WATER-USE DYNAMICS OF ALIEN PLANT INVADED RIPARIAN FORESTS IN SOUTH AFRICA

by

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PREFACE

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

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

Signed: Colin Everson

Date: 29 June 2018

ABSTRACT

In South Africa the invasion of riparian forests by alien trees has the potential to affect the country's limited water resources. It is difficult for government initiatives, such as the Working for Water (WfW) alien clearing programmes, to justify alien tree removal and implement rehabilitation unless a known hydrological benefit can be seen. Consequently water-use within riparian forests at three climate diverse research catchments within South Africa were monitored using the heat ratio method. The use of the Soil Water Assessment Tool (SWAT) and a Sequential Uncertainty Fitting (SUFI-2) algorithm allowed for the auto-calibration of the SWAT model at each research site using measured water-use data. Within the winter rainfall region of the Western Cape the alien stand used nearly six times more water per unit area than the indigenous stand annually. The combined accumulated daily sap flow over a two year period for three *Vepris lanceolata* and three *Acacia mearnsii* trees was 36 000 L and 55 700 L respectively, clearly demonstrating the higher water-use of the alien *A. mearnsii* trees. In contrast, the water-use of alien species within the summer rainfall region of KwaZulu-Natal was double that of the indigenous species. The accumulated seasonal water-use was the least in the indigenous *Searsia* (~2 100 L), moderate in the indigenous *Maytenus* (~7 100 L) and high in the alien *A. mearnsii* (~15 900 L) trees. The spatial distribution of water-use within northern Zululand showed that the commercial forestry areas were the dominant water-users in the catchment. These findings indicate that there would be a hydrological gain if the alien species are removed from riparian forests and rehabilitated back to their natural state. The use of the SWAT model provided substantial insights into the spatial distribution of total evaporation (ET) throughout the selected catchment areas and is a suitable hydrological model for examining the impacts of different land-uses in catchments in South Africa. Given the quantified hydrological benefit, indigenous trees should be promoted for use in rehabilitation programmes where the natural vegetation is or was forests. This is especially relevant in light of South Africa's limited water resources.

Key Words: Indigenous trees, alien trees, sap flow, transpiration, modelling

DECLARATION 1: PLAGIARISM

I, Bruce Charles Scott-Shaw, declare that:

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

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

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

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

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

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

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

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

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

Signed: Bruce Charles Scott-Shaw

Date: 29 June 2018

DECLARATION 2: PUBLICATIONS

This thesis is written in manuscript format. Details of my contribution and that of others to each manuscript that form part of this thesis are indicated. Some minor editorial differences may exist between the published papers and the thesis chapters. Some parts are republished in a Water Research Commission report entitled, "Rehabilitation of alien invaded riparian zones and catchments using indigenous trees: an assessment of indigenous tree water-use".

Chapter 1 is an introductory chapter and will not be submitted as a manuscript:

The chapter highlights background information, motivation for the research and a detailed research approach. Together this links the overall rationale for the research. The research hypothesis, aims and objectives are further described. Each subsequent chapter links back to the hypothesis, aims and objectives.

Chapter 2 will be submitted as:

Scott-Shaw, B.C. and Everson, C. S.: An overview of tree water-use monitoring in South Africa, Water SA. 2017.

This manuscript provides a detailed and up to date overview of both local and international scientific knowledge of techniques used to measure tree water-use. A brief background to each technique is provided indicating the advantages and disadvantages of implementing these techniques. Water-use findings obtained from these techniques, with an emphasis on South Africa, is provided that aims to contribute to a national database of tree water-use findings. The knowledge review was undertaken by both authors.

Chapter 3 will be submitted as:

Scott-Shaw, B.C. and Everson, C. S.: Technical application of sap-flow techniques for tree water-use measurements, Water SA. 2018.

This manuscript provides a technical approach to the installation and use of three commonly used tree water-use measurement techniques in South Africa. A detailed background of these techniques and a detailed description on their practical application is provided. Supporting measurements are further described to assist in up-scaling measurements to tree-level and stand-level transpiration.

Chapter 4 is published as:

Scott-Shaw, B.C., Everson, C. S., and Clulow, A. D.: Water-use dynamics of an alien invaded riparian forest within the Mediterranean climate zone of the Western Cape, South Africa, Hydrol. Earth Syst. Sci., 21, 4551–4562, 2017.

Water-use within a riparian forest along the Buffeljags River in the Western Cape of South Africa was monitored over a three year period. The heat ratio method of the heat pulse velocity sap flow technique, was used to measure the sap flow of a selection of indigenous species in an indigenous stand and a selection of *A. mearnsii* trees and two clusters of indigenous species within an alien stand. The publication was written by B. C. Scott-Shaw and C.S. Everson, with assistance from A.D. Clulow. Field work, equipment maintenance and data analysis was undertaken by B. C. Scott-Shaw and C.S. Everson with technical support from A.D. Clulow.

Chapter 5 has been accepted for review by the editor of the journal Hydrology and Earth System Sciences (HESS) and is currently under review and can be cited as:

Scott-Shaw, B.C., and Everson, C. S.: Water-use dynamics of an alien invaded riparian forest within the summer rainfall zone of South Africa, Hydrol. Earth Syst. Sci. Discuss.

Water-use within a riparian forest in the upper Mgeni catchment of KwaZulu-Natal in South Africa was monitored over a two year period. The site consisted of an indigenous stand of eastern mistbelt forest that had been invaded by *Acacia mearnsii*, *Eucalyptus nitens* and *Solanum mauritianum*. The heat ratio method of the heat pulse velocity sap flow technique and the stem steady state techniques were used to measure the sap flow. The authors contributed to site selection and undertook numerous field excursions to maintain equipment and download data. B.C. Scott-Shaw was responsible for data processing and the publication was written by both B. C. Scott-Shaw and C.S. Everson.

Chapter 6 will be submitted for publication to a relevant journal with authors:

Scott-Shaw, B.C. and Everson, C. S.: Validation of a modelling approach on riparian water-use dynamics.

The Soil Water Assessment Tool (*SWAT*) was used to model three climatically diverse research catchments within South Africa. Model inputs were modified based on observations in order to appropriately represent each specific area. A model calibration and sensitivity analysis, using observed streamflow and total evaporation, was performed to allow for data extrapolation and parameterization in a South African context. B. C. Scott-Shaw and C.S. Everson performed the model input modification and B. C. Scott-Shaw undertook the modelling and calibration processes. Both authors contributed to the compilation of the manuscript.

Signed: Bruce Scott-Shaw

Date: 29 June 2018

EXECUTIVE SUMMARY

There is a widespread belief in South Africa that indigenous tree species, in contrast to exotic trees, are water efficient and should be planted more widely in land restoration programmes. Stand water relations are crucial for valuing site conditions to support this belief. In addition, long term observations are necessary for a better understanding of inter- and intra-annual water-use variability, including responses to extremes or management effects. Due to the availability of accurate techniques to quantify this large, and often poorly understood, component of the hydrological cycle, modelled estimates can be improved and therefore better understood, as can direct measurements. The purpose of this research was to determine the most appropriate techniques for measuring water-use (through the process of transpiration only) in riparian forest systems. These techniques were then used to quantify the water-use of a selection of introduced and indigenous trees for incorporation into a modelling framework for water-use predictions to determine their potential use in land restoration programmes.

Various climatic regions were considered in order to investigate the water-use of species suitable for forest expansion and rehabilitation programmes throughout South Africa. The presence of a Working for Water alien plant clearing programme was a requirement for site selection. Riparian forests within the Western Cape Afro-temperate forest (Buffeljagsrivier) and the Eastern Mistbelt Forest (New Forest) were selected to meet the study objectives. A site in the Maputaland Coastal Belt (Vasi pan) was used to extend the modelling assessment. Tree species were selected that occurred in the forest biome over various climatic regions. The heat ratio method of the heat pulse velocity (HPV) technique was used to determine the long-term water-use at each site. Small, multiple stemmed species were selected for instrumentation with stem steady state (SSS) collars. In addition to tree water-use measurements, data on the size and age of all selected trees were collected to suitably compare the different tree species. Measurements included tree height, diameter and leaf area index as well as soil moisture, rainfall, air temperature and relative humidity.

A detailed assessment of documented tree water-use in South Africa was undertaken. There is consensus among numerous studies that introduced tree species use more water than the vegetation they replace. This is particularly true in areas where the indigenous vegetation contained deciduous species or grasslands that are dormant in the winter period. Within riparian forests, sap-flow systems are often the only viable option to understand water-use dynamics, particularly in areas with limited aerodynamic fetch. A detailed technical analysis of sap-flow techniques indicated that the HPV and SSS techniques

are suitable for riparian forest assessments. With recent improvements of the heat ratio method (HRM), spatial tree distribution has been accounted for, power efficiency increased and data corrections have been reduced. Tree water-use measurements require in-depth measurements of the climate, which was carried out at the measurement sites.

At Buffeljagsrivier the long term mean annual precipitation (MAP) was 636 mm. The 36 month study period between the 25th January 2012 and 12th December 2014 was characterised by higher than average rainfall (903 mm). The solar radiation was lowest in June (winter) and highest during January/December (summer). An average daily temperature of 22.1 ºC was recorded in the summer months (October to March). During these months, daily maximum temperatures reached an excess of 40 ºC. During the wet winter months (April to September), the temperatures averaged 12.1 ºC. The mean daily ETo ranged from approximately 1 mm in the winter period to 4 mm during summer. The daily ETo peaked at 7.5 mm, which is considered very high for grassland/fynbos cover. The mean annual precipitation at New Forest was 941 mm with an average daily summer temperature of 18.4 ºC. Daily maximum temperatures reached in excess of 30 ºC. During the dry cold winter months, the temperatures averaged 11.7 ºC. The total rainfall during the study period was 1 118 mm and wind speed fluctuated between 1 and 2 $m.s^{-1}$.

The indigenous trees in the wattle stand at Buffeljagsrivier showed significant differences in the daily sap flow rates varying from 15 to 32 $L.day^{-1}$ in summer (sap flow being directly proportional to tree size). In winter (June) this was reduced to only 5 $L.day^{-1}$ when less available energy was available to drive the transpiration process. The water-use in the *Acacia mearnsii* trees showed a peak in transpiration during the months of March 2012, September 2012 and February 2013. These periods corresponded to high average temperatures (21.45 ºC), and rainfall (76 mm in 2012) and high daily water vapour pressure deficits (VPD) (average of 1.26 kPa). The average daily sap flow ranged from 15 L to 35 L. The combined accumulated daily sap flow over the two year period for the three *Vepris lanceolata* and three *Acacia mearnsii* trees was 36 000 and 55 700 L respectively, clearly demonstrating the higher water-use of the exotic *Acacia* trees. From the above it was concluded that, annually, the alien stand uses nearly six times more water per unit area than the indigenous stand.

The results showed that indigenous trees in an established riparian stand in a Western Cape Afro-temperate forest can use high volumes of water throughout the year (little seasonal rainfall change in this region). The variability of water-use between species and tree size was large as this variable is largely dependent on location, tree condition and light dynamics. This further highlights the need for measurement replication. The comparison between individual trees indicated that the largest trees (*Celtis africana* and *Vepris lanceolata*) used the most water. However, when extrapolated by stem density, the alien species (*Acacia mearnsii*) used significantly more water per unit area (up to five times more water in certain stand locations). The modelling results revealed that a significant amount of water can be conserved if alien invaded forest stands are rehabilitated.

At New Forest farm, three of the trees studied (*Searsia pyroides*, *Maytenus peduncularis* and *Acacia mearnsii*) are evergreen species and showed little seasonal variation in their daily water-use patterns. The accumulated seasonal water-use was the least in the *Searsia* (~2 100 L), moderate in the *Maytenus* (~7 100 L) and high in the *Acacia* (~15 900 L) trees. This again showed the more conservative water-use of indigenous when compared with exotic tree species. The results showed that small invasive sapling species (< 30 mm) in the understorey can use up to 2 000 $L \cdot year^{-1}$, which is important for up-scaling to stand water-use. Up-scaled comparisons showed that due to the invasion by *A. mearnsii* and *E. nitens* (21 % invasion), the stand water-use has increased by 40 %. This is an important finding as it provides clear evidence to justify the hydrological benefit of clearing programmes. If the stand were to be completely invaded, at the same stem density as the indigenous stand, the water-use would double for this particular area. The findings from the understorey suggest that the water-use from this zone should not be excluded from future studies, especially where there is no canopy closure.

The results for the Eastern Mistbelt forest, which had a highly disturbed/invaded stand, showed very low water-use volumes in comparison to the Western Cape site. Nevertheless, the alien species used significantly more water than the indigenous species, which had approximately the same stem density in the measurement area. A key finding from this site was that the smaller trees (diameter 1 - 2.5 cm) in the understorey of pioneer species such as *Buddleja salviifolia* (indigenous), *Solanum mauritianum* and *Acacia mearnsii* (introduced) used up to 4 $L.day^{-1}$ individually. It is recommended that deciduous species in addition to low consumptive evergreen species be used for forest rehabilitation as they use very little water during the drier winter months when water is needed the most.

Of particular importance, during the wetter season (May to August), the deciduous trees in the winter rainfall region were not using any water. This is in contrast to the deciduous species in the Eastern Mistbelt region that are dormant during the dry season when water is most scarce. In the Western Cape area, it is recommended that evergreen species be used for forest rehabilitation as they use less water than the deciduous trees during the drier months when water is needed the most.

Internationally, the Soil and Water Assessment Tool (SWAT) model has emerged as one of the most widely used water quality watershed- and river basin–scale models worldwide, and has been applied extensively for a broad range of hydrologic and/or environmental problems. In order to apply the model to South African conditions, a new set of *SWAT* input parameters for each vegetation type measured was constructed. These inputs were constructed using site observations and model calibration and parameterization (using sequential uncertainty fitting). Pre- and post-calibration simulations indicated that the model performed well and is a suitable model to use for land use scenario testing over a range of spatial scales. As this model is quasi-distributed it is ideal for spatially explicit studies, particularly evaporation studies. Modelled total evaporation (ET) was consistently higher for the invaded riparian zone when compared with the pristine scenario by 1 to 2 mm daily. The post-calibration results for the SWAT model at Buffeljags River provided good simulations of the peaks and low flows. At New Forest, during the winter periods, when rainfall is low, the introduced vegetation used approximately 15 mm more water per month than the indigenous vegetation. The simulations undertaken for Vasi Pan showed the variable distribution of ET throughout the site. However, it was concluded that the surface water model should be coupled with a groundwater model in order to improve the simulations at the groundwater dependent site.

In this thesis it is clear that the water-use differences between plant communities is a critical component of the hydrological cycle and therefore is important for land management decisions and the implementation of policies. Rehabilitation or clearing programmes need to consider the seasonal rainfall variability of a site as planting of deciduous indigenous trees may provide larger benefits in summer rainfall areas due to no transpiration occurring during periods when water resources are limited. This study provides an ideal opportunity to validate remotely sensed ET data which could also be used to identify spatial variations in vegetation water-use. This, and similar future research would allow for the broader extrapolation of alien plant water-use and benefits of clearing ripaian zones to riparian forests outside of the immediate study areas.

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I am in debt to my supervisor, Colin Everson, whose enthusiasm in the field, vast experience and immense knowledge guided me through my research. Without his continuous support, exceptional work ethic and of course introducing me to the joys of caffeine, this thesis would not be possible.

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- Manzengwenya Plantation (DAFF, Vasi Pan)

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To my now wife, Liandra, thank you for your support throughout our time together and time yet to come.

To my mum & Kate for their forbearance

To my dad for introducing me to a world that will stay with me forever

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CHAPTER 1. INTRODUCTION

This chapter introduces the background and motivation that led to the construction of the research hypothesis for riparian tree water-use in South Africa. An outline of the thesis structure is provided.

1.1 Rational for the Research

1.1.1 Background

Riparian areas are defined by the National Water Act (1998) as the physical structure and vegetation distinctly different from adjacent land areas that are associated with a water course, which is characterized by alluvial soils (inundated or flooded). Riparian zones can be described as the interface between terrestrial and aquatic ecosystems (Richardson *et al*., 2007). Through the process of evaporation and transpiration, riparian plants influence streamflow rates, ground water levels and local climates (Richardson *et al*., 2007). Vegetation along riverbanks filters surface and subsurface water moving across and through the soil to the river channel and therefore helps to maintain channel water quality, by regulating the water temperature (through shading), bank stability and turbidity, which controls erosion and traps debris (Askey-Dorin *et al*. 1999). Riparian vegetation can access a wide range of water sources within the riparian zone, which includes rainfall, soil water, stream water and groundwater (O'Grady *et al*., 2005).

Rates of total evaporation and groundwater use vary widely between plant species, depending on factors such as rooting depth, leaf area and ability to regulate stomatal conductance (Scott *et al*., 1999; Dahm *et al*., 2002). Plants influence many properties of soils, such as salinity, organic matter, and C:N ratios, depending on their rate of litter production and on the chemical composition of the litter. There is consensus among scientists that the vegetation in the riparian zone has a significant impact on the hydrology of a catchment due to the close proximity of riparian vegetation to the water table. Most riparian trees are phreatophytic, which means they have access to a permanent source of water because their rooting system is able to use shallow ground water. The deep fertile soils, with high soil moisture content associated with riparian areas, make them ideal for plant establishment and growth (Everson *et al*., 2007). Recently, some attention has been placed on selecting riparian plant species that pose little risk to the environment, but the ease and rapid benefits of alien species frequently override such considerations (Richardson, 1998). Riparian areas are extremely vulnerable to invasion by pioneer plant species, particularly alien hybrid species that have historically been introduced for commercial forestry.

While extensive research has been undertaken on the water-use of terrestrial ecosystems in South Africa, little is known about riparian tree water-use and growth of both indigenous and introduced tree species. This knowledge gap, as well as the poor ecological condition of South African riparian habitats, has led to uncertainty and contention over riparian rehabilitation techniques and/or methods. Commercial forestry has been blamed for increasing the green water (water lost by total evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Jewitt, 2006). There is a widespread belief in South Africa that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land restoration programmes. This is based on observations that indigenous trees are generally slow growing, and that growth and water-use are broadly linked (Everson *et al*., 2008; Gush, 2011). However, tree water-use is technically difficult and expensive to measure, and so there is scant evidence of low water-use by indigenous trees.

1.1.2 Motivation

a) **The Problem:** While extensive research has been undertaken on the water-use of terrestrial ecosystems, little is known about riparian tree water-use and growth for both indigenous and introduced tree species. This gap of knowledge has led to uncertainty and contention over riparian restoration and rehabilitation techniques.

b) **Towards a Solution:** There is an increasing trend towards the promotion of indigenous trees with economic value that can be used to restore riparian forests. In this research, the water-use was measured for various indigenous and introduced species that have been identified as economically or ecologically viable. This information was used to validate a modelling approach to extend the findings both temporally and spatially.

c) **Reasoning:** This research was undertaken in order to gain greater insights into understanding and quantifying riparian water-use. Results from this study may facilitate the more realistic modelling of possible forest management approaches and may provide guidelines towards suitable indigenous alternatives.

1.1.3 The Research Approach

The experimental approach for this study was to:

- Summarize both local and international literature on techniques and results of tree water-use;
- Investigate the best techniques to use in the determination of riparian tree water-use;
- Compare the differences in water-use between indigenous and introduced tree species in selected riparian forests;
- Improve modelling scenarios in order to assist in decision making; and
- Provide conclusions on how this knowledge can assist riparian rehabilitation programmes.

1.2 Research Hypothesis

1. Introduced tree species growing in riparian areas use more water seasonally than indigenous tree species that they replace. The greater sapwood area in introduced species, as well as their fast establishment, tree density and rapid growth, results in a greater transpiration rate than indigenous species per unit area.
2. The heat pulse velocity system is a suitable technique for the long-term estimation of riparian tree water-use. On-going research by experts, technical support, the relative ease of implementation and the lower cost of this technique, render it suitable for riparian tree water-use measurement.
3. Individual tree water use is linked to the structural properties of the tree. Sapwood depth, xylem health (linked to conductivity), radial symmetry and tree age can all be related to the rate of sap flow, as well as the location of sap flow within the tree, and are highly variable between species.
4. Tree water-use measurements can be used to validate model simulations to provide confidence in model extrapolations and sufficiently capture the complex nature of vegetated surfaces and hydrological conditions.

1.3 Aims and Objectives

In order to address the research hypothesis, the objectives of this project are:

1. to review available knowledge on water-use investigations and the techniques used both locally and globally;
2. to provide a technical approach on the best techniques to measure water interactions in riparian areas;
3. to investigate the water-use (transpiration rates) of a selection of pioneer indigenous tree species that may be suitable for rehabilitation programmes and riparian zone restoration over various climatic regions; and
4. to incorporate the data into a modelling framework for the temporal and spatial extrapolation of water-use observations.

1.4 Outline of the Thesis Structure

The thesis structure follows guidelines as recommended by the Centre for Water Resources Research, University of KwaZulu-Natal (UKZN). This document is comprised of a series of papers, which have been presented in the form of chapters. These papers have either been published, in press, submitted or intended for submission. Some unavoidable overlap occurs between papers, particularly in the methods, literature and research site descriptions sections. Each paper differs in that it represents a different area of research or location. Reference lists have been provided at the end of each chapter and conform to the style recommended by the journal in which that paper was published or submitted. The outline of each paper are as follows:

Chapter 1 provides a background to the introduced research topic, motivation for the study, the research objectives and hypotheses. As this is an introductory chapter, it has not been structured in the form of a paper.

Chapter 2 provides a detailed overview of tree water-use measurements in South Africa. Both local and international scientific knowledge of techniques are discussed. A detailed assessment of water-use findings for both introduced and indigenous tree species throughout South Africa is provided. This chapter sets the scene for the techniques used in riparian tree water-use measurements, the general scientific consensus and aims to contribute to a national database of tree water-use findings.

Chapter 3 provides a technical insight into the commonly used sap-flow techniques used to measure tree water-use. The practical theory behind each technique, requirements for installation and monitoring is discussed in detail. Additional detail on supporting measurements and the up-scaling of sap-flow measurements to whole tree and stand estimates is provided. The improvement of the heat pulse velocity technique to address limitations identified in the field is documented in this chapter.

Chapter 4 covers three years of intensive tree water-use measurements within a riparian forest along the Buffleljags River in the Western Cape of South Africa. The heat ratio method of the heat pulse velocity sap flow technique, was used to measure the sap flow of a selection of indigenous species in an indigenous stand and a selection of *A. mearnsii* trees and two clusters of indigenous species within an alien stand. These data were unscaled to stand water-use for the indigenous and introduced forests.

Chapter 5 mimics Chapter 4 in that it provides intensive tree water-use measurements, but for a summer rainfall region in the upper Mgeni catchment of KwaZulu-Natal in South Africa. The site consisted of an indigenous stand of eastern mistbelt forest that had been invaded by *Acacia mearnsii*, *Eucalyptus nitens* and *Solanum mauritianum*. The heat ratio method of the heat pulse velocity sap flow technique and the stem steady state techniques were used to measure the sap flow. The results from this Chapter are later used to compare water-use in climatically contrasting areas with different levels of invasions.

Chapter 6 details a modelling framework using the Soil Water Assessment Tool (SWAT) at three climate diverse research catchments within South Africa. The focus of this chapter is to adapt this spatially explicit model to South African conditions. This involves adjusting model inputs, particularly vegetation components. A model calibration and sensitivity analysis, using observed streamflow and total evaporation, was performed to allow for data extrapolation and parameterization in a South African context.

The final chapter, Chapter 7, assimilates the results of Chapters 3 to 6. The overall findings are summarised into practical scientific statements for the benefit of decision makers. This chapter paves the way for future research and/or areas that should be improved upon in subsequent studies.

The three research sites that have been discussed within this thesis are Buffeljagsrivier (Western Cape), New Forest Farm and Vasi Pan (KwaZulu-Natal). These three sites were chosen due the presence of indigenous forest areas with suitable species, a range of invasion intensities by introduced species (including the presence of alien tree clearing programmes) and a contrast in climatic conditions.

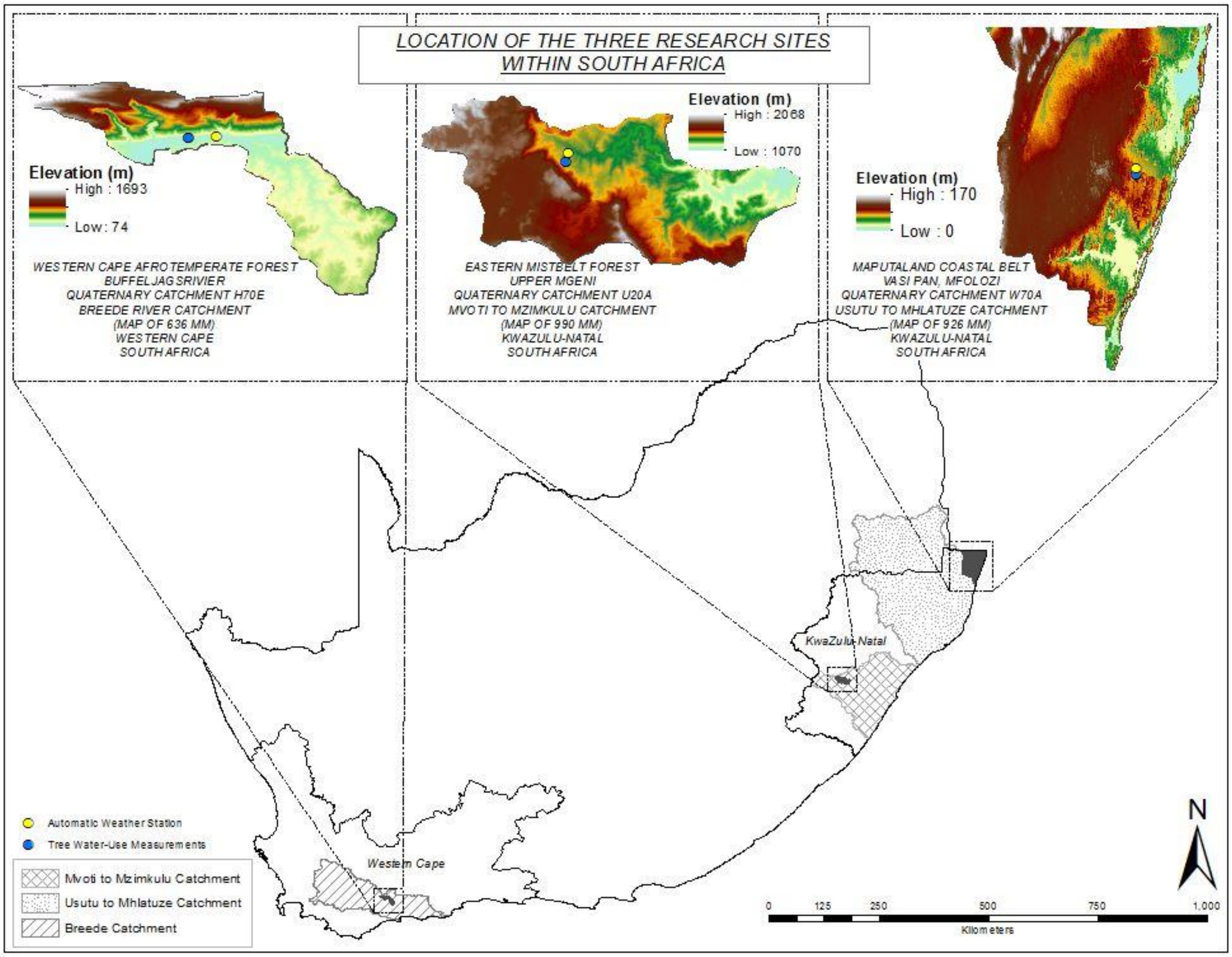

Figure 1.1 Location of the three research sites at Buffeljags River in the Western Cape, New Forest farm (upper Mgeni) and Vasi Pan in KwaZulu-Natal, South Africa

1.5 Concluding Remarks

Much of the South African tree water-use research is based on forest hydrology and has focused on introduced or exotic tree species and their impacts on streamflow. In order to support the South African government's rural tree programmes, there is a need to expand current research to include the water-use of indigenous trees used in forest expansion, the rehabilitation of degraded lands and the restoration of riparian zones. One of the biggest problems with current rehabilitation programmes is that exotic species are used to restore the ecosystem services (e.g. water production and reduced soil erosion). However, this ignores the importance of ecosystem structure and functioning (e.g. biodiversity). Research and policy support in South Africa is required to promote and scale-up indigenous tree planting and growing initiatives in degraded areas and riparian zones. The impact of expanding the use of indigenous trees to catchment hydrology is of critical importance in a water-scarce country. It is therefore important to understand the plant water-use (transpirational changes) brought about by introducing indigenous trees into degraded landscapes and alien-cleared riparian zones. This can be achieved by using the HPV techniques described in Chapter 3 for single tree or stand estimates of the energy balance techniques (e.g. Eddy Covariance and scintillometry) for whole canopy total evaporation.

The use of indigenous trees for rehabilitation has the potential to increase income generation for rural communities through the provision of ecosystem services, while simultaneously improving the condition of badly degraded catchments.

CHAPTER 2. AN OVERVIEW OF TREE WATER-USE MEASUREMENTS IN SOUTH AFRICA

2.1 Abstract

In South Africa the invasion of riparian forests by alien trees has the potential to affect the country's limited water resources. There is a need to expand tree water-use research based on forest hydrology and the effects of introduced tree species on streamflow to include the water-use of indigenous trees used in forest expansion, and the rehabilitation of degraded lands and riparian zones. It is difficult for South African government initiatives, such as the Working for Water (WfW) alien clearing programme, to justify alien tree removal and implement rehabilitation unless hydrological benefits are known. There are several methods that can be used to measure the transpiration and evaporation of tree species and, therefore, their water-use. Micrometeorological methods can provide estimates of flux on an aerial basis, which allows for direct comparisons with other hydrological components over a site or stand. Internationally, improved sap-flow techniques have been used on various vegetation types and the accuracy of these studies has been validated using gravimetric methods (Burgess *et al*., 2001; Granier and Loustau, 2001; O'Grady *et al*., 2006; Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013; Uddin *et al*., 2014). Studies undertaken throughout South Africa have shown a generally higher water-use of commercial forest species, particularly in areas where the natural vegetation was grassland. Given the heterogeneous nature of riparian ecosystems, there is a need for further investigations of the hydrological partitions within these critical resource areas.

2.2 Introduction

2.2.1 Background

Invasive plant species are rapidly altering large portions of the Earth's terrestrial surface and are considered to be one of the most important direct drivers of change in ecosystems (Millennium Ecosystem Assessment, 2005). While extensive research has been undertaken on the water-use of terrestrial ecosystems in South Africa, little is known about riparian tree water-use and growth of both indigenous (native) and introduced (exotic) tree species. This knowledge gap, as well as the poor ecological condition of South African riparian habitats, has led to uncertainty and contention over riparian rehabilitation techniques. It is assumed that invasive plants consume disproportionately more resources than indigenous plants, resulting in negative impacts on ecosystem services such as depleted groundwater reserves (Brauman *et al*., 2007). The deep fertile soils, with high soil moisture contents associated with riparian areas, make them ideal for plant establishment and growth (Everson *et al*., 2007). As such, these areas are extremely vulnerable to invasion by pioneer plant species, particularly alien hybrid species that were historically introduced for commercial forestry. It is widely believed that riparian zone vegetation, which can be described as the interface between terrestrial and aquatic ecosystems (Richardson *et al*., 2007), has a significant impact on the hydrology of a catchment due to the close proximity of riparian vegetation rooting systems to the water table. Most riparian trees are phreatophytic, meaning they have access to a permanent source of water because their rooting system is within the shallow ground water.

Through the process of evaporation and transpiration, riparian vegetation influences streamflow rates, ground water levels and local climates (Richardson *et al*., 2007). Vegetation along riverbanks filter surface and subsurface water moving across and through the soil to the river channel and therefore assists in maintaining channel water quality, by regulating the water temperature (through shading), bank stability and turbidity and traps debris (Askey-Dorin *et al*., 1999). Riparian vegetation can access a wide range of water sources within the riparian zone, which includes rainfall, soil water, stream water and groundwater (O'Grady *et al*., 2006). According to Clausnitzer *et al*. (2011), future riparian area conditions may not only include increasing temperatures and evaporative demands but also a higher frequency of extreme events. Ecohydrology and invasive ecology have thus become increasingly important in the context of global climate change (Cavaleri and Sack, 2010). Stand water relations are crucial for evaluating site conditions, and long term observations are necessary for a better understanding of inter- and intra-annual variability including responses to extremes or management effects (Clausnitzer *et al*., 2011). The government-funded WfW programme clears catchment areas of invasive alien plants with the aim of restoring hydrological functioning while also providing poverty relief to local communities (Turpie *et al*., 2008).

The aim of this study was to measure tree water-use to quantify the potential hydrological benefit of these forest management practices, improve the realistic modelling of these management approaches and provide guidelines towards suitable indigenous alternatives. Trees can be used for catchment rehabilitation and riparian zone management as well as to support global climate change initiatives. In order to use trees for these purposes, it is necessary to find alternatives to the use of fast growing exotic tree species which are high water-users.

Commercial forestry has been blamed for increasing the green water (water lost by total evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Jewitt, 2006). There is a widespread belief in South Africa that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land restoration programmes. Early successional or faster growing species tend to use more water than later successional or slower growing species (Vertessy *et al*., 2001; Irvine *et al*., 2013), and in many cases invasive species grow faster than their indigenous counterparts with growth and water-use being broadly linked (Grotkopp *et al*., 2002; Daehler, 2003; Everson *et al*., 2008; Gush, 2011). However, tree water-use is technically difficult and expensive to measure, and so there is scant evidence of low water-use by indigenous trees.

For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Modelled estimates are often used without proper validation, and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. Total evaporation (often referred to as evapotranspiration) is an important process within a wide range of disciplines, including ecology, hydrology and meteorology (Wilson *et al*., 2000). There is currently no single method capable of providing both good spatial and temporal data of evaporation (Jarmain *et al*., 2009). However, numerous methodologies have been developed to measure total evaporation, or its components (transpiration, soil evaporation and interception), over a range of spatial scales from individual plants and entire watersheds (Wilson *et al*., 2000). Micrometeorological methods can provide estimates of water flux on an areal basis which allows for direct comparisons with other hydrological components over a site or stand (Hatton *et al*., 1995). *In situ* measurements of tree water use (i.e. sap flow) enable the role of transpiration in trees to be quantified (Hatton *et al*., 1995). However, these techniques are suited only to mono-specific stands of trees and are problematic when up-scaling to stand measurements (Jarmain *et al*., 2009). Modelling can provide estimates of vegetation water use where measurements are not possible or available. However, the accuracy of modelling depends largely on the quality of the input data used and on studies to validate the simulated results.

2.2.2 Indigenous and Introduced Forest Systems

The natural indigenous forests of South Africa, although limited in extent, are scattered over a wide latitudinal gradient along the eastern and southern margins (escarpment, mountain ranges and coastal lowlands) of the country (Gush, 2011). Approximately only 4 700 km^2 (0.1 %) of South Africa's land surface is colonised by natural forests, where at least 7% of the country provides favourable climate and substrate for indigenous forest to inhabit (Mucina and Geldenhuys, 2006). South Africa, which is extremely rich in natural arboreal diversity, has over 1 000 species of indigenous trees (von Breitenbach, 1990). The natural capital of the indigenous forests has value to society through the direct and indirect goods/products, services and values they provide (Geldenhuys, 2004; Lowe *et al*., 2004; Seydack and Vermeulen 2004; Cawe and Geldenhuys, 2007). Much of the literature on indigenous forests highlight the problem of forest degradation, loss of forest cover and associated biodiversity, threatening spread of invasive alien plants and climate/environmental change (FAO, 2005; Roberts, 2008).

After the introduction of commercial plantations to South Africa in 1876, the favourable growing conditions led to the subsequent rapid spread of these species, particularly in riparian areas. Historically, commercial tree species were introduced for the extensive applications of the wood products, rapid growth, ease of management, availability of seed and scientific knowledge (Zobel *et al*., 1993; Mather, 1993). A National Invasive Plant survey indicates a high distribution of alien plants along the entire eastern seaboard of South Africa, which coincides with the higher rainfall regions (Kotze and Lawes, 2007). According to Richardson (1998), species that frequently recruit seedlings in very large numbers, and at distances of more than 100 meters from the parent plants, can be termed invaders. Alien plants have invaded an estimated 10.1 million ha of South Africa and Lesotho (Le Maitre *et al*., 2000). There are numerous species of invasive alien trees that pose a major problem throughout South Africa (Versfeld *et al*., 1998). Many of these species form dense stands, maintain high leaf areas (advantageous under high light and nutrient conditions), greater phenotypic plasticity (particularly advantageous in disturbed environments where conditions are in frequent flux) and are particularly numerous in riparian zones (Daehler, 2003). The species that have invaded the largest total area in South Africa are *Melia azedarach*, Pine species (mainly *Pinus pinaster* and *Pinus patula*), followed by *Acacia mearnsii*, *Prosopis* spp. and *Lantana camara*, each of which has invaded more than 2 million ha (Le Maitre *et al*., 2000).

Worldwide, riparian zones have been degraded due to a large scale invasion of alien species (Holmes *et al.*, 2008). Active rehabilitation of invaded areas is beneficial in facilitating the recovery of ecosystem structure and function. Conventional tree plantations with species from the genera *Pinus, Eucalyptus* and *Acacia* in single-species stands have addressed the economical need for wood products but have been criticised for contributing little to ecosystem functioning and biodiversity (Lamb *et al*., 2005).

2.2.3 Contributions to Ecosystem Services

Ecosystem services can be grouped into those that meet basic human needs (supporting, regulating, and provisioning services) and those that enhance human well-being (cultural services). Supporting services underpin the basic life-support processes required to sustain all ecosystems while regulating services control the flow of benefits and treatment of wastes, pests, and diseases (van Wilgen *et al*., 2014). Provisioning services provide products for human use, and cultural services enhance the quality of human life and human wellbeing (van Wilgen *et al*., 2014). Maintenance of ecosystems in South Africa is of great importance in order to ensure the continuation of services produced under pristine or near pristine conditions.

South Africa is generally a water scarce country with an uneven distribution of rainfall and runoff in space and time (Schulze, 2007). Therefore, a key policy response has been to ensure that water allocations have an equitable foundation, in which the water needs of people and riparian ecosystems are of high priority and protected (Scholes and Biggs, 2004). The South Africa National Water Act (NWA, 1998) stipulates that South Africa's water resources be protected, used, developed, conserved, managed and controlled. This requires numerous factors to be considered, including ecosystem protection and the prevention of water resource degradation (Everson *et al.*, 2007), both of these being components of ecosystem services. A 4-year global assessment of the world's ecosystem services (Millennium Ecosystem Assessment, 2005) found that 60% of the services assessed were in a declining condition due to a suite of anthropogenic drivers (such as habitat loss and alteration, water abstraction, overexploitation, and invasive alien species). The invasion of ecosystems by alien plant species has been identified as a large and growing threat to the delivery of ecosystem services (Drake *et al*., 1989). In developing countries such as South Africa, where short-term economic growth and social delivery take precedence over conservation, placing a monetary value on the ecosystem services is the only solution to ensuring intervention (Alylward and Barbier, 1992).

An uncontrolled increase of Invasive Alien Plants (IAPs) has the potential to threaten biodiversity by altering ecosystem processes and displacing native species. The dominance of IAPs can eventually lead to environmental and economic losses (Pimentel *et al*., 2005; Sakai *et al*., 2001). IAPs also change the natural landscape by destabilizing catchments by their total evaporation rates being higher than those of the natural vegetation and significantly altering hydrology and fire regimes, increasing soil erosion, as well as changing the physical and chemical composition of the soil (Le Maitre *et al*., 1996; Tabacchi *et al*., 2000; Joshi *et al*. 2004). For these reasons, invasive alien vegetation is considered to be a major threat to biodiversity globally (Solarz, 2007; Wal *et al*., 2008; Reid *et al*., 2009). From a hydrological perspective, the water-use of these vegetation types can be related to numerous services introducing a more complex economical component to measurements which are otherwise ignored.

2.2.4 Water-use Research in South Africa

Catchment based hydrological research was initiated in South Africa in response to the rapid expansion of commercial forestry in 1935 (Everson *et al*., 2011). Early studies involved long-term paired catchment experiments to assess the impact of land use changes on streamflow (Scott *et al*., 2000). Subsequent studies have shown changes in streamflow following riparian clearing (Dye *et al*., 1996; Scott and Lesch, 1995; Scott and Prinsloo, 2008). In the late 1980s, a shift towards direct measurements of hydrological processes began, with a particular emphasis on the importance of total evaporation losses from land surfaces (Dye and Bosch, 2000). Consequently, by the mid-1990s micrometeorological methods such as the Bowen ratio energy balance and eddy covariance techniques were increasingly applied to estimate evaporative losses from land surfaces (Everson *et al*., 2011). With the promulgation of the National Water Act (Act No. 36 of 1998) and the declaration of commercial forestry as a streamflow reduction activity (SFRA), further interest on understanding and quantifying transpiration and evaporative losses from different land uses.

2.3 Evaporation Measurement Techniques

With the on-going development of micrometeorological techniques, it is possible to accurately quantify the various components of the water cycle over various terrestrial surfaces. The use of micrometeorological techniques is largely dependent on location, time constraints and available funds. Nevertheless, due to continuous research by experts, the implementation of these techniques has become faster and more easily understood. In addition, comparisons between techniques and up-scaling have become possible, allowing for greater freedom in the choice of techniques and the duration of measurement (Savage *et al*., 2004; Jarmain *et al*., 2008).

There are several methods that can be used to measure the transpiration and evaporation of tree species and, therefore, their water-use. The techniques used are dependent on the scale at which the measurements are required (Figure 2.1). Techniques such as infrared gas analysis or mass spectrometry are some of the options available for leaf scale measurement studies. However, there can be a large disconnect if these techniques are used to upscale measurements to the plant or ecosystem scale (Cavaleri and Sack, 2010). Plant scale techniques such as stem steady state (SSS) collars or heat dissipation probes can be used to a high level of accuracy but errors may occur when up-scaling to the ecosystem scale if there is a limited knowledge of the stand diversity and density. Ecosystem scale techniques such as eddy covariance or scintillometry provide an accurate measurement of above stand total evaporation provided that the fetch of the stand area measured is not limited (Cavaleri and Sack, 2010). An understanding of the hydrological dynamics at each of these scales is imperative when selecting techniques for forest hydrology research.

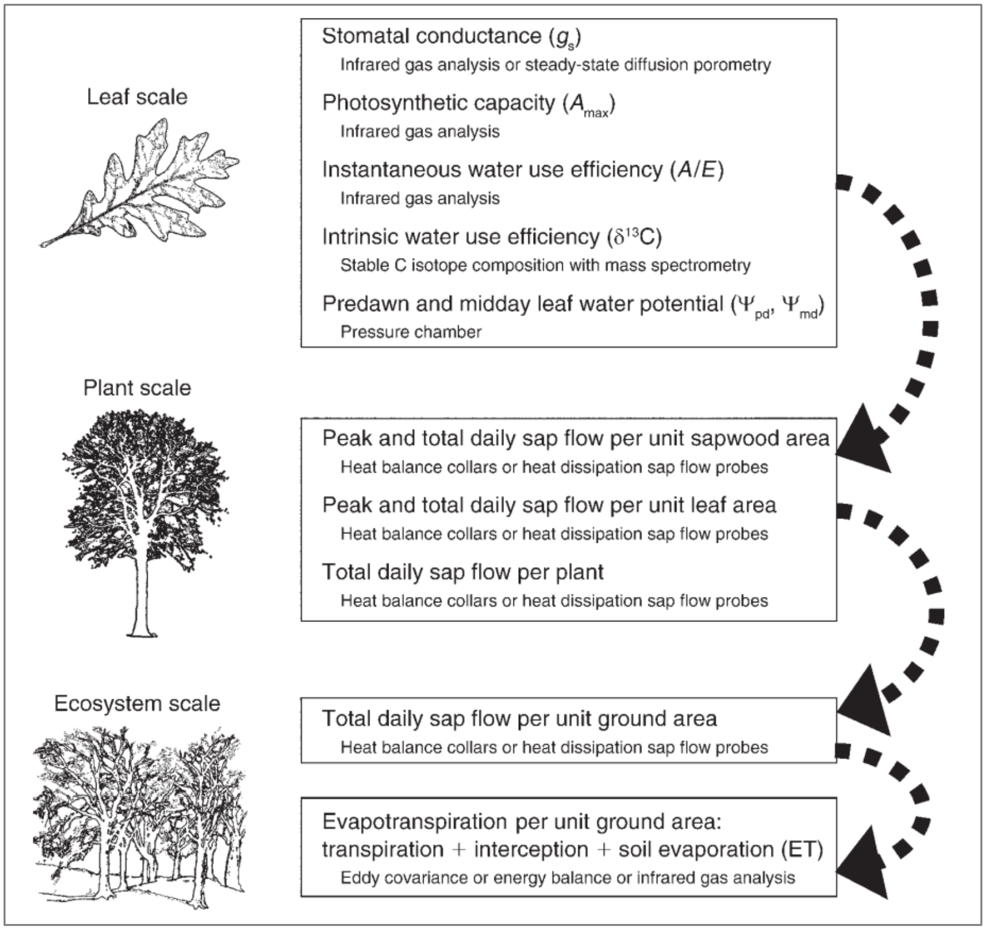

Figure 2.1 The leaf, plant and ecosystem scale and their respective water-use measurement options for forest hydrology studies (Cavaleri and Sack, 2010)

Micrometeorological methods can provide estimates of flux on an aerial basis, which allows for direct comparisons with other hydrological components over a site or stand (Hatton *et al*., 1995). *In situ* measurements of tree water-use (i.e. sap-flow) enable the role of transpiration in forest and woodland hydrology to be determined (Hatton *et al*., 1995). Numerous techniques can be used to estimate water vapour exchange rates between the surface and the atmosphere, but these techniques often vary, in that each technique is only representative within a particular spatial and temporal scale, and either interpolation or extrapolation is necessary to infer evaporation rates outside these scales (Wilson *et al*., 2000; Jarmain *et al*., 2008). These techniques may also differ in whether they measure total evaporation, or just one, or several, of its components (e.g. in energy balance techniques the net irradiance and the sensible and soil heat fluxes are used to determine the latent heat flux). In addition, each of the techniques introduces a unique set of assumptions, technical difficulties, measurement errors and biases (Wilson *et al*., 2000). A summary of some of the evaporation measurement techniques available has been provided in Table 2.1.

Table 2.1 Summary of a selection of techniques used in the measurement of transpiration or total evaporation (after Savage *et al*., 2004)

Method	**Measurement area, distance or height**	**Averaging period**	**Theoretical basis/comment**	**Comment**
Reference evaporation	Point measurement (2 m above short grass) of solar irradiance, air temperature, wind speed, water vapour pressure	Hourly/daily	Penman-Monteith method for reference evaporation estimation (FAO 56), and use of a crop factor (Allen *et al*., 2006) for short grass (0.1 m tall) and tall crops (0.5 m tall)	Only reference evaporation and estimated crop evaporation calculated
Lysimeter	< 10m^2	20 to 60 min	$LE_{lysimeter} = \frac{L\rho_w(\frac{\delta W}{\delta t})}{A_{lysimeter}}$	By definition, $H = R_n - G - LE$
Bowen ratio energy balance (BREB)	Vertical measurement distance of 1 m (grassland) to 2 m (forests)	20 to 30 min	$LE = \frac{(R_n - G)}{(1+\beta)}, \beta \neq 1$ Where β is the Bowen ratio; $H = \beta LE$	By definition, $LE + H = R_n - G$
Eddy Covariance (EC) (1 sensor)	Sonic path length of 100 to 150 mm	20 to 60 min	$H = \rho_a C_P \overline{w'T'}$ (ρ_a is the air density and w' and T' are fluctuations in vertical wind speed and air temperature)	By definition, $LE + H = R_n - G$
Surface layer scintillometer (SLS)	Beam length between 50 and 250 m	2 min and 60 min	Monin-Obukhov similarity theory (MOST) to estimate H and LE using $LE = R_n - H - G$	By definition, $LE + H = R_n - G$
Large aperture scintillometer (LAS)	Path length between 0.25 and 3.5 km	2 min and 60 min	Measures C_n^2, the structure parameter for refractive index fluctuations; MOST is assumed	By definition, $LE + H = R_n - G$
Surface renewal (SR)	Point measurement	2 min and 60 min	$H \propto$ amplitude of the air temperature ramps	By definition, $LE + H = R_n - G$
Heat pulse/sap flow	*In situ* measurement (<200 mm)	Hourly	Rate of movement of stem heat pulse, stem energy balance with continuous heat applied	Transpiration measurements only
Cut stem method	Destructive weight measurements of a plant portion	Hourly	Change in stem mass per unit time = transpiration rate	Transpiration measurements only

2.4 Water-use Findings

A comprehensive study by Cavaleri and Sack (2010) assessed over 40 published and unpublished studies worldwide covering the eco-hydrological differences of several hundred invasive and native (indigenous) species pairs. Pairwise combinations were examined of co-occurring native and invasive species to determine the frequency and degree at which a given invasive species used more water than a given native species (Figure 2.2). There exists a global tendency for higher water use by invasive species. Generally, the impacts were explained by differences between invasive and native species in transpiration rates, phenology, biomass of photosynthetic tissue or rooting depth (Levine *et al.,* 2003). Locally, numerous studies have shown that the overall water-use of the indigenous trees is substantially lower than for introduced plantation species (Gush *et al*., 2015).

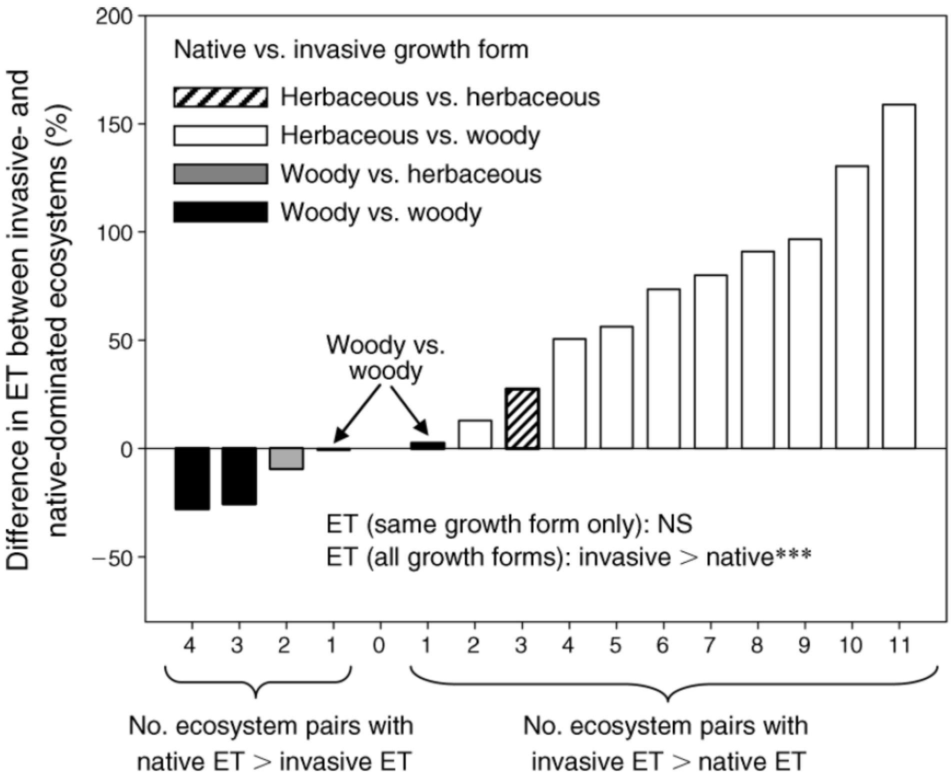

Figure 2.2 The percentage difference in the ecosystem scale total evaporation (ET) between indigenous (native) and invasive dominated ecosystems (Cavaleri and Sack, 2010)

2.4.1 Water-use of Introduced Tree Species

Invasive alien plants are consumptive water-users, and may have reduced river flows in South Africa by approximately 6.7% according to ecosystem-scale studies (Le Maitre *et al*., 2002). The total incremental water-use of invading alien plants is estimated at 3 300 million m^3 of water per year (Le Maitre *et al*., 2000), of which, most is associated with alien trees. Globally, invasive plants use up to 136 % more water than the indigenous species at the leaf scale (Baruch and Fernandez, 1993; Dixon *et al*., 2004; Pratt and Black, 2006). At the plant scale there is a diverse range in water-use ranging from the invasive species using 100 % less to 150 – 300 % more water than the indigenous species (Cleverly *et al*., 1997; Nagler *et al*., 2003; Kagawa *et al*., 2009). At the ecosystem scale studies indicate that invasive species use 189 % more water than indigenous dominates areas, particularly in tropical moist forests (Nosetto *et al*., 2005; Yepez *et al*., 2005; Fritzsche *et al*., 2006). These findings, typically outside of South Africa are limited to mostly herbaceous species with very few recent studies focusing on measurement of introduced trees. In contrast, South Africa is rapidly developing a comprehensive database of tree water use over a range of climatic growing conditions.

Invasions of areas by alien vegetation typically show a sigmoid growth curve over time, involving an initial lag period, a period of rapid expansion and the final period when expansion slows as the available habitat becomes fully invaded (Richardson, 1998). The Conservation of Agricultural Resources Act (no. 43 of 1983) and the National Environmental Management Act (NEMA No. 107 of 1998, amended 2014) legislates against the spread of invasive alien plants. However, this has been poorly enforced which has led to growing concerns related to water resource management (Richardson, 1998). Experiments have shown that afforestation by alien tree species significantly decreases streamflow where pre-afforestation vegetation was seasonally dormant mountain grassland or fynbos (Versfeld, 1994). Dye *et al*. (1996) noted a substantial increase in stream flow after clearing *Pinus patula* and *Acacia mearnsii* from riparian areas. Scott and Prinsloo (2008) also found that stream flow increased by up to 1.2 mm day^{-1} following riparian clearing. It has become a recognised fact that the rate of alien tree water-use is relatively high and results in substantial decreases in catchment water yields (Dye *et al*., 2008).

The natural vegetation that is replaced by introduced species commonly exhibits pronounced seasonal dormancy brought about by soil dryness or frost (Dye and Jarmain, 2004). The potential for increased total evaporation, and therefore reduced catchment water yield, following invasion by these species is great. Based on a combination of model and sap flow estimates, Dye and Jarmain (2004) documented that differences in evaporation following the invasion or removal or black wattle can be as high as 600 mm. It is also evident that alien vegetation has a high potential total evaporation suggesting that the more water available, the more water an alien tree will use as opposed to a lower threshold potential evident in natural vegetation. Over long periods of afforestation, the runoff was reduced by between 130 and 340 $mm.yr^{-1}$ for all catchments studied in KwaZulu-Natal and the Western Cape. This equates to between 10 and 30 % of the mean annual precipitation (MAP). The short-term average streamflow increase after riparian clearing ranged from between 0.9 to 3.1 mm day^{-1} of cleared vegetation, where generally the largest increases were evident following clearing of *Pinus* species. Total evaporation measurements indicated that wattle in the riparian areas of Jonkershoek used 157 mm yr^{-1} more water than the natural fynbos. Similarly, but to a greater extent, the wattle in the Karkloof used 424 mm yr^{-1} more water through transpiration than the natural grasslands. This suggests a significant increase in water-use in comparison to the natural vegetation.

Although alien plant control can be expensive, it has been shown that control programmes are cost-effective, when compared with alternative water supply schemes (Le Maitre *et al*., 2000). The need for information on the water-use of both indigenous and exotic trees is therefore essential for water resource management decision-making.

2.4.2 Water-use of Indigenous Tree Species

Little information is available on the water indigenous forests water-use in various climatic zones, and very few of the results are specific to riparian areas. Differences between individual species are highly variable and generalisations about the impact of exotic versus indigenous trees are risky. There has been significant research on the comparative water-use of alien trees and the indigenous vegetation that it replaces in South Africa (Olbrich *et al*., 1996; Dye *et al*., 2001; Everson *et al*., 2007; Dye *et al*., 2008; Gush and Dye, 2008, 2009). The slow growth rate of indigenous tree species suggests that these trees would use less water over time per unit area. In theory, a comparison of an indigenous and an alien tree of the same age should indicate that less water is used by the indigenous tree as it would be smaller, have less established roots and a lower leaf area. Research to support and quantify these assumptions is limited as the extent of these changes is highly variable with location and vegetation type. In addition to this, few catchments where removal programmes are in operation have weirs to monitor the hydrological changes.

A study on indigenous riparian trees in the Kruger National of *Ficus sycomorus*, *Berchemia zeyheri*, *Diospyros mespiliformis*, *Trichilia emetica* subsp. *emetica*, and *Spirostachys africana* was undertaken using four intensive water-use sampling surveys (Birkhead *et al*., 1996). Integrated transpiration, bank storage, and river hydraulics modelling in the Kruger Park showed an average seasonal daily consumptive water-use by the riparian trees to be low at 1.6 mm day^{-1} and 2.8 mm day^{-1} during winter and summer, respectively (Birkhead *et al*., 1996). Gush *et al*. (2015), examined the water-use and water-use efficiency (WUE, i.e. biomass produced per unit of water transpired, termed productive green-water-use) of indigenous and exotic trees. When considering WUE in terms of the volumes of wood produced relative to the amount of water-used by the trees, the exotic plantations were consistently greater. However, the overall water-use in indigenous trees was low, making them an attractive option in water-constrained catchments (Gush and Dye, 2009). If further research supports this finding, it would promote the use of indigenous trees in riparian areas and add to the already attractive list of ecosystem services produced from this landuse type. Research conducted on specific trees at Winterskloof (*Trema orientalis*; above average rainfall), Karkloof (*Celtis africana*, *Podocarpus falcatus*, *and Ptaeroxylon obliquum*; slightly below average rainfall) and Weenen (*Olea europaea* subsp. a*fricana* and *Berchemia zeyheri*; significantly below average rainfall) showed that volumes for all of the indigenous species at the various sites peaked during the wet summer months and declined during the cool, dry winter months (Gush and Dye, 2009). The variations in results were based on some of the trees being fully-deciduous, others semi-deciduous and the rest being evergreen species which are more conservative throughout the year but use more water in the dry periods (Gush and Dye, 2009).

Figure 2.3 indicates the difference in the annual transpiration rates between various alien and indigenous tree species. The annual cumulative sap flows of the indigenous species were all less than 8.5 kL tree^{-1} yr^{-1} compared to 20 kL tree^{-1} yr^{-1} for alien trees (Gush and Dye, 2009). The significant difference in transpiration rates can be explained by the extremely high stem mass increment to cumulative sap flow ratio present in exotic species. The research on indigenous trees was mostly conducted under wet conditions suggesting that the threshold water-use is significantly lower in indigenous trees and supports the assumption that these trees are better suited for diverse conditions or water constrained/sensitive areas such as the riparian zone (Gush and Dye, 2009).

In the Richard's Bay area, average annual transpiration totals for *V. kosiensis* trees ranged from 1 701 L y^{-1} (289 mm) for the smallest tree to 4114 L y^{-1} (699 mm) for the largest tree, with an average of 2515 L y^{-1} (427 mm), while totals for the *E. grandis* and *C. equisetifolia* trees were significantly higher at 7 721 L y^{-1} (858 mm) and 8 264 L y^{-1} (918 mm), respectively (Gush *et al*., 2015).

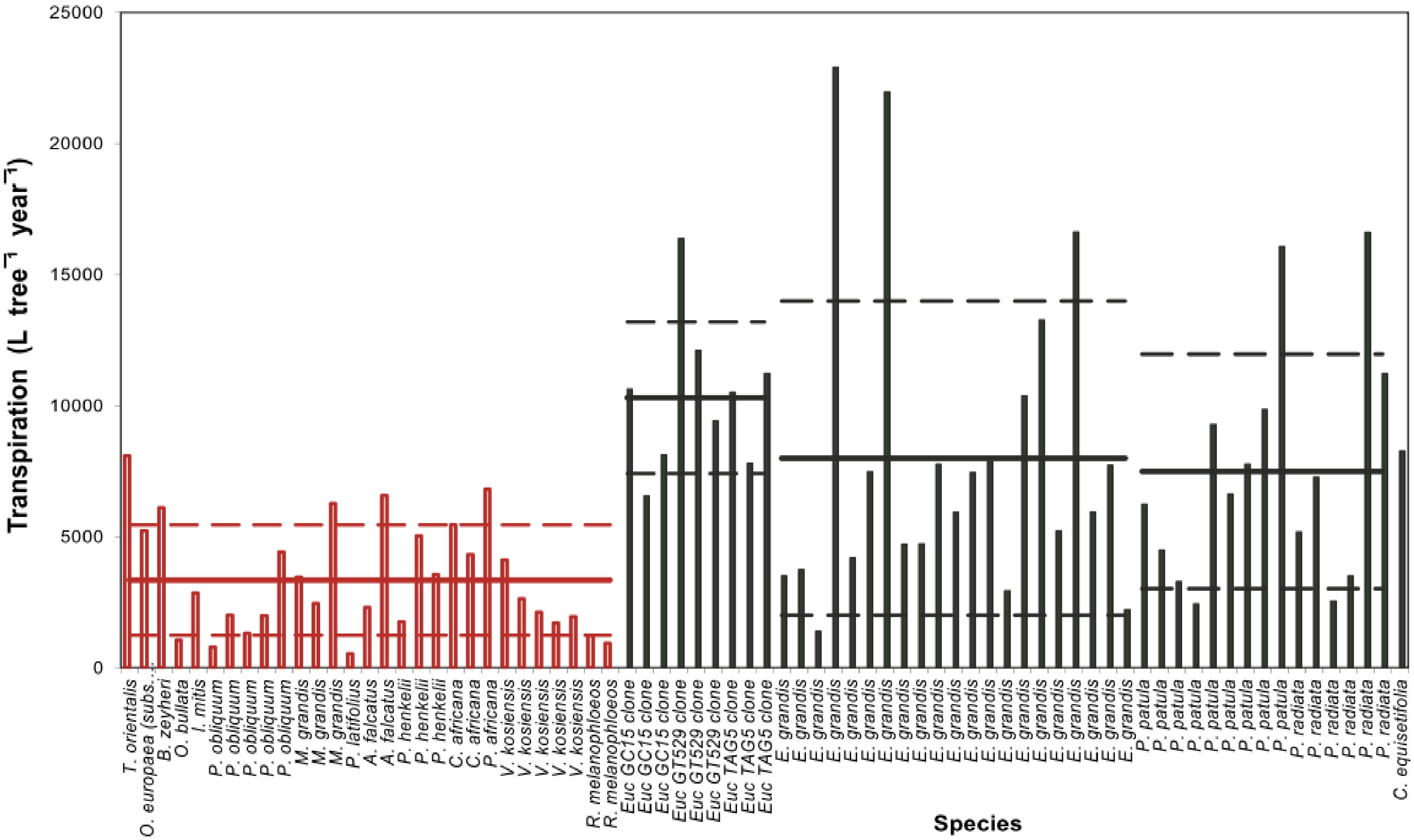

Figure 2.3 A comparison of 1-year sap flow (transpiration) between alien tree species (shown in black, Olbrich *et al*., 1996; Dye *et al*., 2001) and indigenous tree species (shown in red, Gush *et al*., 2015) measured in South Africa

2.5 General Conclusions

The large-scale invasion of previously pristine catchments by invasive alien plants (IAPs) in South Africa has been shown to reduce streamflow more than that which would occur under naturally vegetated conditions (Everson *et al*., 2011). This is largely attributed to the high water-use values associated with commercially introduced tree species. Maintenance of ecosystems in South Africa is of great importance in order to ensure the continuation of services produced under pristine or near pristine conditions. Invasive alien plant species are considered to be a major threat to biodiversity locally and globally (Solarz, 2007; Wal *et al*., 2008; Reid *et al*., 2009). It is difficult for government initiatives, such as the Working for Water (WfW) alien clearing programmes, to justify alien tree removal and implement rehabilitation unless a known hydrological benefit can be seen. The quantification of tree water-use can provide valuable information on the economic and environmental advantages to clear invaded areas, particularly in light of South Africa's limited water resources.

Natural forest areas in South Africa are confined to small, narrow areas that limit the use of total evaporation techniques such as eddy covariance and scintillometry. Sap-flow measurements undertaken within South Africa and abroad have introduced a cost effective approach to capturing comparative inter- and intra-species water-use differences. Furthermore, whole stand measurements are possible in conjunction with a comprehensive understanding of the stand dynamics. The HPV technique in particular has been shown to provide accurate estimates of sap flow in both introduced tree species such as *A. mearnsii* and *Eucalyptus grandis*, and indigenous tree species such as *Podocarpus henkelii* and *Celtis africana* (Smith and Allen, 1996; Dye *et al*., 2001; Everson *et al*, 2007; Dye *et al*., 2008). The findings from various South African studies contribute to an ever-growing database on tree water-use that has allowed for comparisons to be made over a range of climatic zones and between introduced and indigenous species. Litter interception is one variable that may significantly influence stand water-use. Bulcock *et* al. (2014) documented that a non-productive canopy and litter interception for *P. henkelii* accounted for 29.8% and 6.2%, respectively of the gross precipitation.

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CHAPTER 3. TECHNICAL APPLICATION OF SAP-FLOW TECHNIQUES FOR TREE WATER-USE MEASUREMENTS

3.1 Abstract

The use of sap-flow techniques to quantify plant water-use has become well recognised in scientific communities. Numerous sap-flow techniques are available and can be differentiated by those that measure sap-flow rate and those that measure sap-flux density. The technical application of three commonly used techniques: Heat Pulse Velocity, Thermal Dissipation and Stem Steady State are provided in detail. These methods for quantifying sap-flow are highly sophisticated and data intensive, requiring careful installation, regular maintenance and meticulous data management. Measurements of the local climate, soil-water interactions and tree to stand-level characteristics are important as they allow for any missing data to be in filled and for measurements to be scaled to whole tree and stand-level transpiration. Additional information on the re-design of the Heat Pulse Velocity method for improved field applications has been provided.

Key Words: Heat Pulse Velocity, Sap-flow, Stem Steady State, Thermal Dissipation

3.2 Introduction

In recent years the application of sap-flow measurement techniques has increased as a result of on-going technological developments and the recognition that alternative approaches are often inapplicable (Hatton *et al*., 1995). Sap-flow measurements provide a specific estimate of transpiration *per se*, as opposed to total evaporation measurements (ET), therefore reducing additional measurements and analyses required to isolate the transpiration component (Hatton *et al*., 1995). Sap-flow techniques are typically used at stem level and allow for whole-tree water-use measurements without influencing transpiration conditions (Schurr, 1998; Smith and Allen, 1996). Techniques used to measure tree water-use can be grouped into those measuring the sap-flow rate (g h^{-1}) or those measuring sap-flux density (cm^3 cm^{-2} h^{-1}) (Vandegehuchte & Steppe, 2013). Sap-flow rate techniques involve the continuous application of heat using a constant or variable power to a section of stem to solve the heat balance (Smith & Allen, 1996). Common variations of this technique include the Stem Steady State (SSS) or the Stem Heat Balance (SHB) method. The sap-flux density approach can include techniques that apply point source continuous heat to the tree (such as the thermal dissipation and heat field deformation techniques) or techniques that apply heat pulses to points within the tree, such as the compensation heat pulse velocity or the heat ratio methods (Vandegehuchte & Steppe, 2013).

In South Africa, three commonly used sap-flow measurement techniques are the Heat Pulse Velocity (HPV), Thermal Dissipation (TD) and Stem Steady State (SSS) methods. A brief background to these techniques and a detailed description on their practical application is provided. Supporting measurements are required to scale measured data to tree-level and stand-level transpiration and are described further.

3.3 Background to Sap-Flow Measurements in South Africa

3.3.1 The Heat Pulse Velocity Technique

The Heat Ratio (HR) method of the Heat Pulse Velocity (HPV) technique (Burgess, 2001) is a theoretical approach based on the heat conduction-convection equation (Marshall, 1958). A line heater probe, (80 mm long and of 1.8 mm outside-Ø stainless steel tubing) that is enclosed by a constantan filament, is powered for 0.5 seconds providing a heat source. A pair of thermocouple (TC) probes (consisting of type T copper-constantan thermocouples embedded in 2 mm outside-Ø PTFE tubing) are then used to measure temperatures upstream and downstream of the heater probe (Figure 3.1). The heat pulse velocity (V_h) is then calculated from:

$$V_h = \frac{k}{x} \ln\left(\frac{V_1}{V_2}\right) 3600 \quad (1)$$

where, k is the thermal diffusivity of green (fresh) wood, x is the distance (5 mm) above and below the heater (representing upstream and downstream), and v_1 and v_2 are increases in the downstream and upstream temperatures (from initial average temperatures) respectively. A thermal diffusivity (k) of 2.5×10^{-3} $cm^2 \cdot s^{-1}$ (Marshall 1958) is used. Wounding or damaged xylem (non-functional) around the thermocouples is accounted for using wound correction coefficients described by Swanson and Whitfield (1981). Sap-flux density is then calculated by accounting for wood density and sapwood moisture content as described by Marshall (1958). Sap-flux density is then converted to tree water-use or sap-flow ($L \cdot h^{-1}$) by calculating the sum of the products of sap velocity and cross-sectional area for individual symmetrical tree stems

(Clulow *et al.*, 2013). This method allows for flow measurement ranging from reverse flows to greater than 45 $cm^3\ cm^{-2}\ h^{-1}$ (Vandegehuchte and Steppe, 2013). Further detail on the wiring of the HRM technique to the logger is provided in Appendix 1.

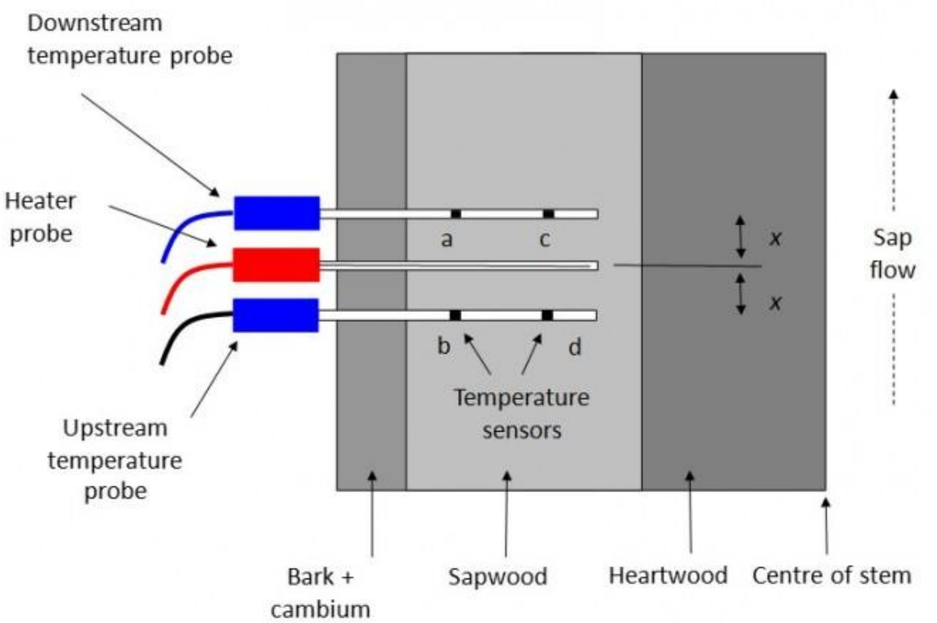

Figure 3.1 Schematic representation of the Heat Ratio Method (ICT International, 2016)

3.3.2 The Thermal Dissipation Technique

The Thermal Dissipation (TD) method (Granier, 1985, 1987) is widely used globally due to its simplicity and low costs (Lu *et al*., 2004; Vandegehuchte and Steppe, 2013). The system consists of two stainless steel probes (1.2 mm diameter) that are inserted radially into the sapwood (Figure 3.2), a set distance apart (Dynamax Inc., Houston, TX, USA). The upper probe contains a line heat source and a copper-constantan thermocouple junction, referenced to a junction in the lower needle (Steppe *et al*., 2010). A constant voltage is applied to the heater, allowing for the change in temperature to be measured between the two probes. The temperature difference is related to the sap-flux density, with a lower difference indicating a greater sap-flux density due to a high heat dissipation (Vandegehuchte and Steppe, 2013). Under thermal equilibrium between the sensor and the surrounding wood and sap during a constant sap-flux density, the input of heat by the Joule effect is equal to the quantity of heat dissipated by convection and conduction at the wall of the probe (Cabibel and Do, 1991; Lu *et al*., 2004). The TD method calculates sap-flux density (SFD) from:

$$SFD = 0.000119\left(\frac{\Delta T_0 - \Delta T}{\Delta T}\right)^{1.231} \quad (2)$$

where, ΔT_0 is the temperature difference measured during zero flow periods and ΔT is the temperature difference measured between the upper and lower probe (Granier, 1985).

A range of probe lengths are available that allow for various tree sizes to be measured at various depths within the tree, allowing for a detailed investigation into the tree's hydraulic traits. This empirical method allows for a large flow measurement range (from 0 to greater than 80 cm^3 cm^{-2} h^{-1}) although it cannot measure flow direction and hence reverse flows. This method is species independent but species and tree specific calibrations are required to obtain accurate results (Vandegehuchte and Steppe, 2013). A wound correction factor has not been incorporated into this system (Sun *et al*., 2011; Vandegehuchte and Steppe, 2013), which may result in an underestimation of the sap-flux density. However, an empirical correction based on comparisons to gravimetric measurements has been proposed by Wiedemann *et al*. (2016)

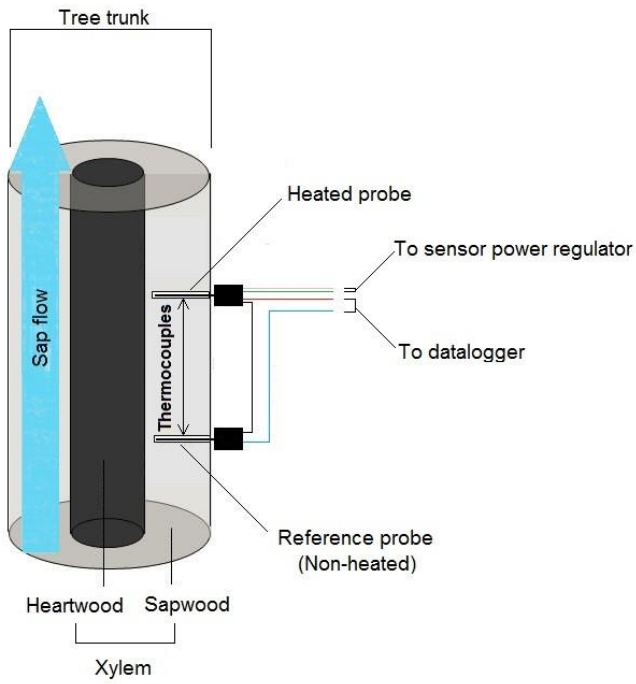

Figure 3.2 Schematic representation of the Thermal Dissipation Method (Ehsani *et al*., 2016)

3.3.3 The Stem Steady State Technique

The SSS technique estimates sap flow by solving a heat balance for a segment of stem that is supplied with a known amount of heat (Grime and Sinclair, 1999). This method uses insulated collars which have direct contact with a smooth stem surface (Grime and Sinclair, 1999). Continuous constant heat is applied to the entire circumference of the stem which is encircled by the heater (Baker and van Bavel, 1987). A foam insulation and weather shield surrounds the stem and extends above and below the heater in order to sufficiently minimize extraneous thermal gradients that may influence the heated section of stem (Smith and Allen, 1996). The conduction of heat vertically upwards and downwards is calculated by measuring voltages which correspond to the temperature difference between two points above and below the heater (Savage *et al*., 2000). The radial heat is calculated by measuring the temperature difference of the insulated layer surrounding the heater (Savage *et al*., 2000). Finally the voltage applied to the heater is measured allowing for sap-flow (kg s^{-1}) to be determined from sap convection energy (J s^{-1}), the sap specific heat capacity (J kg^{-1} K^{-1}) and the temperature difference between the above and below heater (Savage *et al*., 2000). Detail on this technique is well documented (Taylor *et al*., 2013) and hence the algorithms used have been provided in Appendix 2. Figure 3.3 (a) indicates the directional heat flux components and Figure 3.3 (b) shows the conceptual design and sensor components of the technique.

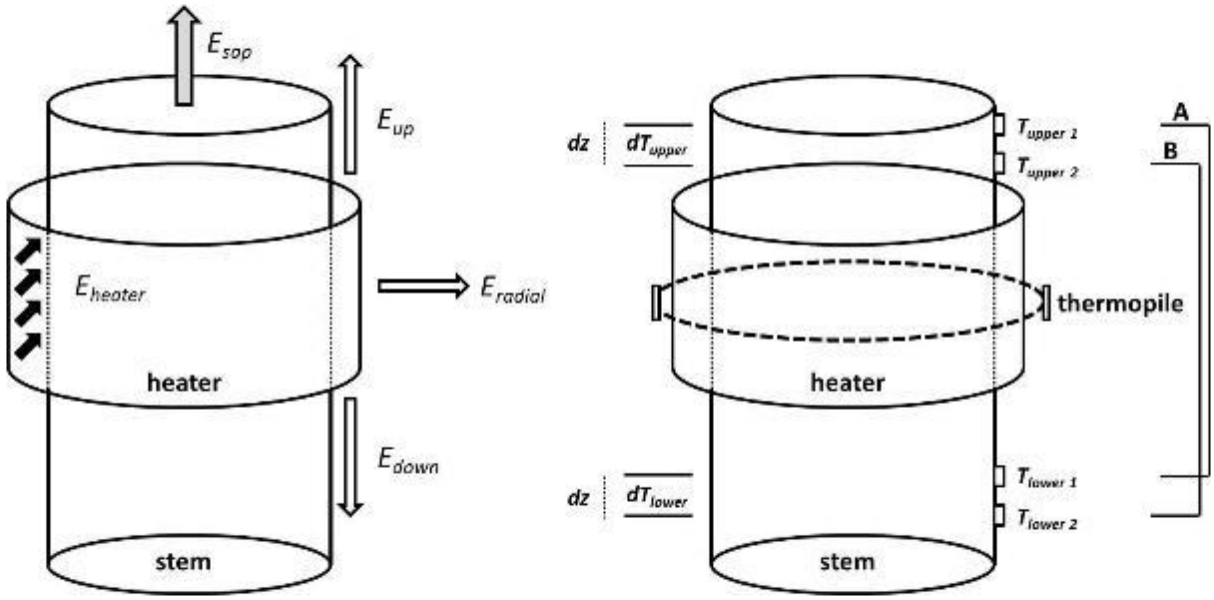

Figure 3.3 Schematic representation of the stem heat balance method (Savage *et al*., 2000).

Advantages of this technique include its applicability to both woody and herbaceous plants, its ease of installation, its use on multi-stemmed plants and its representation of the symmetrical sap wood area. Disadvantages include the high power requirement of the equipment and the limitation of collar sizes for larger tree species. Further detail on the calculation of water-use in the SSS technique is provided in Appendix 2.

3.4 Installation and Measurement Protocol

An overview of the installation of the techniques, the supporting measurements, the analysis of data and the modification of the design of the HPV system is discussed in this Section.

3.4.1 Meteorological Station

A meteorological station provides important data that allows for relationships to be derived between measured sap-flow data and the climate during the same period. Rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) at a height of 1.2 m from the ground is measured with additional measurements at a height of 2 m for measurement of air temperature (HMP45C, Vaisala Inc., Helsinki, Finland), relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp & Zonen, Delft, The Netherlands) windspeed and direction (Model 03002, R.M. Young, Traverse City, Michigan, USA) at regular intervals and averaged at a 60 minute frequency. Figure 3.4 provides a schematic of the typical components used to collect meteorological data.

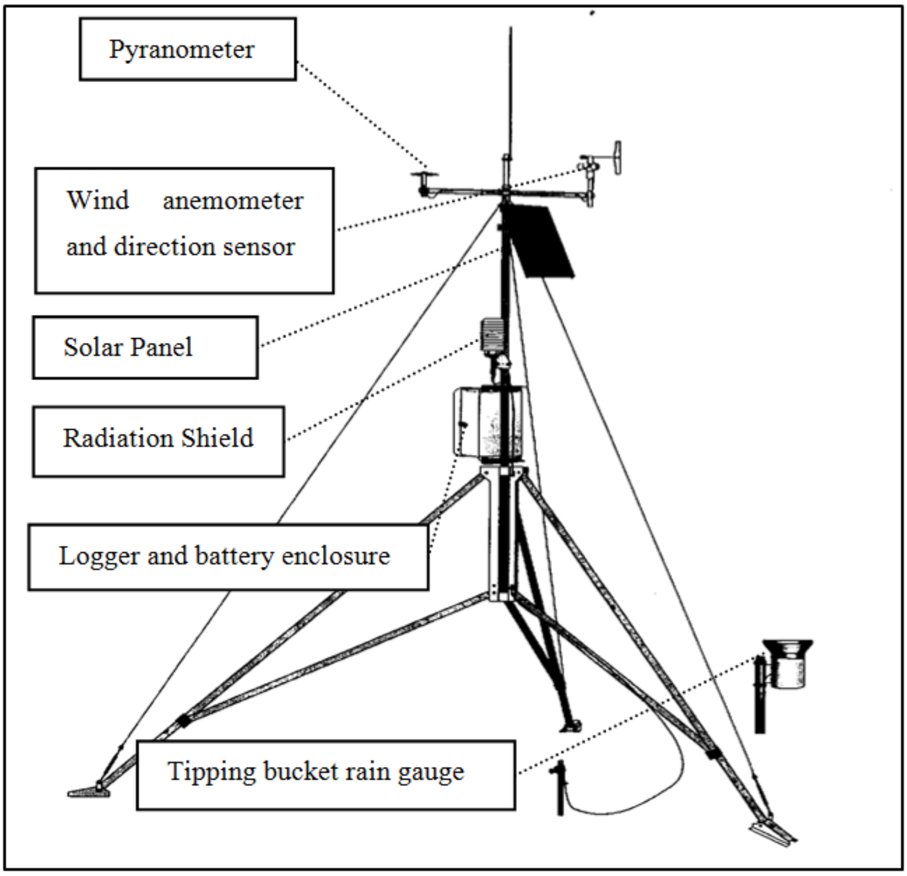

Figure 3.4 CM10 Weather Station design (Campbell Scientific, 1998)

3.4.2 Volumetric Water Content

Volumetric soil water contents can be measured using time domain reflectometry (TDR) probes (Campbell Scientific. model CS 616) installed horizontally at specified depths. The TDR probes can be wired in spare channels on the HPV system datalogger (CR1000). Hourly volumetric water contents are typically measured, showing the response of trees to rainfall events, or stressed conditions, in conjunction with the HPV measurements. Soil samples should be taken to determine the distribution of roots, bulk density and soil water content for calibration purposes.

3.4.3 Sap Flow Measurements

A key component for sap-flow studies is the selection of a suitable site and tree species of varying sizes that are representative of the area being measured. This is largely dependent on the study requirements and the equipment available. However, species and size replications are required if up-scaling or extrapolations are applied. The spacing between selected trees can also be a limitation due to the length of sensor wiring. More symmetrical single stem tree samples are required to minimize measurement errors.

3.4.3.1 Heat Ratio Method (HRM)

The thermocouple (TC) probes of the HRM method are inserted at incremental depths below the cambium in order to appropriately represent the entire sapwood area, as sap flow velocities are known to vary radially across the xylem (Wullschleger and King, 2000). An increment borer (Haglöf, Sweden) can be used to sample the sapwood depth and determine the bark thickness of the tree (or that of a replicate tree). This allows for the determination of the sapwood depth and the placement of TC probes throughout the sapwood. TCs should not be inserted into the non-conducting heartwood.

It is important that the heater and the TC probes are correctly positioned and aligned. Each TC should be carefully marked to indicate the insertion depth below the cambium. A drilling template is used to ensure that the drill holes are parallel. Specially designed drill bits are used (1.8 mm for TCs and 2.0 mm for the heater) with an electric or battery powered drill to create the holes. Two holes are drilled 5 mm above and 5 mm below the heater probe. Each set of probes should be drilled evenly around the tree to their required depth. The thermocouples are wired to a multiplexer (AM16/32) and datalogger (usually a CR1000, Campbell Scientific, 1998), while the heater probes are connected to a relay control module and a 12 V battery (Clulow *et al*., 2012). Generally, 4-12 sets or pairs of probes (each pair comprises upper and lower TCs and a heater) are implanted in a tree stem, depending on the size of the tree. To account for long-term changes in position as a result of stem diameter growth, the TCs should be removed from the tree and repositioned to their correct depths at least once a year.

The data loggers are programmed to initiate measurements at pre-determined intervals (generally hourly). Pre-heat pulse temperatures in the upper and lower TCs are measured and logged using an average of 10 measurements. Directly thereafter, a short (0.4 second) pulse of heat is released through the entire set of heater probes (Clulow *et al*., 2009). The pulse of heat diffuses through the adjacent wood and is taken up by the sap moving upwards through the xylem of the tree or downwards during reverse flow periods. As the heat pulse is conducted up the tree by the sap, the upper thermocouple begins to warm (generally to a greater extent than the lower thermocouple due to heat transport by the sap, although there is some conduction of heat to the lower thermocouple). Following a 60 second interval, post-heat pulse temperatures are measured every second for 40 seconds (Burgess *et al*., 2001). The heat ratio is then calculated for each probe set consecutively. These individual heat ratio values are accumulated for each TC pair (with a thermocouple reference junction), and at the end of the measurement the average ratio is calculated for each TC pair individually (Clulow *et al*., 2009). The Heat Ratio algorithm (Eq 1) is then applied.

3.4.3.2 Thermal Dissipation (TD) Method

Once the trees to be measured have been selected, the outer bark should be lightly scraped or sanded at a small, non-irregular section of the tree at approximately breast height. A drilling template should be placed over the cleared area to allow for drilling of the two TD probe holes. The depth drilled is dependent on the size of the probes used. The holes should be drilled at approximately 40 mm apart at a vertical orientation. Ambient temperature gradients can be reduced significantly by wrapping an insulating jacket of flexible porous foam at least 5 cm thick and twice as long as the tree diameter around the trunk, centred on the midpoint between the two needles (Dynamax Inc., 2016). The TD probes are then inserted with the heater probe in the upper hole and the reference temperature probe in the lower hole.

A putty or wax sealer should be installed around the needles, to provide a waterproof seal. This will prevent water from touching the needle shaft, and causing a heat sink effect (Dynamax, Inc, 2016). Foam blocks or similar material should be secured around the probes followed by reflective bubble wrap to prevent external temperature gradients.

3.4.3.3 Stem Steady State (SSS)

Dynamax Flow 32-K systems (Dynamax, Houston, TX, USA) are commonly used to solve the heat balance equation for the SSS technique. These systems are powered by a 12V battery system or alternative power source, which is controlled by an AVRD Dual Voltage regulator. Each system is managed by a data logger (usually a CR1000) and a multiplexer (AM16/32B). There is a voltage control unit which regulates the voltage output depending on the number of collars and the size of the collars used. The gauge’s insulating sheath (referred to as a ‘collar’) contains a system of thermocouples that measure temperature gradients associated with conductive heat losses vertically (up and down the stem), and radially through the sheath (Allen and Grime, 1994).

It is critical to ensure good thermal contact between gauge and the stem and therefore the stem where the heater collar is installed needs to be as straight as possible, without swelling or lumps (Smith and Allen 1996). In addition, silicone-grease should be placed on the stem prior to installation to ensure good contact, to allow slippage of the gauge during installation, to prevent water and condensation from accumulating between the stem and gauge and to allow movement of the gauge with expansion and contraction of the stem. Careful monitoring of the stem for any constrictions is required if the gauges are left on stems for long periods of time. It is important that water is prevented from entering the set-up as it can cause considerable damage to the electrical components.

Practical considerations (after Smith and Allen, 1996; Savage *et al.*, 2000) are:

- Gauges should be installed on straight section of stem (stem/bark should be manually smoothed);
- An electrical insulating compound should be applied to the stem prior to installation and an electrical check should be undertaken on the gauges;
- A conical collar should be installed above and below the collar to prevent water from entering the heated system and to prevent damage to the sensor;

- The voltage across the heater should be adjusted according the size of the gauge and the sap flow rates. This is usually tested in the laboratory and may prevent overheating of the stem; and
- The correct evaluation of K_{sh} (thermal conductivity of the sheath) must be undertaken when the sap flow is zero (using wooden dowels).

3.4.4 Tree Anatomy Measurements

Knowledge of tree anatomy may assist in the extrapolation of insertion depth measurements to single-tree water-use measurements. Tree density and crown size estimates may assist in estimating the stand transpiration. In addition, knowledge of the anatomy and physiology of the tree may support and/or explain the transpiration measurements. Figure 3.5 shows some of the tree specific anatomy measurements.

Figure 3.5 Samples taken for moisture content, density, wounding, sapwood depth and diameter

3.4.4.1 Sapwood Depth

Tree diameters at breast height should be measured for all the selected tree species using forestry grade callipers or a tape measure. Increment core wood samples should be taken from the measured trees as well as nearby trees of the same species for sapwood depth information.

Methyl orange (chemical dye) can be used as a visual enhancement in trees where there is no clear differentiation between the sapwood and heartwood. Allometric relationships between the sapwood to heartwood ratio for tree diameter classes can be investigated for further up-scaling from individual to whole canopy tree water-use.

3.4.4.2 Wood Density and Moisture Content

Wood density and moisture measurements are used in the calculation of sap-flux density for each probe which is then summed to calculate the daily water-use in L day^{-1}. The density is calculated based on the oven-dry mass and the green volume, which is determined by its water displacement (according to Archimedes' Principle, TAPPI, 1994; Malan, 2005). Multiple samples from each tree should be extracted and the wet mass measurement taken. Enough samples need to be taken to measure both the wood density and moisture content. To determine the moisture content, samples must be oven dried, allowing for the calculation of the under bark moisture content.

Additional samples to measure the wood density must be immersed in water for 30 minutes. These samples are then used to measure the weight of the displaced water in a water filled container. A needle should be used to submerge the sample without touching the sides of the container. The measured weight of the displaced water is equal to the volume of the wet sample. These samples are then oven dried to constant mass at 105 °C for 24 hours and the measurements are used to calculate the basic wood density.

3.4.4.3 Tree Size and Density

Leaf area index (LAI) measurements should be measured at regular intervals (monthly) within the stand (e.g. Li-COR 2200 plant canopy analyser). This allows for an understanding of the light dynamics under specific trees or stands. This is particularly important under stands with deciduous species. Tree heights and density should be measured at regular intervals (Haglöf vertex laser VL 402 hypsometer). Tree diameter at breast height should be measured at the same interval. Alternatively, a dendrometer could be used to measure continuous tree growth and minimise user measurement error.

3.5 Data Analysis, Corrections and Patching

Data patching is an important component in data analysis, as it allows for the construction of a complete data set by means of extrapolation and interpolation and provides information on the nature of a relationship between two or more sets of data. When working with high frequency data such as hourly sap-flow, it is common to have periods of no data or ‘noisy’ data. Poor data may be a result of, *inter alia*, broken equipment, animal and weather disturbance and power shortages. All available sap-flow data for an individual tree or plant are screened to identify periods of missing data. The first step in the gap-filling process is to determine if there are good quality data available from any of the other probes or collars for the period in question. The sensors with the highest correlation to the sensors being analysed are identified through a data correlation approach (such as a regression). This relationship is then applied to the period during which data are missing. If longer periods are missing from all trees being measured, data from the meteorological station should be used to determine a statistical relationship. The reference total evaporation (ET_0), which is derived using the Penman-Monteith equation, provides a good correlation with hourly sap flow rates. An example of the relationship between sap-flow and ET_0 for an *Acacia mearnsii* at Buffeljagsrivier in the Western Cape has been provided in Figure 3.6. A relationship was derived using good quality observed data over a time period before and after the missing data. This was done in order to preserve the seasonal variability in water-use existing in most species (deciduous or evergreen).

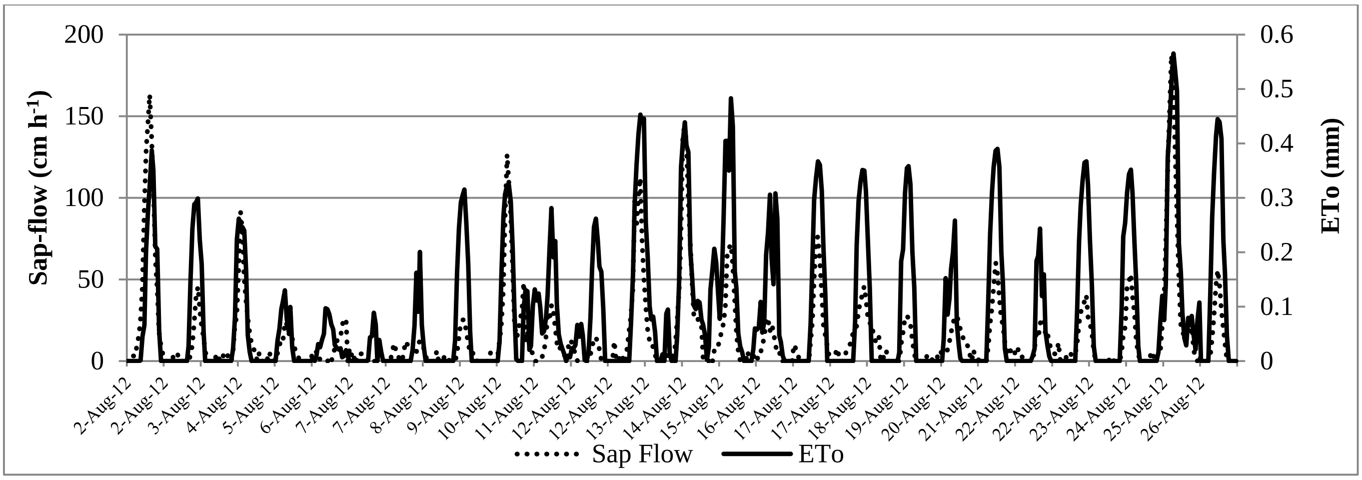

Figure 3.6 Relationship between *in situ* Sap-flow Measurements and the reference total evaporation for an *Acacia mearnsii* at Buffeljagsrivier

The sum of squares due to error (SSE), the R-squared (how successfully the fit explains the variation in the data), the residual degrees of freedom (DFE, number of response values minus the number of fitted coefficients estimated from the response values) and the root mean squared error (RMSE, standard deviation of the data's randomness) were considered in the model fit (Table 3.1). Using the best model fit, patched data can be created and in filled to the dataset (Figure 3.7). For the example provided, the Fourier model was used.

Table 3.1 Comparison of curve fitting techniques used on the sap-flow and reference total evaporation data at Buffeljagsrivier

Fit Type	SSE	R-squared	DFE	Adj R-squared	RMSE	Model *Coefficients with 95 % confidence bounds
Gaussian	229	0.74	971	0.74	0.48	$f(x) = 3.119 \times e^{\left(\frac{x-0.5511^2}{0.3353}\right)}$
Custom	223	0.75	971	0.75	0.48	$f(x) = -566 \times e^{(-0.01008 \times x)} + 566.1$
Exponential	283	068	972	0.68	0.54	$f(x) = 0.3555 \times e^{(4.503 \times x)}$
Fourier	221.8	0.75	970.0	0.76	0.47	$f(x) = 2.407 - 2.272\cos(x \times 2.057) + 2.137\sin(x \times 2.057)$
Polynomial 1st	223.5	0.75	972.0	0.75	0.48	$f(x) = 5.704 \times x + 0.1119$
Polynomial 3rd	221.8	0.75	970.0	0.75	0.47	$f(x) = -4.228x^3 + 5.09x^2 + 4.371x + 0.1348$

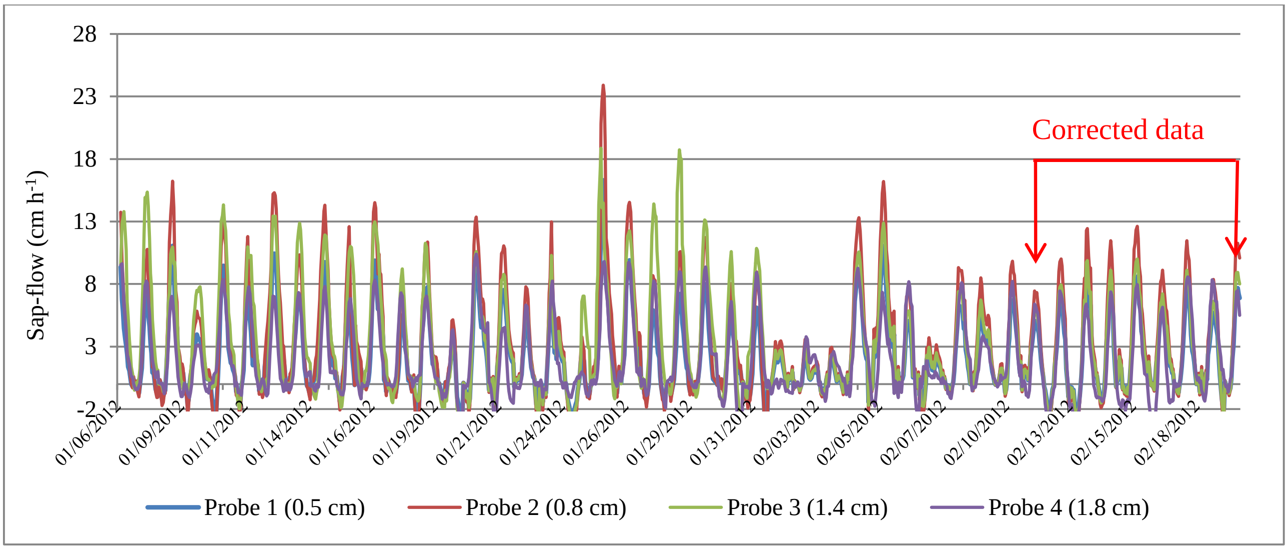

Figure 3.7 An example of some of the patched data used for *an Acacia mearnsii*

Once data checking and patching has been undertaken, a "zero flux" value (i.e. those times of the day when HPV values / transpiration would be expected to be zero) is determined using night time periods. This is then used to apply a daily offset to the data, which may not stabilize on zero. However, from published literature it is known that some tree species may show reverse sap flow at night (negative night-time HPV values) or actual night-time sap flow (positive night-time HPV values) (Benyon, 1999; Burgess *et al*., 2001). In order to resolve this, it is necessary to determine the ambient conditions under which zero sap-flow (zero HPV values) are most likely to occur, and assume that at these times there is zero sap-flow.

The wounding depth is used to determine a wounding coefficient (Burgess *et al*., 2001), to account for an underestimation of flow due to damaged xylem vessels. Subsequently, wood density measurements and moisture content (Marshall, 1958) are used to convert the heat pulse velocity to sap velocity. The extent of wounding is highly variable between tree species. The sap velocities are then converted to whole-tree sap flow by calculating the sum of the products of sap velocity and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). In this way, point estimates of sap velocity are weighted according to the amount of conducting sapwood in the annulus they represent (Gush, 2011). Sap-flow data are then aggregated from hourly values to daily totals.

3.6 Up-scaling Tree Water-Use Measurements

Up-scaling methods have evolved significantly in the past. Ladefoged (1963) considered a scalar relating crown size and area occupied by each tree to sapflow. Čermák and Kuæera (1987) used allometric relationships, based on tree basal area, while Werk *et al*. (1988) used leaf area estimates. The best relationship, as documented by Thorburn *et al*. (1993), was between the sap flux density and sapwood area and has since been used by Granier *et al*. (2001) and Dunn and Connor (1993). This indicates that more appropriate parameterisations of forest stands are required, to represent variation in site conditions and structural parameters including stand age, stand height, tree density, forest composition and the long-term range of flux rates (Cienciala *et al*., 1999).

Techniques that measure total evaporation over a spatial area are usually ideal for up-scaling sap-flow measurements. However, at sites with limited fetch, techniques such as eddy covariance may not always be used in the up-scaling process. With the availability of detailed stem density data, up-scaling whole-tree measurements to stand-level measurements can be done. However, limitations exist in heterogeneous stands. A methodology that was developed using this approach is provided here (Ford *et al*., 2007; Miller *et al*., 2007):

- Medoid (representative of the population) trees should be selected for sap flow measurements
  - most commonly occurring species (canopy and understorey).
  - a range of size classes for each species.
- A species density analysis should be undertaken (species diversity and diameter (>50 mm) in multiple 400 m^2 plots).
- Heat Pulse Velocity should be converted to whole tree water-use (Qtree) using various tree/wood properties (as per Section 3.5). SSS and TD methods are included for the whole tree water-use measurements.
- A relationship is then derived between Qtree and each representative size class and species class identified in the density measurements. This allows for the estimation of the stand water flux (Qstand).
- The Qstand is divided by the plot area (400 m^2) so that spatial values of transpiration could be calculated.

3.7 Advancement of the HPV Technique

The authors of this paper have used the heat ratio method extensively. During numerous previous monitoring studies using the heat ratio method, certain limitations in the equipment used for this technique were identified. The most significant of these was that the length of cable from the logger box to the trees was limited to 3 m. This resulted in a difficulty in finding suitable trees in close proximity to one another. Additionally, tree species that do not grow in dense stands, as is common with indigenous species, may not be replicated to the study requirements. Furthermore, the system is not power efficient, requiring large batteries, often in remote areas. The longer heater cables resulted in a greater loss of power from the battery. The result was (given that solar power is not feasible under tall stands of forests) that the battery needed to be changed every eight to ten weeks. Certain trees are highly acidic and can result in corrosion of the heater probes, while some trees which are prone to movement in the wind can result in the heater probes falling out of the trees or breaking inside the tree.

Professor C.S. Everson designed a new modified HPV system with the objective of overcoming these limitations. A multi-core copper wire was used to connect the new remote control boxes (Figure 3.8) to the multiplexer and logger. This required a reference temperature (thermistor) at the junction of the Copper/Constantan thermocouples. The 22 multicore cable enabled trees as far away as 50 m to be instrumented and reduced the length of the expensive thermocouple wire.

A new heater was designed from a standard 18 gauge needle with a 10 mm coil of constantan wire at the distal end. This heater is controlled by an adjustable constant power supply. Each heater unit was 15 Ω and the ideal current to generate 0.2 Watts for each of the four heaters is 0.115 A (Power = Current^2 × Resistance), which required a voltage of 6.4 V, which was set on the 0-1 000 kΩ potentiometer on the circuit board. A constant current (0.2 Watts) for 5 s was found to provide a suitable heat pulse (Figure 3.9). This allowed for the heaters to be powered from the remote control boxes. The short heater cables and dedicated battery (7 to 9 A h) has allowed for these systems to run for approximately 20 weeks before the battery needs to be replaced. A protective brass sheath was used to prevent the corrosion from acidic trees and from heater movement in the more flexible tree species. The addition of this sleeve resulted in a reduction of the separation distance from the heater to each thermocouple in the tree. The calculation used in the logger programme was modified to accommodate this change (from 5 to 4 mm).

Figure 3.8 The new heater box enclosure and probes

To date, this modified technique has been tested on *Pinus elliottii*, *Acacia mearnsii*, *Eucalyptus grandis, Albizia adianthifolia, Shirakiopsis ellipticum, Warburgia salutaris, Croton megalobotrys, Faidherbia (Acacia) albida, Philenoptera violacea,* and *Vachellia (Acacia) xanthophloea.* All of the results thus far have been of good quality with long periods using the same battery. This has minimised the disturbance to the probes that, in the past, occurred when batteries were frequently changed and the probes became misaligned due to tension on the wires. Very few corrections (offsets) were required for ‘zero flow’ conditions. This technique was calibrated by checking the timing of the temperature recordings. Figure 3.9 shows the pre-heat pulse measurements, the application of the heater trace and the post-heat pulse measurements. The calibration showed that a 60 s period after the heat pulse was suitable to capture the upstream and downstream heat ratios with enough discrimination to provide good sap velocities. Furthermore, the one hour period between sap flux density measurements was adequate to allow for the heat in the tree to stabilize so that subsequent measurements were not affected.

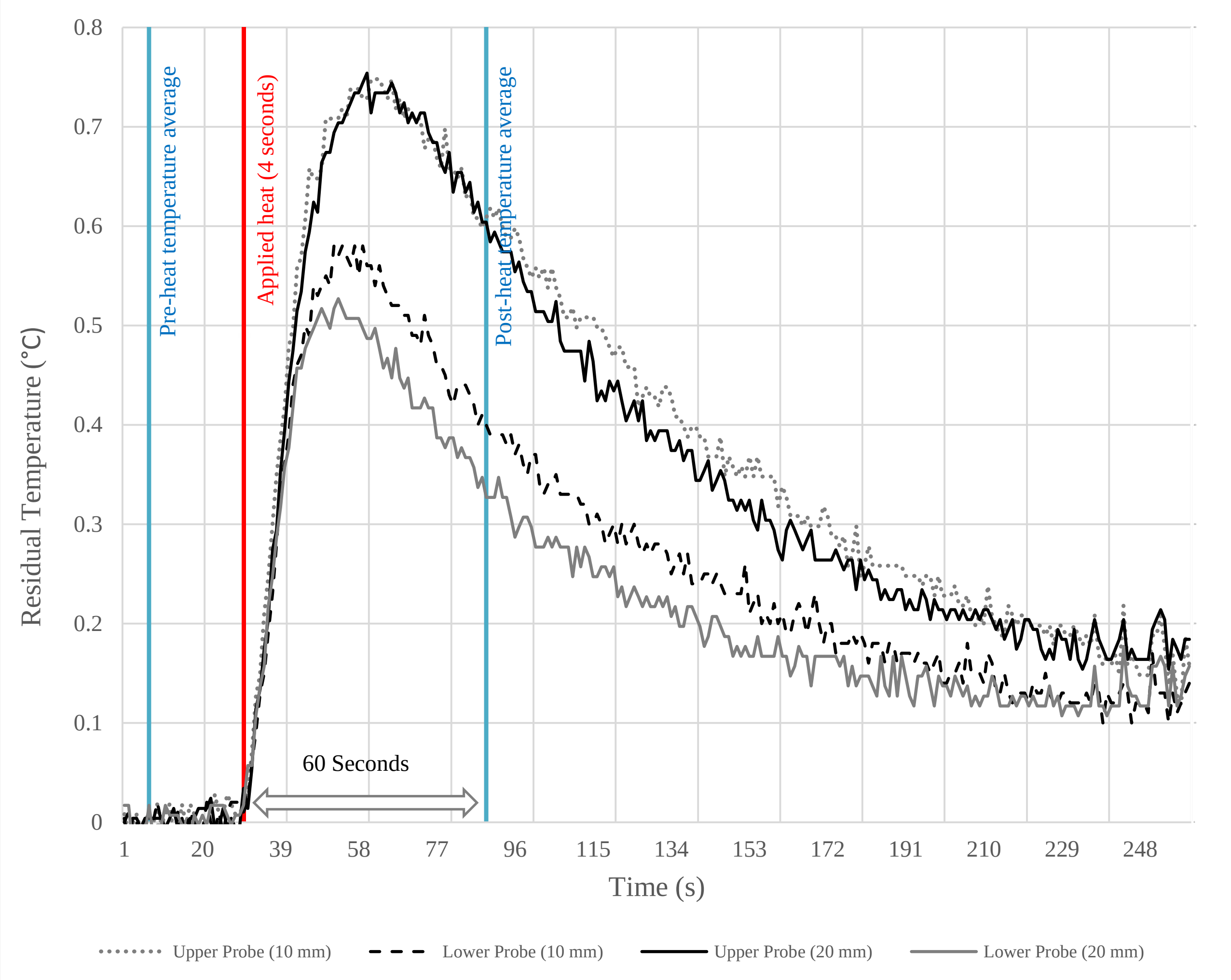

Figure 3.9 Testing of the modified HPV system on pairs of probes installed at depths of 10 and 20 mm.

3.8 Discussion and Conclusion

Sap-flow systems are often the only viable options to understand water-use dynamics, particularly in areas with limited aerodynamic fetch. A technical overview of the Heat Pulse Velocity (HPV) technique, the Stem Steady State (SSS) and Thermal Dissipation (TD) techniques has been provided. The correct installation of these techniques is essential to ensure that the water-use data measured are of good quality. Each technique has a different set of requirements and measures water-use using different empirical and theoretical approaches. As such, comparison of these techniques needs to involve meticulous data analysis and scaling to the whole-tree scale. Supporting measurements, including meteorological data, volumetric soil water content and tree anatomy measurements are imperative to understand the findings in a greater context and to ensure that potential measurement errors are accounted for. The improvement of the HRM method has resulted in spatial tree distribution to be accounted for, power efficiency to be increased and data corrections to be reduced.

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CHAPTER 4. WATER-USE DYNAMICS OF AN ALIEN INVADED RIPARIAN FOREST WITHIN THE MEDITERRANEAN CLIMATE ZONE OF THE WESTERN CAPE, SOUTH AFRICA

4.1 Abstract

In South Africa the invasion of riparian forests by alien trees has the potential to affect the country's limited water resources. Tree water-use measurements have therefore become an important component of recent hydrological studies. It is difficult for government initiatives, such as the Working for Water (WfW) alien clearing programmes, to justify alien tree removal and implement rehabilitation unless a known hydrological benefit can be seen. Consequently water-use within a riparian forest along the Buffeljags river in the Western Cape of South Africa was monitored over a three year period. The site consisted of an indigenous stand of Western Cape afrotemperate forest adjacent to a large stand of introduced *Acacia mearnsii*. The heat ratio method was used to measure the water-use of a selection of representative indigenous species in the indigenous stand, a selection of *A. mearnsii* trees in the alien stand and two clusters of indigenous species within the alien stand. The indigenous trees in the alien stand at Buffeljags river showed significant intraspecific differences in the daily sap flow rates varying from 15 to 32 $L \cdot day^{-1}$ in summer (sap flow being directly proportional to tree size). In winter (June) this was reduced to only 7 $L \cdot day^{-1}$ when less energy was available to drive the transpiration process. The water-use in the *A. mearnsii* trees showed peaks in transpiration during the months of March 2012, September 2012 and February 2013. These periods corresponded to favourable climatic conditions of high average temperatures, rainfall and high daily water vapour pressure deficits (VPD - average of 1.26 kPa). The average daily sap flow ranged from 25 L to 35 L in summer and approximately 10 L in the winter. The combined accumulated daily sap flow per year for the three *Vepris lanceolata* and three *A. mearnsii* trees was 5 700 and 9 200 L respectively, clearly demonstrating the higher water-use of the introduced *Acacia* trees during the winter months. After spatially upscaling the findings, it was concluded that, annually, the alien stand used nearly six times more water per unit area than the indigenous stand. This finding indicates that there would be a hydrological gain if the alien species are removed from riparian forests and rehabilitated back to their natural state.

Key Words: Indigenous trees, introduced trees, sap flow, transpiration, upscaling

4.2 Introduction

While extensive research has been undertaken on the water-use of terrestrial ecosystems in South Africa, little is known about riparian tree water-use and growth of both indigenous and introduced tree species. This knowledge gap, as well as the poor ecological condition of South African riparian habitats, has led to uncertainty and contention over riparian rehabilitation techniques. The deep fertile soils, with high soil moisture contents associated with riparian areas, make them ideal for plant establishment and growth (Everson *et al*., 2007). As such, these areas are extremely vulnerable to invasion by pioneer plant species, particularly alien hybrid species that have historically been introduced for commercial forestry. It is widely believed that riparian zone vegetation, which can be described as the interface between terrestrial and aquatic ecosystems (Richardson *et al*., 2007), has a significant impact on the hydrology of a catchment due to the close proximity of riparian vegetation rooting systems to the water table. Most riparian trees are phreatophytic, meaning they have access to a permanent source of water because their rooting system is within the shallow ground water.

Through the process of evaporation and transpiration, riparian vegetation influences streamflow rates, ground water levels and local climates (Richardson *et al*., 2007). Vegetation along riverbanks filter surface and subsurface water moving across and through the soil to the river channel and therefore helps to maintain channel water quality, by regulating the water temperature (through shading), bank stability and turbidity and traps debris (Askey-Dorin *et al*. 1999). Riparian vegetation can access a wide range of water sources within the riparian zone, which includes rainfall, soil water, stream water and groundwater (O'Grady *et al*., 2005). Commercial forestry has been blamed for increasing the green water (water lost by total evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Jewitt, 2006). There is a widespread belief in South Africa that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land restoration programmes. This is based on observations that indigenous trees are generally slow growing, and that growth and water-use are broadly linked (Everson *et al*., 2008; Gush, 2011). However, tree water-use is technically difficult and expensive to measure, and so there is scant evidence of low water-use by indigenous trees.

For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Modelled estimates are often used without proper validation, and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. With the on-going development of micrometeorological techniques, it is possible to accurately quantify the various components of the water cycle over various terrestrial surfaces. The use of micrometeorological techniques is largely dependent on location, time constraints and available funds. However, due to continuous research by experts, the implementation of these techniques has become faster and more easily understood. In addition, comparisons between techniques and up-scaling have become possible, allowing for greater freedom in the choice of techniques and the length of measurement (Savage *et al*., 2004; Jarmain *et al*., 2008). Sap-flux density studies have been undertaken locally and internationally, and are well documented. Sap flux density measurements give precise information on flow directions and spatial flow distribution (Vandegehuchte and Steppe, 2013). The heat pulse velocity (HPV) method is the most accurate of the available methods when compared against gravimetric methods (Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013).

The Buffeljags River site in the Western Cape has been an ecological research site since 2006 and forms part of a selective thinning experiment designed to assist Working for Water (WfW) clearing programmes. The government-funded WfW programme clears catchment areas of invasive alien plants with the aim of restoring hydrological functioning while also providing poverty relief to local communities (Turpie *et al*., 2008).

The aim of this study was to measure tree water-use to quantify the potential hydrological benefit of these forest management practices, improve the realistic modelling of these management approaches and provide guidelines towards suitable indigenous alternatives.

4.2.1 The Study Area

The Buffeljags river flows southwards along the Langeberg West mountain range into the Buffeljags dam. The Buffeljags river study area is at latitude 34°00’15”S and longitude 20°33’58”E (Figure 4.1), approximately 95-110 m above mean sea level. The research area is within Quaternary Catchment (QC) H70E and falls under the Western Cape Afrotemperate forest type which is characteristic of very small forest patches occurring along boulder screes consisting of streams, gorges and mountain slopes (Geldenhuys, 2010). The Langeberg Mountains consist of Table Mountain Sandstone/quartzite (north of the Buffeljags River) with a ridge of shales to the south of the river. The soils are characterised by structureless sands, a result of previous alluvial deposition. The climate is typical of the Western Cape with hot summers and cold winters. However, the rainfall is fairly evenly spread throughout the year. The long-term (137-year record) mean annual precipitation (MAP) at Buffeljags River is 636 mm. The daily maximum air temperatures range from 17.1 °C in July to 27.5 °C in January. The mean daily minimum air temperature is 15 °C in February and 5 °C in July. A 99-ha riparian forest occurs along the river with 75 ha of invaded forest (lower reach) and 24 ha of pristine indigenous forest (upper reach) (Figure 4.1), comprising of species such as *Celtis africana*, *Vepris lanceolata*, *Prunus africana*, *Rapanea melanophloeos* and *Podocarpus falcatus***.** The stand height ranged from 3 to 15 m in the indigenous stand and 11 to 17 m in the alien stand. The surrounding vegetation is mountainous fynbos and renosterveld.

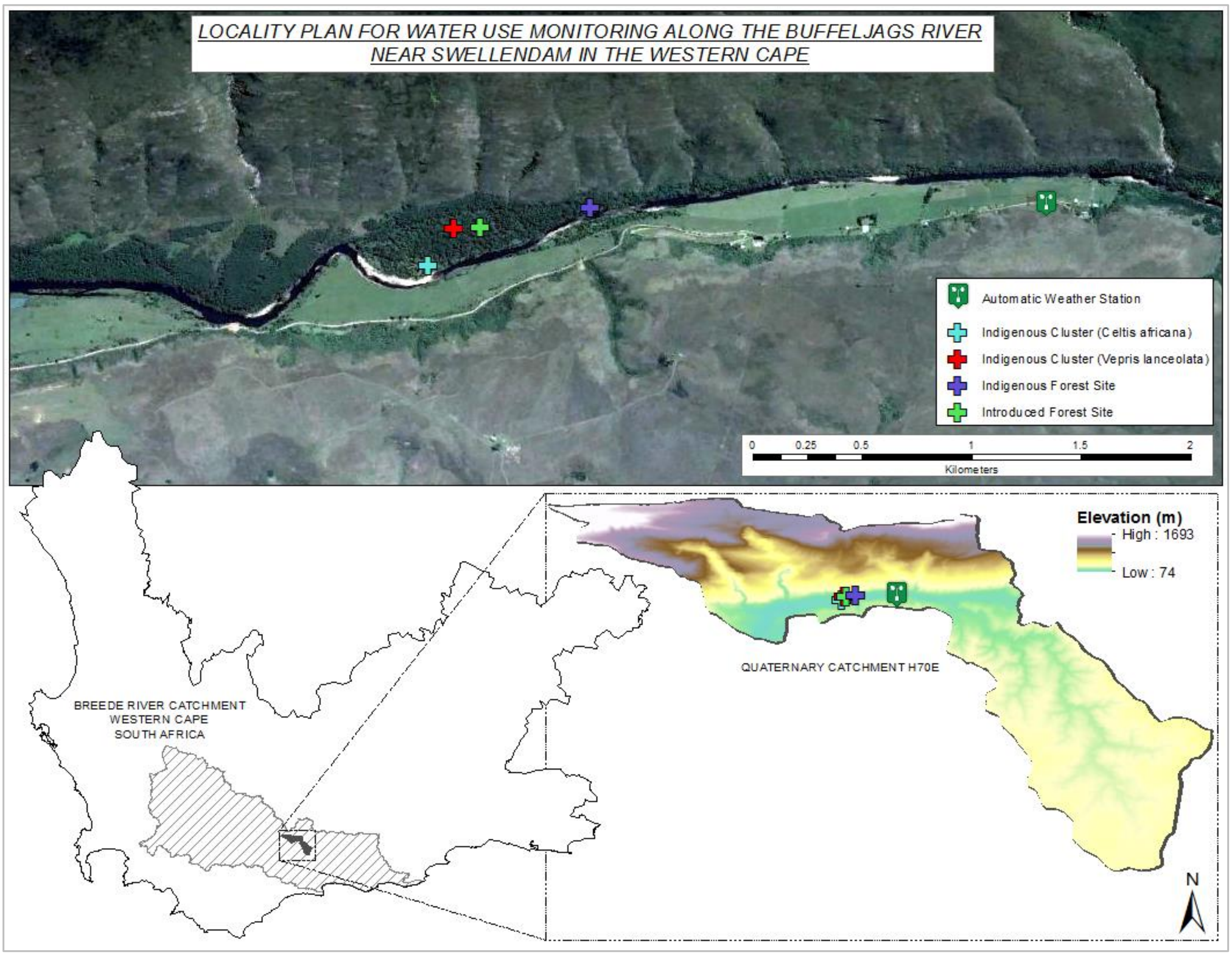

Figure 4.1 Location of the Buffeljags River research area within the Western Cape, South Africa

Historically *A. mearnsii* trees were planted for small scale uses (firewood and building material) on the nearby farms. Working for Water cleared most of the alien trees which have since grown back over the last 15 years. Currently the invasion extends approximately one kilometer along the river.

4.2.2 The Study Sites

Three representative trees within the indigenous stand were instrumented for monitoring sap-flow. These trees included an understorey tree (*Rothmania capensis*), one medium (*Vepris lanceolata*) and one large evergreen tree (*Vepris lanceolata*) that were most common throughout the stand. The leaf area index (LAI) within this stand was 3.6 throughout most of the season with a slight reduction during the winter months. Downstream of this site, within the alien stand (Figure 4.1), three *A. mearnsii* trees were instrumented over the three year study period. In a similar way, small, medium and large diameter classes were chosen to assist in the up-scaling of single tree transpiration measurements of the *Acacia* trees. The LAI of the *Acacia* stand was 3.1 during the summer months and 2.8 during the winter months. Two indigenous tree clusters within the alien stand were also instrumented. The *Vepris lanceolata* cluster contained two medium and one large diameter class trees (LAI of 3.4) while the *Celtis africana* cluster contained two large diameter class trees with a LAI of 3.3 in the summer months and 1.8 during the winter months. The LAI provided an indication of the seasonality of the trees and the light variations between the sites.

Both the indigenous and introduced alien stands were in a climax state with most of the canopy trees falling into the medium or large size classes. Although there were many smaller trees (excluding trees with a stem Ø < 5 mm), these did not contribute significantly to the total transpiration as they were shaded out by the climax trees. An overview of the individual tree characteristics is provided in Table 4.1.

Table 4.1 Tree physiology and specific data required for the calculation of sap flow and up-scaling.

Indigenous Forest site (upper reach)	Wood density ($kg \cdot m^{-3}$)	Moisture fraction ($kg \cdot kg^{-1}$)	Average wounding (mm)	Diameter (mm)	Size class (S/M/L)	Representative stem density ($stems \cdot ha^{-1}$)
Vepris lanceolata	0.66	0.42	3.4	199	L	24
Vepris lanceolata	0.63	0.42	3.7	134	M	65
Rothmania capensis	0.59	0.45	2.8	125	S	120
Introduced/Alien Forest site (lower reach)						
Acacia mearnsii	0.54	0.89	3.2	121	S	650
Acacia mearnsii	0.73	0.47	3.2	167	M	200
Acacia mearnsii	0.61	0.71	3.0	194	L	50
Indigenous Cluster (lower reach)						
Vepris lanceolata	0.66	0.45	3.2	166	M	65
Vepris lanceolata	0.65	0.45	3.2	174	M	65
Vepris lanceolata	0.66	0.47	2.9	202	L	24
Indigenous Cluster (lower reach)						
Celtis africana	0.71	0.52	6.1	319	L	24
Celtis africana	0.71	0.50	6.0	422	L	24

*Note: The stem density was grouped as per size class

4.3 Methods

A meteorological station was established on the 25th of January 2012 at Buffeljags River in a nearby planted *Eragrotis plana* field, 1.6 km from the indigenous site. Rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) at a height of 1.2 m from the ground was measured with additional measurements at a height of 2 m for air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp & Zonen, Delft, The Netherlands) windspeed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA). These were measured at a 10 second interval and the appropriate statistical outputs were recorded every hour.

A Heat Pulse Velocity (HPV) system using the heat ratio algorithm (Burgess, 2001) was set up to monitor long-term sap-flow on all of the selected trees over a three year period. The instrumentation is described by Clulow *et al*. (2013) and included a 0.5 s heat source (sap-flow trace) in the form of a line heater. A pair of type T-thermocouple probes was used to measure pre- and post-temperatures 5 mm above (downstream) and below (upstream) of the heater probe

(Clulow *et al*., 2013). Hourly measurements (CR1000, Campbell Scientific Inc., Logan, Utah, USA) were captured over the three year monitoring period (January 2012 to March 2015).

An assessment of the bark and sapwood depth was undertaken on the selected trees using an increment borer. This assessment assisted in determining the HPV probe insertion depths and the calculation of sapwood area. The heat pulse velocity (V_h) was calculated from:

$$V_h = \frac{k}{x} \ln\left(\frac{V_1}{V_2}\right) 3600 \qquad (3)$$

where, k is the thermal diffusivity of green (fresh) wood, x is the distance (5 mm) above and below the heater (representing upstream and downstream), and v_1 and v_2 are increases in the downstream and upstream temperatures (from initial average temperatures) respectively. A stem thermal diffusivity (k) of 2.5×10^{-3} cm^2 s^{-1} (Marshall, 1958) was used. Wounding or damaged xylem (non-functional) around the thermocouples was accounted for using wound correction coefficients described by Swanson and Whitfield (1981). Sap velocities were then calculated by accounting for wood density and sapwood moisture content as described by Marshall (1958). Finally, sap velocities were converted to tree water-use (Q_{tree}) or sap flow ($L \cdot h^{-1}$) by calculating the sum of the products of sap velocity and cross-sectional area for individual symmetrical tree stems (Clulow *et al*., 2013).

Tree growth was recorded every two months throughout the monitoring period by measuring diameter at breast height with a dendrometer and canopy height using a VL402 hypsometer (Haglöf, Sweden). Riparian forests typically have a narrow canopy with limited reach, which excludes techniques such as eddy covariance and scintillometry being used to support the up-scaling of point water-use measurements to stand water-use values. Given the homogenous characteristics of the alien stand and the dominance of *Vepris* and *Celtis* species within the indigenous stand, a methodology was followed based on recent up-scaling studies (Ford *et al*., 2007; Miller *et al*., 2007). In addition, detailed stem density data were available for the site due to extensive ongoing ecological research (Atsame-Edda, 2014). Medoid (representative of the population) trees were selected for sap flow measurement. This included the most commonly occurring alien and indigenous species (canopy and understorey) and a range of size classes for each species. A species density analysis was undertaken (Ø > 50 mm) in replicated 400 m^2 plots per site. A relationship between total tree water-use (Q_{tree} – $L \cdot day^{-1}$) and each representative size and species class was identified. This allowed for the estimation of the stand water flux (Q_{stand}) which was divided by the plot area (400 m^2) in order to obtain comparative units between the indigenous and alien stands ($L \cdot day^{-1} \cdot ha^{-1}$). These values were then accumulated to annual values so that the effect of alien and indigenous (evergreen and deciduous) stands on the water balance could be quantified throughout a hydrological year.

The *A. mearnsii* site had a thin litter layer consisting mostly of broken branches, bark and leaves compared with the indigenous site which had a thicker litter layer with a large amount of organic matter accumulated from the various tree species and understorey vegetation. Volumetric soil water contents were measured hourly at both the indigenous and alien sites (concurrent to the HPV measurements) with three time domain reflectometry (TDR) probes (Campbell Scientific. CS 615) installed horizontally at each site at depths of 0.1, 0.3 and 0.5 m. The TDR probes were connected to spare channels on the CR1000 datalogger of the HPV system. With hourly volumetric water content measurements, the response of trees to rainfall events, or stressed conditions, were monitored and supported the interpretation of the HPV measurements. An observation borehole was installed at the site to monitor the groundwater recharge as well as to confirm the assumption that all the trees within the riparian forest had direct access to groundwater. Soil samples were taken to determine the distribution of roots, bulk density and soil water content. These samples (taken at various depths throughout the profile) were weighed before and after oven drying to determine the soil characteristics.

4.4 Results

4.4.1 Weather Conditions during the Study Period

The MAP over the three year study was significantly higher than the long-term average (636 mm) by 300-500 mm (2012 to 2014 being 1 017, 902 and 1 127 mm respectively). The rainfall distribution was variable (lacking a seasonal trend) throughout the three years with a mean monthly value of 85 mm (Figure 4.2). There were numerous days of high hourly rainfall (to a maximum of 30mm·h^{-1} and 102 mm·day^{-1}) demonstrating the prevalence of high intensity storms at the site (Figure 4.3). The solar radiation peaked at 34 MJ·m^{-2}·day^{-1} following the same seasonal trend to that of the daily minimum and maximum air temperatures.

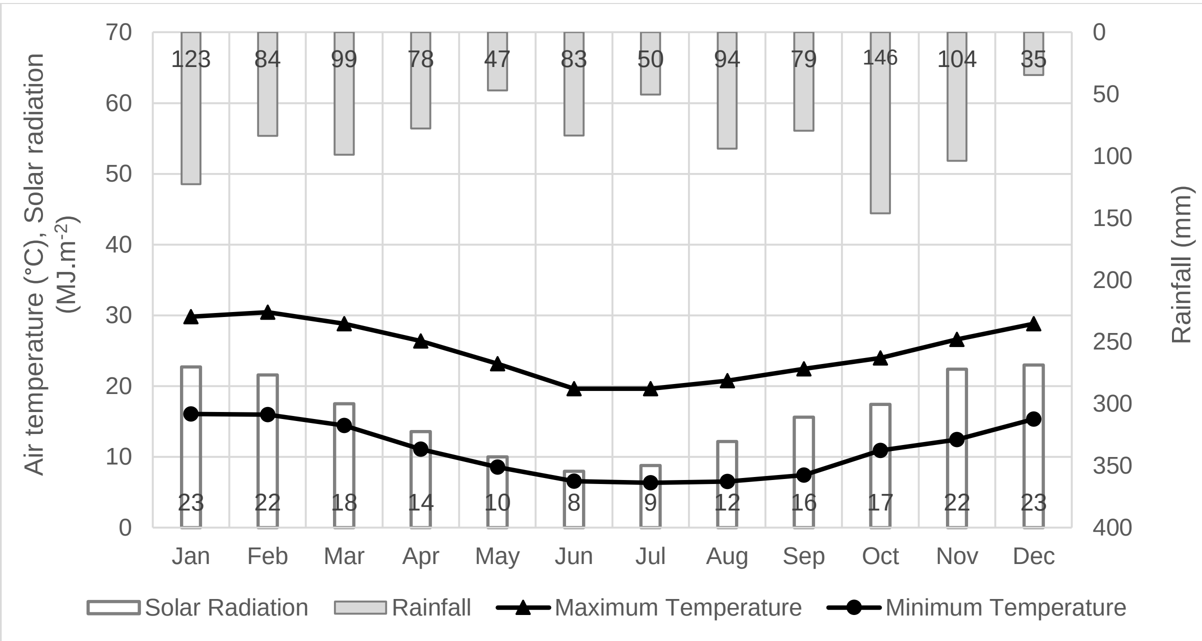

Figure 4.2 The monthly rainfall, solar radiant density, and average monthly maximum and minimum air temperatures at Buffeljags River averaged over three years.

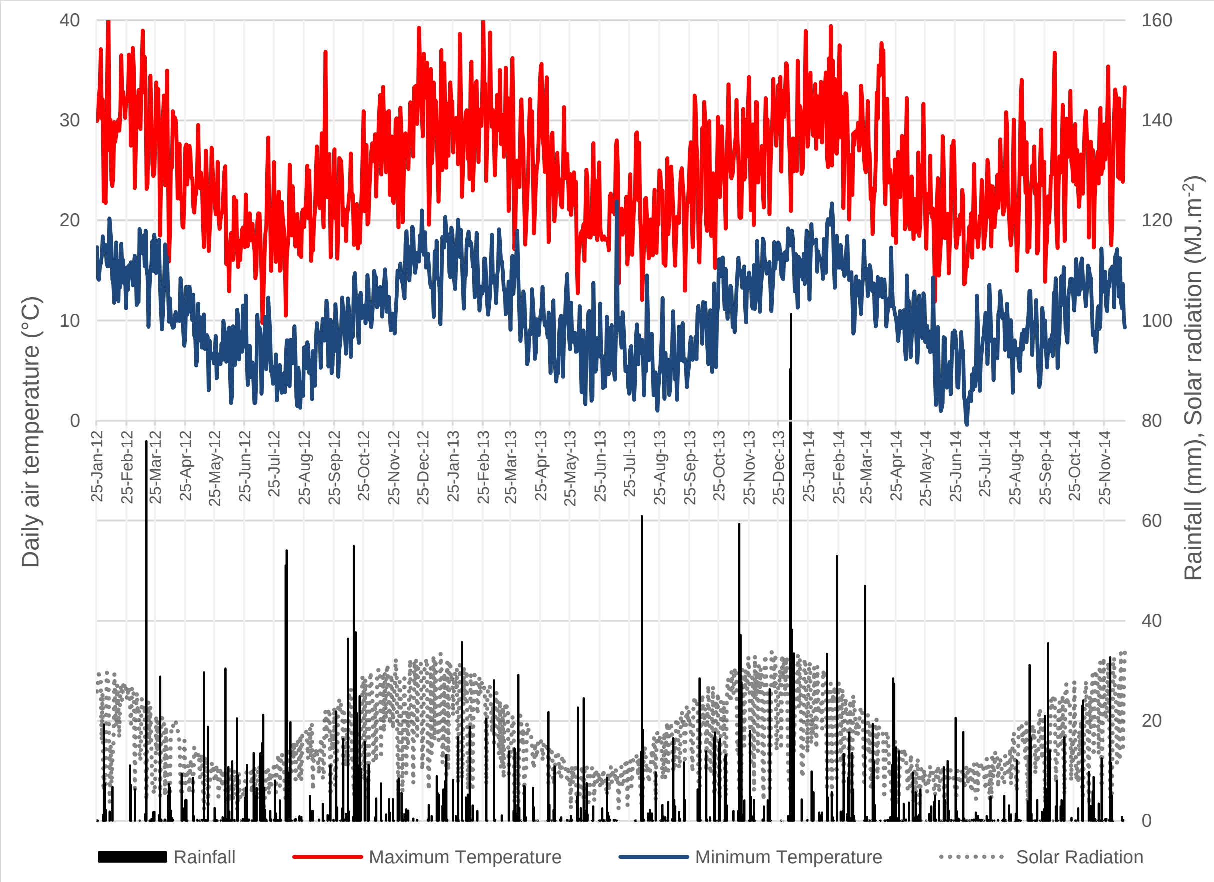

Figure 4.3 The daily rainfall, solar radiant density and maximum and minimum air temperatures at Buffeljags River

The relative humidity (RH) ranged from 20 % to 90 %, with little seasonal trend. During periods of high solar radiation, the atmospheric demand was high and correlated to peaks in transpiration rates. An average daily temperature of 22.1 ºC was recorded at Buffeljags River in the summer months. During these months, daily maximum air temperatures exceeded 40 ºC. During the winter months, the temperatures averaged 12.1 ºC due to numerous days with low solar radiation, such as during rainfall events and cloudy days, and would likely result in little to no transpiration occurring. The daily grass reference total evaporation (ET_o) averaged approximately 1 mm in the winter period to 4 mm during summer. The daily ET_o peaked at 7.5 mm, which correlated to peaks in measured transpiration.

4.4.2 Tree Water-Use

For comparative purposes the water-use of similar sized *Vepris* and *Acacia* trees were compared during the wet and the dry seasons (Figures 4.4 and 4.5). During the summer month of January, the *V. lanceolata* tree water-use exhibited seasonal curves indicative of the clear sunny days and high correlation to the solar radiation. The medium sized *V. lanceolata* (Ø 174 mm) used an average of 24 L·day^{-1} during the summer months and an average of 8 L·day^{-1} during the winter months (Figure 4.4). The medium sized *A. mearnsii* (Ø 167 mm) used an average of 10 L·day^{-1} in the winter months, similar to that of the *V. lanceolata*. In the summer months, the *A. mearnsii* used an average of 39 L·day^{-1}, significantly higher than the indigenous tree (Figure 4.5). During significant rainfall periods (> 5 mm) there was little to no water-use in both trees due to the low evaporative demand and the wet canopy.

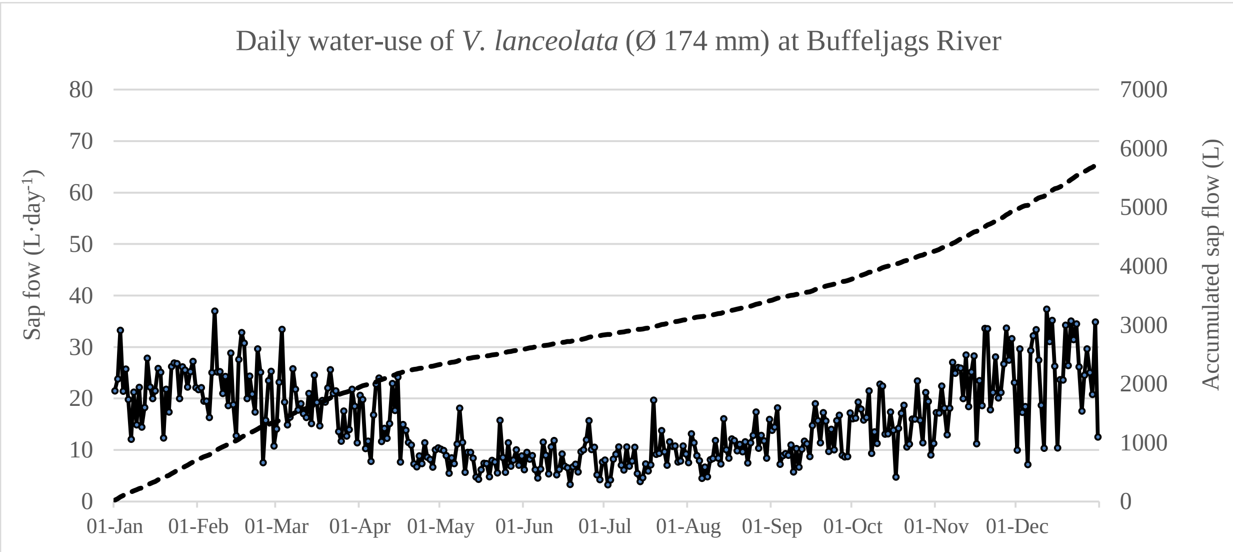

Figure 4.4 Sap flow (daily and accumulated) from a *V. lanceolata* in the lower reach alien stand at Buffeljags River (January 2012 to March 2015) averaged over three years

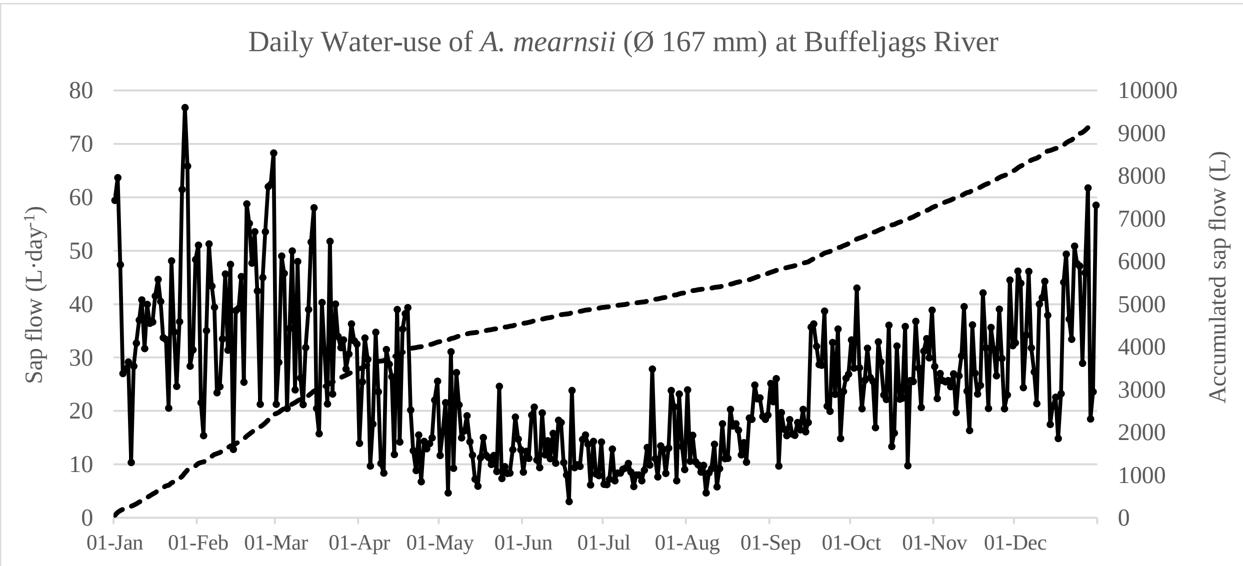

Figure 4.5 Sap flow (daily and accumulated) from an *A. mearnsii* in the lower reach alien stand at Buffeljags River (January 2012 to March 2015) averaged over three years

Individual whole tree water use was significantly reduced in winter (May and June) for most of the trees, decreasing by approximately 75 %. This was attributed to fewer daylight hours in the winter months, which resulted in less available energy flux at this time of year to drive the transpiration process. From November 2012 to March in 2013, all species showed a significant increase in water-use during this hot summer period. The water-use in the *A. mearnsii* trees showed a distinct peak in transpiration during the months of March 2012, September 2012 and February 2013. During March 2012, the high average temperature (21.5 ºC), a 76 mm rainfall event and high daily water vapour pressure deficits (VPD) (average of 1.26 kPa) contributed to a high atmospheric demand. On cloudless days with a high VPD and high soil water, the trees would be expected to use more water. The average daily sap flow ranged from 15 $L \cdot day^{-1}$ in the smaller class tree, 25 $L \cdot day^{-1}$ in the medium class tree and 39 $L \cdot day^{-1}$ in the large class tree (Tables 4.1 and 4.2).

The daily summer water-use of two of the *V. lanceolata* trees (Table 4.2) in the upper indigenous stand showed high water-use with an average of 19 $L \cdot day^{-1}$ (medium class) and 37 $L \cdot day^{-1}$ (large class). The high water-use in the large tree was ascribed to its size and deep rooting system, which is presumed to have had easy access to ground water at this site due to the proximity to the river (10 m horizontal distance). This was verified with the borehole levels and a root analysis at the site. The water level ranged from 3.2 to 4.8 m at the site where roots were observed to 5 m, while installing the borehole. The water-use of the small understorey tree *R. capensis* had a much lower water-use (average of 8 $L \cdot day^{-1}$), which indicated that although the understorey used less water, it still made a significant contribution to the water balance given the abundance of understorey species in the indigenous forest.

The *Celtis africana* trees displayed a high water-use during the summer period. As this is a deciduous tree, little water was used during leaf fall in winter. The largest *C. africana* tree had a canopy area of 75 m^2 and was the largest tree at the site. Approximately 37 700 L of water was transpired by this tree annually during the measurement period (Table 4.2). Given that this species is deciduous, it is important to note that this tree uses a high volume of water in summer when water resources are usually limited. However, in a summer rainfall region, like eastern South Africa, this tree would not use water during the low flow season when water resources are limited. This is important for management decisions throughout rainfall zones in South Africa.

The indigenous cluster in the alien site had a LAI of 3.4, which was higher than the LAI of 3.1 under the nearby *A. mearnsii* trees. The indigenous trees in the upper reach indigenous site had a LAI of 3.6. Although the summer water-use was higher in the introduced trees, the radial sapwood area was larger in the indigenous trees (up to 413 cm^2) than the introduced trees (up to 171 cm^2). Trees with the highest sap velocities are therefore not necessarily those with highest whole tree water-use. However, this does indicate that the alien trees are more effective users of water, relative to their sapwood area.

4.4.3 Soil Profile and Water Content

The volumetric soil water content (VWC) in the alien stand at Buffeljags River was very low dropping to 7 % during dry periods (Figure 4.6). During high rainfall events the soil VWC exceeded 20%, showing a rapid but short response to rainfall. This indicates that the soil water moves through the soil profile rapidly with very little water being stored in the profiles, particularly in the lower profile. The soils had a dry bulk density (ρb) of 1.58 g cm^{-3}, a particle density ($\rho_{particle}$) of 2.66 g.cm^{-3} and a porosity (ϕ) 42 %, typically characteristic of sandy soils. The drying curve, after an isolated event, took on average 22 hours from its peak to the lowest dry level (Figure 4.6). *Acacia* stands are known to have deep rooting systems, with observations of greater than 8 m in South Africa (Everson *et al*., 2006). This suggests that during dry periods, this stand can access water from deeper layers in the soil profile.

In the indigenous stand (Figure 4.7), the middle TDR probe (0.3 m) showed the highest water content. During the warmest period (December to April) there was very little water in the profile (even after rainfall events). This would suggest that the deeper roots from the indigenous species were readily using water below the TDR probe measurement depths as there was no correlation between transpiration and change in VWC. In contrast, the alien stand upper soil profile water content responded to rainfall events suggesting that interception storage (throughfall, stemflow and litter catch) played a significant role when comparing these stands. After an isolated rainfall event, the drying curve, of the soil profile at the indigenous site, took much longer (up to one week) from its peak to the driest level. The average soil water content was 0.05 m^3 m^{-3} (5 %), lower than the alien stand, suggesting a difference in root activity given the same soil characteristics.

The VWC at both sites did not respond significantly to rainfall events under 5 mm unless during consecutive events. The average water table depth, measured using an observation borehole, ranged from 5.2 m below the ground surface during the dry season to 3.2 m below the ground surface during the wet season (excluding extreme events). The water table recharge time showed a strong relationship to the soil wetting and drying response time recorded at both sites. In conclusion, both the indigenous and introduced stands are energy limited rather than water limited as both had root contact with the water table.

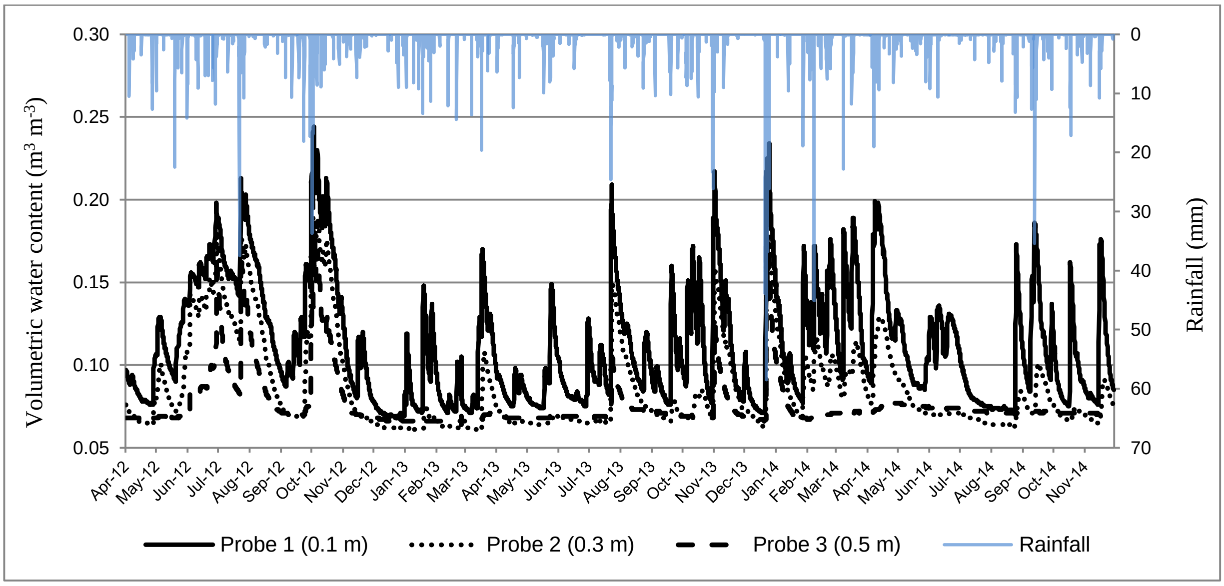

Figure 4.6 Hourly volumetric water content of the lower alien stand corresponding to the hourly rainfall at Buffeljags River

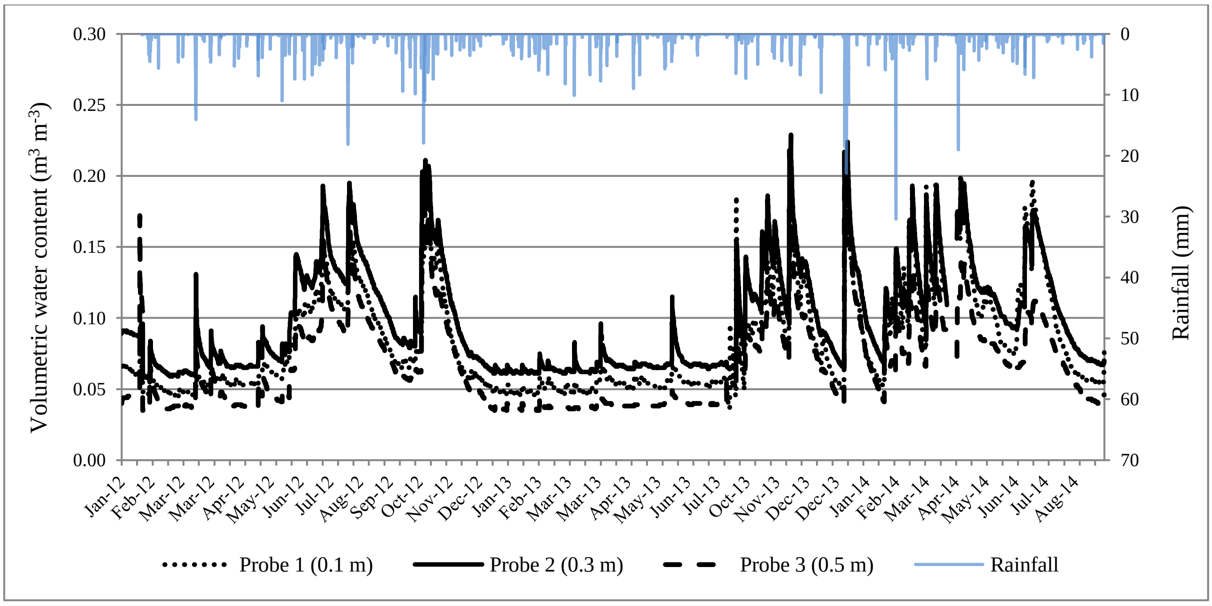

Figure 4.7 Hourly volumetric water content of the upper indigenous stand corresponding to the hourly rainfall at Buffeljags River

4.4.4 Upscaling Tree Water-Use

The results obtained from the research area were used to determine an actual annual water-use per unit area for both the invaded alien and pristine indigenous tree stands. Using the stem density per size class, stands of forest were compared rather than individual trees. The upscaled water use of the *A. mearnsii* stand was 587.9 mm ha^{-1} for the small size class, 763.9 mm ha^{-1} for the medium size class and 998.1 mm ha^{-1} for the large size class. When upscaled for all species and size classes the total stand water use was approximately 5.85 $ML \cdot ha^{-1} \cdot year^{-1}$ (585 $mm \cdot yr^{-1}$). This was 57 % of the average annual precipitation recorded during the monitoring period (1021 mm).

The annual water-use of the indigenous stand was 120.9 $mm \cdot ha^{-1}$ for the small size class, 632.1 $mm \cdot ha^{-1}$ for the medium size class and 1 890 $mm \cdot ha^{-1}$ for the large size class. The upscaled indigenous stand used 1.01 $ML \cdot ha^{-1} \cdot year^{-1}$ (101 $mm \cdot yr^{-1}$). Based on these results we concluded that the alien stand uses nearly six times more water per unit area annually than the indigenous stand. This roughly correlated to the growth rate of each stand, where the stem breast height diameter increase over the study period (recorded on each tree measured) was between three to eight times greater than similar sized indigenous trees.

The inter-species and size class water-use variations, particularly within the indigenous stand, highlight the importance of good replications of a representative sample tree species and size classes. These results also highlight that individual indigenous trees, such as the *C. africana*, can use more water than an individual alien *A. mearnsii* tree. An example of this is the largest Celtis using 14 000 L more water annually than the largest *A. mearnsii*. However, the *C. africana* tree had a much larger diameter and had a large canopy area under which no other trees grew, whereas approximately ten medium sized *A. mearnsii* trees could occupy the same area as this particular tree. The importance of upscaling using representative samples of species and size classes is clearly demonstrated by the study.

Table 4.2 Sap flow (daily and accumulated) for each species measured at Buffeljags River (January 2012 to March 2015)

Forest Type / Location	Species	Daily Average Summer Sap Flow (L)	Daily Average Winter Sap Flow (L)	Annual Accumulated Sap Flow (L)
Indigenous Forest site (upper reach)	*Vepris lanceolata*	19	7	6 534
	Vepris lanceolata	37	6	15 565
	Rothmania capensis	11	4	4 133
Introduced/Alien Forest site (lower reach)	*Acacia mearnsii*	25	8	9 226
	Acacia mearnsii	39	10	5 469
	Acacia mearnsii	32	9	7 207
Indigenous Cluster (lower reach)	*Vepris lanceolata*	14	6	5 725
	Vepris lanceolata	24	8	3 430
	Vepris lanceolata	39	14	9 174
Indigenous Cluster (lower reach)	*Celtis africana*	46	0	19 821
	Celtis africana	95	0	37 769

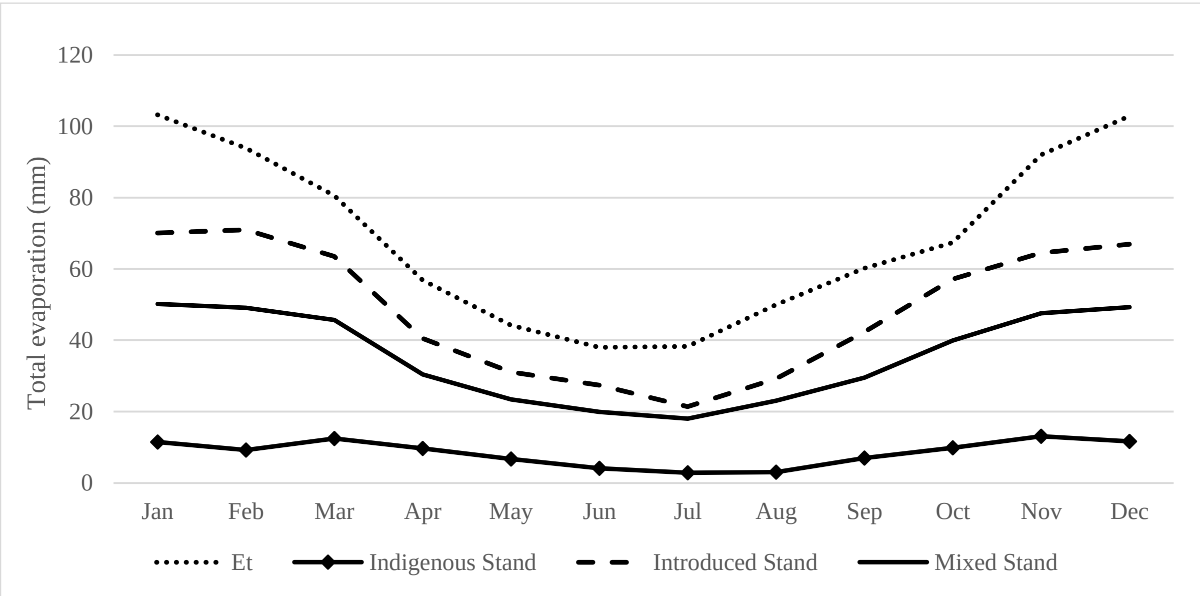

Figure 4.8 Upscaled monthly total evaporation (ET) for the indigenous, introduced and mixed stands in comparison to reference total evaporation

4.5 Discussion and Conclusion

There is a widespread belief in South Africa that indigenous tree species, in contrast to introduced tree species, use less water and should be planted more widely in land rehabilitation programmes (Olbrich *et al*., 1996; Dye *et al*., 2001; Everson *et al*., 2007; Dye *et al*., 2008; Gush and Dye, 2008; Gush and Dye, 2009; Gush and Dye, 2015). A review of relevant literature revealed a general paucity of information relevant to both indigenous and introduced tree water-use, the methods of replication and the techniques used. Internationally, improved HPV techniques have been used on various vegetation types and the accuracy of these studies has been validated using gravimetric methods (Burgess *et al*., 2001; Granier and Loustau, 2001; O'Grady *et al*., 2006; Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013; Uddin *et al*., 2014). In South Africa, the HPV technique has been shown to provide accurate estimates of sap flow in both introduced tree species such as *A. mearnsii* and *Eucalyptus grandis*, and indigenous tree species such as *Podocarpus henkelii* and *Celtis africana* (Smith and Allen, 1996; Dye *et al*., 2001; Everson *et al*, 2007; Dye *et al*., 2008). A key recommendation from the literature, which has been emphasized in a recent study by Gush and Dye (2015), is that more indigenous tree stand management research is needed in South Africa.

Spatial estimates of evaporation and transpiration are required but are difficult to obtain in remote areas with limited reach. A large capital and human effort was invested towards this study in order to extend the monitoring period, with a range of species and replicates. This allowed for an accurate comparison of indigenous and introduced tree water-use. The Buffeljags River site is unique in that it is one of very few sites within South Africa with an extensive rehabilitation programme that aims to assist WfW and similar clearing programmes. The results showed that individual tree water-use varies depending on size and species. Upscaled comparisons showed that stem density is important to the accurate representation of stand water-use. An introduced stand of *A. mearnsii* can use up to six times more water than a mixed indigenous stand. This finding is significant in that it provides clear evidence to justify the highly expensive clearing programmes from a hydrological perspective, which have in the past lacked quantifiable data on the potential hydrological benefits of alien plant clearing. The results also indicate that rehabilitation or clearing programmes need to consider the seasonal rainfall variability of a site as planting of deciduous indigenous trees may provide larger benefits in summer rainfall areas due to no transpiration during periods when water resources are limited.

This study provides an ideal opportunity to validate remotely sensed ET data which could also be used to identify spatial variations in vegetation water use. This future research will allow for the broader extrapolation of alien plant water-use and benefits of clearing riparian zones to similar areas outside of the immediate study area. Results may be used to further validate transpiration simulations from hydrological models, particularly in riparian areas.

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CHAPTER 5. WATER-USE DYNAMICS OF AN ALIEN INVADED RIPARIAN FOREST WITHIN THE SUMMER RAINFALL ZONE OF SOUTH AFRICA

5.1 Abstract

In South Africa the invasion of riparian forests by alien trees has the potential to affect the country's limited water resources. Tree water-use measurements have therefore become an important component of recent hydrological studies. It is difficult for South African government initiatives, such as the Working for Water (WfW) alien clearing programme, to justify alien tree removal and implement rehabilitation unless hydrological benefits are known. Consequently water-use within a riparian forest in the upper Mgeni catchment of KwaZulu-Natal in South Africa was monitored over a two year period. The site consisted of an indigenous stand of eastern mistbelt forest that had been invaded by *Acacia mearnsii*, *Eucalyptus nitens* and *Solanum mauritianum*. The heat ratio method of the heat pulse velocity sap flow technique and the stem steady state techniques were used to measure the sap flow of a selection of indigenous and introduced species. The indigenous trees at New Forest showed clear seasonal trends in the daily sap flow rates varying from 8 to 25 $L \cdot day^{-1}$ in summer (sap flow being directly proportional to tree size). In the winter periods this was reduced to between 3 and 6 $L \cdot day^{-1}$ when limited energy flux was available to drive the transpiration process. The water-use in the *A. mearnsii* and *E. grandis* trees showed a slight seasonal trend, with a high flow during the winter months in contrast to the indigenous species. The water-use in the understorey indicated that multi-stemmed species used up to 12 $L \cdot day^{-1}$. Small alien trees (<30 mm) *A. mearnsii*, and *S. mauritianum* used up to 4 $L \cdot day^{-1}$ each. The combined accumulated daily sap flow per year for the three *A. mearnsii* and *E. grandis* trees was 6 548 and 7 405 $L \cdot year^{-1}$ respectively. In contrast, the indigenous species averaged 2 934 $L \cdot year^{-1}$, clearly demonstrating the higher water-use of the introduced species. After spatial up-scaling, it was concluded that, at the current state of invasion by 21 %, the stand used 40 % more water per unit area than if the stand were in a pristine state. If the stand were to be heavily invaded, at the same stem density of the indigenous forest, a 100 % increase in water-use would occur over an average rainfall year.

Key Words: Indigenous trees, introduced trees, sap flow, transpiration, upscaling

5.2 Introduction

Parts of South Africa experience up to 87% alien tree invasions (Working for Water, 2011), with most of these being in riparian areas that have readily available water and are difficult to manage. In South Africa there is a limited understanding of the extent to which tree species (particularly those in the riparian area) contribute to total evaporation. As such, it is difficult for government organizations and scientists to justify alien tree removal and rehabilitation unless a known hydrological benefit can be seen. The deep fertile soils, with high soil moisture contents associated with riparian areas, make them ideal for plant establishment and growth (Everson *et al*., 2007). In South Africa, these areas are extremely vulnerable to invasion by pioneer plant species, particularly species that have historically been introduced for commercial forestry. There is a widespread belief (which has been supported by numerous studies: Olbrich *et al*., 1996; Dye *et al*., 2001; Everson *et al*., 2007; Dye *et al*., 2008; Gush and Dye, 2008; Gush and Dye, 2009; Gush and Dye, 2015) in South Africa that indigenous tree species, in contrast to the introduced tree species, use less water and should be planted more widely in land rehabilitation programmes. Little research has been undertaken on the riparian area which excludes water limitations (except in severe drought conditions).

The benefits of healthy riparian zones in providing basic ecosystem services are well known (Askey-Dorin *et al*. 1999; Richardson *et al*., 2007). These benefits and the impacts of degradation through alien plant invasions were fully described in a study by Scott-Shaw *et al*. (2017) on the water use of plants in the Mediterranean climate of the Western Cape region of South Africa (Scott-Shaw *et al*., 2017). Here we summarize the most important aspects relevant to this study.

1. Commercial forestry has been blamed for increasing the green water (water lost by total evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Jewitt, 2006). For these reasons, invasive alien plants, particularly introduced commercial trees, are considered to be a major threat to water resources and biodiversity.
2. There is a widespread belief in South Africa and globally that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land restoration programmes. This is based on observations that indigenous trees are

generally slow growing, and that growth and water-use are broadly linked (Everson *et al*., 2008; Gush, 2011).

3. At the ecosystem scale, studies indicate that invasive species use 189 % more water than indigenous dominated stands, particularly in tropical moist forests (Nosetto *et al*., 2005; Yepez *et al*., 2005; Fritzsche *et al*., 2006). In the high rainfall areas of South Africa, invasive alien plants growing in riparian areas are estimated to reduce annual streamflow by 523 x 10^6 m^3 with a predicted annual reduction estimated to be as high as 1 314 x 10^6 m^3 if allowed to reach a fully invaded state (Cullis *et al*., 2007).
4. Management of invaded riparian zones can result in hydrological gains disproportionately greater than the catchment area affected, with up to three times more streamflow yield than upslope areas (Scott and Lesch, 1996; Scott, 1999).
5. For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Sap flux density measurements give precise information on flow directions as well as spatial and temporal flow distribution (Vandegehuchte and Steppe, 2013). The heat pulse velocity (HPV) method is the most accurate of the available methods when compared against gravimetric methods (Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013).

The New Forest site in KwaZulu-Natal, South Africa is part of a Working for Water (WfW) clearing programme. The government-funded WfW programme clears catchment areas of invasive alien plants with the aim of restoring hydrological functioning while also providing poverty relief to local communities through job creation (Turpie *et al*., 2008). The aim of this study was to quantify the potential hydrological benefit of the conversion of invaded stands to more pristine stands for forest management practices. A detailed ecological study was undertaken in conjunction with the two year hydrological study.

5.3 Methods

An overview of the study site, sampling design and equipment implemented to carry out the study has been provided in this Section. Details on the Heat Pulse Velocity (HPV) technique has been documented in a previous paper (Scott-Shaw *et al*., 2017) and will not been repeated here.

5.3.1 The Study Area

The New Forest riparian area is located at latitude 29°28’30” S and longitude 29°52’48” E at approximately 1760 m above sea level (Figure 5.1). The riparian area occurs along a tributary to the upper Umgeni River, within Quaternary Catchment (QC) U20A. The New Forest riparian area falls within the Eastern Mistbelt forest zone, which is dominated by *Leucosidea sericea, Halleria lucida, Celtis africana* and *Afrocarpus falcatus*. The surrounding natural areas are covered by Highland Sourveld (Acocks’ 1988) or Drakensberg Foothill Moist Grasslands (Mucina and Rutherford, 2006). The study site is typical of invasive alien plant (IAP) invasion, whereby plantations have been grown in traditionally fire dominated grasslands and have subsequently invaded the surrounding riparian areas. Eastern Mistbelt forests can be characterised by cool, tall inland forests (Pooley, 2003). The mountain slopes of the area consist of fractured dolerite dykes and basaltic outpourings (Crowson, 2008). The soils show evidence of high precipitation and age with shallow unstructured soils occurring on the upper slopes, red a-pedal soils on the midslope and soils with a underlying G-horizon dominating the low lying areas.

Approximately 80% of the precipitation occurs in the summer months, which mostly consists of orographically-induced and squall-line thunderstorms (Schulze, 1982). Interception from mist makes a large contribution to the seasonal precipitation and determines the distribution of the mistbelt forest. The long-term mean annual precipitation is between 941 and 1000 mm with a distinct dry season from May to August. Average air temperatures range from 25.2 °C in the summer to 16.9 °C in the winter, with the highest air temperatures occurring on the North-facing slopes. Cool mountain winds occur at night with warm up-valley winds occurring during the day (Crowson, 2008). Strong berg (westerly) winds are prevalent during August to September and play a significant role in the spread of fire (Schulze, 1982).

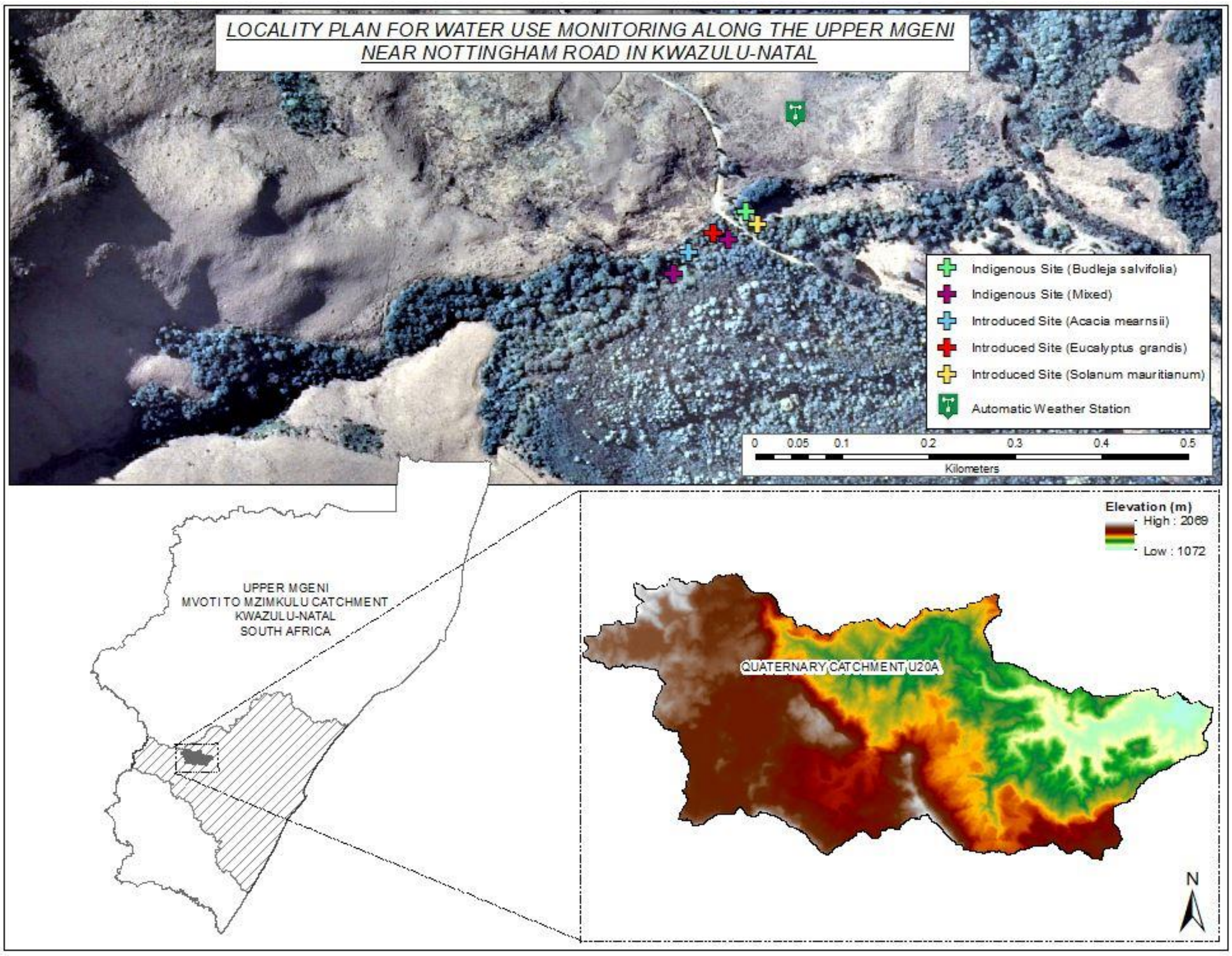

Figure 5.1 Location of New Forest farm research area within KwaZulu-Natal, South Africa.

New Forest farm is privately owned. The area south of the Umgeni tributary has been planted with *Acacia mearnsii* and *Pinus patula* since the 1960s. The riparian area has since been heavily invaded (> 20 %) with *A. mearnsii*, *Eucalyptus nitens* and *Solanum mauritianum*. Riparian invasive alien tree clearing by WfW has been ongoing in the area.

5.3.2 Sampling Design

Five sites, each representing frequently occurring indigenous and introduced tree species, were instrumented for water-use monitoring. These trees included a size range of invasive *A. mearnsii* and *E. nitens* trees; a selection of common indigenous trees such as *Gymnosporia buxifolia*, *Celtis africana* and *Searsia pyroides* and a selection of trees growing in the understory (*S. mauritianum*, *A. mearnsii* and *Buddleja salviifolia*). The leaf area index (LAI) within this stand was 3.1 during the summer months with a reduction to 2.2 during the winter months due to the presence of deciduous species. There was little variation in LAI throughout the forest due to a uniform invasion by introduced trees and the disturbed nature of the indigenous species across the stand.

The trees within the riparian forest were in a disturbed state. The overall canopy height of the indigenous species was low, ranging from 4.1 to 8.3 meters. The invasive species were much taller, ranging from 13.1 to 16.6 meters. The physical characteristics of each monitored tree is provided in Table 5.1. There was variability between the stem moisture content and wood density between species, which can be explained by the different physical characteristics of the trees measured (variations in sap wood depth and active xylem concentration). A forest ecology study (Everson *et al*., 2016) undertaken at New Forest compiled stem density measurements for re-growth forest, invaded riparian areas and on *S. mauritianum* dominated plots. The findings indicated that in the riparian forest, there was a density of 1 632 stems·ha^{-1} invasive species with 6 090 stems·ha^{-1} of indigenous species. In the *S. mauritianum* plots, there were 1 337 stems·ha^{-1} of the invasive species, with 2 600 stems·ha^{-1} of the remaining indigenous species.

Table 5.1 Tree physiology and specific data required for the calculation of sap flow and up-scaling.

Indigenous Forest (Site 1)	Diameter (mm)	Size Class	Moisture fraction	Average wounding (mm)	Wood density ($kg \cdot m^{-3}$)	Representative stem density ($stems \cdot ha^{-1}$)
**Searsia pyroides*	98	Small	0.41	3.1	0.60	
**Gymnosporia buxifolia*	114	Small	0.44	2.6	0.65	6 090
**Gymnosporia buxifolia*	58	Small	0.44	2.6	0.66	
Introduced/Alien Forest (Site 2)						
**Acacia mearnsii*	131	Medium	0.48	3.0	0.69	1 632
**Acacia mearnsii*	166	Medium	0.47	3.0	0.69	
Indigenous Forest (Site 3)						
**Celtis africana*	102	Medium	0.49	4.8	0.68	
**Kiggerlaria africana*	50	Medium	0.46	3.1	0.69	6 090
**Leucosidea sericea*	212	Large	0.47	2.8	0.64	
Introduced/Alien Forest (Site 4)						
**Eucalyptus nitenss*	165	Small	0.51	3.8	0.71	1 632
**Eucalyptus nitens*	96	Small	0.51	3.9	0.71	
Mixed understorey (Site 5)						
#Buddleja salvifolia	28+	Small	N/A	N/A	N/A	2 600
#Solanum mauritianum	25	Small	N/A	N/A	N/A	-
#Solanum mauritianum	10	Small	N/A	N/A	N/A	-
#Solanum mauritianum	19.1	Small	N/A	N/A	N/A	1 337
#Solanum mauritianum	26.7	Small	N/A	N/A	N/A	-
#Acacia mearnsii	25.6	Small	N/A	N/A	N/A	-

*Note: * indicates that the HPV technique was used and # indicates that the SSS technique was used. +indicates average stem diameter for multi-stemmed trees.

5.3.3 Meteorological Station

A meteorological station was established on the 19th of September 2012 at New Forest farm in a nearby natural grassland, 250 m from the tree monitoring sites. Rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), using a tipping bucket rain gauge was measured at a height of 1.2 meters from the ground. Air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp and Zonen, Delft, The Netherlands) wind speed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA) were all measured at a height of 2 m from the ground. These were measured at a 10 s interval and the appropriate statistical outputs were recorded every hour. A flat and uniform short grassland area which was regularly mowed was selected to meet the requirement for FAO 56 reference evaporation calculation.

5.3.4 Tree Water-use Measurements

A Heat Pulse Velocity (HPV) system using the heat ratio algorithm (Burgess, 2001) was set up to monitor long-term sap flow on all of the selected trees over a three year period. The instrumentation is described further by Clulow *et al*. (2013) and Scott-Shaw *et al*. (2017) and included hourly measurements of sap flow heater trace using a pair of type T-thermocouple probes. Regular maintenance was undertaken to ensure sufficient power and operation of the equipment. Measurements of sapwood depth, wood density and moisture content (described by Marshall, 1958) were taken to allow for up-scaling of probe measurements to whole tree water use ($L \cdot h^{-1}$). Non-functional or damaged xylem (referred to as wounding) around the thermocouples was accounted for using wound correction coefficients described by Burgess (2001). Tree growth was recorded during each site visit by measuring diameter at breast height and canopy height using a VL402 hypsometer (Haglöf, Sweden). Leaf area index using a LAI-2200 (LI-COR, Lincoln, Nebraska, USA) was measured regularly throughout the stand. The riparian forest had a limited aerodynamic fetch, which was not appropriate for the eddy covariance and scintillometry techniques. Although the riparian stand had a heterogeneous composition, the availability of detailed stem density measurements allowed for a methodology to be followed based on recent up-scaling studies (Ford *et al*., 2007; Miller *et al*., 2007).

The Stem Steady State (SSS) technique, which estimates sap flow by solving a heat balance for a segment of stem that is supplied with a known amount of heat (Grime and Sinclair, 1999), was implemented on the smaller trees in the under-storey that were not quantifiable using the HPV technique. Two Dynamax Flow 32-K systems (Dynamax, Houston, TX, USA) were installed at New Forest. Each of these systems was powered by a 12V 100Ah battery, and consisted of a CR1000 data logger (Campbell Scientific Inc.) and an AM16/32B multiplexer. A voltage control unit regulated the voltage output depending on the number of collars and the size of the collars. The gauge's insulating sheath (referred to as a 'collar') contains a system of thermocouples that measure temperature gradients associated with conductive heat losses vertically (up and down the stem), and radially through the sheath (Allen and Grime, 1994). A foam insulation and weather shield were installed around the stem in order to sufficiently minimize extraneous thermal gradients that could influence the heated section of stem (Smith and Allen, 1996). The conduction of heat vertically upwards and downwards was calculated by measuring voltages which corresponded to the temperature difference between two points above and below the heater (Savage *et al*., 2000). The radial heat was calculated by measuring the temperature difference of the insulated layer surrounding the heater (Savage *et al*., 2000). Finally the voltage applied to the heater was measured. These measurements allowed the energy flux ($J.s^{-1}$) to be calculated (Savage *et al*., 2000).

5.3.5 Soil Water Measurements

Hourly volumetric soil water contents were recorded at sites 1 and 2 within the riparian forest with three time domain reflectometry (TDR) probes (Campbell Scientific Inc, CS 615) installed horizontally at each site. The probes were installed at depths of 0.1, 0.3 and 0.5 m below the litter layer, due to shallow soils at the site. A thick litter layer was observed throughout the site consisting of mostly indigenous leaves and large broken branches from cattle and climatic disturbances. The hourly volumetric water content measurements provided an understanding of the responses of trees to rainfall events, or stressed conditions. Additional soil samples were taken to determine the distribution of roots, soil bulk density and soil water content.

5.4 Results

5.4.1 Weather Conditions during the Study Period

The historical mean annual precipitation (MAP) for the New Forest area is 941 mm. During the two-year monitoring period the area received 1 164 and 1 110 $mm \cdot a^{-1}$ for 2013 and 2014 respectively. The rainfall distribution had a strong seasonal trend throughout the two years with an exceptionally high amount of 120 $mm \cdot day^{-1}$ in November 2014 (Figure 5.2). The daily solar radiation peaked at 39 $MJ \cdot m^{-2}$ following the same seasonal trend to that of the daily air average temperatures.

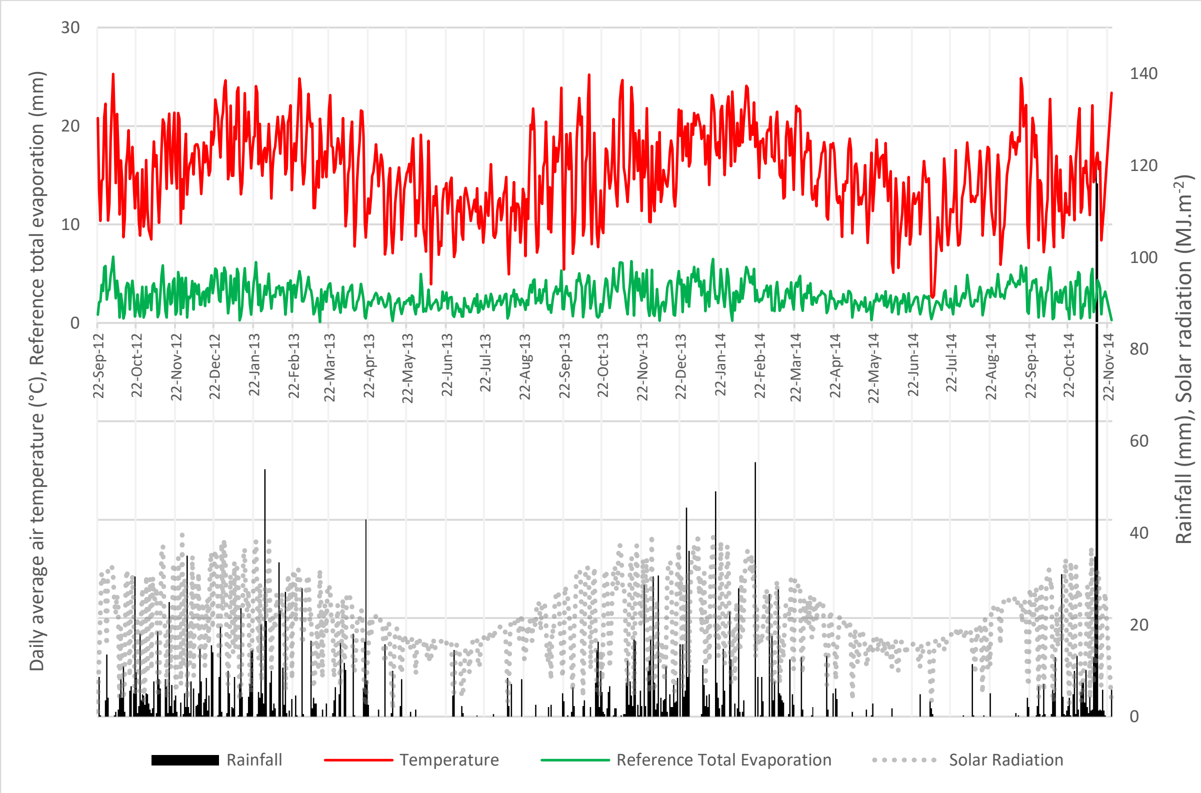

Figure 5.2 The daily rainfall, solar radiation, average air temperatures and reference total evaporation at New Forest.

During periods of high solar radiation, the water vapour pressure deficit was high and correlated to peaks in transpiration rates. An average daily air temperature of 18.4 ºC was recorded at New Forest in the summer months. During these months, daily maximum air temperatures occasionally exceeded 30 ºC. During the winter months, the air temperatures averaged 11.7 ºC due to numerous days with low solar radiation. Periods of low solar radiation correspond to overcast and/or rainfall periods and would likely result in little to no transpiration occurring. The daily reference total evaporation (ET_o), derived from data captured on site, averaged approximately 1 mm·day^{-1} in the winter period to 5 mm·day^{-1} during the summer period. The monthly climate data illustrates the seasonal rainfall and air temperature trend (Figure 5.3). The seasonal distribution of rainfall is important as it is during these periods of water scarcity where the vegetative water-use becomes significant.

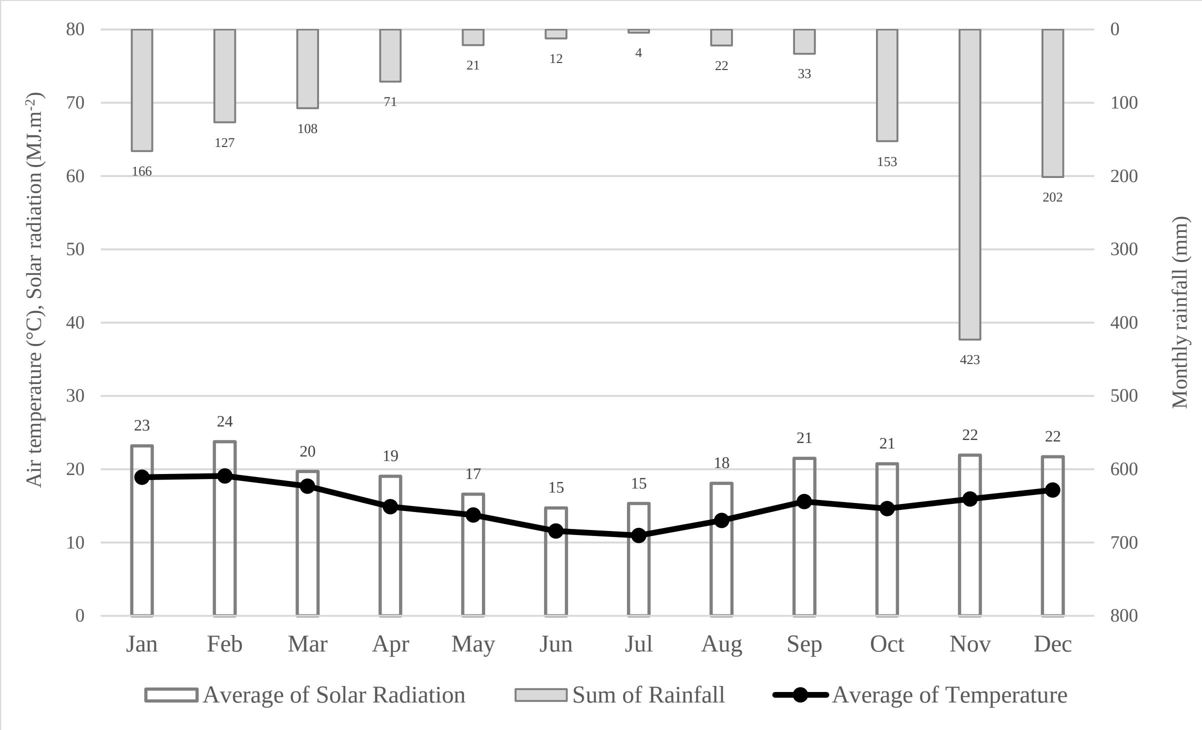

Figure 5.3 The monthly rainfall, monthly solar radiant density, and average monthly air temperatures at New Forest averaged over two years.

5.4.2 Tree Water-Use

The radial heat pulse velocity of a *G. buxifolia* was measured over a short summer period (Figure 5.4). The velocity of water moving through the tree was highest (up to 20 $cm \cdot h^{-1}$) nearest to the bark. Probes inserted deeper in the tree (> 15 mm) measured very little flow suggesting that there was less active xylem at these depths, resulting in a small sapwood area. During the winter period the radial heat pulse velocity of *A. mearnsii* had maximal flow 25 mm below the bark (Figure 5.5). There was still flow occurring at a depth of 35 mm, indicating a much bigger sapwood area than that of the indigenous tree. Furthermore, the sap velocity was high, (> 20 $cm \cdot h^{-1}$) even during the dry winter period. These findings also indicated that correct probe placement is essential in accurately representing the entire sapwood area of each tree.

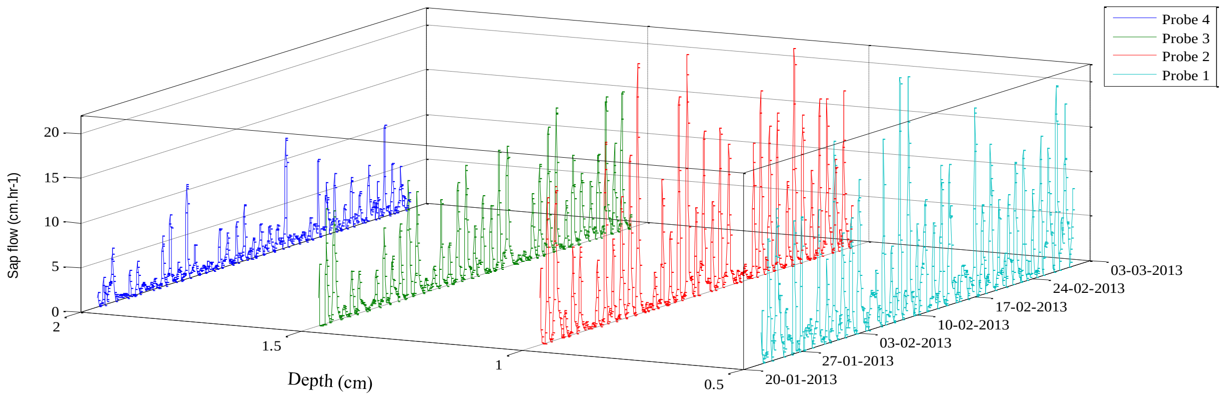

Figure 5.4 Hourly heat pulse velocity of a *G. buxifolia* (Ø: 114 mm) at New Forest

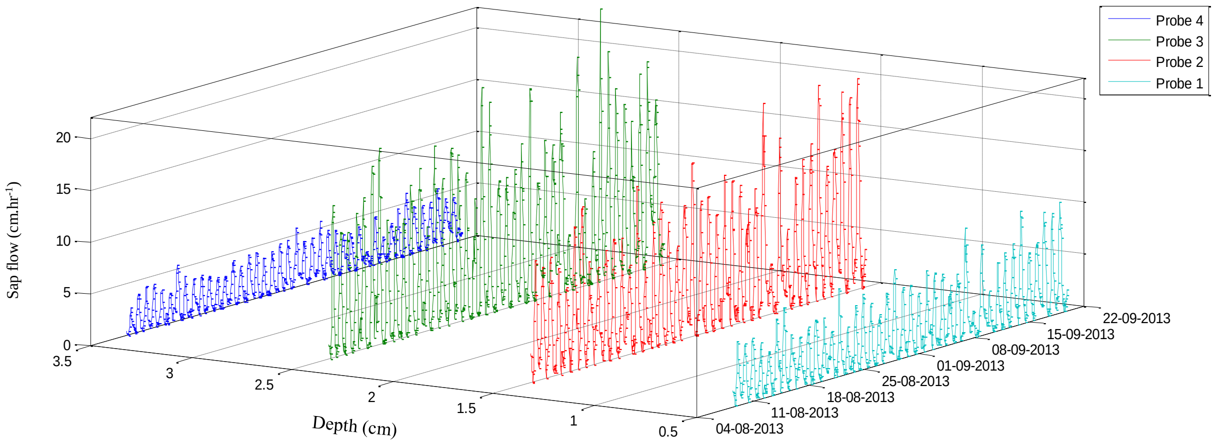

Figure 5.5 Hourly heat pulse velocity of an *A. mearnsii* (Ø: 131 mm) at New Forest

Individual whole tree water-use showed a clear seasonal water-use trend for the semi-deciduous and deciduous indigenous species (Figure 5.6). This was attributed to fewer daylight hours and less heat units during the winter months resulting in reduced available energy; therefore limiting the transpiration process. The daily water-use of *S. pyroides* averaged 8 L·day^{-1}in summer compared to 3 L·day^{-1}in winter, resulting in an accumulated total water use of 1 639 L·year^{-1} (Figure 5.6 a). The deciduous *C. africana* used large amounts of water in the summer, with an average of 25 L·day^{-1}. In the winter periods, after leaf fall, this species used no water, resulting in a reduction of the total annual water-use (4 307 L·year^{-1}). In contrast, *G. buxifolia* used approximately 15 L·day^{-1} in summer compared to 6 L·day^{-1}in winter, resulting in an accumulated total water use of 3870 L·year^{-1} over the same period (Figure 5.6 a, b, c).

The introduced *A. mearnsii* of a similar stem diameter showed little seasonal variation (Figure 5.6 d). This tree averaged 22 L·day^{-1} during summer periods and 14 L·day^{-1} during winter periods yielding a total of 5 743 L·year^{-1}, higher than that of the indigenous species and comparable to other large introduced species measured throughout South Africa (Gush *et al.*, 2015).

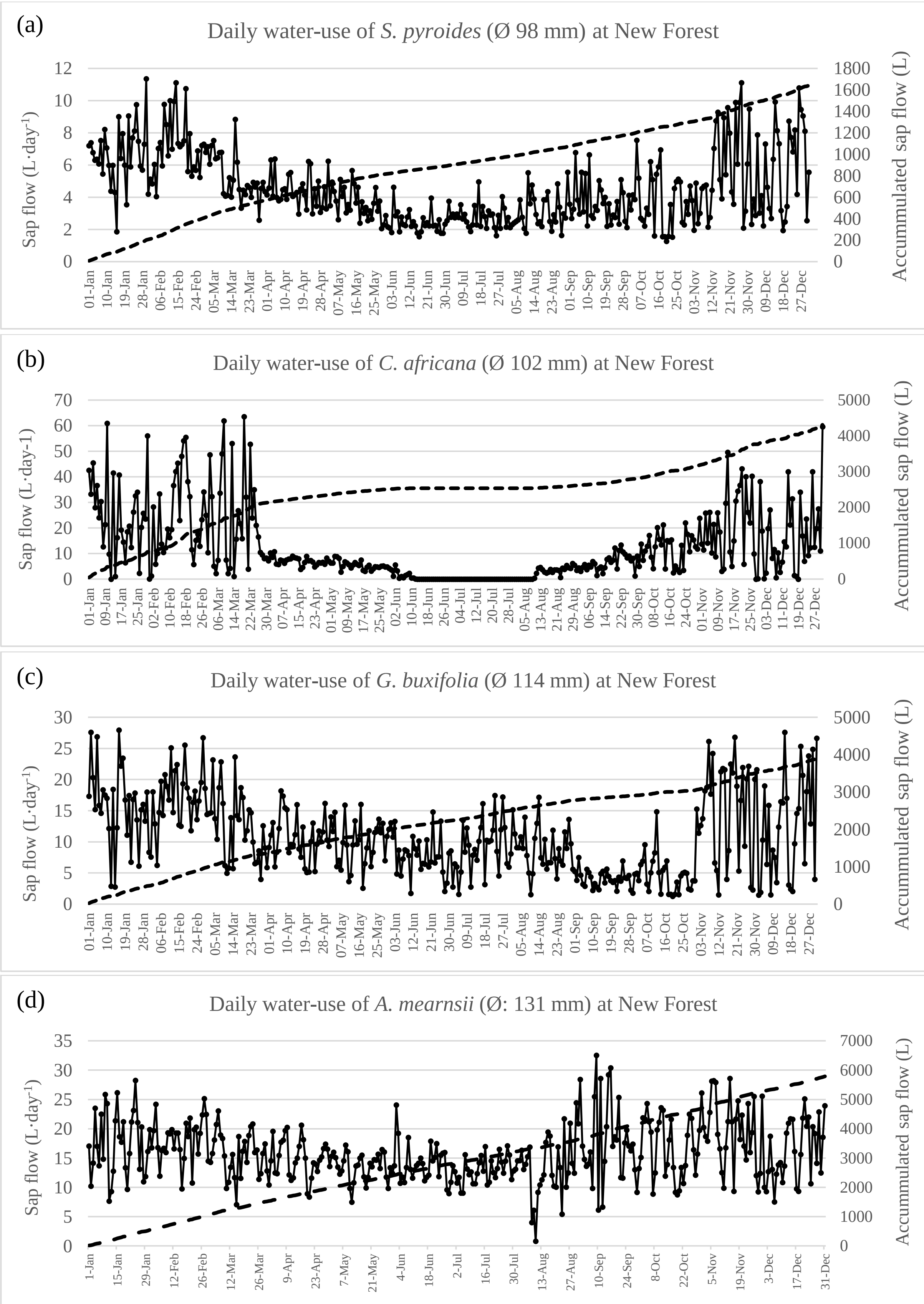

Figure 5.6 Sap flow (daily and accumulated) averaged over two years (2013 & 2014) from an indigenous *S. pyroides* (a), *C. africana* (b), *G. buxifolia* (c) and an introduced *A. mearnsii* (d) at New Forest.

The water use of the multi-stemmed *B. salviifolia*, measured using the SSS technique, had the highest daily water use (up to 12 $L.day^{-1}$) (Figure 5.7). This tree, although short, had the greatest canopy area due to its lateral growth patterns with its numerous stems. In comparison, the smaller *A. mearnsii* used considerably less water, with a peak of 4 $L.day^{-1}$. The three *S. mauritianum* trees were highly variable, ranging from very low flows (0.4 $L.day^{-1}$) to in excess of 4 $L.day^{-1}$. Although these values are small in comparison to the larger trees measured, it does show the importance of the understorey in-stand measurements. These trees, particularly the *S. mauritianum*, have a high density suggesting that the cumulative water-use of these trees is important when scaling up to the total forest water use.

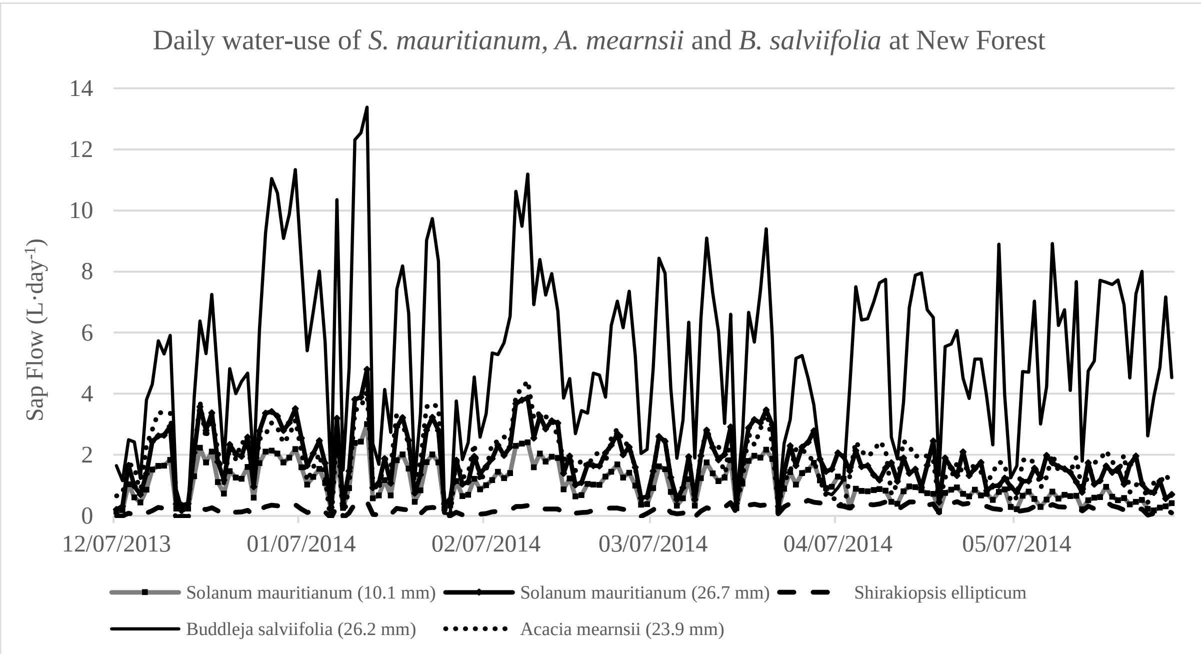

Figure 5.7 Daily water-use for three *S. mauritianum*, a multi-stemmed *B. salviifolia* and an *A. mearnsii* using the SSS technique at New Forest from December 2013 to June 2014

The daily summer water-use of indigenous trees at site 1 (Table 5.2) showed low water-use with an average of between 9 and 15 $L{\cdot}day^{-1}$ in the summer months. Likewise, the indigenous trees at site 3 were low water users. Despite being deciduous, the *C. africana* used the most water of all the indigenous trees measured. This tree was the tallest of the indigenous trees measured and was not shaded by other species. Given that this species is deciduous, it is important to note that this tree uses a minimal amount of water in the winter when water resources are limited. The indigenous *B. salviifolia*, measured using the SSS technique had a similar water-use to that of the lower climax species.

The daily summer water-use of the *A. mearnsii* and the *E. grandis* were high in comparison to the indigenous species. These trees used between 18 and 27 L·day^{-1} in the summer months and between 14 and 17 L·day^{-1} in the winter months. On average, the introduced species used 2.4 times more water than the average indigenous species. However, this is a direct comparison and would differ to up-scaled comparisons due to the different stem densities of each species.

Table 5.2 Sap flow (daily and accumulated) for each species measured at New Forest

Forest Type / Location	Species	Diameter (mm)	Daily Average Summer Sap Flow (L.d^{-1})	Daily Average Winter Sap Flow (L.d^{-1})	Annual Accumulated Sap Flow (L)
Indigenous Forest (Site 1)	*S. pyroides*	98	9	3.6	1 639
	G. buxifolia	114	15	3.9	3 901
	G. buxifolia	58	12	3.8	2 883
Introduced/Alien Forest (Site 2)	*A. mearnsii*	131	18	15	5 786
	A. mearnsii	166	23	17	7 310
Indigenous Forest (Site 3)	*C. africana*	102	22	0.9	4 307
	K. africana	50	10	3.7	2 508
	L. sericea	212	9	4	2 369
Introduced/Alien Forest (Site 4)	*E. grandis*	165	27	15	7 668
	E. grandis	96	25	14	7 142
Mixed understorey (Site 5)	*B. salviifolia*	28	5.9	5.5	2 080
	S. mauritianum	25	0.4	0.3	127
	S. mauritianum	10	2.0	0.9	529
	S. mauritianum	19.1	2.9	1.2	748
	S. mauritianum	26.7	3.3	1.6	894
	A. mearnsii	25.6	3.4	1.8	949

5.4.3 Soil Profile and Water Content

The volumetric soil water content (VWC) measured at New Forest was highly responsive to rainfall events (Figure 5.8, 5.9). During the wet summer season, the VWC at the indigenous site 1 (Figure 5.6) ranged from 27 % in the upper horizon to 35 % in the lower horizon. This indicated a higher clay content in the lower horizon. Towards the dry season, as the vegetation continues to use water, the VWC was depleted to 10 % in the upper horizons. At the introduced site 2, the soils were uniform throughout the horizons. During the summer periods, the profile soil water averaged 27 % whereas it depleted to 9 % or 11 mm of water per 100 mm depth of soil during the dry periods.

The soils had a dry bulk density (ρb) of 1.22 g.cm^{-3}, a particle density ($\rho_{particle}$) of 2.54 g.cm^{-3} and a porosity 0.52, typically characteristic of sandy-loam soils. Introduced forestry species are known to have deep rooting systems, with observations of greater than 8 m in South Africa (Everson *et al*., 2006). This suggested that during dry periods, this stand can access water from deeper layers in the soil profile. However, given the shallow depth of all the soils and the close proximity of the sites to the stream, it is clear that the vegetation in this area was not limited by water availability.

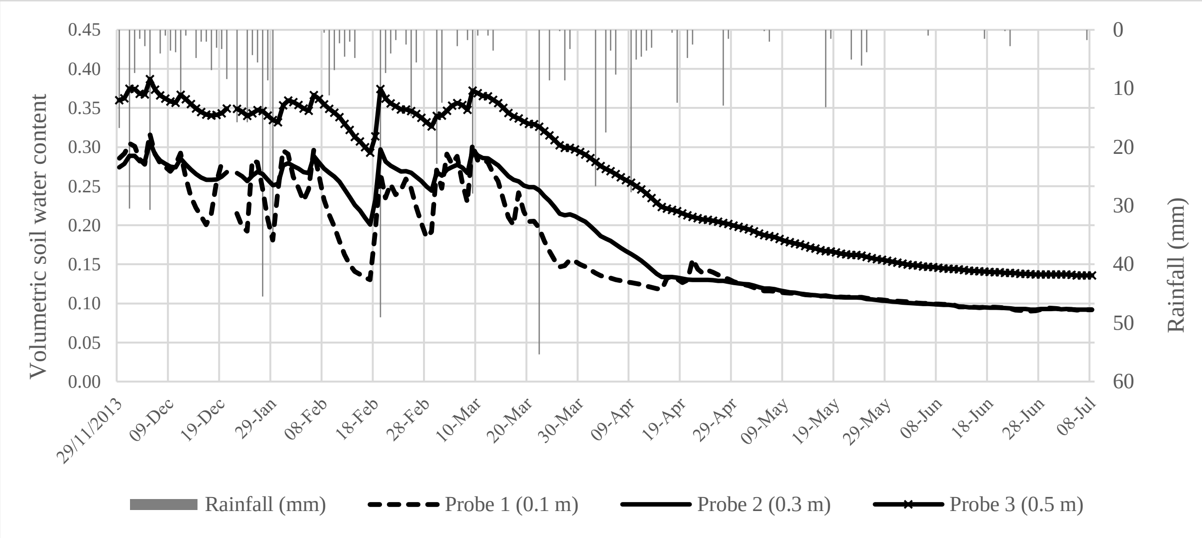

Figure 5.8 Hourly volumetric soil water content and the hourly rainfall at site 1 at New Forest.

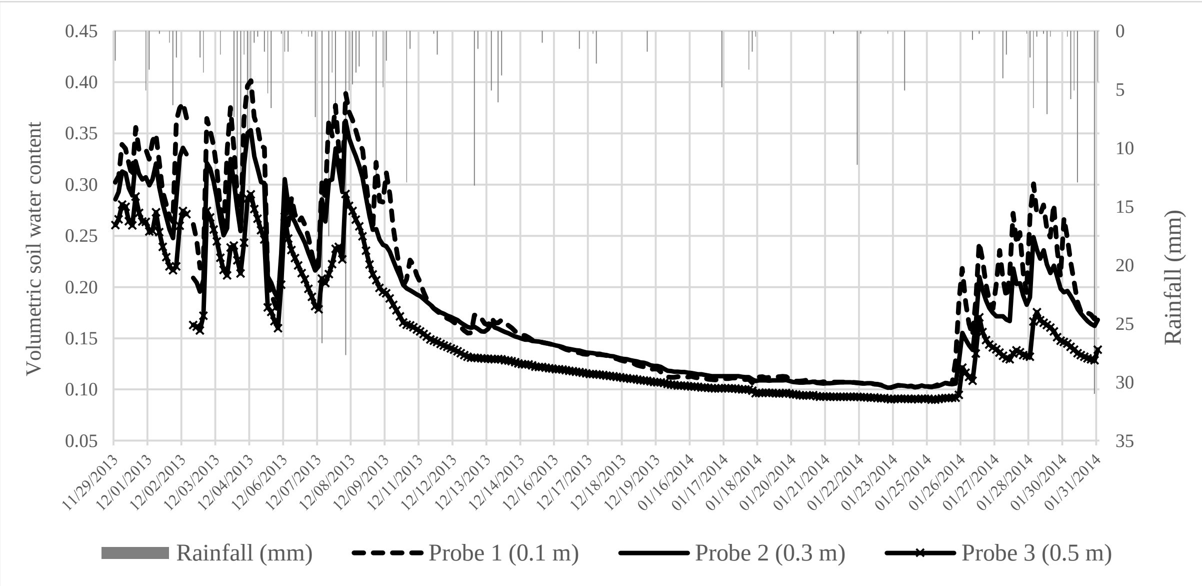

Figure 5.9 Hourly soil volumetric water content and the hourly rainfall at site 2 at New Forest.

The VWC at both sites did not respond significantly to rainfall events under 6 mm·h^{-1} unless during consecutive events. Based on seasonally high transpiration rates we conclude that deep rooted plants in the riparian zone at the site are energy flux limited rather than moisture limited.

5.4.4 Upscaling Tree Water-Use

The results obtained from both the HPV and SSS techniques were used to determine an actual annual water-use per unit area of the invaded mistbelt forest. Two hypothetical scenarios, a pristine forest and a heavily invaded forest, were also tested. Using the stem density per size class taken from ecological research completed in the area (Everson *et al*., 2016), stands of forest were compared. As the forest did not have a closed canopy, understorey trees were numerous as more photosynthetically active radiation (PAR) was available throughout the stand. The water-use for a two-year average of the riparian forest in its current state (21 % invaded) was upscaled for all species and size classes. The total stand water-use was approximately 3.3 ML·ha^{-1}·a^{-1} (330 mm·a^{-1}). This was 29 % of the average annual precipitation recorded during the monitoring period (1 030 mm·a^{-1}).

Assuming that the site was rehabilitated to a more pristine state, using stem density for non-invaded areas, the upscaled indigenous stand would use 2.39 ML·ha^{-1}·a^{-1} (239 mm·a^{-1}). This would be 21 % of the average annual precipitation. If the stand were to degrade further and bcome heavily invaded, the upscaled invaded stand would use 4.88 ML·ha^{-1}·a^{-1} (488 mm·a^{-1}). This would be 43 % of the average annual precipitation. Based on these results we conclude that the invaded stand uses 40 % more water per unit area annually than a pristine indigenous stand. If the stand were to become heavily invaded, a two-fold increase in water-use would occur (104 % increase) with concomitant impacts on the water balace (streamflow). The inter- and intra-species water-use variations, particularly within the heterogenous indigenous stand, highlight the importance of good replications of a representative sample tree species and size classes. The results also show that it is important to highlight the slope position, physiological characteristics and climatic variations occurring during measurement periods.

Due to a severe drought in this area, subsequent to the measurement period, these reults are more likely to provide substance to land managers and decision makers, indicating the hydrological benefit of restoration and rehabilitation activities.

5.5 Discussion and Conclusion

In South Africa, it has been well documented that introduced commercial tree species, in contrast to indigenous tree species, use more water and, if removed, would result in a net hydrological gain (Olbrich *et al*., 1996; Dye *et al*., 2001; Everson *et al*., 2007; Dye *et al*., 2008; Gush and Dye, 2008; Gush and Dye, 2009; Gush and Dye, 2015). The HPV and SSS techniques have been used, both locally and internationally, on numerous vegetation types. The accuracy of these measurements has been validated using gravimetric methods (Burgess *et al*., 2001; Granier and Loustau, 2001; O'Grady *et al*., 2006; Steppe *et al*., 2010; Vandegehuchte and Steppe, 2013; Uddin and Smith, 2014; Forster, 2017). In South Africa, the HPV technique has been shown to provide accurate estimates of sap flow in both introduced tree species such as *Acacia mearnsii, Pinus patula* and *Eucalyptus nitens,* and indigenous tree species such as *Rapanea melanophloeos, Podocarpus henkelii* and *Celtis africana* (Smith and Allen, 1996; Dye *et al*., 2001; Everson *et al*, 2007; Dye *et al*., 2008). There is consensus in the literature that rehabilitation or restoration measures can result in maximising benefits such as goods and services, while minimising water consumption (Gush, 2011).

A recent study, that was undertaken in conjunction with this study, showed that introduced stands could use up to six times more water than indigenous species in the riparian area (Scott-Shaw *et al*., 2017). However, this difference was largely related to stem density at a site where high winter rainfall and deep sandy soils were conducive to a high density mature introduced stand. The stand at New Forest, which was highly disturbed and was in a constant state of recovery, did not have a high stem density of mature trees in its current state. The measurements undertaken at this site have allowed for an accurate direct comparison of indigenous and introduced tree water-use. Additionally, the measurements of trees growing in the understorey have provided interesting findings, indicating significant water-use in the sub-canopy layer. The results showed that individual tree water-use is largely inter-species specific. As the introduced species remain active during the dry winter periods, their cumulative water-use is significantly greater than that of the indigenous species. Small tress (< 30 mm) in the understorey can use up to 2000 $L{\cdot}year^{-1}$, which is important for up-scaling to stand water-use. Up-scaled comparisons showed that due to the invasion by *A. mearnsii* and *E. grandis* (21 %), the stand water-use has increased by 40 %. This is an important finding as it provides clear evidence to justify the hydrological benefit of clearing programmes. If the stand were to be completely invaded, at the same stem density as the indigenous stand, the water-use would double for this particular area.

The findings from the understorey suggest that the water-use from this zone should not be excluded from future studies, especially where there is no canopy closure. The promotion of indigenous deciduous trees for rehabilitation or clearing programmes may be important as there would be no transpiration during periods when water resources are limited.

Spatial estimates of evapotranspiration are required but are difficult to obtain in remote areas with limited aerodynamic reach. Remote sensing could be one area where this could be useful given appropriate validation. However the nature of the "thin" riparian strip will require finer scales than provided by most remote sensing products used for evaporation modelling (e.g. Landsat 8). The use of drones could provide the best option for these narrow riparian strips in the subsequent studies. Management dynamics are important in these environments. There is potential for these data to be used in a modelling framework with specific inputs for invaded mixed riparian forests. This would provide a suitable land management tool.

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CHAPTER 6. VALIDATION OF A MODELLING APPROACH ON RIPARIAN FOREST WATER-USE DYNAMICS

6.1 Abstract

Hydrological modelling is a useful approach to investigate the interactions of climate, land-use and soil on the water-use of forest systems, particularly where spatial heterogeneity exists. South Africa has a spatially variable climate and land-use, resulting in many of the available models not being suitable across these conditions. The Soil and Water Assessment Tool (SWAT) model has evolved into one of the most widely used catchment scale models that has been used extensively and expansively to better understand hydrological processes. The SWAT model was adopted for three research sites within South Africa, each with the presence of indigenous forest areas, a range of invasion intensities by introduced species and a contrast in climatic conditions. User defined vegetation growth input parameters were constructed for each study area based on site observations. These parameters were subsequently modified using the Sequential Uncertainty Fitting (SUFI-2) analysis routine to calibrate the models. At all of the sites, the calibrated models captured the seasonal trends existing in the observed transpiration and streamflow data. Modelled total evaporation (ET) was consistently higher for the invaded riparian areas in contrast to pristine forests and grasslands. The SWAT model, using site specific input parameters, provides a useful platform for further hydrological modelling in South Africa.

Key Words: Modelling, SWAT, Total Evaporation

6.2 Introduction

There is a need for suitable hydrological models to assist in predicting the impacts of land and water management alternatives, such as rehabilitation programmes (Everson *et al*., 2007). Models used in water-use studies need to find a balance between simplicity and reliability, while at the same time they need to have an appropriate regional scale for the research being conducted (Le Maitre *et al*., 2002). It is mandatory that vegetation dynamics be included in integrated simulations of biophysical and hydrological processes (Strauch and Volk, 2013). Modelling studies have often relied upon coarse, empirical estimates of vegetation total evaporation (ET) to validate their modelling calibrations (Scott *et al*., 2008). Riparian areas constitute an important and variable land-use within a catchment, which means that models used to simulate these areas need to be spatially explicit (Everson *et al*., 2007). Models such as the Agricultural Catchments Research Unit (ACRU), the Soil Water Assessment Tool (SWAT), Système Hydrologique Européen (SHE) model group and SCS-SA (design flood estimation model) are just some of the models used in South Africa.

Internationally, the Soil and Water Assessment Tool (SWAT) model has emerged as one of the most widely used water quality watershed- and river basin–scale models worldwide, applied extensively for a broad range of hydrologic and/or environmental problems (Gassman *et al*., 2007, 2014). SWAT is a conceptual continuous time model developed in the early 1990s, to assist in water resource management, to assess the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins (Arnold & Fohrer, 2005). Recently SWAT has been applied in tropical regions of Africa (Schuol *et al*., 2008; Easton *et al*., 2010), Asia (Thampi *et al*., 2010; Wagner *et al*., 2011), and Latin America (Strauch *et al*., 2013). It is physically-based, uses readily available inputs and is computationally efficient to operate on large catchments over extended time periods (Everson *et al*., 2007). The SWAT model has an extension to Arcview and ArcGIS, which has increased the versatility of the model, and this spatial component makes it attractive to modelling hydrological components. This spatial detail was a key component for the selection of SWAT over other potential models. Evaporation and transpiration is calculated using the reduction of potential total evaporation (PET) by soil water content (Arnold *et al*., 1998). The input required for ArcSWAT are spatially explicit soils data, land use/management information, and elevation data to drive flows and direct sub-basin routing (Arnold, 2005). ArcSWAT lumps the parameters into hydrologic response units (HRU), effectively over-riding the underlying spatial distribution.

The SWAT model uses the water balance equation (Equation 6.1) in its simulation of the hydrological cycle (Arnold *et al*., 2009).

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad \text{Eq. 6. 1}$$

where SW_t is the final soil water content (mm); SW_0 the initial soil water content on day i (mm); R_{day}: the precipitation on day *i* (mm); Q_{surf} the surface runoff on day *i* (mm); E_a the total evaporation on day *i* (mm); W_{seep} the water entering the vadose zone on day *i* (mm) and Q_{gw} the return flow on day *i* (mm).

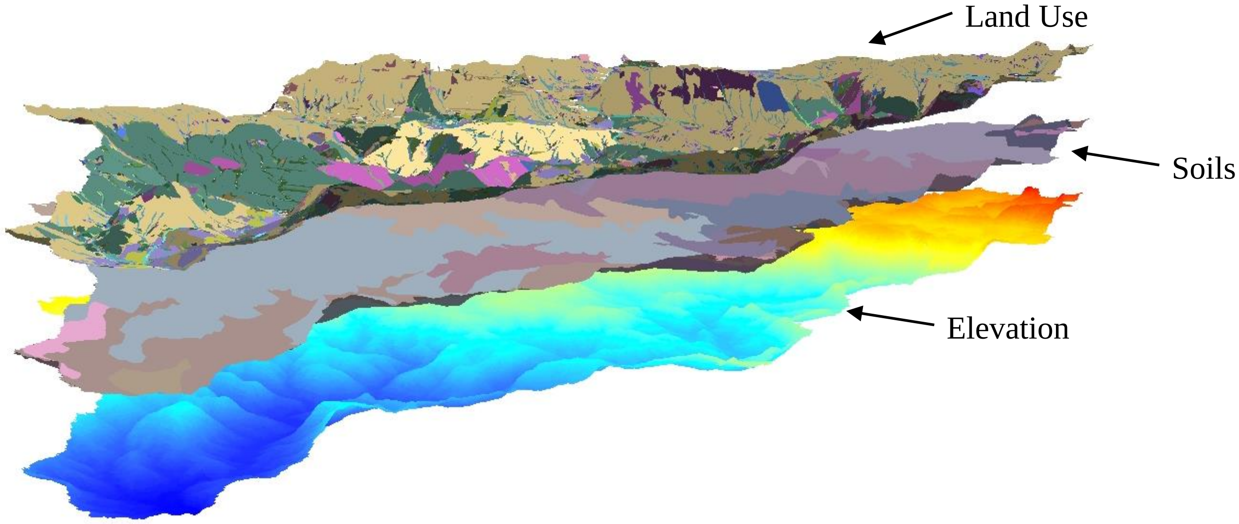

Figure 6.1 Conceptual layout of the ArcSWAT model input

One of the most important drivers is the meteorological data, which has been vastly improved in this model over recent years. ArcSWAT has options to use measured solar radiation, wind speed, relative humidity and evaporation data. Daily rainfall and air temperature data may be generated if unavailable or missing for the simulation period and there are no limitations to the number of rainfall and air temperature gauges that can be used in the simulation (Neitsch *et al*., 2011).

Although the SWAT model has been used in some catchments of South Africa, it has had limited applications as a research and teaching tool. A major reason for the limited use is the lack of available knowledge in South Africa for particular input parameters required by the model and a lack of skills to run the model. The objective of this research is to develop a methodology to apply the SWAT model throughout climatically diverse catchments in South Africa. This involves adjusting crop model input parameters to represent natural vegetation types in South Africa, with a focus on riparian areas. Three research sites are discussed, Buffeljagsrivier in the Western Cape, New Forest Farm and Vasi Pan in KwaZulu-Natal, South Africa. These three sites were chosen due the presence of indigenous forest areas with suitable species, a range of invasion intensities by introduced species and a contrast in climatic conditions.

6.3 The Study Areas

Various climatic regions were considered in order to extrapolate water-use measurements of tree species monitored throughout the study areas and to improve a modelling framework for water-use predictions. Sites within the Western Cape Afro-temperate forest (Buffeljagsrivier), Eastern Mistbelt Forest (New Forest) and Maputaland Coastal Belt (Vasi pan) were selected (Figure 6.2). The detail used for each catchment is further described in Table 6.1.

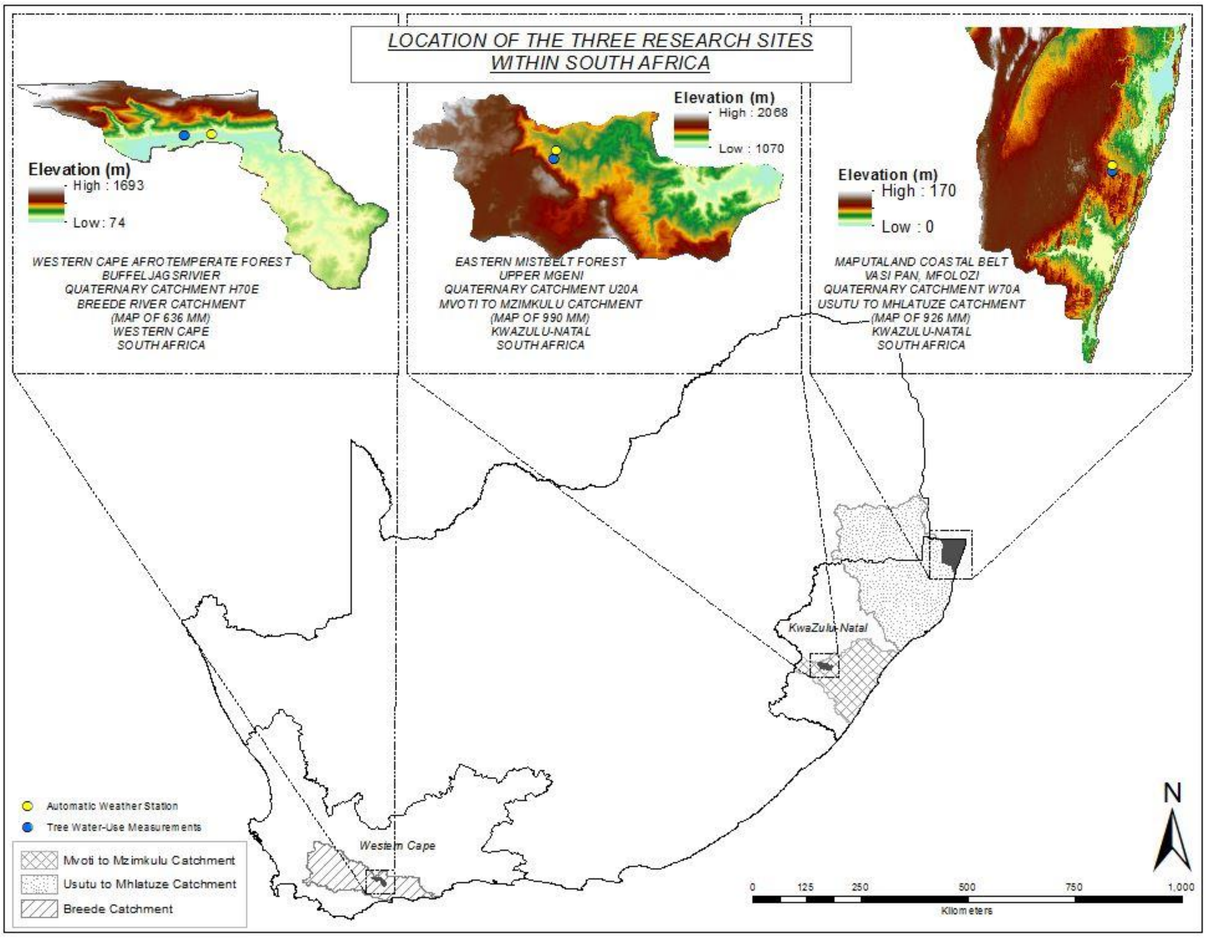

Figure 6.2 Location of the three study sites within South Africa

The Buffeljags River flows southwards along the Langeberg West mountain range into the Buffeljags dam. The Buffeljags River study area is at latitude 34°00’15”S and longitude 20°33’58”E, approximately 95-110 m above mean sea level. The soils are characterised by structureless sands, a result of previous alluvial deposition. The long-term (137 year record) mean annual precipitation

(MAP) at Buffeljags River is 636 mm. A 99 ha riparian forest occurs along the river with 75 ha of invaded forest (*Acacia mearnsii*) and 24 ha of pristine indigenous forest, comprising of species such as *Celtis africana*, *Vepris lanceolata*, *Prunus africana*, *Rapanea melanophloeos* and *Podocarpus falcatus*.

The New Forest riparian site is at latitude 29°28'30" S and longitude 29°52'48" E at approximately 1760 m above sea level. The riparian area occurs along a tributary to the upper Umgeni River. The mean annual precipitation is between 980 and 1 000 mm. There is a distinct dry season from May to August. Average air temperatures range from 16.9°C in the winter to 25.2°C in the summer, with the highest air temperatures occurring on the north-facing slopes. The riparian area has since been heavily invaded with *Acacia mearnsii*, *Eucalyptus grandis* and *Solanum mauritianum*. Common indigenous tree species present in the forest are *Celtis africana*, *Podocarpus latifolius*, *Halleria lucida*, *Leucosidea sericea* and *Buddleja salviifolia*.

The Vasi Pan site is at latitude 27°10'50" S and longitude 32°41'22" E at approximately 68 m above sea level. The pan area is just inland of the greater Isimangaliso Wetland Park protected area. The surrounding natural areas are covered by a mixture of densely forested areas, interspersed dry grasslands (dominantly palm veld), hygrophilous grasslands and thicket. The area, has in the past, been exploited for timber use. The soils show evidence of high precipitation and leaching with the deep tertiary sands and pliocene/miocene beds overlaying cretaceous mudstone. The mean annual precipitation is between 750 and 800 mm and the area experiences very hot summers during which most of the annual rainfall occurs.

Table 6.1 Summary of catchment characteristics and primary measurement stations

Research Catchment	Catchment Area (km^2)	Dominant Indigenous Species	Dominant Indigenous Species	Rainfall Station No.	Gauging Station No.
Buffeljagsrivier (Western Cape)	614.1	*Vepris lanceolata* *Celtis africana*	*Acacia mearnsii*	0025450 W	H7H013
New Forest (KwaZulu-Natal)	298.3	*Searsia pyroides* *Gymnosporia buxifolia* *Celtis africana*	*Acacia mearnsii* *Solanum mauritianum*	0239002 W	U2H013
Vasi Pan (KwaZulu-Natal)	555.6	*Albizia adianthifolia* *Phoenix reclinata* *Hyminocadia ulmoides*	*Eucalyptus grandis* *Pinus eliottii*	0412485 W	Military Bridge

6.4 Model Set-up

SWAT is highly dependent on the resolution of the input data, in particular the elevation, land use, soils and climate data. A large amount of manipulation is required for modelling outside of the United States. Therefore, considerable time is spent translating data into suitable SWAT input data.

6.4.1 Elevation and Topography

A digital elevation model (DEM) is used to configure the catchment by dividing it into a sub-basin or sub-catchments. The automatic watershed delineation tool allows for the creation and selection of outlet nodes and the determination of sub-catchment properties and river reach attributes. Depending on the resolution of the DEM used, either a manual or automatic setup can be chosen. The 30 m Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM was used at each site. The resolution of this DEM is 30 m by 30 m. However, this DEM does not provide accurate heights in areas of tall vegetation. Verified point and contour data were used to correct these errors and interpolate a higher resolution model. WGS 1984 UTM Zone 34S & 36S was used as the projection for these areas (ArcSWAT requires all layers to be projected uniformly and UTM is the most commonly used projection for hydrological studies). An outlet, corresponding to the location of each gauging station (*c.f.* Table 6.1), was specified for each catchment. The slope definition defines user specified slope classes using the base DEM.

6.4.2 Land-Use

The Ezemvelo KwaZulu-Natal Wildlife (EKZNW) land cover database for periods corresponding to the climate data was used at each catchment. A user defined layer was constructed for the Western Cape site. Leaf area index using a LAI-2200 (LI-COR, Lincoln, Nebraska, USA) was measured regularly throughout the monitored stands. The land use definition tool was used in ArcSWAT. This tool clips the land use to the catchment boundary and provides it with a code as determined by the user in GIS. A text file containing this code and the subsequent SWAT land code was compiled by the authors. This text file was then used to reclassify the land use layer to match attributes contained in the SWAT database.

An important addition to this component was land-uses that were either different in South Africa or that did not exist in the SWAT database. In this case, new land-uses were added to the SWAT database. This can be done either through the Access database file or through the user interface. Where physical observations were not available, such as for fynbos, a substitute default parameter was used (e.g. rangeland brush – RNGB). The following changes were made to the model database (*c.f.* Table 6.2) to match South African conditions:

- Pine, Eucalyptus and Wattle have been modified to match South African species and hybrids grown in KwaZulu-Natal and the Western Cape;
- A new set of input parameters for indigenous riparian forests at each site was included; and
- A new set of input parameters for invaded riparian forests was included.

6.4.3 Soil Properties

A soil survey was undertaken at each site. However, given the extent of the catchment areas, detailed data were not available throughout these areas. Where available, the South African Soil Classification system (Soil Classification Working Group, 1991) was used to determine the soil form/family and to translate the information into SWAT required values. The soil hydrologic group (NRCS, 1996), structure, depth, number of layers, texture and saturated hydraulic conductivity were used to construct a spatial soil layer with up to five variable soil layers in some areas. The database (Usersoils) was edited with the attributes for each representative polygon code. A text file was used to code the data from the spatially explicit polygon (Figure 6.3) to match the code in the database. Soil data were checked using the GIS interface and modified if required.

Figure 6.3 provides a summary of the steps taken to derive the final Hydrological Response Units (HRUs).

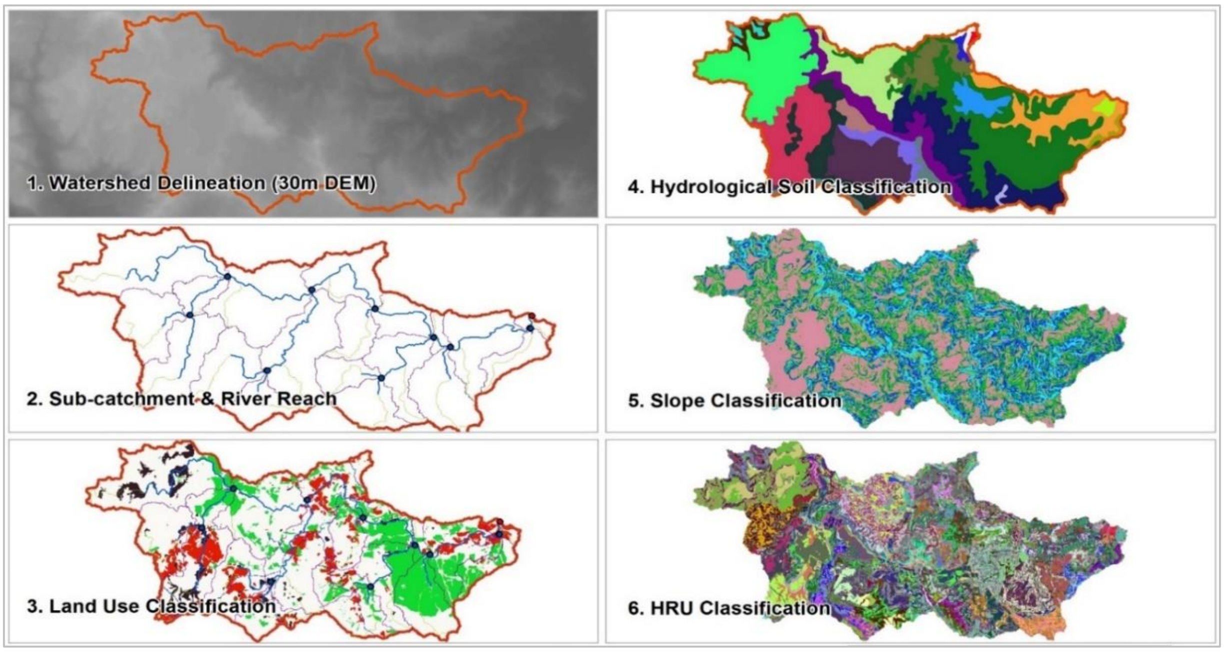

Figure 6.3 Steps taken to classify HRU classes in ArcSWAT at New Forest

6.4.4 Meteorological Data

A meteorological station was established at each site in a nearby grassland area. Daily rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) at a height of 1.2 m from the ground was measured with additional measurements at a height of 2 m for air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp & Zonen, Delft, The Netherlands) windspeed and direction (Model 03002, R.M. Young, Traverse City, Michigan, USA). Weather Data Definitions were subsequently modified to allow for the measured data to be included. A table was created for each rainfall station including the Station ID, location and altitude. This was edited into the file *SWAT2012.mbd*. Individual text files containing daily rainfall, air temperature, solar radiation, relative humidity and wind speed were created that could be linked to the modified database. Climate data available elsewhere in the catchment were used where available, particularly if the catchment had an uneven climate distribution. Three years of observed data were used as a warm up period for the daily simulations.

6.4.5 Management

Land management can have a large impact on hydrological responses and, as such, is important in catchments where agriculture is dominant. The management operations were modified in ArcSWAT to specify the initial growing state, periods during planting and harvest (plant and kill operations) and fallow lands. For the commercial tree species, a ten-year rotation was applied for *Eucalyptus* and *Acacia* species, while a 15-year rotation was applied for pulp *Pinus* species.

6.5 Model Calibration using SWAT-CUP

The effectiveness of the SWAT-CUP parameter sensitivity and optimization model (Abbaspour, 2015) was tested with daily observed streamflow data and monthly observed total evaporation (ET) data. Streamflow data were compiled for the outlet of each catchment using verified data obtained from the Department of Water and Sanitation. Initial plant growth input parameters (Table 6.2) were derived based on field measurements, expert opinion and documented literature. A sensitivity analysis was performed for 12 parameters that were identified as being crucial in the calculation of ET. Throughout all of the study sites, the maximum stomatal conductance (GSI), plant uptake and soil evaporation compensation factor (EPCO and ESCO), initial SCS runoff curve number for moisture condition II (CN2) and the maximum potential LAI and decline of LAI (BLAI and DLAI) had an impact of the actual ET output. The groundwater delay time (GW_DELAY) and “revap” coefficient (GWREVAP) influenced the actual ET, particularly at the Vasi Pan site.

The calibration and validation process did show that these models were of sufficient accuracy to use for scenario based modelling. It must be noted that each year during the measurement period, these sites experienced a higher than average depths of rainfall.

Table 6.2 Summary of modified land-use attributes used for the SWAT model

PARAMETER DESCRIPTION	CROP CODE	UNITS	MODIFIED LAND-USE											
			Lightly Invaded Riparian Forest		**Heavily Invaded Riparian Forest**		**Indigenous Riparian Forest**		**Pine *(Pinus elliottii)***		**Gum (*Eucalyptus grandis*)**		**Wattle (*Acacia mearnsii*)**	
			Initial	Parameterized	Initial	Parameterized	Initial	Parameterized	Initial	Parameterized	Initial	Parameterized	Initial	Parameterized
CROP CODE	CPNM	N/A	WETF	WETF	WETI	WETI	RFOR	RFOR	PINE	PINE	EUCA	EUCA	ACME	ACME
RADIATION-USE EFFICIENCY	BIO_E	MJ/m2	15	15	15	15	15	15	15	15	15	15	15	15
MAXIMUM POTENTIAL LAI	BLAI	m2/m2	4.5	4.5	5	5	4.5	4.5	5	5	5	4.2	5	4.5
FRACTION OF GROWING SEASON LEAF DECLINE	DLAI	m2/m2	0.6	0.45	0.6	0.9	0.6	0.4	0.6	0.99	0.6	0.99	0.6	0.99
MAXIMUM CANOPY HEIGHT	CHTMX	m	18	20	24	24	20	20	24	24	26	26	22	22
MAXIMUM ROOT DEPTH	RDMX	m	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
OPTIMAL TEMPERATURE FOR PLANT GROWTH	T_OPT	C	25	25	25	30	25	25	30	30	30	30	30	30
MINIMUM TEMPERATURE FOR PLANT GROWTH	T_BASE	C	5	5	5	5	5	5	0	0	0	0	0	0
LOWER HARVEST INDEX	WSYF	kg/ha	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
MAXIMUM STOMATAL CONDUCTANCE	GSI	m s-1	0.002	0.005	0.01	0.015	0.0004	0.0004	0.01	0.012	0.012	0.015	0.002	0.013
VPD ON STOMATAL CONDUCTANCE CURVE	VPDFR	kPa	1	1.2	1	1.6	1	1	1	1.6	1	1.6	1	1.6
FRACTION OF MAXIMUM STOMATAL CONDUCTANCE	FRGMAX	Frac	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
DECLINE IN RADIATION-USE EFFICIENCY	WAVP	g/MJ/kPa	8	8.5	8	8.5	8	8.5	8	8.5	8	8.5	8	8.5
ELEVATED CO2 EFFICIENCY	CO2HI	uL Co2/L	660	660	660	660	660	660	660	660	660	660	660	660
PLANT UPTAKE COMPENSATION FACTOR	EPCO	N/A	1	0.2	1	0.2	1	0.2	1	0.2	1	0.2	1	0.2
SOIL EVAPORATION COMPENSATION FACTOR	ESCO	N/A	0.01	0.9	0.01	0.9	0.01	0.9	0.01	0.9	0.01	0.9	0.01	0.9
MINIMUM LAI DURING DORMANCY	ALAI_MIN	m2/m2	2	2	2.5	2.5	1.4	1.4	2.8	2.8	2.6	2.6	2.8	2.8
YEARS UNTIL FULL DEVELOPMENT	MAT_YRS	Years	30	30	30	30	30	30	30	30	30	30	30	30
MANAGEAMENT SCHEDULE	OpSchedule	N/A	FRSD	FRSD	FRSE	FRSE	FRSD	FRSD	FRSE	FRSE	FRSE	FRSE	FRSE	FRSE
INITIAL SCS RUNOFF CURVE NUMBER (II)	CN2	N/A	60	45	60	40	80	50	60	38	60	35	60	38
GROUNDWATER "REVAP" COEFFICIENT	GWREVAP	N/A	0.4	0.05	0.8	0.05	0.2	0.05	0.8	0.05	0.8	0.02	0.8	0.05

6.6 Results and Discussion

Three types of data are available through the ArcSWAT model interface. An annual water balance can be obtained from the summary files. This is useful as it provides an indication firstly as to whether the model simulations are realistic and secondly to determine how the hydrological cycle is partitioned in each catchment. Depending on the time step simulated, a time series output of any of the output parameters can be obtained from the output database. Finally, a spatial output may be obtained by linking data from each HRU or sub-basin back to the original watershed shapefiles.

The post-calibration results for the SWAT model at Buffeljags River (Figure 6.4) provided good simulations of the peaks and low flows. The model efficiency had a regression coefficient (R^2) of 0.62. Some of the intermediate peaks were not well simulated during this period. The reason for these differences was attributed to the highly variable nature of the catchment, where half of the catchment was represented by the steep Langeberg mountain range which is poorly gauged. It is likely that more rainfall occurred in the upper reaches of the catchment and was not represented in the climate input. Although the focus of this study was not primarily on streamflow responses, it is still important to show that the model sufficiently simulates flows accurately.

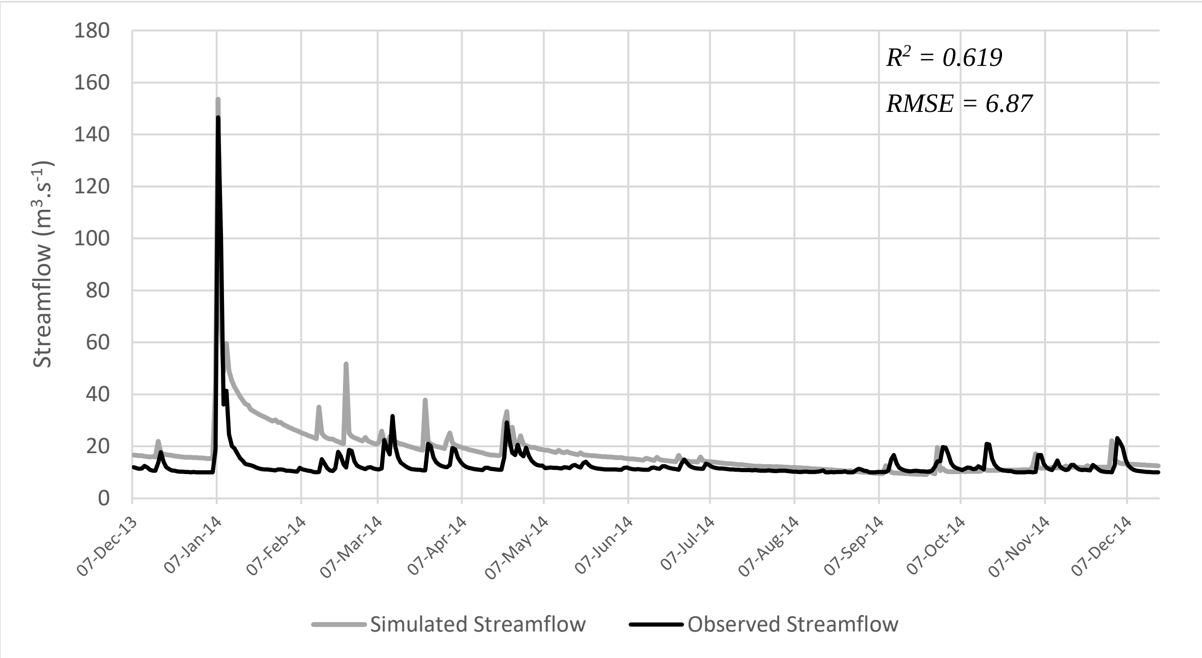

Figure 6.4 Relationship between simulated and observed streamflow downstream of Buffeljags dam

The post-calibration simulation of ET at New Forest emphasised the clear differences between the natural vegetation and the indigenous vegetation that it replaces. During the winter periods, when rainfall is low, the introduced vegetation uses approximately 15 mm more water per month (Figure 6.5). This difference is higher during the warm high rainfall periods. This contrast is similar to the documented differences measured at the site (Scott-Shaw & Everson, 2018).

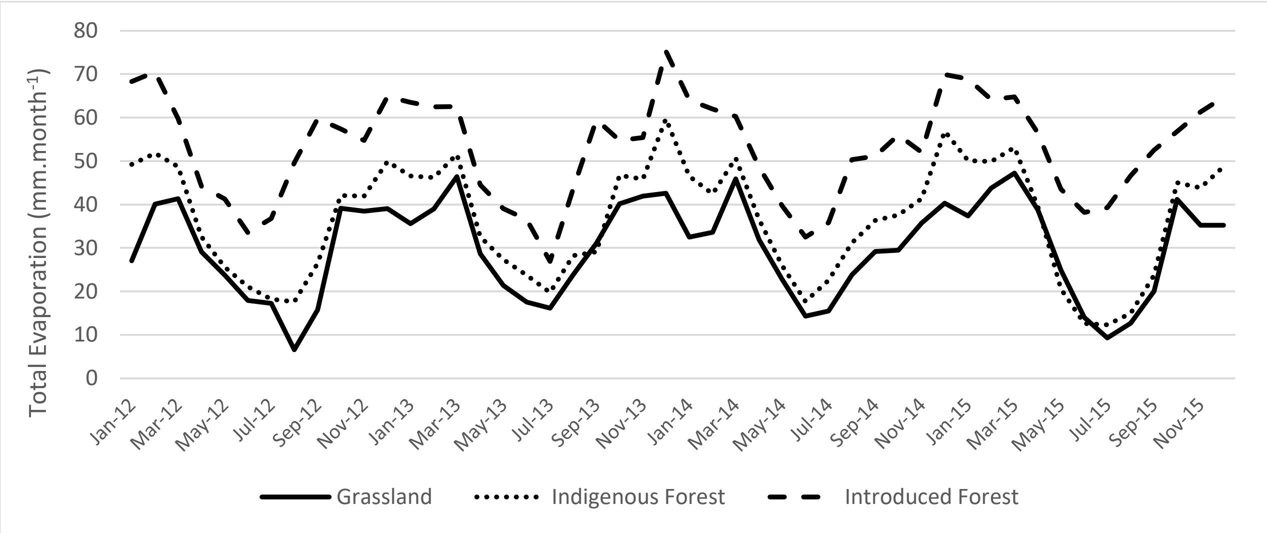

Figure 6.5 Relationship between simulated total evaporation (ET) between the dominant land-uses around New Forest

The spatial distribution of total evaporation (ET) provides a valuable approach for scenario testing. Given the detailed time series data, an average summer and winter month was calculated for each catchment. The results at Buffeljags River (Table 6.3 and Figure 6.6) clearly shows the high evaporation amounts for areas where water bodies, agriculture and introduced species occur. *A. mearnsii* has the highest total evaporation (425 mm) and the lowest groundwater contribution to streamflow (462 mm). Although this is higher than the indigenous forest, it is not of the same magnitude to that of the observations. Further calibration may be required to increase the LAI inputs for *A. mearnsii* and increase the curve number for indigenous forests for this area. The use of the rangeland brush (RNGB) as a substitute for fynbos (which was not measured) resulted in outputs of high ET values for both summer and winter periods (annual total of 417 mm). This suggests that this input parameter used for South Africa requires improvement. Although the simulated values are in agreement with the observed values, further site investigations and model calibrations would be required for the areas of the catchment which were not measured.

Table 6.3 Annual hydrological output summary per land use class at Buffeljags River

Research Catchment	Area (km^2)	Curve Number	Total Evaporation (mm)	Sediment Yield ($t.ha^{-1}$)	Groundwater Contribution (mm).
Grassland	498.78	68.55	266.80	0.49	541.80
Cultivated Lands	92.16	72.36	329.63	30.16	390.99
Acacia mearnsii	5.70	45.00	425.45	9.81	462.97
Indigenous Forest	0.21	48.05	359.71	0.07	579.28
Rangeland/Fynbos	15.92	48.07	417.81	0.68	480.86

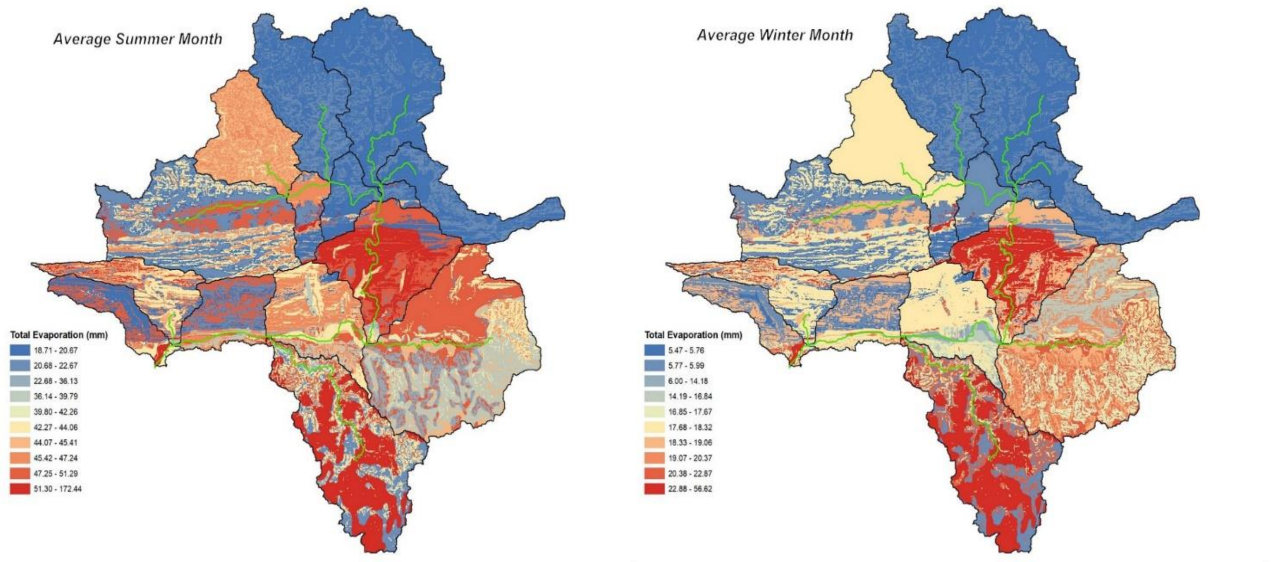

Figure 6.6 Spatial distribution of total evaporation (ET) for an average summer and an average winter month (January 2012 to December 2015) at Buffeljags River

The results for the catchment area of New Forest (Table 6.4 and Figure 6.7) showed a high contrast in water-use across the catchment and between seasons. This catchment is utilised for cultivated lands and commercial forestry. Some areas of natural grassland and forest occur at the high altitude areas. High ET corresponds to areas of high rainfall, plantations and riparian areas. The annual summary indicates that *A. mearnsii* and *E. nitens* exhibit the highest ET, in contrast to indigenous forest and grasslands. This correlates to site observations. As this is the major catchment for Midmar Dam and Umgeni water management area (supporting both the cities of Pietermaritzburg and Durban) sound management of the area is essential. More than half of the rainfall in this catchment is lost to ET. As such, identifying the areas of greatest loss such as invaded riparian areas, would assist catchment management agencies.

Table 6.4 Annual hydrological output summary per land use class at New Forest

Research Catchment	Area (km^2)	Curve Number	Total Evaporation (mm)	Sediment Yield ($T.ha^{-1}$)	Groundwater Contribution (mm).
Grassland	165.65	61.06	260.89	3.66	369.86
Cultivated Lands (close grown)	5.45	73.00	399.73	8.87	279.10
Acacia mearnsii	7.02	60.00	422.08	31.28	381.18
Eucalptus nitens	39.99	66.00	420.77	61.72	341.78
Pinus patula	7.24	55.00	393.13	1.31	328.48
Indigenous Forest	4.30	60.00	304.77	0.64	419.69
Indigenous Forest (invaded)	1.84	55.00	415.09	54.56	341.27

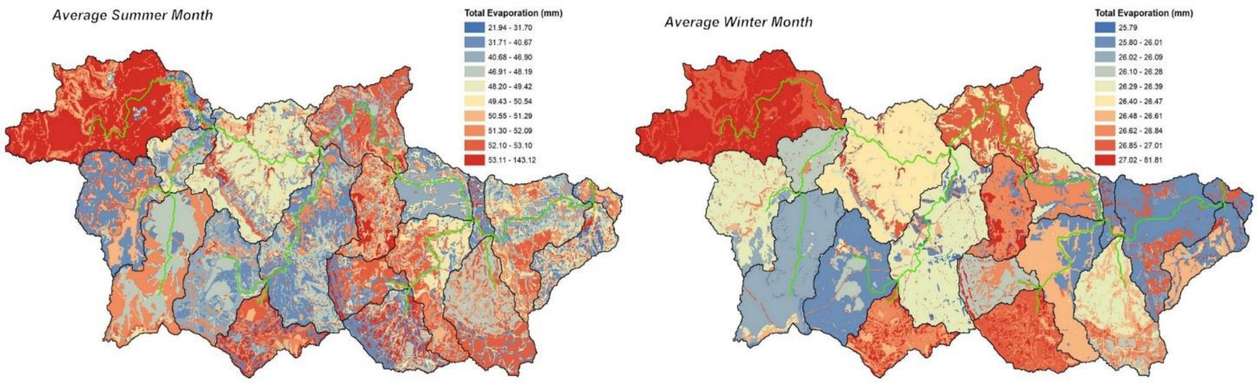

Figure 6.7 Spatial distribution of total evaporation (ET) for an average summer and an average winter month (January 2012 to December 2015) at New Forest

The spatial distribution of ET at Vasi Pan (Figure 6.8) showed that the commercial forestry areas were the dominant water-users in the catchment. This area has a shallow water table, which allows for the rapid growing and deep rooted introduced species to readily uptake water. The annual summary shows that *E. grandis* has a high ET (799 mm) with the indigenous forest (582 mm) and the grassland (519 mm) using significantly less water. Furthermore, the contribution to groundwater and streamflow is significantly higher for grassland areas (297 mm). At this site, having no true surface water components, the groundwater fluctuations and interactions with the surface components should be further investigated. Although the groundwater routines in SWAT are not detailed, the interactions with the shallow and deep aquifers could be undertaken if coupled with a suitable groundwater model.

Table 6.5 Annual hydrological output summary per land use class at Vasi Pan

Research Catchment	Area (km^2)	Curve Number	Total Evaporation (mm)	Sediment Yield ($T.ha^{-1}$)	Groundwater Contribution (mm).
Grassland	301.77	49.00	519.96	1.30	297.72
Cultivated Lands (irrigated)	8.58	67.00	757.20	4.23	131.30
Eucalyptus grandis	73.85	36.00	799.09	1.71	134.79
Pinus elliotti	80.12	39.00	749.09	1.32	155.81
Indigenous Forest	0.21	49.00	582.44	0.49	245.72
Cashews (irrigated)	9.75	45.00	755.05	0.22	46.15

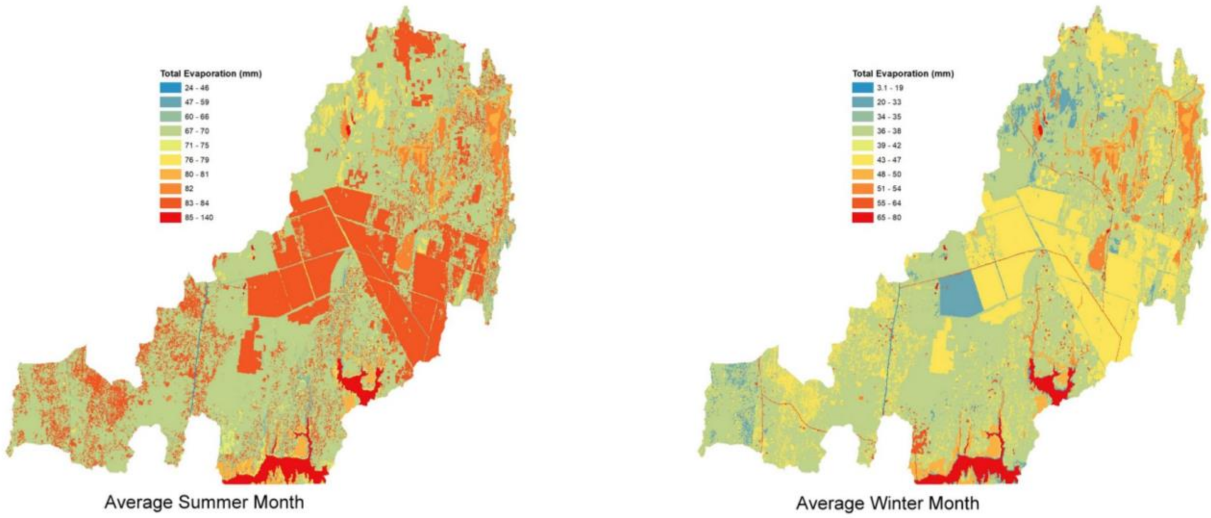

Figure 6.8 Spatial distribution of total evaporation (ET) for an average summer and an average winter month (January 2012 to December 2015) at Vasi Pan

These results provide an ideal platform to test scenarios. Additionally, areas of high hydrological impact, such as invaded riparian areas could be identified and prioritized for rehabilitation. This provides a tool for decision makers as it is based on observations and extrapolations through the model. In areas such as Vasi Pan, components of the groundwater routines can be interrogated, especially if the SWAT-MODFLOW user interface is adopted. When calibrating using streamflow, all land use input parameters should be properly defined. If this is not undertaken, the calibration and parameterisation process may be inaccurate.

6.7 Conclusion and Recommendations

The use of the SWAT model throughout the world is extensive and well documented. However, there is a general lack of studies where sufficient results of uncertainty and sensitivity analyses as well as model validations are presented. This is especially true for studies focusing on evaporation outputs and calibration. The use of the Sequential Uncertainty Fitting (SUFI-2) algorithm within the SWAT-

CUP programme in this study has allowed for the auto-calibration of the SWAT model at each research site. Most hydrological model calibration and validations are based on flow discharge, which does not necessarily provide any accuracy for internal catchment processes (Strauch and Volk, 2013). The availability of detailed observed streamflow and total evaporation (ET) datasets has allowed for an assessment of the objective function for a multi-variable calibration. This is important in extending the application of the model to areas with limited observations. The distributed calibration approach using spatially explicit hydrological response units (HRUs) lends itself to the use of spatial observations such as scintillometry, eddy covariance and remote sensing. A study in Vietnam, using remotely sensed ET and LAI data to calibrate SWAT, showcases the feasibility of this approach, particularly as spatial data are becoming more readily available.

This study provides substantial insights into the spatial distribution of total evaporation (ET) throughout the selected catchment areas. This information is particularly useful for land management decisions, such as riparian clearing programmes, as areas of high water-use can be easily identified and prioritized for rehabilitation. The use of default SWAT plant growth values in South Africa is problematic as the natural vegetation differs substantially to that of the natural vegetation growing in the United States. In order to meet the study objectives, a new set of SWAT input plant growth parameters for introduced and indigenous riparian forests has been provided. This can be seen as a starting point for the development of a South African plant growth database. The results showed higher ET values in the introduced and invaded forest stands in contrast to the indigenous vegetation, correlating to the observed data. This difference was enhanced during the winter period of the summer rainfall regions where deciduous trees experienced leaf fall and grasslands became dormant.

Simulations from the groundwater driven Vasi Pan catchment, with the absence of surface water features, does not provide realistic results on the surface to groundwater interactions. A potential approach to overcome this issue is to link SWAT with the physically-based, spatially-distributed groundwater model (MODFLOW). This would potentially address short-comings of the current groundwater routines. As vegetation dynamics differ in South Africa, an approach to automatically initiate annual growing cycles using changes in soil moisture should be investigated. This approach may be more suitable for South African vegetation and would negate the need to define management operations to initiate growth at a fixed date.

It is clear from the results that the SWAT model is a suitable hydrological model for examining the impacts of different land-uses in catchments in South Africa and can provide high resolution temporal and spatial output data. The SWAT-CUP calibration interface provides a useful tool to determine the sensitivity of input parameters, improve the simulation efficiency and provide an indication of the model uncertainty.

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CHAPTER 7. SYNTHESIS

7.1 Overview

Parts of South Africa experience up to 87 % alien tree invasions (Working for Water, 2011), with most of these being in the riparian areas that have readily available water and are difficult to manage. In South Africa there is a limited understanding of the extent to which tree species (particularly those in the riparian area) contribute to total evaporation. As such, it is difficult for government organizations and scientists to justify alien tree removal and rehabilitation unless a known hydrological benefit can be seen.

An extensive review was undertaken to gain an understanding of the current *status quo*, gaps in the available literature that could be explored, expert scientists that could be consulted (both locally and internationally), tree species that have been measured or suggested for measurement and the techniques used in various locations throughout South Africa. There is a widespread belief, which has been supported by numerous studies in South Africa (Olbrich *et al*., 1996; Dye *et al*., 2001; Everson *et al*., 2007; Dye *et al*., 2008; Gush and Dye, 2008; Gush and Dye, 2009; Gush and Dye, 2015) that indigenous tree species, in contrast to the introduced trees species, use less water and should be planted more widely in land rehabilitation programmes. International studies indicate that at the plant scale, introduced invasive species can use up to between 150 to 300 % more water than indigenous dominated landscapes. Furthermore, there can be a significant disconnect between up-scaling plant scale measurements to an ecosystem scale (Cavaleri and Sack, 2010). Limited research has been undertaken within riparian areas, which are not limited by water availability (except in severe drought conditions). The knowledge review highlighted the need to understand this riparian zone component as well as to expand the species measured which are usually diverse in these ecosystems. A key recommendation from the literature, which has been emphasized in a recent study by Gush and Dye (2015), is that indigenous tree stand management and carbon sequestration research is needed in South Africa. This could be in the form of manipulated stands (agroforestry), stands that have been successfully rehabilitated and government linked research stands. This study addresses part of this recommendation.

Two climatically diverse catchments (Buffeljags River in the Western Cape and New Forest in the KwaZulu-Natal midlands) were selected that contained invaded riparian forest. The *Acacia mearnsii* invaded forest in the Western Cape contained the indigenous *Celtis africana* and *Vepris lanceolata* while the *Eucalyptus nitens*, *A. mearnsii* and *Solanum mauritianum* invaded mistbelt forest in

KwaZulu-Natal had abundant populations of *Gymnosporia buxifolia, Searsia pyroides* and *C. africana.* Vasi Pan in the Maputaland Coastal Belt was selected as an additional catchment to extend the modelling study. Results have been provided for long-term tree water-use of various tree species, soil water content, as well as local meteorological conditions. The high frequency water-use findings add to a continually growing database of tree water-use. The Heat Pulse Velocity (HPV) system was tested and improved during this study by improving the dependency on wire lengths which allowed trees to be measured at up to 50 m from the central data logger, improving the power efficiency, reducing the potential for damage and minimizing noisy data. Riparian tree water-use was determined using the HPV and Stem Steady State (SSS) techniques. The techniques chosen were site specific due to limitations in fetch, accessibility and stand dynamics/variability. Many of the species measured had not been measured prior to this study. The results showed that indigenous trees in an established riparian stand in a Western Cape Afro-temperate forest (little seasonal rainfall change in this region) had a high variability of water-use between species and tree size and this variability was largely dependent on location, tree condition and photosynthetically active radiation (PAR) dynamics. This further highlights the need for measurement replication. The comparison between individual trees indicated that the largest indigenous trees (*C. africana* and *V. lanceolata*) used the most water. These trees were significantly larger with an extensive canopy cover. Indigenous trees of a similar size to that of the alien trees used significantly less water. When extrapolated by stem density, the evergreen alien species (*A. mearnsii*) used up to six times more water than the indigenous stand. This finding was significant in that it provided clear evidence to justify the highly expensive clearing programmes, which have in the past lacked quantifiable data on the potential hydrological benefits and potential reduction in carbon sequestration of alien plant clearing. Importantly, rehabilitation or clearing programmes should consider the seasonal rainfall variability of a site, as planting of deciduous indigenous trees may provide larger benefits in summer rainfall areas due to no transpiration during periods when water resources are limited.

The results for the Eastern Mistbelt forest (New Forest) study, which had a highly disturbed/invaded stand, showed very low water-use volumes in comparison to the invaded Western Cape site. The results showed that individual tree water-use is largely species-specific. As the introduced, evergreen species remained active during the dry winter periods, their cumulative water-use was significantly greater than that of the indigenous species at this site. Small pioneer species in the understorey (indigenous *Buddleja salviifolia*, introduced *S. mauritianum* and introduced *A. mearnsii*) can use up to 2 000 L·year^{-1}, which is important to include for up-scaling to stand water-use. Up-scaled comparisons showed that due to the invasion, the stand water-use has increased by 40 %. In this area, it is recommended that deciduous species in addition to low consumptive evergreen species be used for forest rehabilitation as they use very little water during the drier winter months when water is needed the most. In comparison, the degraded forest in the Western Cape used 585 mm·year^{-1} whereas the pristine indigenous forest used 101 mm·year^{-1}. The invaded stand in KwaZulu-Natal used 488 mm·year^{-1} compared to 239 mm·year^{-1} under pristine conditions. The higher water-use in the Western Cape was largely attributed to more water being available throughout the year and a more established and dense stand.

A hydrological modelling study was undertaken to support the extrapolated ecological and hydrological observations. Using the data from the two variables collected in this study (up-scaled transpiration and streamflow), model inputs could be refined for pristine and invaded riparian forests through a multi-variable calibration and parameterisation process. The use of the Sequential Uncertainty Fitting (SUFI-2) algorithm within the SWAT-CUP programme in this study has allowed for the auto-calibration of the SWAT model at each research site. The distributed calibration approach undertaken in this study uses observed ET within the catchment and observed streamflow at the catchment outlet and parameterizes each spatially explicit hydrological response unit (HRU). The use of spatial observations such as scintillometry, eddy covariance and remote sensing could assist further to improve calibrations for the un-gauged areas of the catchment. This information, along with the water-use observations, will be invaluable for land management decisions, such as riparian clearing programmes, as areas of high water-use can be easily identified and prioritized for rehabilitation. However, in areas with an absence of surface water features (e.g. the groundwater driven Vasi Pan catchment), simulations did not provide realistic results on the surface to groundwater interactions. A potential approach to overcome this issue is to link SWAT with the physically-based, spatially-distributed groundwater model (MODFLOW).

It is important to compare the findings from this research with results from similar studies within South Africa. Table 7.1, with additional finding provided in Section 2.4, indicates that the water-use of both introduced and indigenous tree species (Chapter 4 and 5) are relatively low in contrast to other studies. The modelled results, particularly from the New Forest site has a low ET in comparison to other sites and other vegetation types. This suggests the need for follow-on micrometeorological techniques to assist in the up-scaling of point measurements where heterogeneous stands exist. Additional measurements of total LAI, stomatal conductance and water potential would be beneficial to improve water-use upscaling and model input refinement.

Table 7.1 Summary of the water-use from similar studies within South Africa

Research Site	Species/Vegetation Type	Mean Annual Precipitation (mm)	Average Stand Water-use (mm)
Gilboa	*A. mearnsii*	867	1077
Jonkershoek	*A. mearnsii*	1324	1318
Seven Oaks	*A. mearnsii*	727	700.7
Karkloof	*P. patula*	1100	1058
Kwambonambi	*E. grandis*	1043	1000
Skukuza	Savanna	570	490
Nylsvley	Savanna	623	469
Groenkop	Southern Cape Forest	860	680
Usutu	*P. patula*	1124	930
Wilgeboom	*E. grandis*	1297	870
Buffeljagsrivier	*A. mearnsii*	1015	585
New Forest	*A. mearnsii/ E. nitens*	1137	488
Karkloof	*P. henkelii*	1100	403
New Forest	Eastern Mistbelt Forest	1137	239
Buffeljagsrivier	Southgern Cape Afrotemperate	1015	101

It is clear from the results that the larger tree species, although able to utilize soil water, have access to the groundwater table throughout the year as is evident from the low volumetric soil water content and high water-use. These species growing in the riparian areas are energy limited and their water-use correlates to the seasonal leaf area index (LAI). It is likely that during drought conditions, these species may become water limited, particularly in summer rainfall areas such as KwaZulu-Natal. There is a clear contrast between introduced tree water-use and the water-use of the indigenous trees that they replace, which correlates to previous studies in South Africa and other water scarce countries. Given the quantified hydrological benefit presented in this thesis, indigenous trees should be promoted for use in rehabilitation studies where the natural vegetation is/was forests. This is especially relevant in light of South Africa's limited water resources.

7.2 Revisiting the Aims and Objectives

The overall aim of the research described in this thesis was to provide new knowledge and advance our understanding of the plant water-use dynamics of both the indigenous and introduced/invaded riparian forest systems over different climatic gradients. This, with the support of model validations and extrapolations provides critical data for decision makers on alien plant clearing and rehabilitation programmes.

The objectives of the research were:

1. to review available knowledge on water-use investigations and the techniques used both locally and globally;
2. to provide a technical approach on the best techniques to measure water interactions in riparian areas;
3. to investigate the water-use (transpiration rates) of a selection of pioneer indigenous tree species that may be suitable for rehabilitation programmes and riparian zone restoration over various climatic regions;
4. to incorporate the data into a modelling framework for the temporal and spatial extrapolation of water-use observations;

7.3 Contribution to New Knowledge

Specific contributions to new knowledge and how these contributions addressed the objectives of the research are summarised. This research:

- investigated and collated documented research on tree water-use globally, with a focus on South Africa to provide a consolidated platform to assist future researchers (Objective 1);
- identified the suitability of various evaporation measurement techniques, such as the heat pulse velocity (HPV), stem steady state (SSS) and thermal dissipation (TD) for measurement in highly variable riparian areas (Objective 1);
- provided a technical framework for the selection, installation and maintennace of three commonly used sap-flow measurement techniques (HPV, SSS and TD) to ensure accurate measurements (Objective 2);
- improved the heat ratio method by modifying the wiring, redesigning the heater probe and including a reference temperature (thermistor) at the junction of the Copper/Constantan thermocouples to allow for a reduction in power requirements, spatial flexibility in tree selection and a reduction in post-measurement corrections (Objective 3);
- quantified the water-use in three introduced and eight indigenous riparian tree species within a mediterranean climate zone over a three year period (Objective 3);
- quantified the water-use in nine introduced and seven indigenous riparian tree species within a summer rainfall zone (Objective 3);
- identified a suitable modelling approach for catchments with highly variable land use and management (Objective 4);
- incorporated water-use observations and site measurements into a modelling framework for the temporal and spatial extrapolation of water-use observations (Objective 4);

- undertook a model calibration using observed streamflow and total evaporation to improve plant growth input parameters and model simulations (Objective 4); and
- provided detailed explanations and conclusions on the research findings and how these findings should be interpreted and used by decision makers.

7.4 Research Limitations and Challenges Faced

Although a large amount of support and experience was available for this research, some unavoidable challenges were faced during the monitoring period. Riparian areas are generally characterised as narrow linear sections of vegetation that can differ from the adjacent inland vegetation. As such, with limited aerodynamic fetch and challenging terrain, the use of total evaporation techniques were not feasible. Sap flow techniques for measuring water-use were therefore selected. These techniques can be further limited by budget constraints, size and flow measurement range, practical expertise and power availability. They also require frequent maintenance (five-day site visits) to ensure continuous measurements and accuracy. The selection of tree species suitable for measurement and representativity of the stand can be challenging since wire length limitations results in trees within close proximity to one another being selected. However, this limitation was overcome during the research period by the development of an improved HPV system. Species replications is also limited by available equipment and hence budget and time constraints.

After site installation, external disturbances such as theft, fire, intense winds and animal interference are common. Frequent maintenance and animal exclosures were required to ensure minimal external interference. Due to high power requirements, batteries had to be replaced regularly (every eight weeks), and stored in secure safe boxes before the new HPV system was developed. During the measurement period, damage by baboons and cows occurred, which required the replacement of thermocouple wires and heaters. Some fire damage and theft was experienced at New Forest and Vasi Pan.

The use of default plant growth values in the SWAT model is problematic in South Africa, as the natural vegetation differs substantially from that of the natural vegetation growing in the United States. As only some of the vegetation types within the catchment area were studied, default or assumed values had to be used.

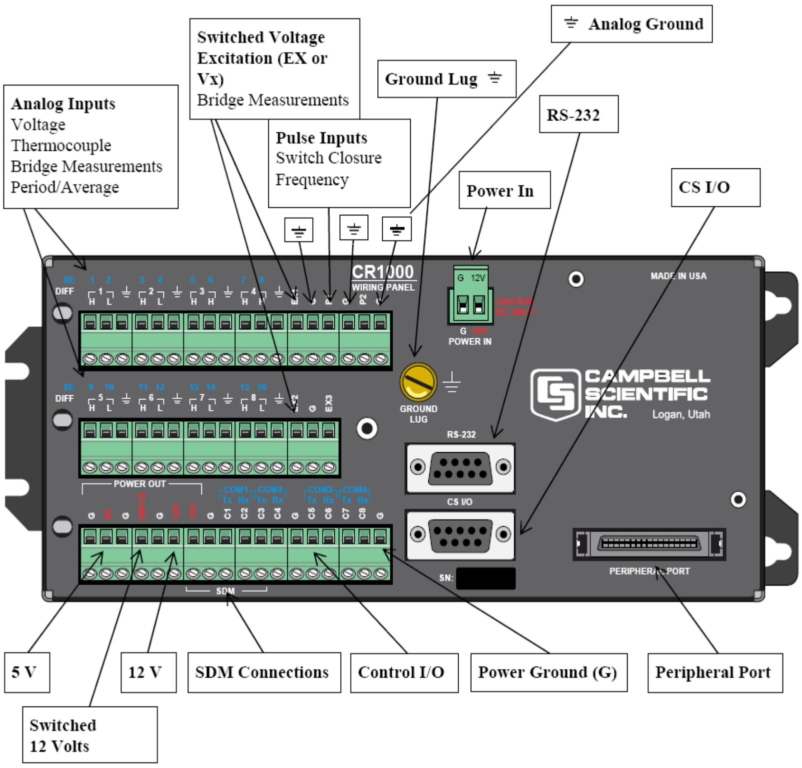
7.5 Future Research

Any gaps or shortcomings from the research undertaken during this study have been brought forward as areas needing future research. These potential follow-on studies or investigations are:

- to minimize the effect of spatial heterogeneity, more replications are needed for tree water-use measurements. This is limited by time and cost but is essential in accurately representing a larger stand area;
- water-use measurements of grassland dominated riparian areas would contribute to water-use comparisons where this is the natural vegetation type;
- spatial estimates of total evaporation are required but are difficult to obtain in remote areas with limited aerodynamic fetch. Sites permitting, window periods using total evaporation techniques should be used to validate sap-flow techniques and assist in stand upscaling;
- remote sensing should be investigated for spatial extrapolation and derivation of input parameters such as LAI and ET distribution;
- management dynamics play an important role in the temporal distribution of water-use. Management practices need to be identified and investigated to assist in understanding water-use results and to reduce the uncertainty in the modelling of water-use; and
- the Maputaland Coastal belt has been identified as an area of priority for research by the Department of Water and Sanitation (DWS) and the Department of Economic Tourism and Environmental Affairs (EDTEA). A strong focus on groundwater modelling coupled with tree water-use, meteorological techniques and management practices should be considered if any work continues in the area.

CHAPTER 8. APPENDICES

Appendix 1. Modified wiring of a CR1000 logger for the HPV system



Wiring Diagram for new HPV system			
AM16/32B Tree 1 Tree2 Tree 3 **Tree 4**			
Orange/Grey	1H 5H 9H **13H**	Yellow/red	17H 21H 25H **29H**
Orange	1L 5L 9L **13L**	Yellow	17L 21L 25L **29L**
Grey/blue	2H 6H 10H **14H**	White/red	18H 22H 26H **30H**
Grey	2L 6L 10L **14L**	White	18L 22L 26L **30L**
Blue/black	3H 7H 11H **15H**	Green/red	19H 23H 27H **31H**
Blue	3L 7L 11L **15H**	Green/blue	19L 23L 27L **31L**
Red/blue	4H 8H 12H **16H**	Yellow/blue	20H 24H 28H **32H**
red/black	4L 8L 12L **16L**	Yellow/green	20L 24L 28L **32L**
Odd on 16/32 Cu wire		CR1000 Diff 3H,3L	
Even on 16/32 Cu wire		Cr1000 Diff 4H,4L	
Res		C1	
Clk		C2	
+12V		12V	
Gnd		G	

Set multiplexer to 4 by 16 mode

CR1000	
Red	C3 (C4, C5, C6 for box 2,3 & 4 respectively)
Pink	Diff 1H,1L,2H,2L (T1,T2,T3,T4)
Purple	AG
Turquoise	VX2 (all boxes wired into this port)
Black	AG

Heater Enclosure on Tree 1	
Orange/Grey	1H
Orange	1L
Yellow/red	2H
Yellow	2L
Grey/blue	3H
Grey	3L
White/red	4H
White	4L
Blue/black	5H
Blue	5L
Green/Red	6H
Green/blue	6L
Red/blue	7H
Red/black	7L
Yellow/blue	8H
Yellow/green	8L

This can be a little confusing depending on the direction the board is facing. Normally delivered with numbering from right to left. confirm that 1H & 1L on enclosure match on the multiplexer

On Heater Enclosure Board

Red (heavy wire)	Bat + ve in red Koki on green blocks	2 pairs connectors on top of board
Black (" wire)	Bat – ve in red Koki	
Red	+ (from C3..6 on CR1000)in red Koki	
Black	G (Any AG from CR1000) in red Koki	
Pink	HI	Connectors on right side of board
Purple	AG	
Turquoise	EX	

Appendix 2 Theory behind the Stem Steady State Energy Balance (SSS) after Taylor *et al*. (2013), WRC –Project K5/2275//4.

Continuous constant heat is applied to the whole circumference of the stem and the mass of sap flow is obtained from the balance of the fluxes of heat into and out of the heated section of the stem (Baker and van Bavel 1987) by accounting for conduction both vertically upwards and downwards (axially) through and radially from the stem and heat stored in the plant limb. The theory is presented according to Savage *et al*. (2000). The heat component convected in sap can then be determined as follows:

$$E_{sap} = E_{heater} - E_{axial} - E_{radial} - E_{storage} \quad (11)$$

Sap flow (kg s^{-1}) can then be determined from sap convection energy (J s^{-1}), the sap specific heat capacity (J kg^{-1} K^{-1}) and the temperature difference between the above and below heater, as follows:

$$M_{sap} = \frac{E_{heater}-E_{axial}-E_{radial}-E_{storage}}{C_w \times dT_{stem}} \quad (12)$$

where

$$E_{sap} = C_w \times dT_{stem} \times M_{sap} \quad (13)$$

and where C_w is the specific heat capacity of sap, assumed to be the same as that for water (4186 J kg^{-1} K^{-1}), dT_{stem} (K) is the mean sap temperature difference (frequently assumed from measurements on the stem surface) between the two pairs of vertical point, each upstream and downstream of the heater and M_{sap} is the sap flow (kg s^{-1})

The heat energy supplied by the heater is calculated from the potential difference (V_{heater}) and electrical resistance (R_{heater}) across the heater

$$E_{heater} = \frac{V_{heater}^2}{R_{heater}} \quad (14)$$

The radial component (E_{radial}) can be calculated from the thermopile measured voltage difference ($V_{thermopile}$) between the inner and outer surfaces of the cork layer surrounding the heater using a proportionality constant which is usually the effective thermal conductance of the sheath materials making up the gauge (K_{gauge})

$$E_{radial} = K_{gauge} \times V_{thermopile} \quad (15)$$

K_{gauge} can be calculated from heat transport theory under conditions of zero sap flow (Baker and van Bavel 1987). Zero flow conditions are assumed to occur before dawn (Steinberg *et al*. 1989), but sap flow can occur at night and therefore care must be taken when calculating this term.

The heat energy balance term to describe heat storage is described by:

$$E_{storage} = V\rho C_p \frac{\Delta T}{\Delta t} \tag{16}$$

where V is the heated segment volume (m^3), ρ is the density of the stem (kg m^{-3}), C_p is the stem specific heat capacity (J kg^{-1} K^{-1}) and $\Delta T/\Delta t$ is the rate of temperature change in the stem (K s^{-1}).

The vertically conducted (axial) energy flux can be determined using the potential difference between two thermocouples (A and B), such that:

$$E_{axial} = \left(\frac{V_{thermocouple\ A} - V_{thermocouple\ B}}{S \times dz}\right) \times A_{stem} \times K_{stem} \tag{17}$$

where S (µV K^{-1}) is the Seebeck coefficient for copper-constantan thermocouples, dz (m) is the distance between the thermocouples, A_{stem} is the stem area (m^2) and K_{stem} is the stem thermal conductivity (W m^{-1} K^{-1}).

Practically dT_{stem} is measured by the same thermocouples (A and B) used to measure E_{axial} as follows:

$$dT_{stem} = \frac{\left(\frac{V_{thermocouple\ A} + V_{thermocouple\ B}}{2}\right)}{S} \tag{18}$$

It is critical to ensure good thermal contact between gauge and the stem and therefore the stem where the heater collar is installed needs to be as straight as possible, without swelling or lumps (Smith and Allen 1996). In addition, silicone-grease should be placed on the stem prior to installation to ensure good contact, to allow slippage of the gauge during installation, to prevent water and condensation from accumulating between the stem and gauge and to allow movement of the gauge with expansion and contraction of the stem. Careful monitoring of the stem for any constrictions is required if the gauges are left on stems for long periods of time. It is important that water is prevented from entering the set-up as it can cause considerable damage to the electrical components. Due to the convoluted nature of citrus stems this technique will not be suitable and will not be evaluated in this study.