exhausted cultivated land when it is abandoned and fix nitrogen from the atmosphere thereby helping to restore soil fertility. One particular *Vachellia* species meriting further study in this regard is *V. kosiensis* (Dune Sweet Thorn). The species was recently separated from the *Vachellia karroo* complex[8] and occurs in a narrow strip along the KwaZulu-Natal north coast (Boon, 2010). Its quick-growing nature and physiological similarity to the broader suite of *Vachellia* species, which are widely distributed across South Africa, make it a relevant and suitably representative indigenous tree species for further research. Consequently, the water-use, growth rates and resultant water use efficiency of *V. kosiensis*, as well as nearby *Eucalyptus grandis* and *Casuarina equisetifolia* trees as a control, were quantified within mature stands of these trees situated on rehabilitated dune mining land in the Richards Bay area of South Africa.

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[6] When making reference to this section, please cite as follows:

Gush, M.B. and Naiken, V. 2015. *Vachellia (Acacia) kosiensis*, *Casuarina equisetifolia* and *Eucalyptus grandis* plantations at Richards Bay. In: Gush, M.B. and Dye, P.J. (Eds). 2015. Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees: Volume 2 (Site-Specific Technical Report). Water Research Commission, Pretoria, RSA, WRC Report 1876/2/15, Section 5.

[7] A retypification of African species of the genus Acacia into two distinct genera, namely Vachellia and Sengalia, was approved in 2011 (Boatwright *et al*. 2014; Dyer, 2014).

[8] *Vachellia kosiensis* recently separated from the *Vachellia karroo* complex (see: http://www.acacia-world.net/index.php/africa-me/south-africa/the-vachellia-karroo-complex). South African National Tree No. 172.2.

5.2 Materials and Methods

Measurements conducted during the study consisted of continuous (hourly) monitoring of a full suite of weather variables; continuous (hourly) sap flow (transpiration) measurements on individual trees; stem biomass increment (growth) measurements on individual trees, and monitoring of soil water content at the study sites. Monitoring of all variables began on 21 September 2012, and continued for nearly 2 years until 20 August 2014, incorporating two summer growing seasons. Results were compared to similarly sampled data from previous studies for introduced *Eucalyptus* and *Pine* plantation species (Olbrich *et al*. 1996; Dye *et al*. 2001).

5.2.1 Site description

The research was carried out at Richards Bay Minerals (RBM) mining operations site (-28.608766°S; 32.291917°E; elevation 48 m), which lies between the port town of Richards Bay and Mapelane nature Reserve, on the north coast of KwaZulu-Natal (Figure 57). The area is characterized by longitudinal sand dunes, lying parallel to the coastline, and rising to an elevation of 40-90 m above sea level. Soils are mostly sandy throughout the area. Most rain falls between January and March, with a mean annual precipitation of 1292 mm. Extended droughts are uncommon and approximately 30% of annual precipitation occurs in the winter. Daily maximum temperatures range from 22.6°C to 30.0°C and minimum temperatures from 10.0°C to 20.6°C in June and January, respectively (Wassenaar and van Aarde, 2001).

The area has been mined since 1977 for heavy metals (zircon, rutile and ilmenite) extracted from dune sands. RBM (now managed by Rio Tinto) has a longstanding dune rehabilitation programme of previously-mined areas which commenced in 1978. Mining is followed by a rehabilitation process during which sand tailings are reshaped to dimensions of original dunes, covered with pre-mining harvested topsoil, re-vegetated with a cover crop of annuals and grasses, protected against erosion by means of 1.5 m high netted windbreaks, and then left to regenerate naturally, ideally with convergence towards original coastal dune forest. Post-rehabilitation management is limited to the removal of alien vegetation and reseeding of die-offs in the first two years. The rapid germination and predominance of *V. kosiensis* trees at the outset of the rehabilitation process often results in a series of known-aged stands of these trees (van Aarde *et al*. 1996; Wassenaar *et al*. 2005).

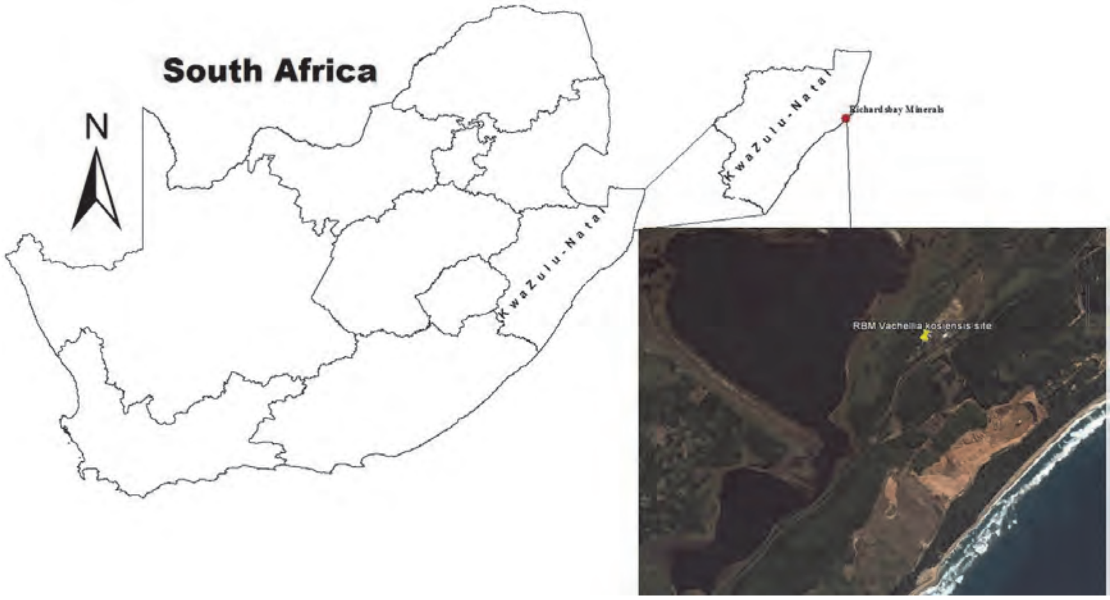

Figure 57. Location of the Richards Bay Minerals *V. kosiensis* study site.

The *V kosiensis* trees on which this study was performed constituted part of this dune rehabilitation programme and were located within a 1 ha block of naturally regenerated trees established shortly after the site was rehabilitated 20 years previously. At the time of this study they had formed a closed canopy forest of even-aged and fairly uniform trees dominated by *V kosiensis,* with a dense undergrowth of grasses, climbers, and some shrubs, but without a true subcanopy layer. Consequently, the site presented an ideal opportunity to conduct comparative transpiration and growth measurements in what could be considered a naturally regenerated indigenous tree plantation. In a 20 m X 20 m area (400 m^2) there were 68 *V. kosiensis* trees, equating to approximately 1700 stems per hectare.

The control site, used for comparative measurements of *Eucalyptus grandis* and *Casuarina equisetifolia* trees, consisted of a growth trial established by the CSIR as part of the RBM dune rehabilitation programme (Komakech and Hettasch, 2011). The selected stand (Trial 3 – 1010202EA0002.03) at RBM's so-called Alternative Land Use (ALU) site (-28.706101°S; 32.191691°E; elevation 86 m), contained a combination of *Eucalyptus* species and hybrids interspersed with *Casuarina equisetifolia* trees growing together in a 0.6 ha block. Establishment had consisted of site preparation by means of manual pitting with hoes, planting with water and Stockasorb/Aquasol, irrigation once a week for one month after planting, fertilisation with 150 g of 5.1.2 per tree within the first four weeks following planting, blanking and manual weed control through hoeing. The trees were planted at 3 x 3 m spacing (1111 spha) in Nov 2007 and were consequently 5 years old at the time of monitoring. Five individual *V. kosiensis* trees, together with two control

Eucalyptus grandis and *Casuarina equisetifolia* trees, were monitored in this study (Table 21).

Table 21. Details of the trees monitored in this study.

Tree	Tree Height (m)	Diameter at Breast Height (cm)
V. kosiensis 1	14.2	19.1
V. kosiensis 2	12.3	17.8
V. kosiensis 3	12.4	15.0
V. kosiensis 4	11.2	12.0
V. kosiensis 5	13.3	14.4
E. grandis	14.0	15.8
C. equisetifolia	14.4	15.1

5.2.2 Field measurements

Weather

Continuous hourly measurements of temperature and relative humidity (HMP50, Vaisala, Helsinki, Finland) were conducted in the tree stands for the duration of the study. Between September 2012 and December 2013 additional weather data was sourced from the Richards Bay airport (-28.740999°S; 32.092098°E; elevation 33 m). From 4 December 2013 until monitoring was concluded on 20 August 2014, data was obtained from an independently installed automatic weather station (AWS) positioned in an open grassed area approximately 100 m from the *V. kosiensis* stand. The AWS was equipped with a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA), and measured rainfall (TE525-L, Texas Electronics, Dallas, Texas, USA), solar radiation (LI-200SA, LI-COR Inc., Lincoln, NE, USA), temperature and humidity (HMP50, Vaisala, Helsinki, Finland), wind speed and wind direction (Model 03001, RM Young, Traverse city, Michigan, USA). Sensors were mounted 2 m above the ground, and variables were measured at 10 s intervals, and stored in the logger at hourly intervals over the monitoring period. Hourly values were further processed into daily averages or totals, and the data were used to calculate daily reference evaporation (ET_o) for the site according to the FAO-56 approach (Allen *et al*. 1998).

Sap Flow (Transpiration) and Soil Water

The heat ratio method (HRM) (Burgess *et al*. 2001) of the heat pulse velocity (HPV) technique was utilised for the sap flow measurements in this study. It is essentially a tracer technique which measures the rate of flux with which heat pulses applied to the conductive xylem (sap wood) portion of woody stems are transmitted vertically by the flow of sap (Gush *et al*. 2014). It has been extensively applied in South Africa on both indigenous and commercial forestry tree species (Dye & Olbrich, 1993; Dye, 1996; Dye, Soko & Poulter, 1996; Dye *et al.* 1996; Gush, 2008; Gush & Dye, 2009).

Sap flow (water use) of the study trees was monitored with the HRM/HPV technique, requiring line-heaters to be inserted into the xylem (sapwood) of the sample trees at the vertical midpoint (commonly 5 mm) between two temperature sensors (thermocouples). Thermocouple (TC) pairs and heater probes were positioned 100 cm up the main stem of each tree, below the first branches. TC's were inserted to four different depths within the sapwood (10, 15, 20, and 25 mm below outer-bark surface) to determine radial variations in sap flow (i.e. each tree contained four TC pairs). While performing the drilling, a drill guide was strapped to the tree, to ensure that the holes were as close to parallel as possible. CR1000 data loggers connected to AM16/32 multiplexers (Campbell Scientific Inc., Logan, UT, USA) were programmed to initiate the heat pulses and record hourly data from the respective TC pairs. This instrumentation, together with relay control modules to regulate the heat pulses and batteries to power the system, were all housed in heavy steel boxes for security reasons. To account for lateral stem growth the HPV probes were removed and repositioned to their correct depths periodically during the monitoring period.

Additional supplementary information required to complete the HPV data analysis was collected at the conclusion of the monitoring period (Table 22). Small wood samples were excised and tree cores were taken using an 8 mm inside-diameter increment corer (Haglöf, Sweden) to determine bark width, sapwood depth, sapwood water content, wood density and the width of wounded (non-functional) xylem around the thermocouples ('wound widths'). Measured heat-pulse velocities were corrected for sapwood wounding caused by drilling, using wound correction coefficients described by Burgess *et al*. (2001). 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 volumes 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 volumes were aggregated into daily, monthly and annual totals for each tree, and were assumed to equate to transpiration (T). Individual tree sap flow volumes (L.month^{-1}) were scaled up to a hectare using the planting density to also derive sap flow (transpiration) totals in mm-equivalent volumes.

Table 22. Properties of the sample trees required for sap flow analysis.

Tree	Sapwood Depth (cm)	Bark Width (mm)	Wound Width (mm)	Wood Density (g cm^{-3})	Sapwood Water Content (%)
V. kosiensis 1	3.5	5.0	4.0	0.70	37.9
V. kosiensis 2	3.5	5.0	4.0	0.70	37.9
V. kosiensis 3	3.0	5.0	4.0	0.70	37.9
V. kosiensis 4	2.5	5.0	4.0	0.70	37.9
V. kosiensis 5	3.0	5.0	4.0	0.70	37.9
E. grandis	4.0	7.0	4.0	0.46	51.9
C. equisetifolia	6.5	3.0	4.0	0.78	31.9

Volumetric soil water content within the tree stands was also recorded hourly in the top 100 mm of the soil profile using CS616 soil water content probes (Campbell Scientific Inc., Logan, Utah, USA). Data were corrected using gravimetric soil water content data determined from soil samples collected in the vicinity of the probes during the monitoring period.

<u>Stem Growth Measurements</u>

Stem biomass increment surveys were conducted on all the sample trees in conjunction with sap flow measurements. An initial stem size survey was carried out shortly after the individual trees had been instrumented with the HPV systems, and the final surveys were done at the end of the monitoring period. Stem diameters at increasing heights up the tree were measured. These measurements were converted to volumes according to the method described by Gush and Dye (2009), and individual stem section volumes were totalled for each tree. This allowed for the calculation of stem volume growth increases over the monitoring period. Biomass increments were converted from volume to mass using wood densities determined for each species (Table 2). In conjunction with the sap flow (water-use) results this allowed the calculation of a bio-physical measure of water use efficiency (WUE), defined as stem mass increment (g $tree^{-1}$ yr^{-1}) per unit of water transpired (L $tree^{-1}$ yr^{-1}).

5.2.3 Modelling

Daily values of reference total evaporation (ET_o), transpiration (T) and total evaporation (ET) were used to calculate monthly T/ET_o and ET/ET_o ratios for the Eucalyptus stand. In order to estimate ET for the stand it was necessary to account for additional evaporative losses from canopy and litter interception. Canopy rainfall storage capacity was assumed to be 0.4 mm per rainfall event, while litter storage capacity was assumed to be 2.6 mm per rainfall event up to or exceeding 3 mm, based on studies by Bulcock and Jewitt (2012).

5.3 Results and Discussion

5.3.1 Weather and soil water content

Monitoring yielded two years of weather data typical of the warm and wet sub-tropical climate in this summer rainfall site (Figure 58). While most of the rainfall was received in the summer months between October and February, substantial falls were also recorded as late as April/May, and rainfall occurred in every month of the monitoring period. Total rainfall for the first year (21 Sep 2012 to 20 Sep 2013) was 1119 mm, while for the subsequent period (21 Sep 2013 to 20 Aug 2014) it was 1013 mm. High temperatures were also in evidence, with maximum daily temperatures in excess of 35° C recorded regularly, and daily minimum temperatures rarely dropping below 10° C. The coldest temperature recorded at the site was 7.6°C on 1 Sep 2013, while the warmest was 40.2°C on 19 Mar 2014. Seasonal variation in solar radiation was evident and daily average values peaked at 25 MJ m^{-2} day^{-1} in summer (January 2014), dropping to 11 MJ m^{-2} day^{-1} in winter (June 2012). Daily wind-speed was also relatively consistent, averaging 1.3 m s^{-1}. The data were used to calculate reference total evaporation (ET_o) according to the FAO-56 approach (Allen *et al*. 1998), which showed typical daily and seasonal fluctuations (Table 23).

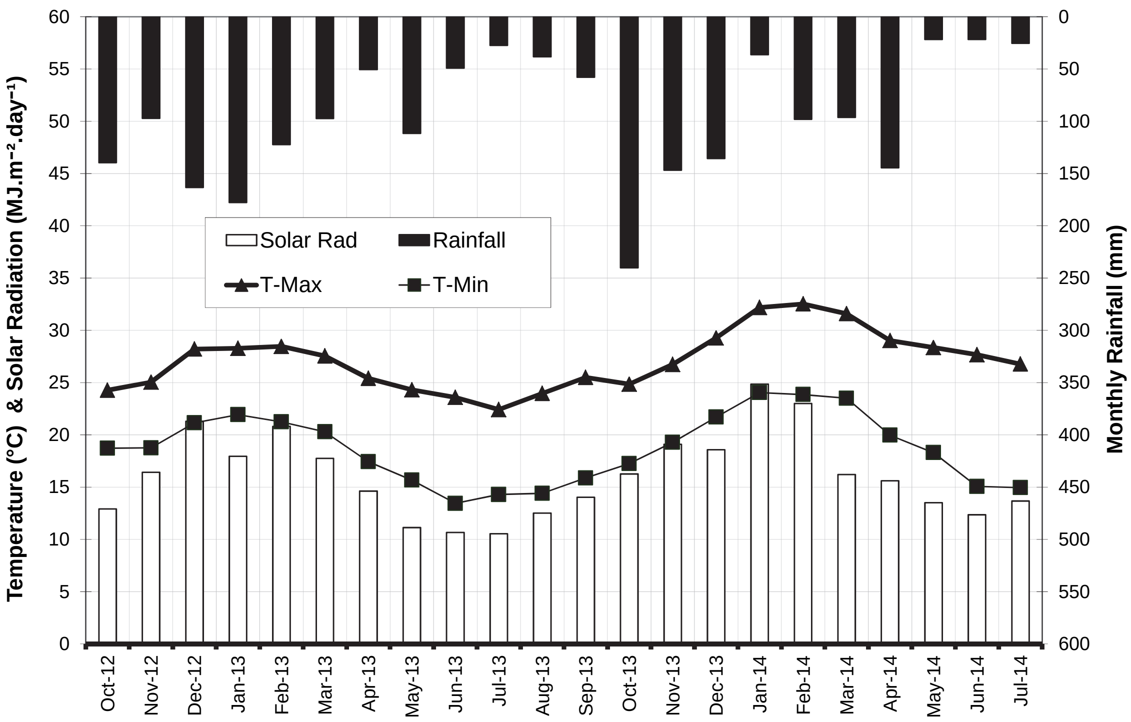

Figure 58. Monthly values of mean daily maximum/minimum temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), and rainfall totals (mm) at the RBM site from October 2012 to July 2014.

Table 23. Monthly reference total evaporation (ET_o) totals for the RBM site.

Month	Oct-2012	Nov-2012	Dec-2012	Jan 2013	Feb 2013	Mar 2013	Apr 2013	May 2013	Jun-2013	Jul-2013	Aug 2013	Sep 2013	Total
ET_o (mm)	113	128	169	154	150	146	117	91	93	83	123	120	1487

The numerous rainfall events and resultant soil water responses recorded at this site suggest that the trees were under minimal water stress, as is evident from the time series of volumetric water content recorded in the upper soil layer (Figure 59). Nevertheless the overall soil water content never exceeded 20 % following rainfall, and consistently dropped quickly to below 5% thereafter, which is an indication of the very sandy soils and rapid infiltration rates at this site.

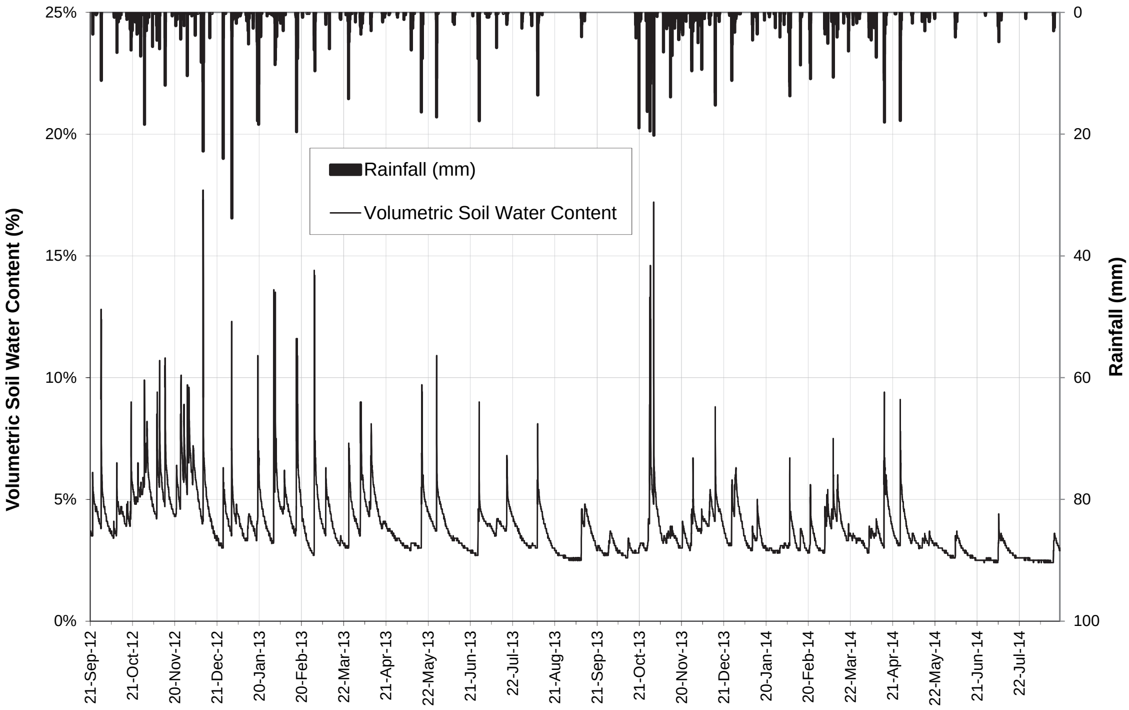

Figure 59. Fluctuations in volumetric soil water content at the *Vachellia kosiensis* site between 21 Sep 2012 and 20 Aug 2014.

5.3.2 Sap flow (transpiration), stem growth and water use efficiency

Average daily sap flow (transpiration) volumes observed in the *V. kosiensis* trees typically ranged from 10 L tree^{-1} day^{-1} in summer to 3 L tree^{-1} day^{-1} in winter, with peaks of up to 14 L tree^{-1} day^{-1}, but dropped virtually to zero during days of very wet weather. *E. grandis* showed summer transpiration rates commonly in the region of 30 L tree^{-1} day^{-1}, with occasional peaks of over 40 L tree^{-1} day^{-1}, and dropped to winter lows of approximately 15 L tree^{-1} day^{-1}. *C. equisetifolia* exhibited the highest average daily water use with summer transpiration values generally around 35 L tree^{-1} day^{-1}, occasional peaks of around 50 L tree^{-1} day^{-1}, but winter lows of 5-10 L tree^{-1} day^{-1}. Average annual transpiration totals for individual *V. kosiensis* trees ranged from 1701 L yr^{-1} (289 mm) for the smallest tree to 4114 L yr^{-1} (699 mm) for the largest tree, with an average of 2515 L yr^{-1} (427 mm), while totals for the *E. grandis* and *C. equisetifolia* trees were substantially higher at 7721 L yr^{-1} (858 mm) and 8264 L yr^{-1} (918 mm) respectively (Table 24).

Table 24. Annual transpiration (water use) totals recorded in *Vachellia kosiensis*, *Eucalyptus grandis* and *Casuarina equisetifolia* trees at Richards Bay.

Tree	DBH (mm)	Tree Height (m)	Water use (L $tree^{-1}$ yr^{-1})	Water use (mm)
V. kosiensis 1	191	14.2	4 114	699
V. kosiensis 2	178	12.3	2 626	447
V. kosiensis 3	150	12.4	2 115	360
V. kosiensis 4	120	11.2	1 701	289
V. kosiensis 5	144	13.3	1 943	330
V. kosiensis Average	151	12.7	2 515	427
E. grandis	158	14.0	7 721	858
C. equisetifolia	151	14.4	8 264	918

Compared to previously published data on introduced plantation species, results showed that the indigenous *V. kosiensis* trees used noticeably less water (Figure 60), although their growth rates were also lower (Figure 61).

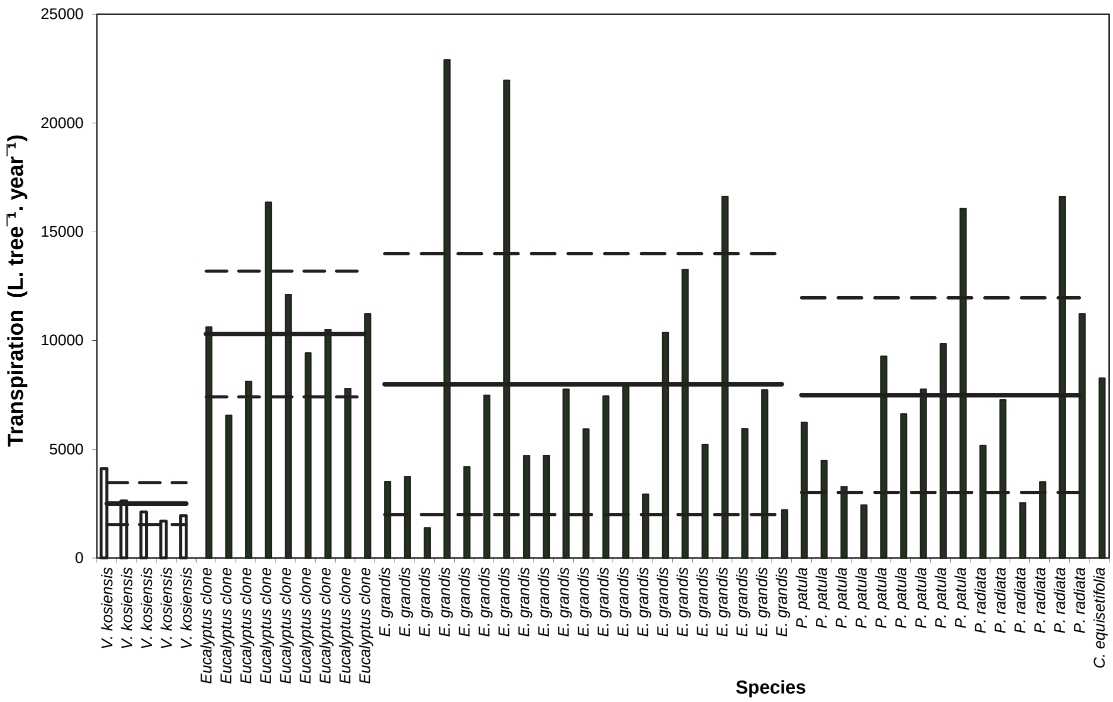

Figure 60. A comparison of 1-year total sap flow (transpiration) between indigenous *Vachellia (Acacia) kosiensis* trees (open bars – this study) and introduced plantation tree species and clones (solid bars – Olbrich *et al*., 1996; Dye *et al*., 2001; this study). The means (solid lines) and standard deviations (dashed lines) for the data sets are shown.

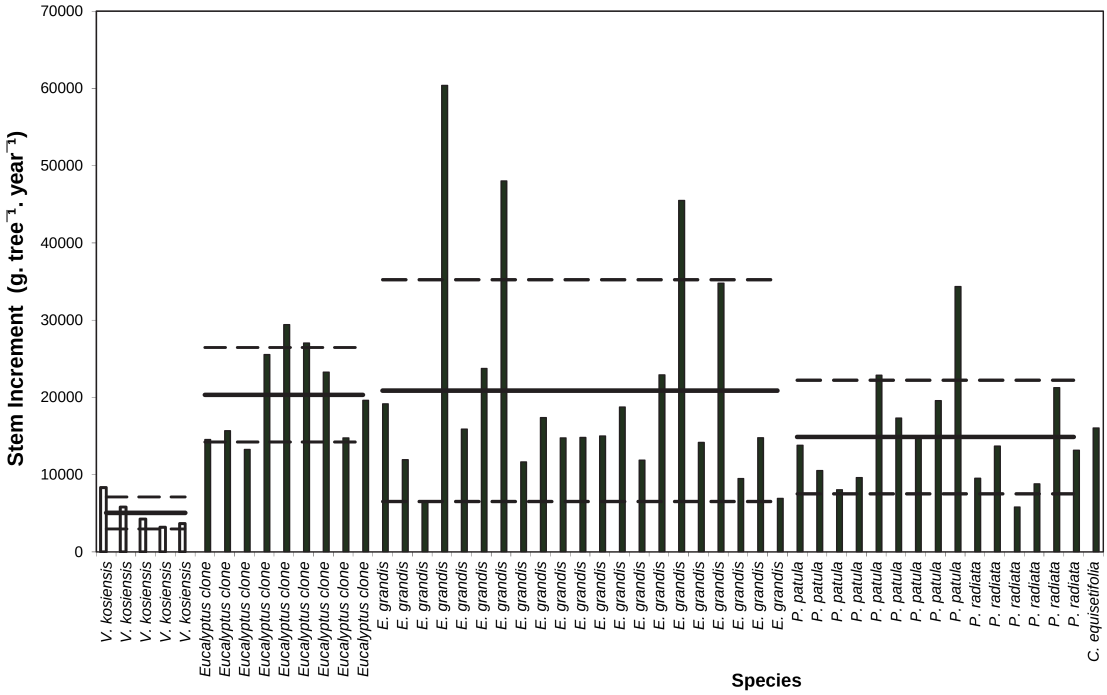

Figure 61. A comparison of 1-year stem mass increment (growth) between indigenous *Vachellia (Acacia) kosiensis* trees (open bars – this study) and introduced plantation tree species and clones (solid bars – Olbrich *et al*., 1996; Dye *et al*., 2001; this study). The means (solid lines) and standard deviations (dashed lines) for the data sets are shown.

While the growth rates of individual *V. kosiensis* trees were unable to compete with their introduced species counterparts, the high tree density of the *V. kosiensis* stand yielded a respectable MAI over time. Given a stand age of 20 years and based on stem volume measurements of the sample trees which were representative of the stand, the mean annual increment (MAI) calculated for the *V. kosiensis* stand was 10.3 m^3 ha^{-1} yr^{-1}, while the current annual increment (CAI) over the course of the study was 10.9 m^3 ha^{-1} yr^{-1}. MAI and CAI values for the introduced tree species of this study were 17.3 m^3/ha/year and 20.2 m^3 ha^{-1} yr^{-1} respectively for *C. equisetifolia* and 21.9 m^3 ha^{-1} yr^{-1} and 35.5 m^3 ha^{-1} yr^{-1} respectively for *E. grandis*. Based on 1-year single-tree water use and stem growth, the resultant water-use efficiency ratios indicated that the indigenous *V. kosiensis* trees had similar biophysical water-use efficiency values to clonal *Eucalyptus, Pinus* and *Casuarina* species, but were not as efficient as *Eucalyptus grandis* trees as a whole (Table 25; Figure 62).

Table 25. Transpiration, growth and resultant WUE data for *Vachellia kosiensis*, *Eucalyptus grandis* and *Casuarina equisetifolia* trees at Richards Bay, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use.

Tree no.	1-yr Water-use (L)	1-yr Stem Volume Increment (m^3)	Basic Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
V. kosiensis 1	4 114	0.0119		8 325	2.02
V. kosiensis 2	2 626	0.0083		5 805	2.21
V. kosiensis 3	2 115	0.0061	0.698	4 255	2.01
V. kosiensis 4	1 701	0.0046		3 200	1.88
V. kosiensis 5	1 943	0.0052		3 661	1.89
Average	2 500	0.0072	0.698	5 049	2.00
E. grandis	8 264	0.0205	0.783	16 052	1.94
C. equisetifolia	7 721	0.0319	0.463	14 791	1.92

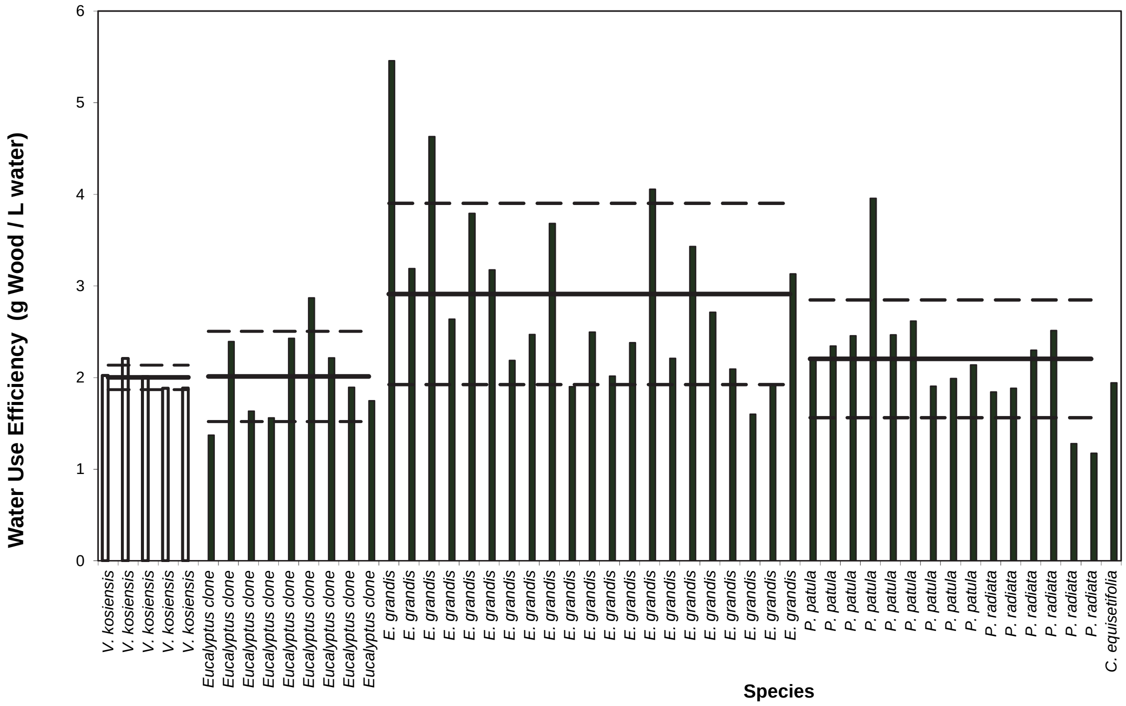

Figure 62. A comparison of 1-year water-use efficiency (stem mass increment per mass of water transpired) between indigenous *Vachellia (Acacia) kosiensis* trees (open bars – this study) and introduced plantation tree species and clones (solid bars – Olbrich *et al*., 1996; Dye *et al*., 2001; this study). The means (solid lines) and standard deviations (dashed lines) for the data sets are shown.

5.3.3 Modelling

Canopy and litter rainfall interception equated to an additional evaporation loss of 288 mm, resulting in a total evaporation (ET) estimate of 1146 mm for the Eucalyptus stand (Table 26).

Table 26. Annual water use components for the *Eucalyptus grandis* tree at Richards Bay.

Water use component	Annual Water use (L tree^{-1} yr^{-1})	Annual Water use (mm)
Transpiration	7721	858
Interception Evaporation		288
total evaporation (ET)		1146

The daily values of Reference evaporation (ET_o), Transpiration (T) and total evaporation (ET) were used to calculate monthly T/ET_o and ET/ET_o ratios for the Eucalyptus stand (**Table 27**).

Table 27. Monthly water use components for the *Eucalyptus grandis* tree at Richards Bay.

Month	ET_o (mm)	T (mm)	ET (mm)	T/ET_o	ET/ET_o
Oct-2012	112.8	61.8	105.4	0.58	1.14
Nov-2012	128.2	90.0	125.8	0.74	1.09
Dec-2012	169.3	100.6	124.8	0.62	0.82
Jan-2013	153.9	91.6	131.0	0.64	1.07
Feb-2013	150.4	77.6	103.2	0.52	0.78
Mar-2013	146.0	89.0	111.2	0.63	0.82
Apr-2013	116.6	73.8	94.8	0.66	1.01
May-2013	91.3	56.7	76.9	0.62	0.96
Jun-2013	92.6	64.9	77.9	0.73	0.94
Jul-2013	82.7	54.0	71. 6	0.66	0.93
Aug-2013	123.2	51.0	58.0	0.44	0.61
Sep-2013	120.5	38.1	62.9	0.33	0.65
Total	**1 487.3**	**848.9**	**1 143.3**		

5.4 Discussion

The rates of growth observed in these *V. kosiensis* trees were more than double those cited in previous studies of *Vachellia* species. Potential maximum stand yields of up to 4 m^3 ha^{-1} yr^{-1} were reported by Gourlay *et al*. (1996) for 20-25 year old *Vachellia karroo* trees growing in a discrete stand

(Altitude of 1181 masl; MAT of 19.6°C; MAP of 541 mm) in Zimbabwe. It is probable that the high growth rates observed in the *V. kosiensis* trees of this study are closely linked to the favourable climatic conditions and site-quality associated with this area.

The low water use rates observed in the *V. kosiensis* trees of this study, combined with reasonable growth rates, resulted in similar rates of water use efficiency to introduced species counterparts. This suggests that utilisation of this species in expanded indigenous forestry systems in South Africa could, under certain conditions, offer attractive alternative land-use scenarios to plantations of introduced timber species, without unduly negative impacts on water resources. This would be particularly pertinent to water-constrained catchments where further expansion of conventional forestry areas is restricted due to water concerns.

Barnes (2001) predicted the expansion of tree breeding in non-industrial forestry species (principally *Vachellia*) in the future, with the anticipated objective of making marginal land more productive, as commercial forestry operations come under pressure to move to increasingly difficult sites. Only a limited number of provenance trials have been conducted in this regard, but some evidence suggests that growth performance of indigenous tree species may be improved through genetic selection, better site/species matching, tree breeding and improved management (Geldenhuys and von dem Bussche, 1997). 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 growth rates of indigenous trees, although the proven link between growth rates and water use is a conundrum. Mindful of the fact that viability needs to be thoroughly evaluated from socio-economic and environmental perspectives, these results nevertheless suggest that commercial stands of *Vachellia kosiensis*, and potentially other *Vachellia* species as well, should be given further consideration.

6 SOUTHERN CAPE AFROTEMPERATE TREE SPECIES AND PINUS RADIATA PLANTATION AT SAASVELD[9]

6.1 Introduction

The southern Cape afro-temperate natural forests are a tree production system that has been managed sustainably over a lengthy period of time (Seydack *et al*., 1995). Of the ten socio-economically important indigenous forest species listed as high priority species for monitoring in this project, three of these were selected for single tree water use monitoring in the Groenkop indigenous forest in the southern Cape region. They were *Ilex mitis* (Cape Holly), *Ocotea bullata* (Black Stinkwood), and *Podocarpus latifolius* (Real Yellowwood). Moreover the Groenkop natural forest is demarcated as a natural forest study site, and has continuous growth measurement plots that were established in 1987 (Geldenhuys, 1998). A forest canopy total evaporation study reported by Dye *et al.* (2008) was also done on this site, and additional single tree water use studies for important species representative of the afro-temperate biome were relevant. The research reported on here sought to expand these studies by determining single tree water use and water use efficiencies as per previous studies. Water use and growth patterns observed in the indigenous species were compared to corresponding assessments for introduced species, and consequently the water use and water use efficiency of *Pinus radiata,* a prominent commercial species in the southern Cape, was also determined.

For the selected species, there had not been any prior field measurements to establish their single tree water use values in the southern Cape region. Furthermore, the few studies done on the growth of these high value indigenous timber species have not been linked to their water use. The search for alternative tree production systems has been prompted by water scarcity, and proposals for such alternatives using indigenous tree species cannot be pursued at unsustainable costs to water availability. Furthermore the southern Cape region has had some of its introduced timber plantations phased out

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[9] When making reference to this section, please cite as follows:

Gush, M.B., Mapeto, T., Dye, P.J., Naiken, V. and Geldenhuys, C.J. 2015. Southern Cape Afrotemperate tree species and *Pinus radiata* plantation at Saasveld. In: Gush, M.B. and Dye, P.J. (Eds). 2015. Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees: Volume 2 (Site-Specific Technical Report). Water Research Commission, Pretoria, RSA, WRC Report 1876/2/15, Section 6.

due to water scarcity and inadequate economic production (De Beer, 2012). Information on the water use and WUE of indigenous species in the southern Cape indigenous forests is consequently of value in assessing the possibility of developing alternative tree production systems.

6.2 Materials and Methods

6.2.1 Site description

The study was carried out in a medium moist indigenous Afro-temperate forest and in a Pine plantation, both of which were located in the southern Cape region of South Africa (-33.954702°S and 22.528881°E). The study sites comprised of three heat pulse velocity (HPV) system stations and a weather station (Figure 63).

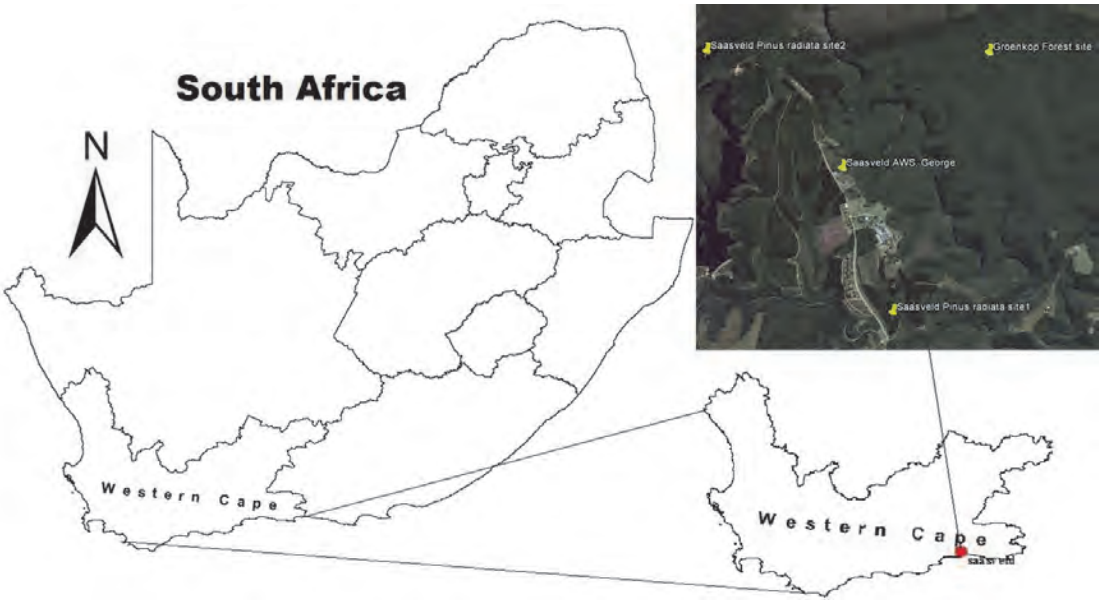

Figure 63. The location of the Saasveld (George) study area and sites.

6.2.2 Field measurements

Weather

An automatic weather station (AWS) equipped with a CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA), and measuring rainfall (TE525-L, Texas Electronics, Dallas, Texas, USA), solar radiation (LI-200SA, LI-COR Inc., Lincoln, NE, USA), temperature and humidity (HMP50, Vaisala, Helsinki, Finland), wind speed and wind direction (Model 03001, RM Young, Traverse city, Michigan, USA) was installed above open short grass at the NMMU Saasveld campus (-33.954702°S and 22.528881°E) approximately 2 km from the study sites. Sensors were mounted at 2 m above the ground, and variables were measured at 10 s intervals, and stored in the logger at hourly intervals for the one-year monitoring period. Hourly values were further processed into daily averages or totals, and the data were used to calculate daily reference evaporation (ET_o) for the site according to the FAO-56 approach (Allen *et al.*, 1998). The AWS became functional on the 9th of April 2013, at 15h00, ran throughout the duration of the study, and was still operational at the time of writing.

Sap flow (transpiration) and soil water

The heat ratio method (HRM) of the HPV technique (Burgess *et al.*, 2001), as described in Chapter 2, was utilised for sap flow measurements in this study. HPV site 1 (33.969501°S; 22.534998°E) was located in compartment B1D of the Cape Pine Jonkersberg plantation (Figure 64), close to the Saasveld entrance. The compartment was a 13 year old *Pinus radiata* compartment with a stocking density of 1111spha, and three trees were monitored. The natural vegetation of the area is Fynbos. The soils are well drained sandy clay loams (oak leaf soil form) classified as high potential soils for Pine saw timber production.

Figure 64. Sap flow monitoring system at site HPV 1 (Photo: M. Gush).

At HPV site 2 (33.943303°S; 22.511593°E) three *Pinus radiata* tree specimens in Compartment B18A (Figure 65) of the Cape Pine Jonkersberg plantation on Saasveld campus were instrumented with the HPV system on 10 April 2013. The compartment was 13 years old with a stocking density of 750spha. The soils are dark grey fine sandy loams which transcend to firm setting clays further down the profile. The soil is a West Leigh soil form which is seasonally wet, sometimes exhibits marginal phosphorous deficiencies but is also classified as a high potential productivity soil for *Pinus radiata* sawn timber production.

Figure 65. Sap flow monitoring system at site HPV 2 (Photo: M. Gush).

Stem diameter surveys were carried out in the plantations in order to determine the range of stem diameters present. The surveyed trees were then classified into diameter classes and representative sample trees were selected per each diameter class. Wood samples were taken from all trees to confirm bark thickness, sapwood depth, sapwood water content, wounding widths and wood density (Table 28). Sapwood depth determination from tree cores revealed no distinction between sapwood and heart wood even after staining with methyl orange. Sap wood (xylem) was assumed to extend to the centre of the tree (subsequently confirmed by sap flow observations), and probes were consequently inserted based on this observation.

Three individual indigenous trees comprising *Ocotea bullata, Ilex mitis* and *Podocarpus latifolius* (Figure 66) were instrumented at the HPV3 Groenkop site (-33˚ 56.406' S; 22˚ 32.879' E at an elevation of 258 m). Installation took place on the 15th of May 2013. All the species had straight trunks which facilitated stem volume calculations. The sapwood depths of *Illex mitis* and *Podocarpus latifolius* were unable to be distinguished visually, and consequently probes were inserted to a range of depths. However, sap velocity results subsequently indicated actual sapwood depth.

Figure 66. Sap flow monitoring system at site HPV 3 (Photo: M. Gush).

Table 28. Details of the individual trees selected for sap flow measurements at Saasveld.

Species	DBH (cm)	Tree height (m)	Sapwood depth (cm)	Wound width (mm)	Bark width (mm)	Wood density ($g.cm^{-3}$)
P. radiata HPV1_1	15.1	11.6	6.6	5.0	6	0.43
P. radiata HPV1_2	20.2	12.1	7.1	5.0	6	0.43
P. radiata HPV1_3	13.3	13.5	6.6	5.0	6	0.43
P. radiata HPV2_1	16.3	17.6	7.7	5.0	6	0.43
P. radiata HPV2_2	26.5	19.4	7.6	5.0	6	0.43
P. radiata HPV2_3	21.4	19.4	7.1	5.0	6	0.43
O. bullata	16.2	19.5	2.5	4.0	3	0.59
P. latifolius	7.8	8.0	3.0	4.0	2	0.47
I.mitis	14.9	13.1	6.0	4.0	2	0.51

Individual tree sap flow volumes (L yr^{-1}) for the Pines were scaled up to a hectare using plantation tree density to determine sap flow (transpiration) totals in mm-equivalent volumes for the year. The scaling up to water use per unit area such as a hectare could not be done for the indigenous species as they occurred in mixed species stands for which species density was unknown.

Volumetric soil water content at sap flow study sites HPV1 and HPV2 were recorded hourly in the top 100 mm of the soil profile throughout the monitoring period, using CS616 Soil water content probes (Campbell Scientific Inc., Logan, Utah, USA). An Aqua Check probe (ID 21226) that measures soil water content to a depth of 1 m at 20 cm intervals was installed at site HPV1. A temperature & relative humidity sensor recoding hourly micro-climatic variation in the plantation was also installed at this site. Two CS616 soil water content probes at a depth of 0.3 m and 1 m respectively, and an additional Aqua Check probe were installed at HPV 3. Soil samples taken in the vicinity of all probes were assessed for gravimetric water content, and assisted in calibration of the soil water data which was adjusted accordingly.

Stem biomass increments and water use efficiency

Stem biomass increments surveys, according to the method described in Chapter 2, were undertaken for all sample trees in order to calculate WUE. Stem volume increment measurements were carried out at the inception of the study in April/May 2013 and subsequently at quarterly intervals until a year later in May 2014. Measurements were taken to a height of 4.5 m up the stem at 0.5 m intervals using a diameter tape. Total tree height of the trees was also taken with a Vertex hypsometer (Haglöf, Sweden). The volume (biomass) as at installation of the instrumented trees was subsequently calculated from these measurements based on the assumption that the stem consisted of a series of truncated cones with a complete cone at the top (Gush & Dye, 2009). The stem volume increments were converted to dry mass using the wood densities determined from samples collected for each species in this study. In conjunction with the sap flow (water-use) results this allowed the calculation of WUE, defined as mass of woody biomass produced (g) per unit of water transpired (L), and results were compared against existing data for indigenous and introduced tree species available from previous studies (Olbrich *et al*., 1996; Dye *et al*., 2001; Gush & Dye, 2009).

6.2.3 Modelling

Understanding the WUE of individual tree species within a forest is necessary to identify those that show promise as possible plantation species. Species comparisons with heterogeneous forest environments is made very difficult by the presence of multi-aged trees of a range of species, and extremely complex canopy structures and spatial leaf distribution, as well as constantly changing patterns of shading by the taller trees in particular. The MAESPA model (see section 4) is an array model which permits simulations of specific trees in spatially complex stands and therefore holds great promise in increasing our understanding of water use and WUE in forests. As a first step in this direction, the MAESPA model was set up to see if the hourly sapflow values of an individual tree (*Ilex mitis*) in the Groenkop forest could be simulated well enough to show the main controls on tree sapflow and duplicate measured sap flow. Available input data and parameter default values were used whilst ensuring that all critical inputs for the model were entered. Critical inputs are identified by the model developers in Duursma and Medlyn (2012). Simulated values were then compared to observed values over the sap flow measurement period.

Plot Structure

The target tree (*Ilex mitis*) was specified to occupy a central position in a 30 m X 30 m square plot in a mixed species stand which displays average physiological properties. The stand was described as having two main canopy layers, a top canopy layer and an understorey layer consisting mainly of *Trichocladus crinitus* (Onderbos). Two other "trees" with square canopies completely filling the plot area were specified to represent the overstory canopy and the understory Onderbos canopy. The model was set up assuming a random distribution of leaves in both canopy volumes, and a combined leaf area index of 3.42. The total plot leaf area was assigned as follows: *Ilex mitis* (target tree) = 20 m^2; overstory canopy = 2278 m^2; understory canopy = 800 m^2. This was based on the total measured LAI recorded at the Ilex mitis tree, the visual assessment of the vertical variation in canopy densities and the relationship between diameter and leaf area for evergreen trees based on Whitehead and Jarvis (1981). The dominant height in the forest stand was 18.3 m while the tallest trees ranged between 25 and 26 m. The canopy of the *Ilex mitis* target tree was assumed to be an ellipsoid shape and the dimensions for the base and upper canopy heights were 5.8 m and 12.8 m respectively (Figure 67), and thus it was partially shaded by surrounding overstory trees.

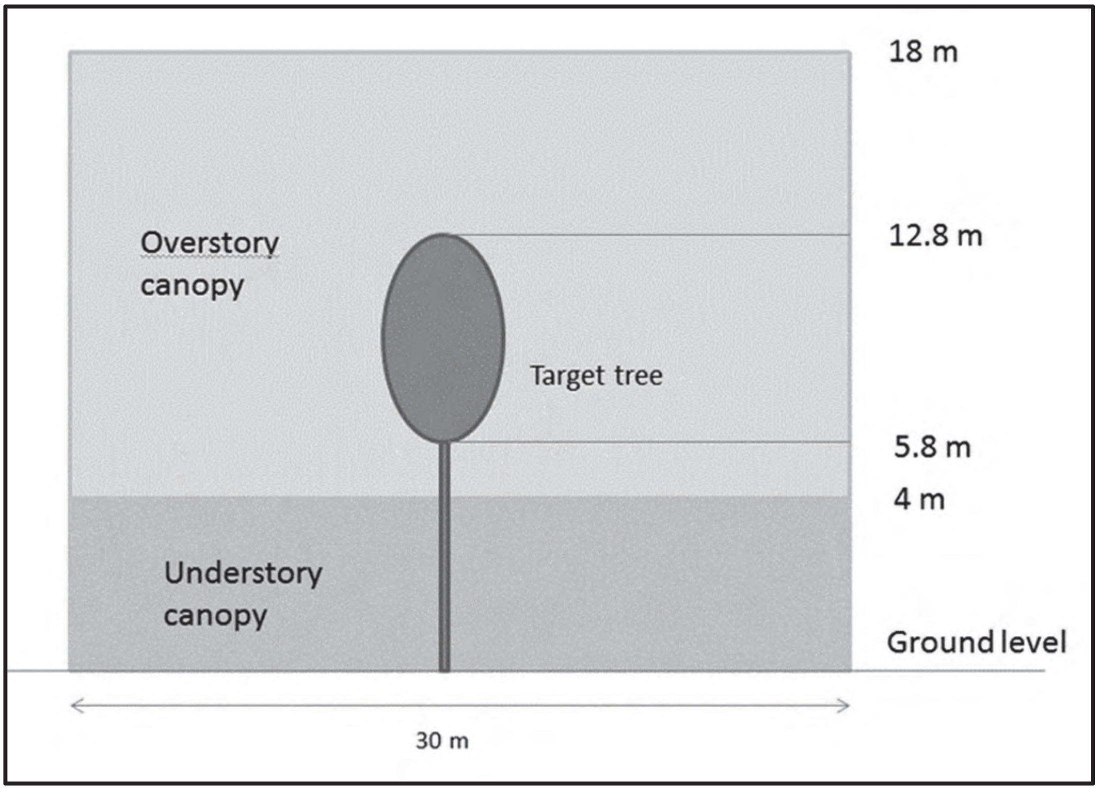

Figure 67. Diagrammatic representation of the position of the target tree (*Ilex mitis*) with reference to the understory and overstory canopy heights as well as the ground level.

Input files for the model are described in Table 29 which also shows major parameters that were specified for this study.

Table 29. Description of input files for the MAESPA model that were specified in simulating hourly sapflow for *Ilex mitis*.

Input files	Description	Specified for this study
trees.dat	Tree size and location	Number of trees, their plot positions, canopy dimensions, aerodynamic conductance parameters, total leaf area.
str.dat	Stand canopy structure	Canopy shape, leaf area density within the canopy volume, mean leaf inclination
confile.dat	Simulation control parameters	Time step, the number of canopy layers to integrate over, choice of stomatal model
phy.dat	Leaf physiology model parameters	Stomatal conductance predictors
met.dat	Meteorological drivers, site location	Hourly solar radiation, temperature, relative humidity, wind speed, rainfall, soil water
watpars.dat	Water balance, soil and plant hydraulics.	Soil depth, number of horizons, water retention attributes per horizon, root density and maximum depth, volumetric soil water contents

Various hourly and daily outputs are generated by the MAESPA model, covering photosynthesis and respiration, sapflow and other water balance components, and the energy balance. However, the model outputs that were most relevant for simulating transpiration and identifying the controls on the process were absorbed photosynthetically active radiation (PAR), net photosynthesis, sapflow per tree and per m^2 of the total canopy, canopy stomatal conductance, canopy boundary layer conductance, leaf water potential, and soil water content.

6.3 Results and Discussion

6.3.1 Weather

Monitoring yielded over a year of weather data typical of this year-round rainfall site (Figure 68). High rainfall events were well spaced throughout the year as the months of August, October, January and April received substantially high rainfall. Total rainfall for the monitoring period (20 May 2013 to 19 May 2014) was 998 mm which is high compared to the mean annual precipitation for the area of 650-750 mm (ICFR, 2013). Average daily solar radiation and temperature values peaked in December and February respectively, while January experienced slightly lower than expected values of these variables due to high rainfall received in that month. Occasional very warm days were recorded, with maximum temperatures in excess of 35° C, however moderate temperatures were the norm with monthly means of daily maximum temperature ranging from 20.1 ° C in August to 27.3 ° C in February (Figure 69). Monthly means of daily minimum temperatures ranged from 8 ° C in August to 16.6°C in February. The coldest temperature recorded at the site was 3.7°C on 30 Aug 2013, while the warmest was 37.6°C on 17 Feb 2014. Daily average solar radiation values ranged from 8.7 MJ m^{2-} day^{1-} in winter (June 2013) to 23.4 MJ m^{2-} day^{1-} in summer (December 2013). While solar radiation is an indicator of available energy for photosynthesis, a more accurate indicator of utilizable radiation to leaves is absorbed photosynthetically active radiation (PAR) which is calculated by Maespa. Daily wind-speed was relatively low, averaging just 0.9 m s^{-1} with June being the windiest month (1.2 m s^{-1}).

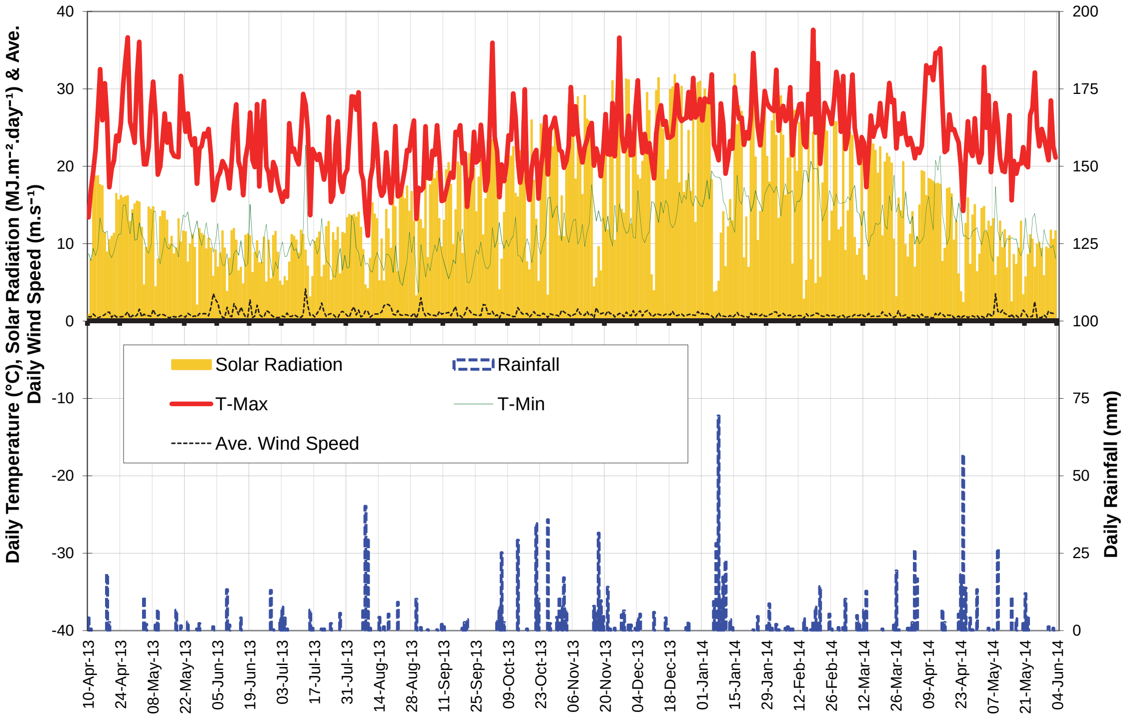

Figure 68. Daily maximum & minimum temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), average daily wind speed (m s^{-1}) & rainfall (mm) at the Saasveld site from 9 Apr 2013 to 4 Jun 2014.

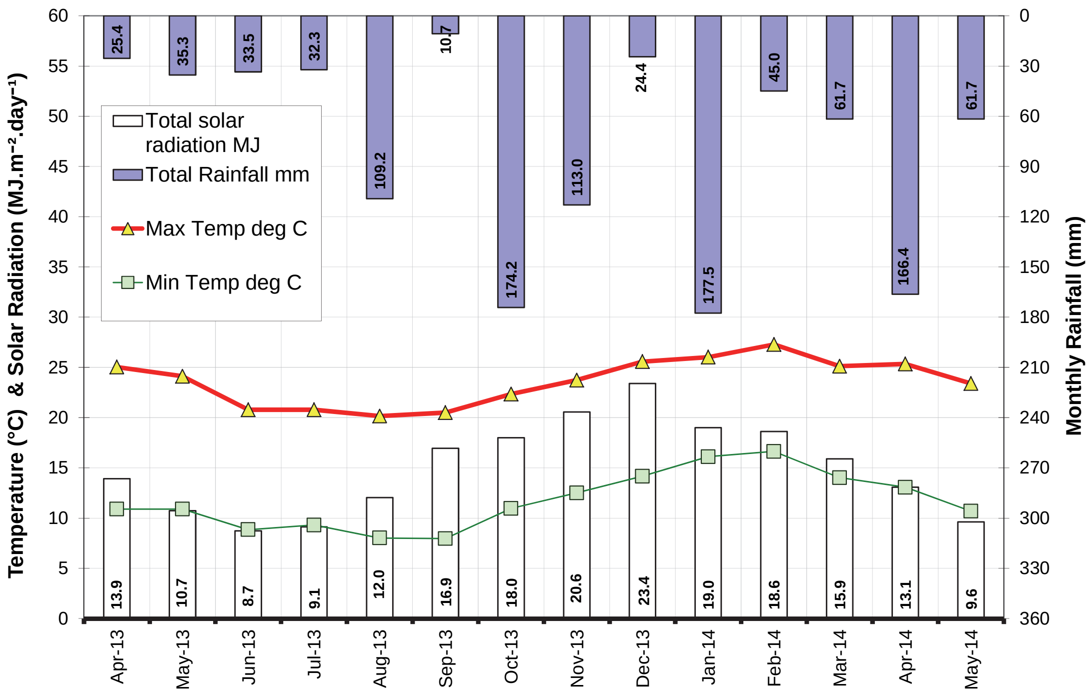

Figure 69. Monthly values of mean daily maximum/minimum temperatures (°C) and solar radiation (MJ m^{-2} day^{-1}), and rainfall totals (mm) at the Saasveld site from April 2013 to May 2014.

6.3.2 Soil water

The numerous rainfall events that occurred during the monitoring year resulted in soil water recharge (increasing soil water levels) being experienced at both the introduced Pine sites (Figure 70) and the indigenous forest site (Figure 71). This suggests that the trees were unlikely to be under any substantial water stress at any stage, although post-rainfall periods saw reductions in soil water which may have temporarily reduced overall transpiration rates.

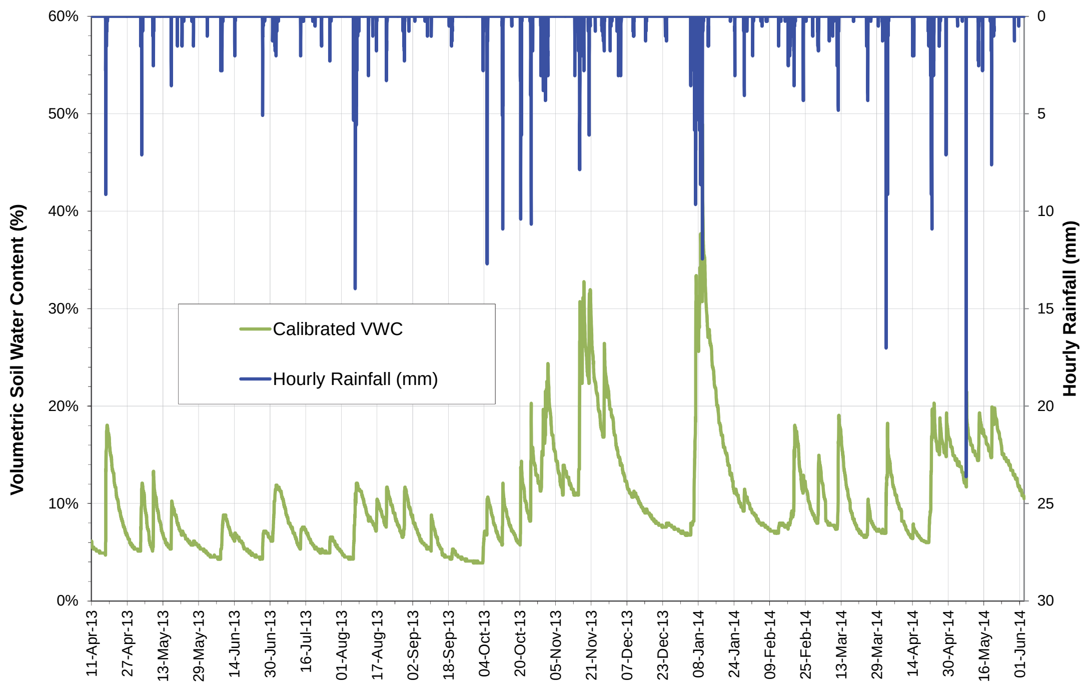

Figure 70. Fluctuations in volumetric soil water content at the Pine HPV1 site between 11 April 2013 and 3 June 2014.

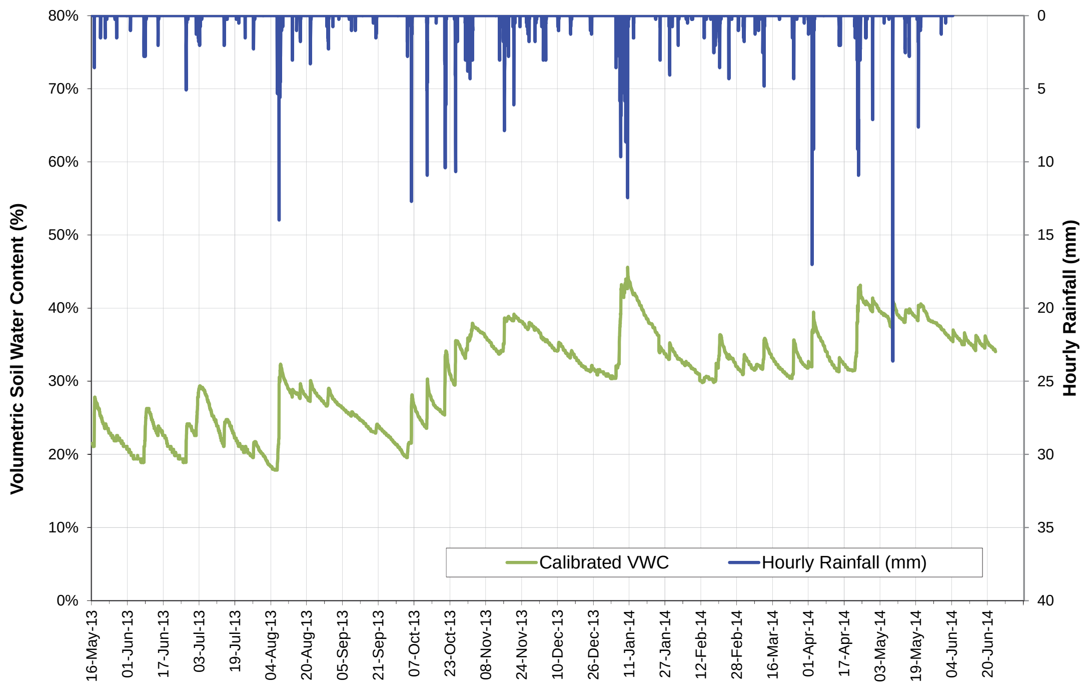

Figure 71. Fluctuations in volumetric soil water content at the Groenkop site between 16 May 2013 and 24 June 2014.

6.3.3 *Tree water use*

Some loss of data occurred in the first month after installation due to damage of thermocouples, heaters and the soil capacitance probe by baboons, and due to power interruptions. However, thereafter the considerable influence of soil water fluctuations (soil water availability) on sap flow patterns of trees at the Pine HPV1 site is evident (Figure 72). Spikes in soil water following rainfall events are characterized by low sap flow rates on those days due to solar radiation energy constraints. However, subsequent peaks in sap flow consistently occur on clear days 2-3 days after each event. Thereafter, there is a logarithmic decay in soil water content, and corresponding decline in sap flow rates, until the next rainfall event.

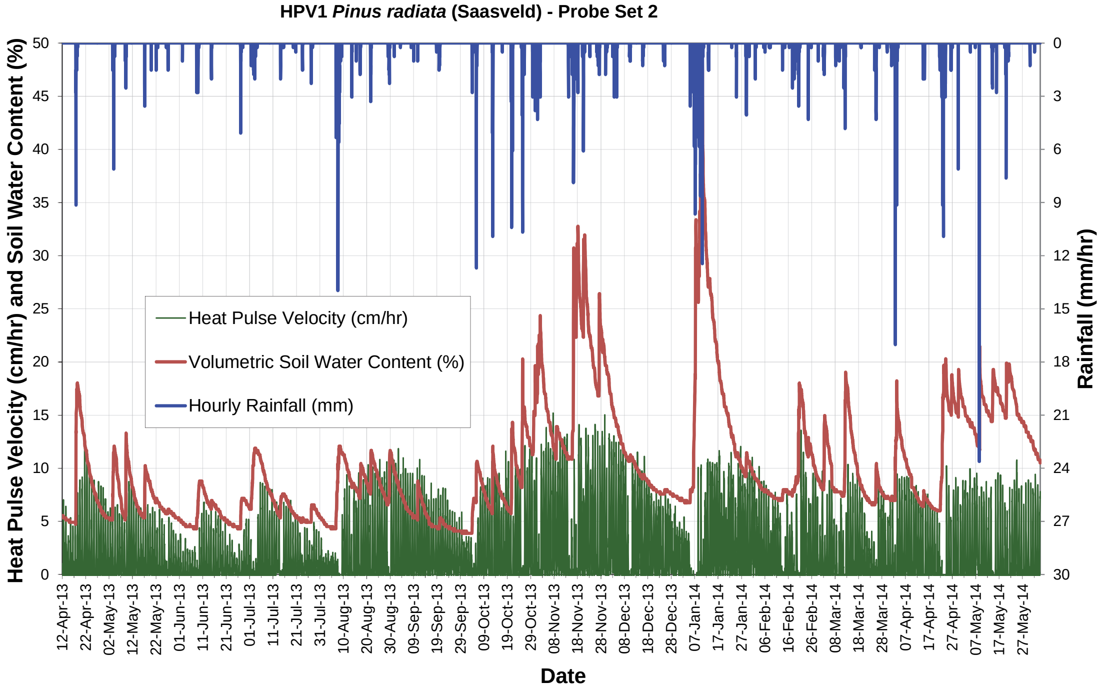

Figure 72. Pinus radiata sap flow velocity in relation to soil water content – HPV1.

Patched and corrected hourly HPV values were corrected for the effects of wounding using wound correction coefficients described by Burgess *et al*. (2001). These were then converted to sap velocities by accounting for wood density and sapwood water content (Pines = 66 %, Ocotea = 40.3 %, Podocarpus = 52.1 %, Ilex = 52.3 %), also taking into account the specific heat capacities of wood and sap (Marshall, 1958). Finally, the sap velocities were converted to whole-tree total sap flow volumes (litres per hour) as described earlier. Hourly sap flow volumes (in litres and mm) were aggregated into daily, monthly and annual totals. Daily sap flow (transpiration) volumes (L day^{-1}), measured in the 6 *P. radiata* trees are illustrated (Figure 73 to Figure 78).

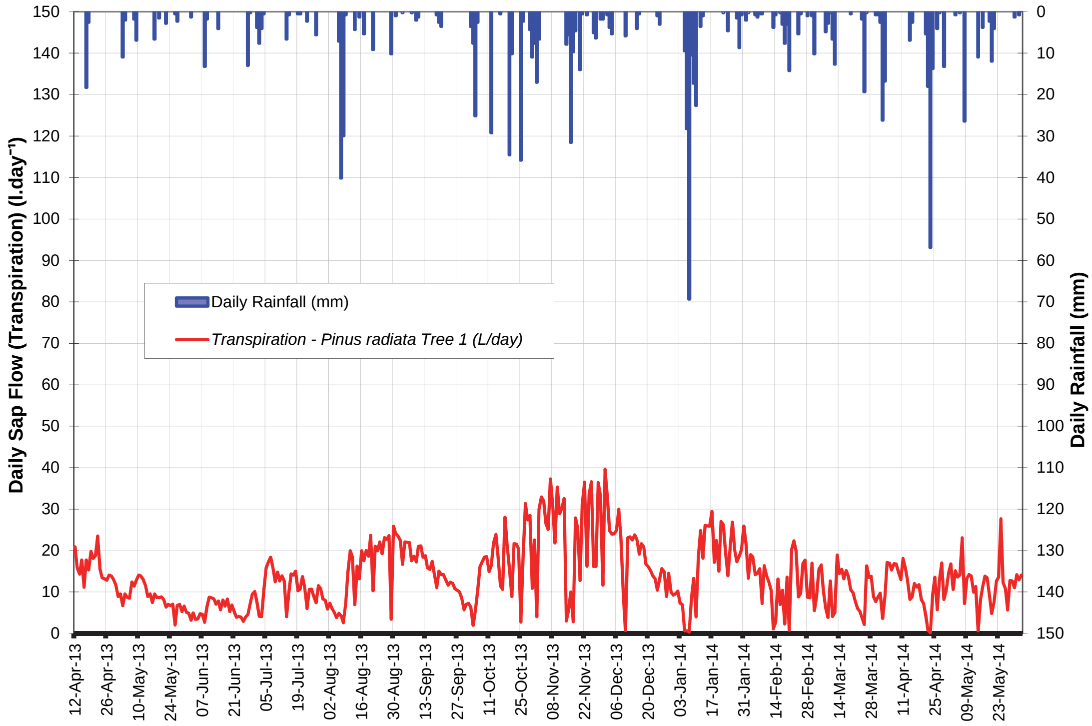

Figure 73. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Pinus radiata* tree (HPV1, tree 1), from 12 Apr 2013 to 2 Jun 2014.

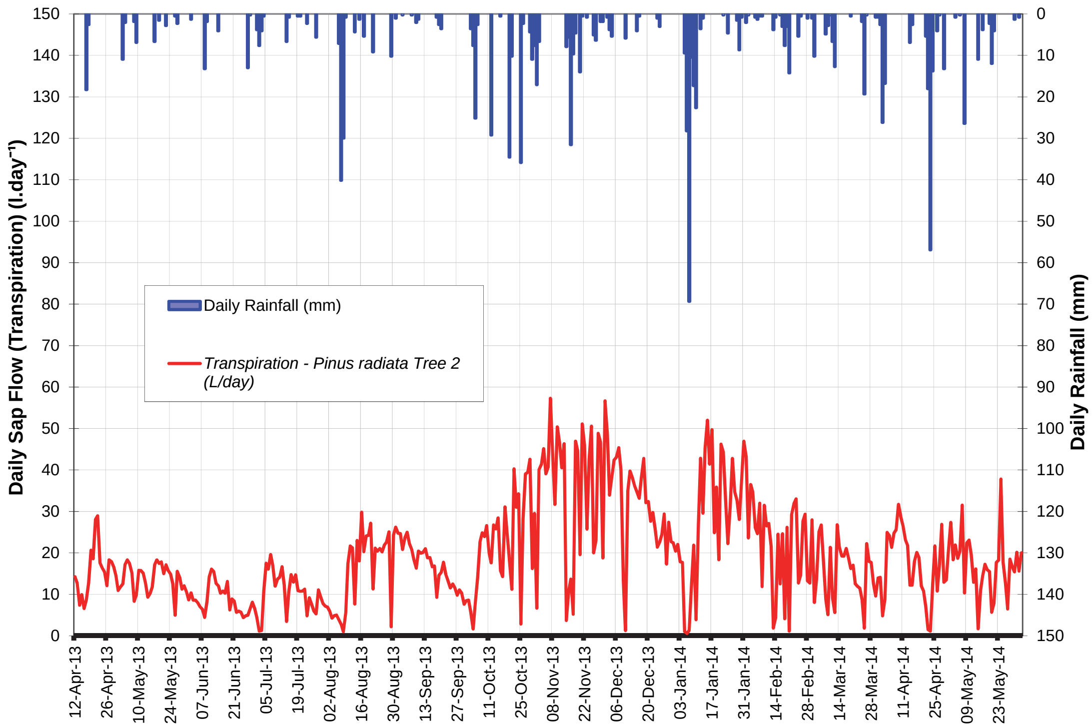

Figure 74. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Pinus radiata* tree (HPV1, tree 2), from 12 Apr 2013 to 2 Jun 2014.

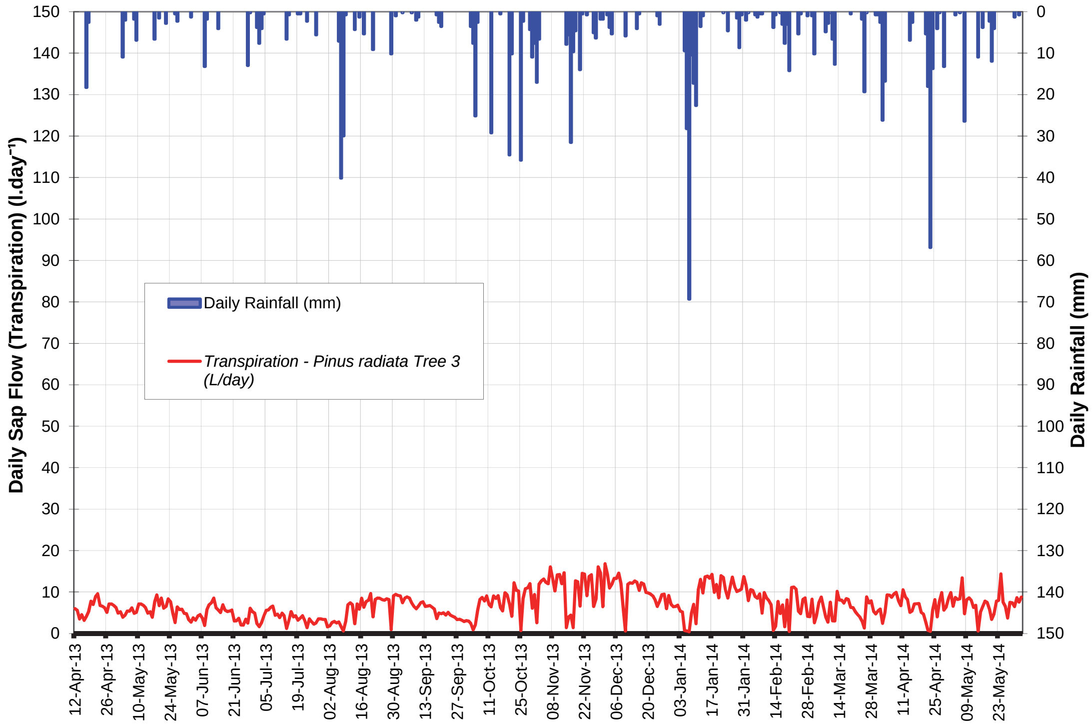

Figure 75. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Pinus radiata* tree (HPV1, tree 3), from 12 Apr 2013 to 2 Jun 2014.

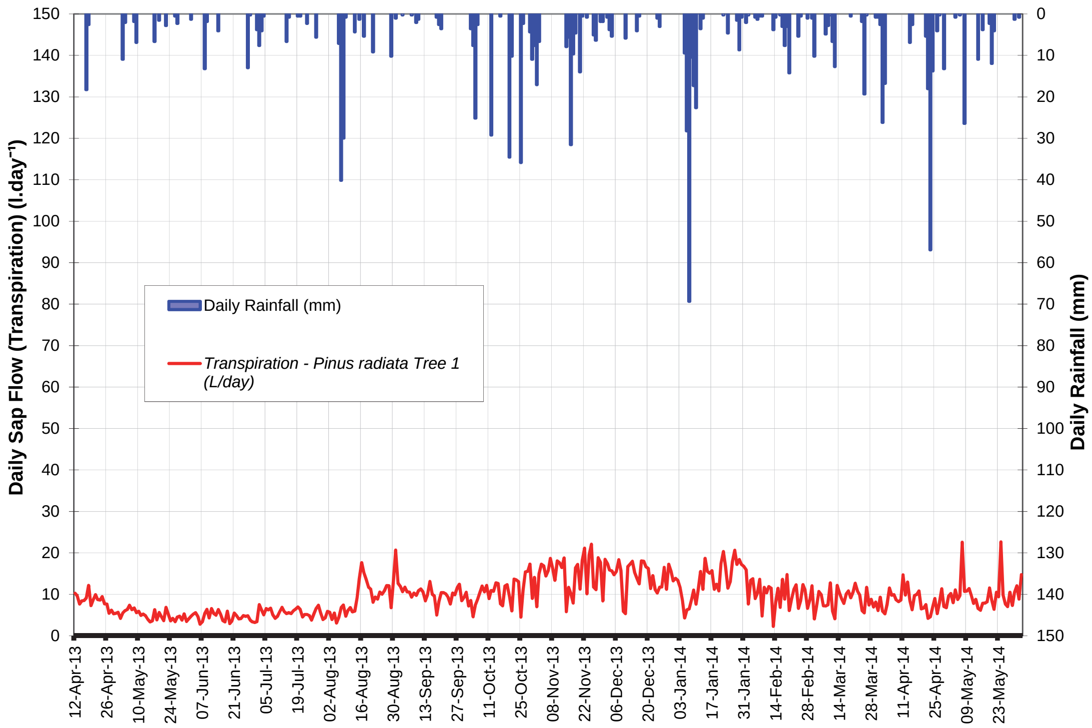

Figure 76. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Pinus radiata* tree (HPV2, tree 1), from 12 Apr 2013 to 2 Jun 2014.

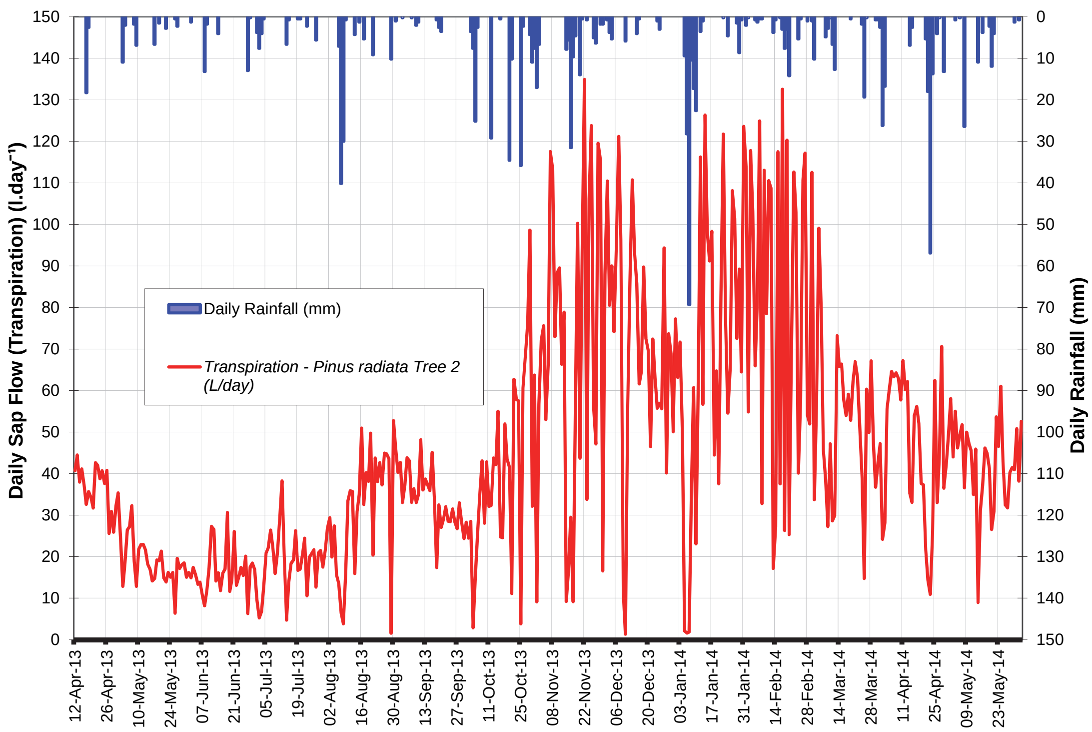

Figure 77. Daily sap flow (transpiration) volumes (L day⁻¹) for a *Pinus radiata* tree (HPV2, tree 2), from 12 Apr 2013 to 2 Jun 2014.

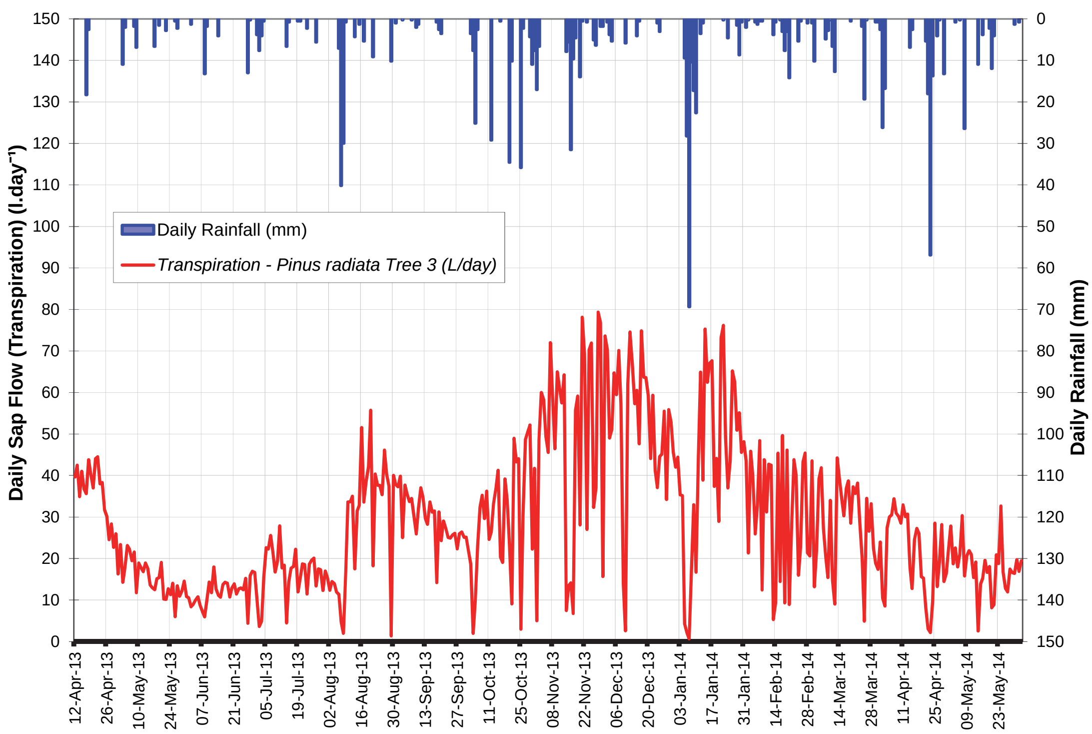

Figure 78. Daily sap flow (transpiration) volumes (L day⁻¹) for a *Pinus radiata* tree (HPV2, tree 3), from 12 Apr 2013 to 2 Jun 2014.

Annual transpiration totals for individual trees ranged from 2530 L yr⁻¹ (281 mm) for the smallest tree to 16612 L yr⁻¹ (1246 mm) for the largest tree, with an average of 4989 L yr⁻¹ (554 mm) for HPV1 and 10445 L yr⁻¹ (784 mm) for HPV2 (Table 30).

Table 30. Transpiration (water use) volumes recorded in *Pinus radiata* trees at Saasveld, near George.

HPV System	Tree No.	DBH (mm)	Tree Height (m)	Water use (L tree^{-1} yr^{-1})	Water use (mm)
HPV1	1	151	11.6	5 174	575
	2	202	12.1	7 264	807
	3	133	13.5	2 530	281
Average		**162**	**12.4**	**4 989**	**554**
HPV2	4	163	17.6	3 505	263
	5	265	19.4	16 612	1 246
	6	214	19.4	11 219	842
Average		**214**	**18.8**	**10 445**	**784**

Examples of the daily sap flow (transpiration) volumes (L day^{-1}), measured in the indigenous tree species are illustrated in Figure 79, Figure 80 and Figure 81.

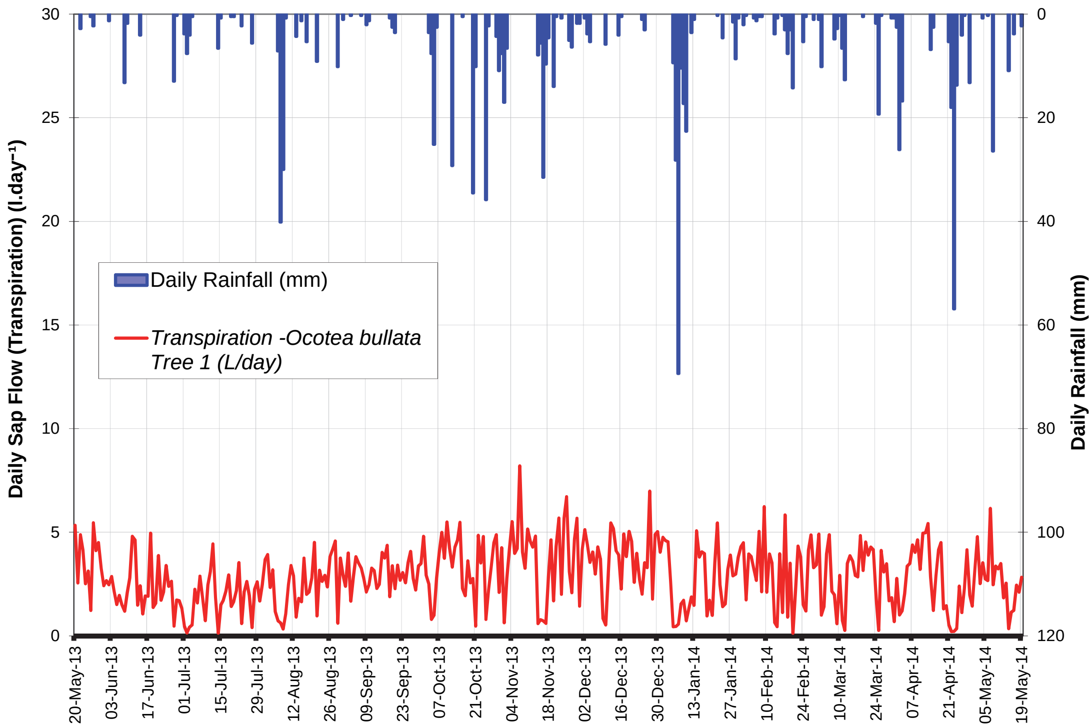

Figure 79. Daily sap flow (transpiration) volumes (L day^{-1}) for an *Ocotea bullata* tree, from 20 May 2013 to 19 May 2014.

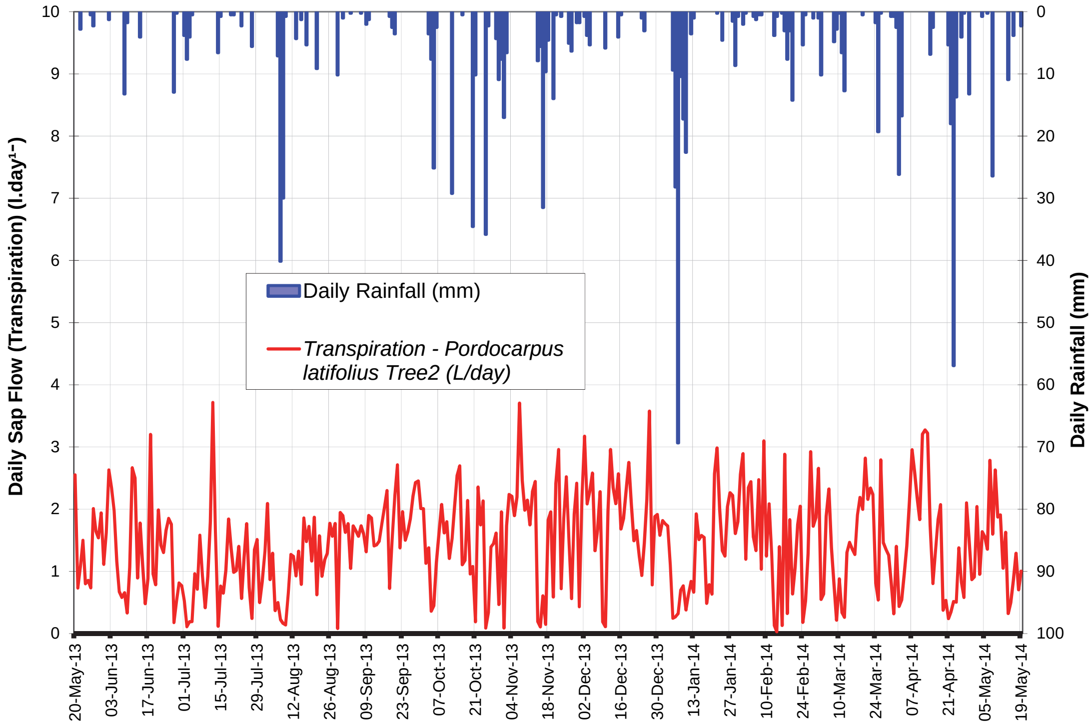

Figure 80. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Podocarpus latifolius* tree, from 20 May 2013 to 19 May 2014.

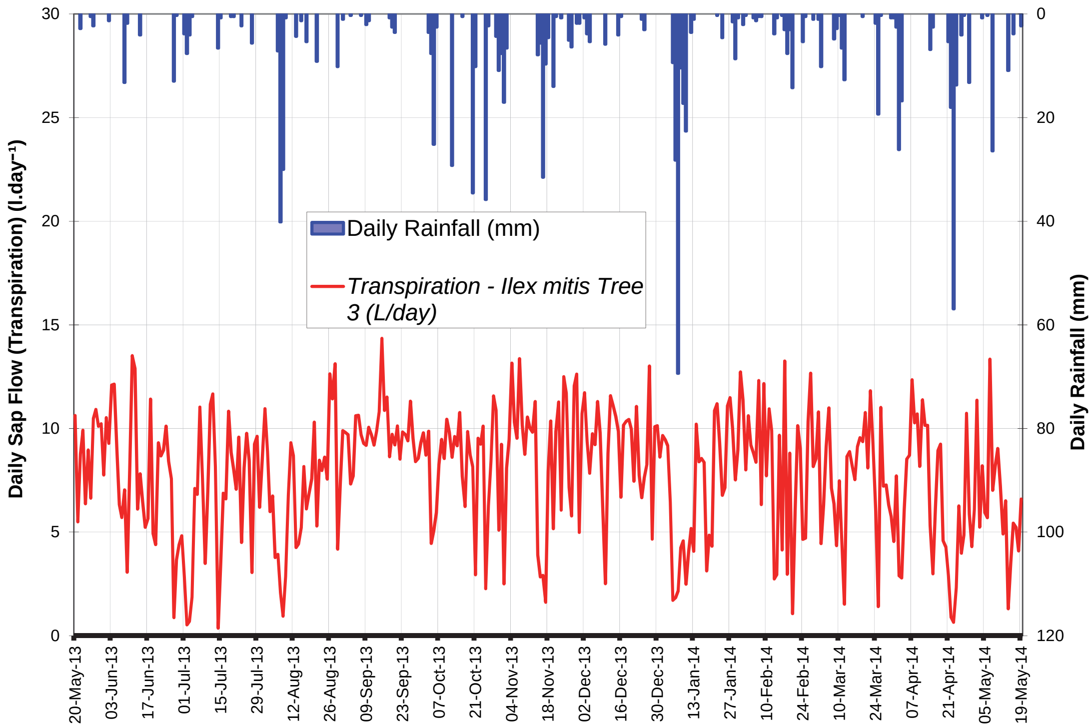

Figure 81. Daily sap flow (transpiration) volumes (L day^{-1}) for an *Ilex mitis* tree, from 20 May 2013 to 19 May 2014.

Annual transpiration totals for these trees ranged from just 528 L yr^{-1} for the small Podocarpus tree to 2849 L yr^{-1} for the Ilex (**Table 31**).

Table 31. Transpiration (water use) volumes recorded for individual indigenous trees in Groenkop forest.

Species	DBH (mm)	Tree Height (m)	Average Water use (L $tree^{-1}$ yr^{-1})
Ocotea bullata	162	19.5	1 052.1
Podocarpus latifolius	78	8.0	528.4
Ilex mitis	149	13.1	2 848.9

6.3.4 Stem biomass increments and water use efficiency

Initial stem biomass surveys were conducted on all the sample trees at the time of installation in April/May 2013. Quarterly surveys were subsequently carried out in August 2013, February 2014 and final ones in May/June 2014, in order to assess stem biomass increment over the monitoring period (Table 32).

Table 32. Average 1-year stem volume increments for the monitored trees.

Species	Tree Height (m)	Initial DBH (cm)	Final DBH (cm)	Initial Stem Volume (m^3)	Final Stem Volume (m^3)	1-yr Stem Volume Increment (m^3)	1-yr Stem Mass Increment (kg)
P. radiata HPV1_1	13.0	16.6	17.3	0.0908	0.1130	0.0223	9.53
P. radiata HPV1_2	13.5	20.6	21.7	0.1734	0.2054	0.0319	13.67
P. radiata HPV1_3	13.3	13.5	14.8	0.0807	0.0943	0.0136	5.81
P. radiata HPV2_1	17.6	15.8	16.7	0.1361	0.1567	0.0206	8.81
P. radiata HPV2_2	20.3	25.6	27.3	0.3605	0.4102	0.0497	21.26
P. radiata HPV2_3	20.0	20.9	21.8	0.2655	0.2963	0.0308	13.17
O. bullata	19.5	162.0	167.0	0.1678	0.1729	0.0052	3.08
P. latifolius	8.0	78.0	81.5	0.0196	0.0213	0.0018	0.82
I. mitis	13.1	149.0	160.0	0.0691	0.0778	0.0087	4.41

In conjunction with the sap flow (water-use) results, it was then possible to calculate WUE, defined as amount of stem biomass produced (g) per unit of water transpired (L) (Table 33).

Table 33. Summary of WUE data for all monitored trees, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use (transpiration).

Species	1-yr Water-use (L)	1-yr Stem Volume Increment (m^3)	Basic Wood Density ($g\ cm^{-3}$)	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
P. radiata HPV1_1	5 174	0.0223	0.43	9 529	1.85
P. radiata HPV1_2	7 264	0.0319		13 674	1.88
P. radiata HPV1_3	2 530	0.0136		5 814	2.30
P. radiata HPV2_1	3 505	0.0206		8 811	2.51
P. radiata HPV2_2	16 612	0.0497		21 259	1.28
P. radiata HPV2_3	11 219	0.0308		13 165	1.17
O. bullata	1 052	0.0052	0.59	3 078	2.93
P. latifolius	528	0.0018	0.47	821	1.53
I. mitis	2 849	0.0087	0.51	4 405	1.55

6.3.5 Modelling

A total of 2 849 litres was measured as total sapflow for *Ilex mitis* for the annual period 20 May 2013 to 19 April 2014. The average daily volume of sapflow for the year (daylight hours only) was 8.0 litres. The MAESPA model estimated a total volume of 3 258.3 litres for the year and the average daily water use based on the PBM was 8.9 litres. A correlation plot of the measured daily sapflow values vs the estimated volumes is shown in Figure 82. The coefficient of determination for the linear relationship (R^2) was equal to 0.70 while the slope of correlation was 0.88 and intercept was 1.84. These measures of the relation between measured and model-predicted values suggest that the major drivers of tree water use are accounted for in the PBM, and that the model predictions of sap flow are reasonably balanced. The deviation of simulated sapflow values from actual measurements was slight as shown by the 1:1 line of unity in Figure 82. At lower daily sapflow volumes, simulated values were higher than actual measurements while at higher volumes of sapflow simulated volumes were lower. The angle of deviation in this regard was however greater for lower volumes of sapflow than higher ones. At sapflow ranges of 10-12 litres per day, the modelled and measured volumes were at par. A cumulative curve for measured and modelled daily sapflow for the year is shown in Figure 83. The minimal difference in total sapflow volumes between actual and estimated values is evident. Soil water data were included in the model inputs. As expected, the model confirmed that daily sapflow was seldom limited by soil water availability. The shallow water table at the site would ensure that the overlying soil contains substantial plant available water despite depletion by the tree roots.

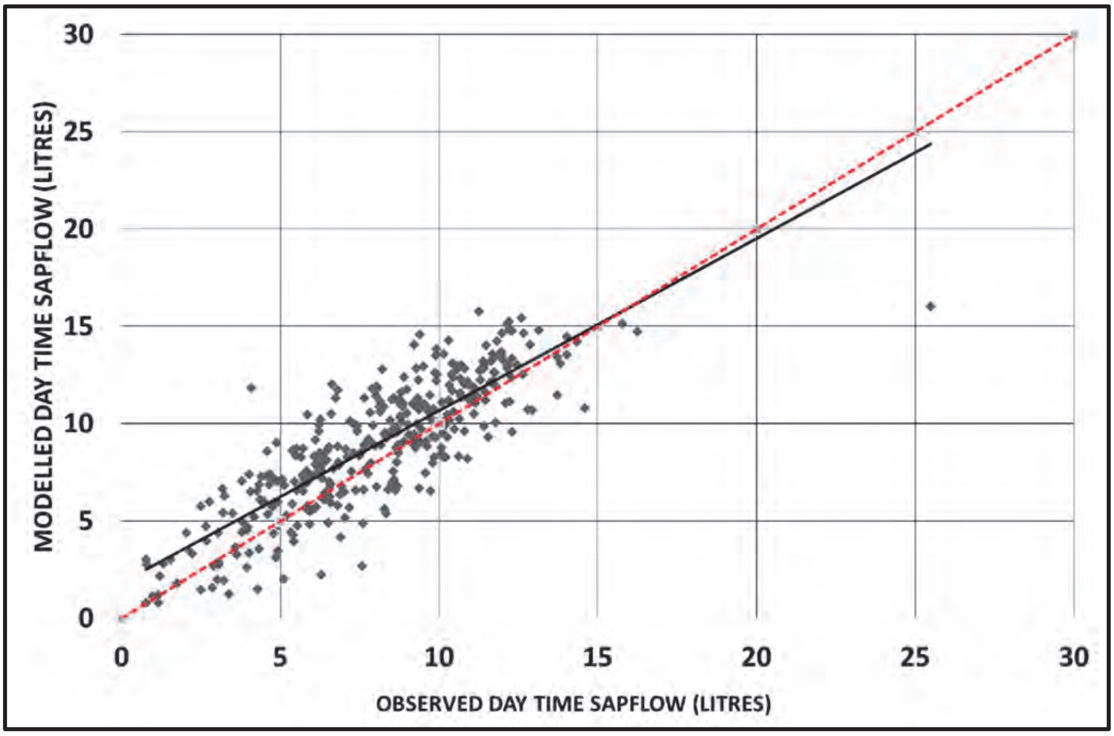

Figure 82. The relationship between observed and MAESPA modelled daytime transpiration. The bold line (black) represents regression line of best fit for modelled daily sapflow as a function measured daily sapflow and the dash line (red) represents the 1:1 line of unity between modelled as measured daily sapflow.

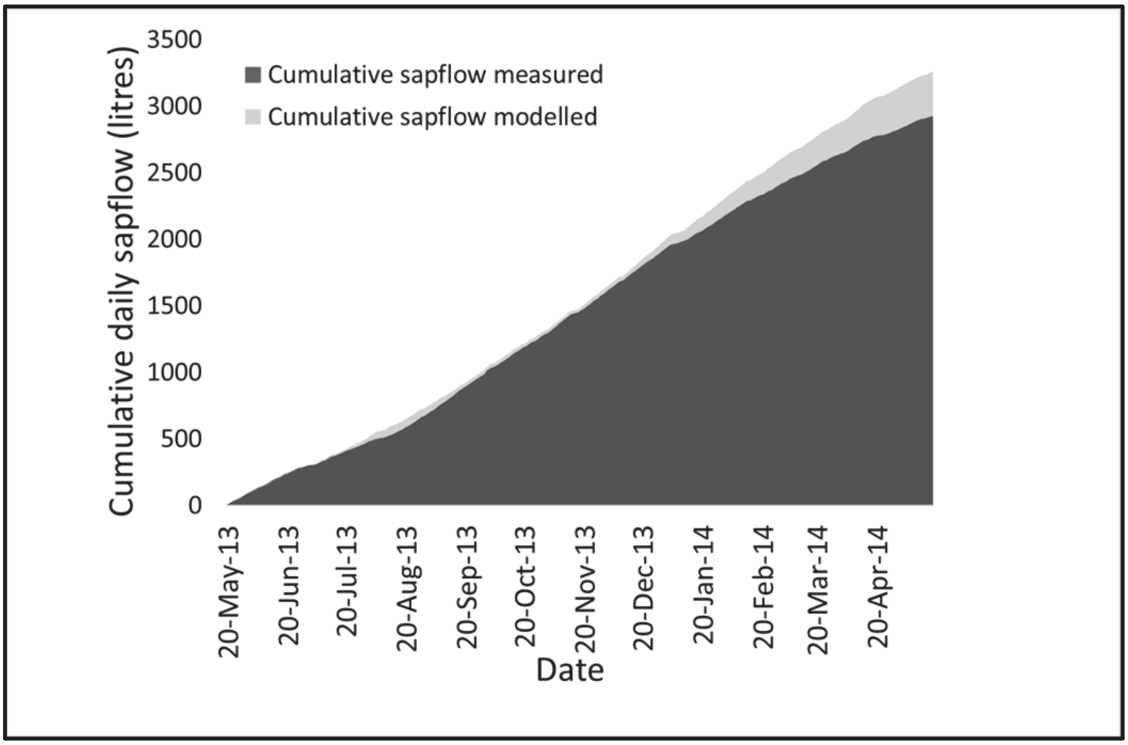

Figure 83. Cumulative totals for measured and modelled daily transpiration for the period 20 May 2013 to 19 May 2014.

Estimated cumulative transpiration totals showed increased deviations from cumulative totals of actual measurements only in the later summer months. In terms of predicting total water use over periods of time the model showed satisfactory performance. However, the summer months exhibit higher totals of rainfall and solar radiation and hence the model's performance under conditions of maximum values for key climatic drivers such as these requires further examination.

One of the model outputs, absorbed photosynthetically active radiation by the canopy, was plotted against measured values of daily sapflow (Figure 84). A parabolic relationship between absorbed radiation and daytime sapflow volumes was indicated. The R^2 value for the curve was 0.60 implying that 60 % of the variance in tree water use was explained using the PAR output component of the MAESPA model. A clear indication of the thresholds in single tree water use due to increasing available and or absorbed radiation energy is represented by a seemingly maximum dipping plateau on the curve. A possible explanation could be the regulation of stomatal opening and closing in order to optimise physiological processes such as photosynthesis whilst at the same time avoiding excessive and detrimental water loss to the functioning of the tree.

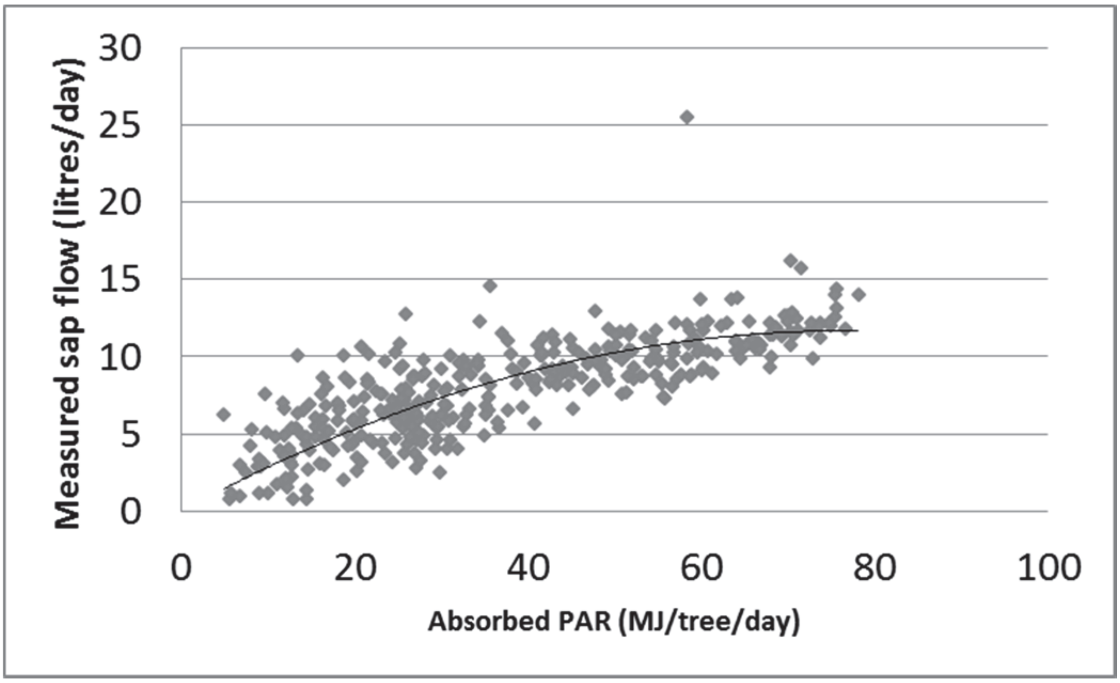

Figure 84. The relationship between photosynthetically absorbed radiation by the *Ilex mitis* canopy and measured daily volumes of sapflow (R^2 = 0.60; p < 0.0001).

6.4 Discussion

Single tree water use was correlated with a range of environmental factors. From the data it is evident that solar radiation, relative humidity, temperature and wind speed had a substantial influence on daily sapflow. The study findings concur with studies done internationally (Allen *et al.*, 1998) on the notion that climate is an important driver of total evaporation in tree production systems. Solar radiation indicated the highest partial correlations with daily water use for all the tree species. A transpiration-climate correlation model developed by Whitley *et al.* (2008) for Australian native forests showed that solar radiation had the strongest positive correlation. Additionally crop water use guidelines developed and issued by Allen *et al.* (1998) support the findings that solar radiation is the principal driver of tree water use, although additional energy sources (e.g. advection) may play a role under certain conditions. The good correlation between total daily solar radiation and mean maximum temperature was expected as temperature is directly influenced by the conversion of radiant energy from light to heat.

The water availability component of transpiration for the species monitored in this study was expressed as soil water content. This was indicated by the good correlations of soil water content with daily sapflow volumes in contrast to the weaker correlations of daily rainfall and daily sapflow. It was also clear that an increase in sapflow volumes was delayed after a rain event. While precipitation is the base source of water for transpiration, this was indicated to be more relevant to daily tree water use. This can be attributed to the soil-plant-atmosphere continuum in which total evaporation takes place.

The duplex, poorly drained soils of the study area also result in a slow response to available water provided through rainfall, and hence available soil water on a particular day was more influential to daily transpiration than the amount of precipitation received on the day. This is also because transpiration is particularly low on days of rainfall, with trees only likely to respond a day or two later when use of the replenished soil water levels could be taken advantage of given adequate levels of solar radiation (energy). An above-average amount (1009 mm) of precipitation was received in the year. This high rainfall amount in conjunction with the water holding properties of the duplex soils in the form of a perched water table can therefore imply that soil water thresholds during the study period were not limiting to the transpiration process. It can thus be purported that daily single tree water use was influenced by how much water the soils could release to the trees and not necessarily how much water was absorbed by the soils from precipitation on a particular day.

The MAESPA model adequately predicted sapflow in individual indigenous forest trees which were partially shaded by larger surrounding trees in natural forest situations. This was despite the use of some default model parameter values, and some uncertainty over the total leaf area of the target tree. More leaf and canopy physiological information and structural measurements are expected to improve accuracy. Soil water data was included in the model inputs. As expected, the model confirmed that daily sapflow was seldom limited by soil water availability. The shallow water table at the site would ensure that the overlying soil contains substantial plant available water despite depletion by the tree roots.

One of the aims of the study was to determine the key drivers for water use. Daily sap flow was correlated to daily PAR absorbed by the *Ilex mitis* canopy which is an important regulator of leaf stomatal opening. Mean daily vapour pressure deficit (VPD) showed a similar trend, but with a poorer correlation to daily sap flow. One causal factor was that mean VPD did not reflect the non-linearity of the relation. Another factor was that stomata often close partially when evaporative demand is particularly high. This might explain why data points appeared to decline when daily VPD was high. While measurements of weather variables and sapflow can be used to analyse which variables correlate with sapflow, sensitivity analyses can also help to answer this question. Uncertainty in outputs is quantifiable and thus specific causatives can be determined. Future studies need to include sensitivity analyses.

The MAESPA model has the potential to be extensively used for predicting water use by different tree production systems using relevant physiological and climate inputs. This study has shown that good sapflow predictions can be achieved for single trees in heterogeneous natural forests with a high degree of shading. The model is able to account for a wide range of leaf properties, allowing simulations of different species with diverse physiological and structural properties. Thus, other sapflow sample trees in the Groenkop forest may also be simulated with MAESPA. Such simulations would be greatly improved by knowledge of some important leaf and canopy attributes which are included in the MAESPA model. Examples of parameters that could be included in future studies to increase the applicability of the model in mixed stands, such as South African indigenous forests, are leaf area as this is often irregular in natural forests; and PAR measurements that are done on the forest floor to validate light interception estimated for the stand.

7 SINGLE TREE *PTAEROXYLON OBLIQUUM* AND *MILLETTIA GRANDIS* STUDIES AT PIETERMARITZBURG[10]

7.1 Introduction

Millettia grandis (Umzimbeet) commonly occurs on the edge of forests while *Ptaeroxylon obliquum* (Sneezewood) occurs deeper in the forest. These two indigenous tree species were considered priority species to monitor in the project, largely because they are extremely useful trees and sought after in particular by rural inhabitants for livelihood purposes (see Volume 1). They have been researched previously, with Sneezewood trees monitored at Karkloof from February 2007 to February 2008 (Gush and Dye, 2009) and both species monitored in the Manubi forest from September 2010 to September 2011 (this report). However, following a project reference group meeting in May 2013 it was advised that additional examples of these two species be monitored to increase the number of sample trees.

7.2 Materials and Methods

7.2.1 Site description

A site visit to Ngoye forest was carried out to seek potentially suitable trees/sites to use, however the trees that were found were located in areas where access or equipment safety was a problem. Visits were carried out to several additional sites with potential (e.g. Twin Streams farm, Mtunzini; Queen Elizabeth Park, Pietermaritzburg), however after unsuccessful searches, an ideal site incorporating the two tree species in question was found at the University of KwaZulu-Natal Arboretum on the Agricultural Campus in Pietermaritzburg (-29.628627° S; 30.402861°' Alt = 678 m.a.s.l.) (Figure 85). The Umzimbeet trees were located in the eastern part of the Arboretum and were planted in September/October 1988 at the inauguration of the Arboretum, while the Sneezewood trees were planted in August/September 1990. Soils within the arboretum are shallow, and

[10] When making reference to this section, please cite as follows:

Gush, M.B. and Naiken, V. 2015. Single tree *Ptaeroxylon obliquum* and *Millettia grandis* studies at Pietermaritzburg. In: Gush, M.B. and Dye, P.J. (Eds). 2015. Water Use and Socio-Economic Benefit of the Biomass of Indigenous Trees: Volume 2 (Site-Specific Technical Report). Water Research Commission, Pretoria, RSA, WRC Report 1876/2/15, Section 7.

composed of Scottsville shale. A field campaign to install instrumentation and take measurements at this site was carried out from 8-9 August 2013. Monitoring at this site took place for a year, and all equipment was removed from the site on 1 August 2014.

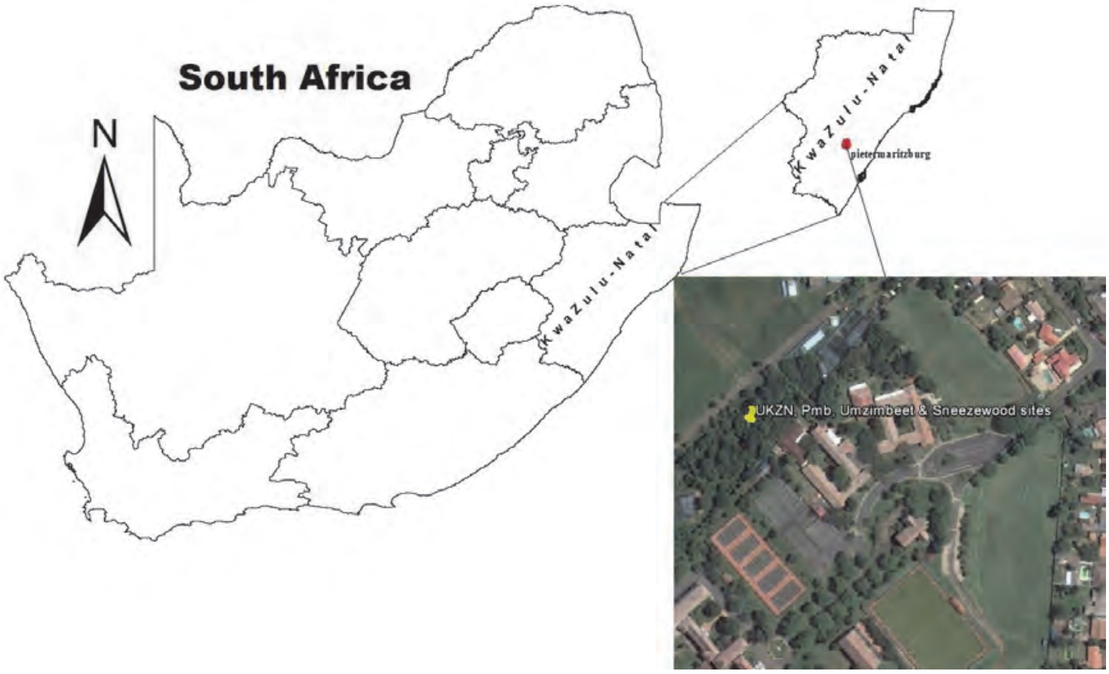

Figure 85. Aerial view of the UKZN Sneezewood/Umzimbeet site.

7.2.2 Field measurements

Weather

Weather data for this site was available from two sources, namely the South African Weather services (SAWS) station, and from Prof MJ Savage, Agrometeorology Discipline, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg (http://agromet.ukzn.ac.za:5355/). Both of these weather stations were located within 500 m of the study trees, on the University campus, and provided a full suite of weather variables at hourly and daily time steps.

Sap flow (transpiration) and soil water

The heat ratio method (HRM) of the HPV technique (Burgess *et al.*, 2001), as described in Chapter 2, was applied to quantify sap flow rates (transpiration) in this study. Raw heat pulse velocity data were checked, patched and analysed according to methods described earlier. Two *Millettia grandis* (Umzimbeet) trees (Figure 86) and two *Ptaeroxylon obliquum* (Sneezewood) trees (Figure 87) were instrumented at the site, using separate HPV systems (Table 34). Volumetric soil water content was recorded hourly in the top

100 mm of the soil profile from 9 Oct 2013 to 5 Sep 2011, using CS616 Soil water content probes (Campbell Scientific Inc., Logan, Utah, USA).

Table 34. Details of the individual trees selected for sap flow measurements at Pietermaritzburg.

Species	Diameter at breast height (cm)	Tree height (m)	Sapwood depth (cm)	Wound width (mm)	Bark width (mm)	Wood density ($g.cm^{-3}$)
M .grandis 1	12.9	7.1	3.5	4.0	4.0	0.79
M .grandis 2	23.5	7.1	3.6	4.0	4.0	0.79
P. obliquum 1	10.0	7.2	2.1	3.5	6.0	0.73
P. obliquum 2	13.1	7.5	2.5	3.5	6.0	0.73

Figure 86. View of the instrumentation and trees at the *Millettia grandis* site in Pietermaritzburg (Photo: M. Gush).

Figure 87. View of the *Ptaeroxylon obliquum* study site in Pietermaritzburg (Photo: M. Gush).

Stem biomass increments and water use efficiency

Stem biomass increments surveys, according to the method described in Chapter 2, were undertaken for all sample trees in order to calculate WUE. An initial stem biomass survey was conducted on all the sample trees at this site shortly after installation on 20 August 2013, and a final one was done on 13 August 2014 after sap flow monitoring had been concluded, in order to assess stem biomass increment over the monitoring period, in conjunction with water-use data from sap flow measurements

7.3 Results and Discussion

7.3.1 Weather

Following typical dry winter conditions, the summer rainfall season started with heavy spring falls in October 2013, but only moderate monthly totals during the summer months thereafter and there was very little rain from April onwards. Total rainfall recorded at this site over the monitoring period was consequently just 606 mm, lower than the MAP of around 700 mm (Lynch and Schulze, 2006). Daily temperatures ranged from maximum values in excess of 35°C between October and March, to minimum values of below 10°C between April and September (Figure 88). Temperature trends were stable during mid-summer (Jan/Feb), with maximums consistently over 20°C and minimums over 15°C. The coldest temperature recorded at the site was

-0.5°C on 9 July 2014, while the warmest was 37.6°C on 11 Oct 2013. Solar radiation ranged widely at the onset of the rainy season in October/November, but subsequently stabilised and consistently reached daily values of 20-30 MJ m^{-2} day^{-1} during periods of dry weather. Daily average solar radiation values were at their highest in the summer month of January 2014 at 21.6 MJ m^{-2} day^{-1}, declining to winter (June 2014) lows of 12.1 MJ m^{-2} day^{-1} (Figure 89). Daily wind-speed ranged from 1.4 m s^{-1} in October to 0.8 m s^{-1} in March.

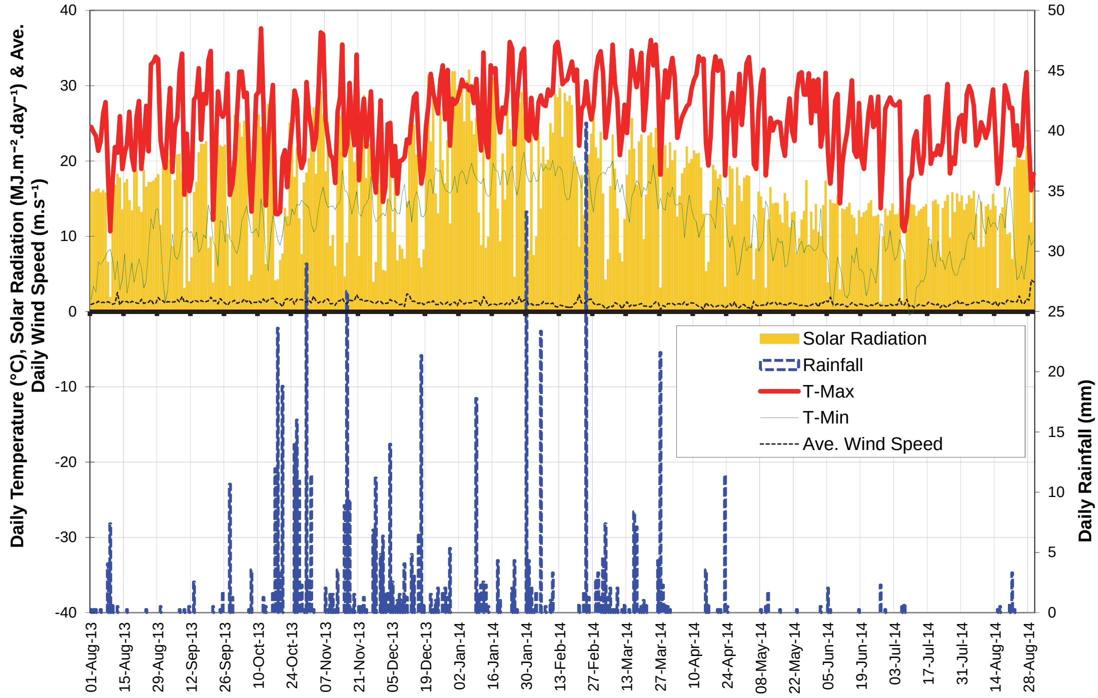

Figure 88. Daily maximum & minimum temperatures (°C), solar radiation (MJ m^{-2} day^{-1}), average daily wind speed (m s^{-1}) & rainfall (mm) at the UKZN site from 1 Aug 2013 to 30 Aug 2014.

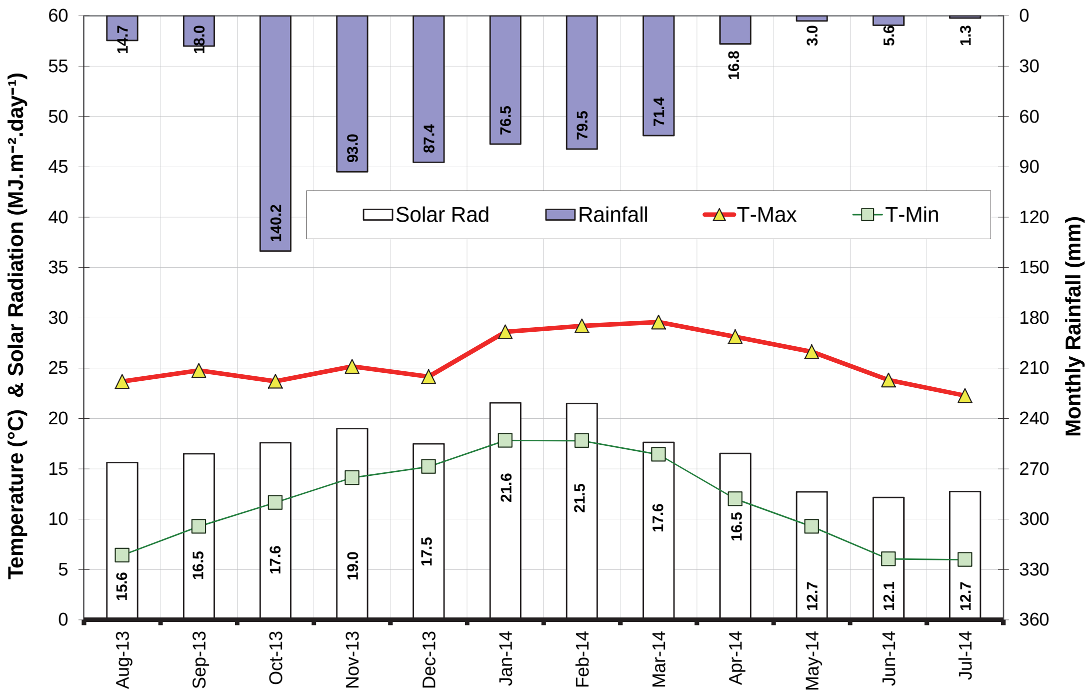

Figure 89. Monthly values of mean daily maximum/minimum temperatures (°C) and solar radiation (MJ m⁻² day⁻¹), and rainfall totals (mm) at the UKZN site from August 2013 to July 2014.

7.3.2 Soil water and tree water use

The Umzimbeet is a semi-deciduous species, losing most of its leaves during winter and in periods of drought stress. It was evident from the raw heat pulse velocity data that sap flows were insignificant during the dry winter months but showed a dramatic increase after the onset of the first spring/summer rains in October. Heat pulse velocities remained consistent over the summer months, but were conservative relative to other species, and declined noticeably from April onwards, as the dry winter months dominated once more. Sneezwood, on the other hand is an evergreen species, transpiring year-round, with less exaggerated seasonal variation. Nevertheless, some temperature/water availability responses were evident in the heat pulse velocity (HPV) data from this species, particularly around the end of June 2014. Sap flows increased dramatically around this time, although no substantial rainfall events were recorded. However the time series of volumetric water content recorded in the upper soil layer at the site indicated a noticeable wetting event at this time, and is likely due to a once-off irrigation/watering event at the site (Figure 90). All other soil water responses appeared to be associated with rainfall events.

Figure 90. Fluctuations in volumetric soil water content at the Pietermaritzburg site between 8 Aug 2013 and 1 Aug 2014.

The final analysis of the raw heat pulse velocity data consisted of the conversion of the hourly HPV values to total daily sap flow volumes, as described earlier. Again, wood samples were taken to confirm bark thickness, sapwood depth, sapwood water content (Umzimbeet = 38.9%; Sneezewood = 31.5%), wounding widths and wood density. Hourly sap flow volumes (in litres and mm) were aggregated into daily, monthly and annual totals. Examples of daily sap flow (transpiration) volumes (L day^{-1}), recorded in Umzimbeet and Sneezewood sample trees are illustrated in Figure 91 and Figure 92, with the resultant annual water use totals in Table 35.

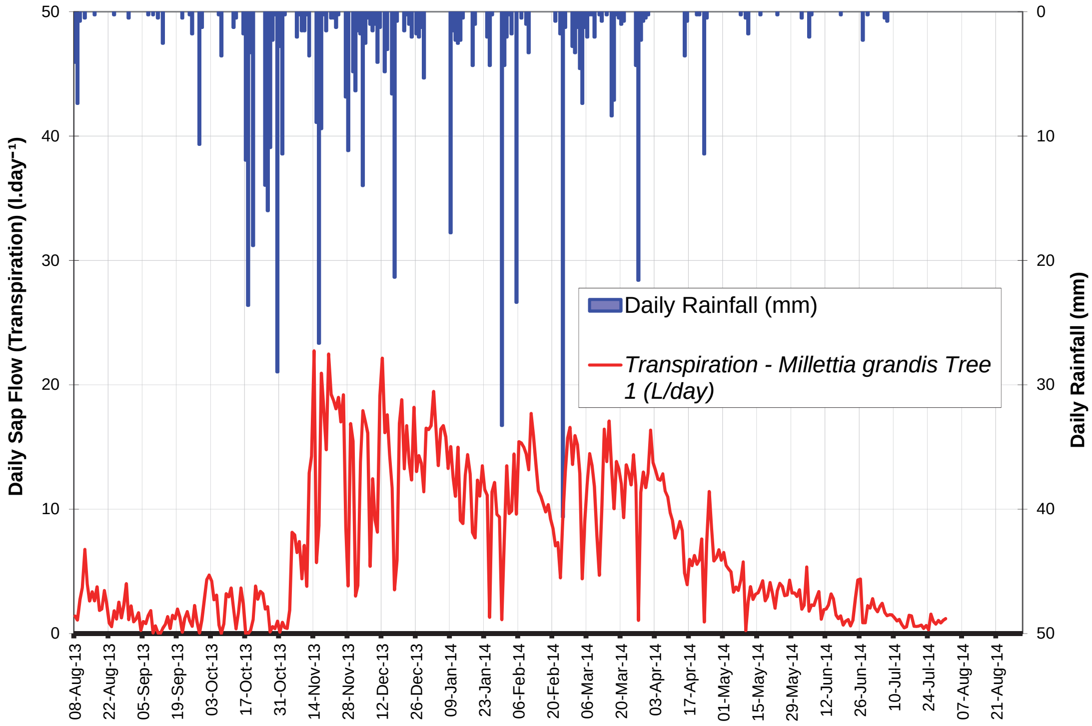

Figure 91. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Millettia grandis* tree at Pietermaritzburg (8 Aug 2013 to 1 Aug 2014).

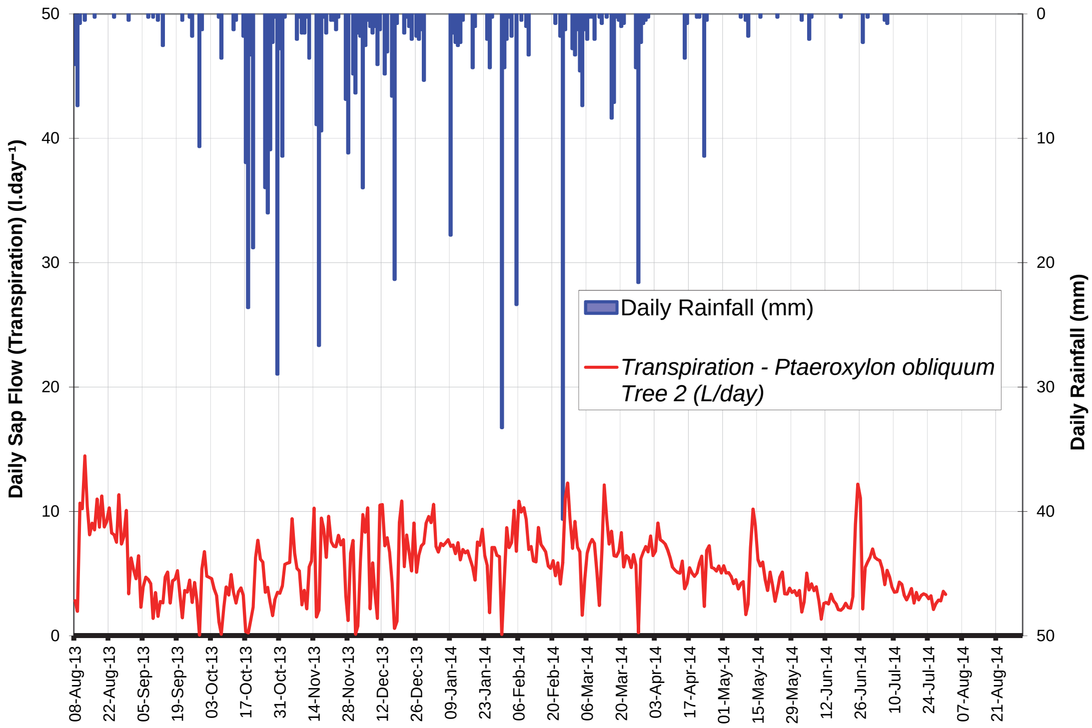

Figure 92. Daily sap flow (transpiration) volumes (L day^{-1}) for a *Ptaeroxylon obliquum* tree at Pietermaritzburg (8 Aug 2013 to 1 Aug 2014).

Table 35. Transpiration (water use) volumes recorded in *Millettia grandis* and *Ptaeroxylon obliquum* trees at Pietermaritzburg.

Tree/Species	DBH (mm)	Tree Height (m)	Annual Water use (L tree^{-1} yr^{-1})
Millettia grandis Tree 1	129	7.1	2 445
Millettia grandis Tree 2	235	7.1	6 266
Ptaeroxylon obliquum Tree 1	100	7.2	1 312
Ptaeroxylon obliquum Tree 2	131	7.5	1 978

7.3.3 Biomass increments and water use efficiency

Tree stem biomass increments were calculated (Table 36), and in conjunction with the sap flow (water-use) results, it was then possible to calculate WUE, defined as amount of stem biomass produced (g) per unit of water transpired (L) (Table 37).

Table 36. 1-year stem volume increments for the *Millettia grandis* and *Ptaeroxylon obliquum* trees at Pietermaritzburg.

Tree/Species	**Initial Height (m)**	**Final Height (m)**	**Initial DBH (cm)**	**Final DBH (cm)**	**Initial Stem Volume (m³)**	**Final Stem Volume (m³)**	**Annual Stem Volume Increment (m³)**	**Annual Stem Mass Increment (kg)**
Millettia grandis Tree 1	7.1	7.6	12.6	13.1	0.0743	0.0824	0.0082	6.46
Millettia grandis Tree 2	7.1	7.5	23.8	24.4	0.2424	0.2665	0.0241	19.09
Ptaeroxylon obliquum Tree 1	7.2	7.6	8.9	9.3	0.0282	0.0315	0.0033	2.39
Ptaeroxylon obliquum Tree 2	7.5	8.0	11.4	11.8	0.0495	0.0534	0.0039	2.84

Table 37. Summary of WUE data for *Millettia grandis and Ptaeroxylon obliquum* trees, as calculated from a mass-based ratio of biomass increment (stem wood) over water-use.

Tree/Species	1-yr Water-use (L)	1-yr Stem Volume Increment (m^3)	Basic Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
Millettia grandis Tree 1	2 445	0.0082	0.79	6 464	2.64
Millettia grandis Tree 2	6 266	0.0241	0.79	19 086	3.05
Ptaeroxylon obliquum Tree 1	1 312	0.0033	0.73	2 390	1.82
Ptaeroxylon obliquum Tree 2	1 978	0.0039	0.73	2 837	1.44

7.4 Discussion

Compared to data from the Manubi forest site, the Umzimbeet trees at the Pietermaritzburg study site exhibited transpiration volumes and stem biomass increments that were both lower (tree 1) and higher (tree 2) than the Manubi example. This is related to the respective sizes of the trees at the two sites, and provides evidence of a reasonable correlation between DBH, water use and stem biomass increment for this species, regardless of site. The Manubi Umzimbeet produced the highest WUE value of all the indigenous trees sampled in this project (3.6 g L^{-1}), and likewise these Pietermaritzburg trees also produced high WUE results (2.6 and 3 g L^{-1}). The Sneezewood trees at this site however, utilised relatively greater volumes of water and yielded lower stem biomass increments than those at other sites (Manubi and Karkloof), with the result that the WUE estimates for the Pietermaritzburg trees were somewhat lower than for trees at other sites. This may possibly be attributed to poorer soils at this site, as well as the lower rainfall that was received over the monitoring year. It consequently appears as if the Umzimbeet is a more tolerant and drought-adapted species than the Sneezewood, maintaining high WUE over a range of site conditions, while the latter tends to be more productive (in terms of biomass production) under more favourable site conditions (high rainfall, nutrient availability).

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 General Conclusions

Prior to this study, and the previous one (Dye *et al*., 2008) from which this project emanated, very little water-use information was available for indigenous South African tree species. In this project six individual studies were conducted to determine the water-use, growth rates and resultant WUE of indigenous tree species under different site and climatic conditions. The 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.

Estimates of water-use and WUE for individual trees were determined using measurements of transpiration (sap flow) and above-ground woody biomass increments. Results show that the range and average of observed 1-year water-use totals (transpiration component) for indigenous tree species (Figure 93) is noticeably less compared to data for introduced plantation tree species (Olbrich *et al*., 1996; Dye *et al*., 2001; this study). Maximum water-use was also 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 8100 L tree^{-1} yr^{-1}, whereas sap flows in the more productive introduced plantation trees exceeded 20 000 L tree^{-1} yr^{-1} in some cases. 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.

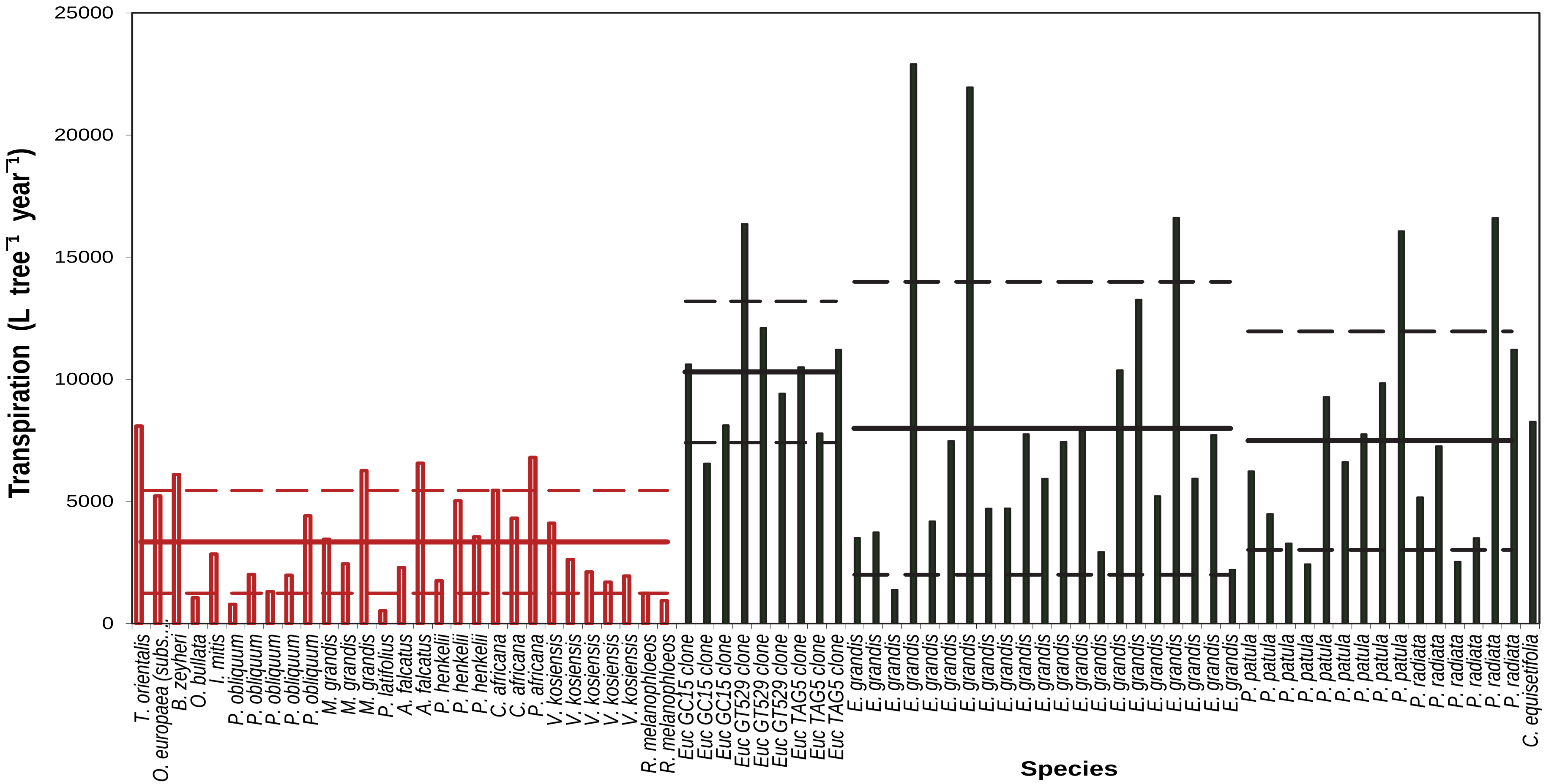

Figure 93. A comparison of 1-year total sap flow (transpiration) volumes for selected South African indigenous tree species (open bars – this study) and introduced plantation tree species and clones (solid bars – Olbrich *et al*., 1996; Dye *et al*., 2001; this study). The means (solid lines) and standard deviations (dashed lines) for the data sets are shown.

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? 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. Much evidence suggests that indigenous forests cannot compete with plantations of introduced tree species for wood production, and this is confirmed through a comparison of the growth rates observed in respective indigenous and introduced tree species in this study (Figure 94). Certain instances of high 1-year stem growth rates in indigenous species were observed in the study, with *Millettia grandis* (Umzimbeet), *Prunus africana* (Red Stnkwood) and *Celtis african*a (White Stinkwood) being the best performing species. However, it should be borne in mind that the conditions under which these particular indigenous trees were growing were far more favourable than the average plantation environment. These trees were free-standing, unshaded trees with little competition for resources and readily available water (the *Celtis* and *Prunus* trees were in a riparian zone). 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, but these have generally shown slow growth rates. From a wood production point of view, it appears unlikely that indigenous species will be competitive in terms of volume production, and their economic viability appears to be limited, apart from certain scenarios (see Volume 1).

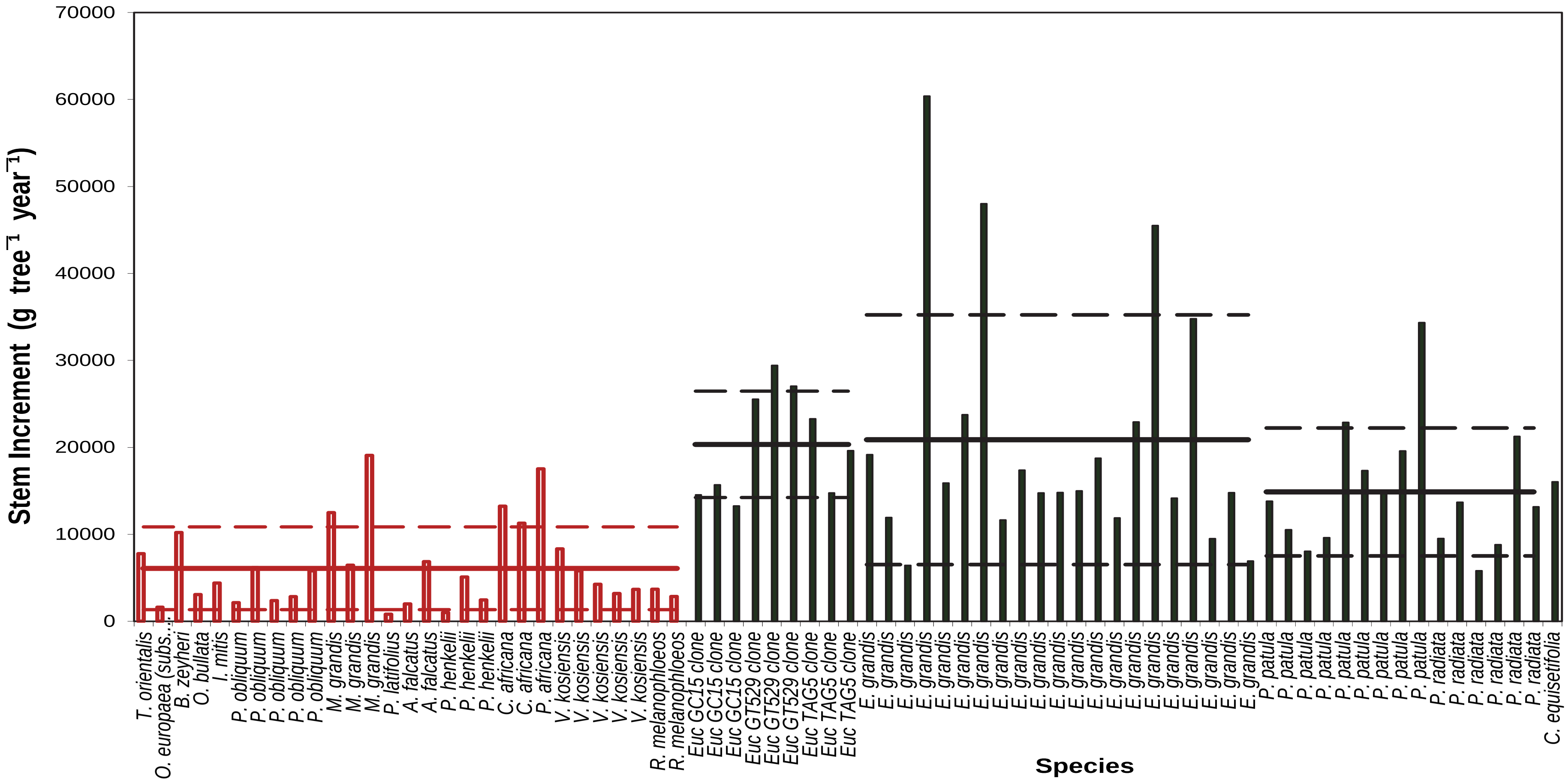

Figure 94. A comparison of 1-year stem growth increments (mass-based) for selected South African indigenous tree species (open bars – this study) and introduced plantation tree species and clones (solid bars – Olbrich *et al*., 1996; Dye *et al*., 2001; this study). The means (solid lines) and standard deviations (dashed lines) for the data sets are shown.

In terms of growth and water-use it can therefore be concluded that while biomass production was much lower for the indigenous tree species, they also used much less water than introduced plantation species. Results therefore indicate that on average indigenous tree species appear to exhibit similar water use efficiencies to introduced plantation tree species (Figure 95, Table 38). This supports the argument of a general correlation between growth and water use. The potential for considerable 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. The link between growth rates and water use suggests that easily obtained growth rates of trees (e.g. 1-yr stem biomass increments) may be used to provide a rough estimate of corresponding water use, without the need for expensive and technically demanding water use monitoring equipment.

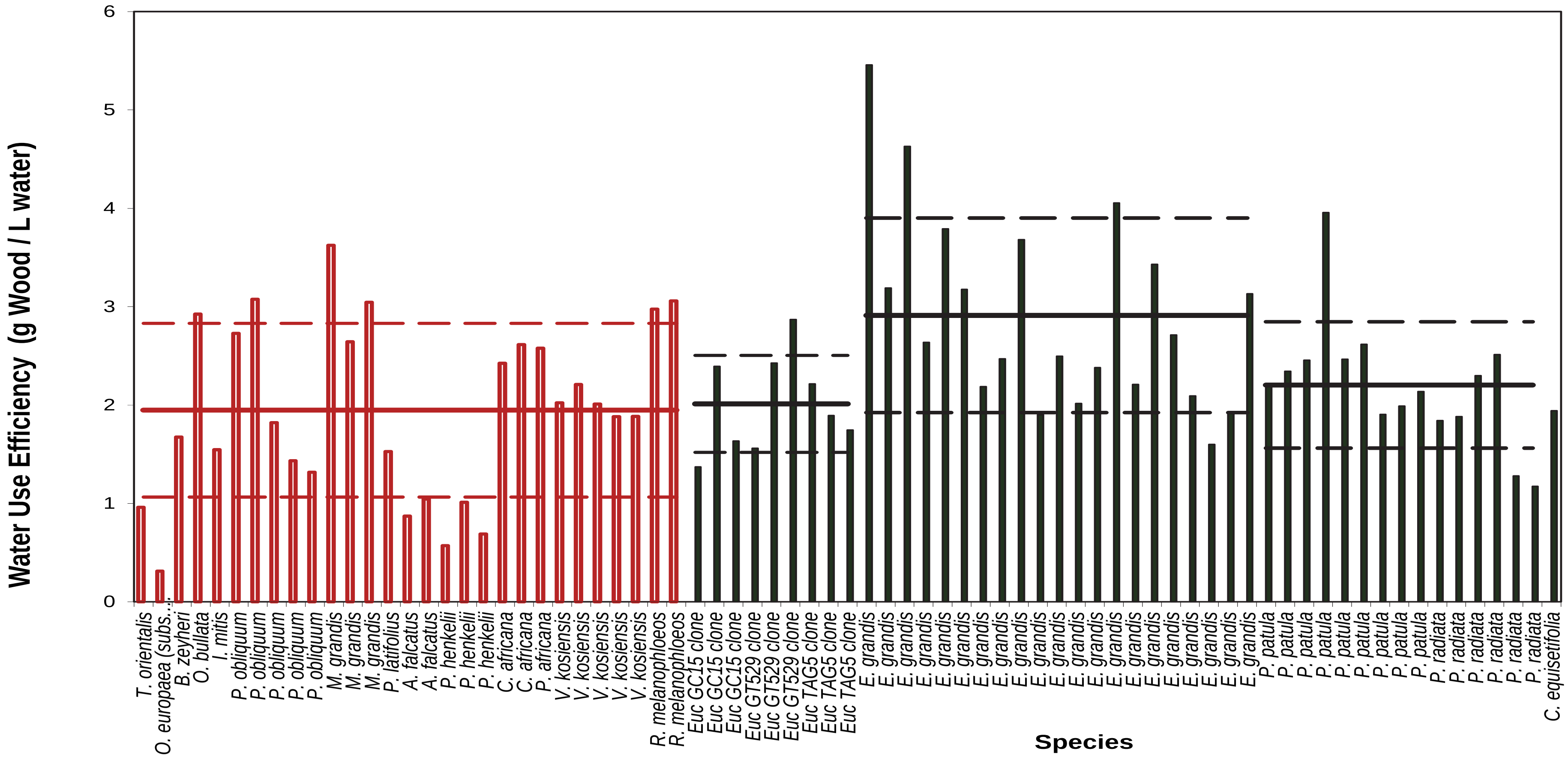

Figure 95. A comparison of water-use efficiency (stem mass increment per volume water transpired) for selected South African indigenous tree species (open bars – this study) and introduced plantation tree species and clones (solid bars – Olbrich *et al*., 1996; Dye *et al*., 2001; this study). The means (solid lines) and standard deviations (dashed lines) for the data sets are shown.

Table 38. 1-year transpiration, stem growth and resultant water use efficiency indicators for selected South African indigenous tree species (this study) and introduced plantation tree species and clones (Olbrich *et al*., 1996; Dye *et al*., 2001; this study).

Tree/Species	1-yr Water-use (L)	1-yr Stem Volume Increment (m^3)	Basic Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
Trema orientalis	8089	0.0184	0.42	7775.7	0.96
Olea europaea (subs. africana)	5223	0.0018	0.92	1634.2	0.31
Berchemia zeyheri	6103	0.0127	0.81	10215.5	1.67
Ocotea bullata	1052	0.0052	0.59	3077.6	2.93
Ilex mitis	2849	0.0087	0.51	4405.8	1.55
Ptaeroxylon obliquum	786	0.0030	0.73	2145.9	2.73
Ptaeroxylon obliquum	2005	0.0085	0.73	6168.2	3.08
Ptaeroxylon obliquum	1312	0.0033	0.73	2390.0	1.82
Ptaeroxylon obliquum	1978	0.0039	0.73	2837.9	1.43
Ptaeroxylon obliquum	4407	0.0081	0.72	5811.7	1.32
Millettia grandis	3450	0.0158	0.79	12507.3	3.63
Millettia grandis	2445	0.0082	0.79	6464.3	2.64
Millettia grandis	6266	0.0241	0.79	19086.2	3.05
Podocarpus latifolius	528	0.0018	0.46	807.1	1.53
Afrocarpus falcatus	2298	0.0044	0.45	2000.9	0.87
Afrocarpus falcatus	6571	0.0147	0.47	6860.6	1.04
Podocarpus henkelii	1755	0.0021	0.47	1004.5	0.57
Podocarpus henkelii	5033	0.0109	0.47	5093.8	1.01
Podocarpus henkelii	3554	0.0052	0.47	2453.7	0.69
Celtis africana	5452	0.0219	0.61	13222.1	2.43
Celtis africana	4317	0.0187	0.61	11291.2	2.62
Prunus africana	6803	0.0254	0.69	17539.9	2.58
Vachellia kosiensis	4114	0.0119	0.70	8324.9	2.02
Vachellia kosiensis	2627	0.0083	0.70	5804.6	2.21
Vachellia kosiensis	2115	0.0061	0.70	4255.2	2.01
Vachellia kosiensis	1701	0.0046	0.70	3200.1	1.88
Vachellia kosiensis	1943	0.0052	0.70	3661.2	1.88

Tree/Species	1-yr Water-use (L)	1-yr Stem Volume Increment (m³)	Basic Wood Density (g cm⁻³)	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
Rapanea melanophloeos	1242	0.0063	0.59	3697.2	2.98
Rapanea melanophloeos	938	0.0049	0.59	2870.5	3.06
Eucalyptus GC15 clone	10620	0.0294	0.50	14553.0	1.37
Eucalyptus GC15 clone	6560	0.0317	0.50	15691.5	2.39
Eucalyptus GC15 clone	8120	0.0268	0.50	13266.0	1.63
Eucalyptus GT529 clone	16360	0.0516	0.50	25542.0	1.56
Eucalyptus GT529 clone	12110	0.0594	0.50	29403.0	2.43
Eucalyptus GT529 clone	9420	0.0546	0.50	27027.0	2.87
Eucalyptus TAG5 clone	10500	0.0470	0.50	23265.0	2.22
Eucalyptus TAG5 clone	7790	0.0298	0.50	14751.0	1.89
Eucalyptus TAG5 clone	11220	0.0396	0.50	19602.0	1.75
Eucalyptus grandis	3510	0.0387	0.50	19156.5	5.46
Eucalyptus grandis	3740	0.0241	0.50	11929.5	3.19
Eucalyptus grandis	1390	0.0130	0.50	6435.0	4.63
Eucalyptus grandis	22900	0.1220	0.50	60390.0	2.64
Eucalyptus grandis	4190	0.0321	0.50	15889.5	3.79
Eucalyptus grandis	7480	0.0480	0.50	23760.0	3.18
Eucalyptus grandis	21960	0.0970	0.50	48015.0	2.19
Eucalyptus grandis	4710	0.0235	0.50	11632.5	2.47
Eucalyptus grandis	4720	0.0351	0.50	17374.5	3.68
Eucalyptus grandis	7760	0.0298	0.50	14751.0	1.90
Eucalyptus grandis	5930	0.0299	0.50	14800.5	2.50
Eucalyptus grandis	7440	0.0303	0.50	14998.5	2.02
Eucalyptus grandis	7880	0.0379	0.50	18760.5	2.38
Eucalyptus grandis	2930	0.0240	0.50	11880.0	4.05
Eucalyptus grandis	10370	0.0463	0.50	22918.5	2.21
Eucalyptus grandis	13260	0.0919	0.50	45490.5	3.43
Eucalyptus grandis	5220	0.0286	0.50	14157.0	2.71
Eucalyptus grandis	16620	0.0703	0.50	34798.5	2.09
Eucalyptus grandis	5940	0.0192	0.50	9504.0	1.60
Eucalyptus grandis	7721	0.0319	0.46	14790.8	1.92

Tree/Species	1-yr Water-use (L)	1-yr Stem Volume Increment (m^3)	Basic Wood Density (g cm^{-3})	Stem Mass Increment (g)	WUE (g stem wood/L water transpired)
Eucalyptus grandis	2210	0.0138	0.50	6919.3	3.13
Pinus patula	6240	0.0363	0.38	13794.0	2.21
Pinus patula	4490	0.0277	0.38	10526.0	2.34
Pinus patula	3280	0.0212	0.38	8056.0	2.46
Pinus patula	2430	0.0253	0.38	9614.0	3.96
Pinus patula	9280	0.0602	0.38	22876.0	2.47
Pinus patula	6620	0.0456	0.38	17328.0	2.62
Pinus patula	7760	0.0389	0.38	14782.0	1.90
Pinus patula	9849	0.0516	0.38	19596.6	1.99
Pinus patula	16067	0.0904	0.38	34333.0	2.14
Pinus radiata	5174	0.0223	0.43	9529.8	1.84
Pinus radiata	7264	0.0319	0.43	13674.2	1.88
Pinus radiata	2530	0.0136	0.43	5814.6	2.30
Pinus radiata	3505	0.0206	0.43	8811.3	2.51
Pinus radiata	16612	0.0497	0.43	21259.6	1.28
Pinus radiata	11219	0.0308	0.43	13165.9	1.17
Casuarina equisetifolia	8264	0.0205	0.78	16051.5	1.94

The relatively low water-use characteristics of indigenous tree species suggests that they are promising for expanding natural and plantation tree production systems in South Africa, maximising benefits (goods and services) while minimising negative impacts (water-use). Apart from the importance of accurate site/species matching, appropriate species for establishment need to be considered from environmental, social and economic perspectives. Potential benefits include suppression of alien invasive plants, biodiversity conservation, provision of ecosystem services, supporting rural livelihoods, ecotourism and urban greening. A 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 bio-diversity value then an indigenous tree cover could be considered preferable. Tangible benefits to this practice have been shown from research in Chile (Little et al., 2015) where streamside buffers of native forest within catchments planted to Pinus radiata and Eucalyptus spp. plantations, reduced adverse effects from the plantations on water provision (quantity and quality). Given the increasing pressure on water resources and a growing demand for timber and non-timber forest products, further exploration of the numerous multiple-use indigenous tree species that are found in this country, matched to the wide range of existing climatic and site conditions, is merited. There is surely potential for managed, productive and sustainable indigenous forest and woodland systems. Considering that further afforestation with commercial forest species is now restricted due to limitations in available land and concerns about reductions in catchment water yields, the possibility of expanding low water-use forms of forestry with indigenous trees deserves to be explored further.

8.2 Recommendations and Future Research Needs

The MAESPA model is viewed as a powerful tool for estimating rates of water use, given the expense of field measurement systems, the security of this equipment in the field, and the complexity of data analysis. MAESPA is able to take into account weather conditions, a variety of soil characteristics governing soil water availability to trees, the structure and physiology of a wide range of tree species, and shading effects by other trees in the vicinity. Rainfall interception loss and understory ET may also be simulated, so the model is capable of describing both individual tree and forest plot water use. Stem growth increments of sample trees are relatively easily measured, permitting the calculation of WUE. Additional work is required to improve model parameterization of tree species. Due to the species-specific input information required, the model is best suited to scenarios where a limited number of different species are being simulated. Under these circumstances data on the following will improve model parameterization and lessen the need for set-up information from the field:

- Leaf area estimation. Allometrics, LA correlation to sapwood area, stem diameter, etc.
- Leaf nitrogen contents of various species and their correlation to site quality.
- Stomatal conductance patterns in a range of different species.
- Rutter model parameter values for estimating rainfall interception rates
- Light penetration and leaf area distribution within different canopies
- Patterns of leaf water potential over seasons on different sites, quantifying temporal pattern of soil water deficits.

It would be useful to apply a similar methodology (windows of EC measurements and MAESPA simulations) to examine other types of indigenous forest in South Africa to assess the variability of ET. Factors such as soil depth, rainfall seasonality and amount, degree of mistiness, soil texture, groundwater availability, hill-slope effects and species composition may all affect ET and cause variable patterns of water use.

Further Recommendations

A number of additional topics associated with indigenous tree production systems have potential for further study. These include:

- The extent to which the WUE of indigenous tree species may be improved through more intensive management; and how the ratios of growth to water-use may change under conditions of increased productivity.
- The environmental and socio-economic costs and benefits associated with various indigenous tree production systems (e.g. single-species even-aged plantation stands, or mixed species mixed-age pioneer stands).
- Future indigenous tree stand management research. These could be in the form of trial plantings of indigenous tree species, in research stands, measuring and/or modelling growth, water use and economic data. Responsibility for the establishment and management of these trails could be assumed by the Dept. Agriculture, Forestry and Fisheries. Trials could consider various silvicultural aspects such as use of "nurse" stands, different planting densities, thinning and pruning regimes, weed control measures and species choices.

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DATA STORAGE

All processed data have been stored at:

CSIR, Natural Resources and Environment (NRE)
11 Jan Cilliers Street
Stellenbosch
7600
South Africa

APPENDIX A: MAESPA MODEL INPUT PARAMETER VALUES: INGELI FOREST ET SIMULATION

CONFILE

Ingeli forest control file

&control
iohrly=1
iotutd=1
ioresp=0
iohist=0
iowatbal=1
/
&histo
binsize=25
/
&dates
startdate = '07/10/11'
enddate = '23/07/13'
/
One tree only.
&treescon
itargets = 13
notrees = 25
/
number of angles and layers to integrate over.
&diffang
nolay = 4
nzen = 5
naz= 11
/
choice of submodels.
&model
modelgs = 6
modelrd = 0
modeljm = 0
itermax = 100
modelss = 0
/
MET
Hourly met data file - Ingeli forest, 7 October 2011 to 24 July 2013

&ENVIRON
DIFSKY= 0.5
PRESS = 84997
CA= 395
SWMIN = 0.07

SWMAX = 0.34
/
&LATLONG
LATHEM = 'S'
LAT = 30 31 56
LONHEM = 'E'
LONG = 29 42 03
TZLONG = 30
/
&METFORMAT
DAYORHR = 1
KHRSPERDAY = 24
STARTDATE = '07/10/11'
ENDDATE = '23/07/13'
NOCOLUMNS = 8
COLUMNS = 'DOY' 'HOUR' 'RAD' 'TAIR' 'RH%' 'WIND' 'PPT' 'VPD'
/
DATA STARTS

280	1	0	9.57	76.86	2.802	0	233
280	2	0	10.41	71.55	3.011	0	334
280	3	0	10.33	71.38	2.815	0	355
280	4	0	10.05	65.89	2.424	0	379
280	5	0	10.62	57.11	2.004	0	480
280	6	7.757	12.77	32.89	1.337	0	792
280	7	175.8	17.69	25.79	3.871	0	1446
280	8	410.1	19.5	23.24	4.334	0	1709
280	9	608.5	21.21	21.03	4.176	0	1953
280	10	802	22.99	18.28	3.986	0	2255
280	11	918	24.79	14.86	2.714	0	2622
280	12	970	26.02	11.98	1.601	0	2889
280	13	953	26.47	12.93	1.92	0	3017
280	14	868	26.31	12.39	1.817	0	2993
280	15	718.3	26.32	12.32	1.947	0	2989
280	16	519.6	26.33	13.91	1.494	0	2977
280	17	278.7	25.14	27.01	1.533	0	2636
280	18	23.43	21.43	41.25	0.664	0	1705
280	19	0.907	16.95	59.08	1.018	0	949
280	20	0	14.44	62.01	1.185	0	658
280	21	0	13.39	54.64	1.206	0	615
280	22	0	11.93	69.66	1.177	0	511 File truncated.

PHY
Physiological parameters for Ingeli forest

Number of leaf age classes requiring physiological parameters
&noages
noagep = 1
/
Reflectance and transmittance for foliage and soil surface
&absorp

nolayers = 1
rhosol = 0.10 0.30 0.05
atau = 0.093 0.34 0.01
arho = 0.082 0.49 0.05
/
&bbgscon
nodates=1
condunits='CO2'
/
Optimal gs model parameters.
&BBTUZ
dates='07/10/11'
g0 = 0.01
g1 = 4.5
SF = 3.2
PSIV = -1.9
nsides = 1
wleaf = 0.03
gamma = 0
/
Specifying Jmax, potential electron transport rate
&jmaxcon
nodates=1
/
Specifying Vcmax, maximum rate of Rubisco activity
&vcmaxcon
nodates=1
/
&jmax
values = 104
/
=&vcmax
values = 47
/
T response parameters for Jmax
&jmaxpars
theta = 0.4
eavj = 37259
edvj = 200000
delsj = 640.02
ajq = 0.324
/
&vcmaxpars
eavc = 47590
/
&rd
values = 0.92
/
&rdpars
rtemp = 25

q10f = 0.067
dayresp = 1.0
effyrf = 0.4
/
Specific leaf area
&slacon
nolayers = 1
noages = 1
nodates = 1
/
&sla
values = 8.58
dates = '07/10/11'
/
STR
Ingeli forest structure file

Specify canopy shape
&canopy
cshape =
'ELIP'
/
Sets parameter for ellipsoidal LAD (with 5 leaf angle classes)
&lia
elp = 0.622
nalpha = 5
/
Leaf area density distribution
&ladd
jleaf = 0
noagec = 1
random = 1.0
/
Assume wind speed declines exponentially with depth in the crown
&aero
extwind = 0.09
/
&allom
coefft = 91.4114
expont = 1.741
winterc = 0.0
/
&allomb
bcoefft = 8.9126
bexpont = 1.341
binterc = 0.0
/
&allomr
rcoefft = 20
rexpont = 2.0

rinterc = 0.0
frfrac = 0.4
/
TREES
Ingeli forest, 50 by 50 m plot

&plot
x0 = 0
y0 = 0
xmax = 50
ymax = 50
xslope = 4
yslope = 0
bearing = 180
notrees = 25
/
Specifying boundary layer conductance
&aerodyn
zht = 20
zpd = 15
z0ht = 2
/
Position of sample trees within plot (m)
&xy
xycoords=
5 5
15 5
25 5
35 5
45 5
5 15
15 15
25 15
35 15
45 15
5 25
15 25
25 25
35 25
45 25
5 35
15 35
25 35
35 35
45 35
5 45
15 45
25 45
35 45
45 45

/
Tree canopy radius in X direction (m)
&allradx
nodates = 1
values = 6
dates = '07/10/11'
/
Tree canopy radius in y direction (m)
&allrady
nodates = 1
values = 6
dates = '07/10/11'
/
Height of tree crown (m)
&allhtcrown
nodates = 1
values = 20
dates = '07/10/11'
/
Stem diameter (m)
&alldiam
nodates = 1
values = 0.25
dates = '07/10/11'
/
Height to base of canopy (m)
&allhttrunk
nodates = 1
values = 1
dates = '07/10/11'
/
Total leaf area (m2) per tree
&alllarea
nodates = 1
values = 250
dates = '07/10/11'
/
WATPARS
Ingeli forest water balance parameters.

&watcontrol
keepwet = 0
simtsoil = 0
simsoilevap = 1
reassignrain = 0
wsoilmethod = 1
retfunction = 1
equaluptake = 0
usemeaset = 0
usemeassw = 0

usestand = 1
/
Throughfall = 1.0 : irrigation is to soil surface
&wattfall
rutterb = 3.7
rutterd = 0.1
maxstorage = 0.8
throughfall = 0.65
/
&watinfilt
expinf = 0.0
/
&rootpars
rootresfrac = 0.4
rootrad = 0.0001
rootdens = 0.5e6
rootmasstot = 1000
nrootlayer = 2
fracroot = 0.5 0.5
/
&plantpars
minrootwp = -1
minleafwp = -2
plantk = 3.0
/
Soil water retentions for each layer (sandy clay)
&soilret
bpar = 10.7 10.7
psie = -0.00258 -0.00258
ksat = 20 20
/
&laypars
nlayer = 2
laythick = 0.6 0.9
porefrac = 0.43 0.43
drainlimit = 0.0 0.0
fracorganic = 0.1 0.1
/
&initpars
initwater = 0.4 0.4
soiltemp = 18 18
/
&soiletpars
drythickmin = 0.01
tortpar = 0.66
/