

**AN ASSESSMENT OF THE WATER USE OF INDIGENOUS
AND INTRODUCED TREE SPP. AND VARYING LAND USES
AROUND VASI PAN, MAPUTALAND, KWAZULU-NATAL**

by

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PREFACE

The research contained in this dissertation 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.

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.

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DECLARATION OF PLAGIARISM

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ABSTRACT

An important aspect of water resource management, is having accurate estimates of total evaporation, as this information can assist water resource managers and local communities in the decision-making process, when determining the best land use practices for the area. Along the Maputaland Coastal Plain, plantations, increased agricultural activities and the expansion of human settlements have reduced the impact of fire in this historical grassland area and has resulted in increased woody vegetation systems. These activities have impacted the ground and surface water in the region, and therefore, it is vital to understand how water use of the area has changed in comparison to the original Maputaland woody grassland vegetation mosaic. In recent years groundwater levels have dropped and limited research has been conducted in the Zululand area to determine the extent to which afforestation and changes in land use have contributed to the decline. The land uses identified in the Vasi Pan area were *Pinus elliottii* and *Eucalyptus grandis* plantations, indigenous forests and hygrophilous grasslands. The water use of the selected species and land uses were monitored, using the heat pulse velocity technique and eddy covariance system. Water use of all the trees monitored was greater in the wet summer than in dry winter seasons and water use was found to be either water- or energy-limited. The indigenous trees were semi-deciduous and average water use peaked in summer (10 L.day^{-1}) and declined with the onset of winter (4.7 L.day^{-1}). The average water use of the pine and eucalyptus trees was 11.4 and 18 L.day^{-1} in summer, respectively. In winter, the water use of the pine (4.7 L.day^{-1}) and large eucalyptus (4.8 L.day^{-1}) trees was water-limited, as the trees experienced reduced transpiration rates and stomatal closure during extended dry periods and transpiration rates increased rapidly in response to rainfall. The water use of the small eucalyptus trees planted on the edge of the Vasi Pan North wetland, were energy-limited and water use declined as a result of seasonal changes in solar radiation and did not respond to winter rainfall. This indicated that the small eucalyptus trees were abstracting water from the groundwater table during dry periods. There was an error in the total evaporation data collected at the hygrophilous grassland site and therefore, the results were excluded from the study. The placement of plantations is critical to determining whether a tree will be water- or energy-limited, and further research is needed to determine the interactions between the small eucalyptus and groundwater table. The data from this study can be used to improve the accuracy of hydrological models and assist in determining the impact of forestry in the Zululand area.

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1. INTRODUCTION

South Africa is generally a country in which water resources are scarce and not evenly distributed across the land (Jarman *et al.*, 2009). This makes water a limited resource throughout South Africa and there is thus a diverse group of water resource consumers competing for a share of it. Over the years, agriculture and forestry have faced increased competition for water from industries, municipalities and other groups (Jarman *et al.*, 2009). There is an ever-growing demand for water, therefore it is important that water resource managers improve and implement management procedures and policies correctly and efficiently (Jarman *et al.*, 2009). In order to improve water resource management practices, one needs to be able to accurately estimate evapotranspiration and understand how it affects water resources across both temporal and spatial scales.

Evapotranspiration (ET) is an integral part of the hydrological cycle and globally accounts for 60 % of the average precipitation (Li *et al.*, 2009). Accurate estimates are needed for many field and modelling applications; however, measurements are often lacking (Scott-Shaw *et al.*, 2016). Numerous techniques that have been developed for estimating ET and, subsequently, for water use. These techniques can measure ET at a range of scales, from individual tree measurements to landscape and regional estimates (Verstraeten *et al.*, 2008). Small-scale ET measurements provide detailed ET estimates, which can be used to improve large-scale ET measurements (Shuttleworth, 2008; Verstraeten *et al.*, 2008). Each technique has a number of advantages and disadvantages and appropriate ET measurement techniques must be chosen, depending on the needs of the specific research.

South Africa has a relatively large forestry industry, which contributes to the economy and job creation. Research has shown that water resource impacts are greater for dry-land cultivation activities, such as forestry, than for natural vegetation (Everson *et al.*, 2011). Therefore, forestry has been declared a Streamflow Reduction Activity (SFRA) in the National Water Act of South Africa (NWA, Act No. 36 of 1998). The forestry industry introduced tree species that have been found to use more water than the indigenous tree species (Dye *et al.*, 2008). Many of these introduced tree species have spread into the surrounding natural ecosystems and pose a threat to the functioning of the natural ecosystems, particularly in the riparian zones (Richardson, 1998). To gain an understanding of the hydrological impacts of a specific plant species or

vegetation systems, it is vital to obtain accurate estimates of plant water use (Everson *et al.*, 2011).

1.1 Justification

The Maputaland Coastal Plain makes for an interesting study area because it has a unique hydrological system that is largely dependent on groundwater for its supply of water. The dominant land use in the area are commercial forestry plantations of pine and eucalyptus species. These provide a significant source of income for the surrounding local communities. It is important for understanding the impact of plantation species on a catchment's hydrology, particularly in a water-scarce system. Along the Maputaland Coastal Plain the planting of plantations, the increased agricultural activities and the expansion of human settlements have reduced the natural impact of fire in historical grassland areas and have resulted in increased woody vegetation systems. These activities have impacted the ground and surface water in the region (Rawlins, 1991; Kelbe and Germishuyse, 2010; Vaeret *et al.*, 2009; Kelbe *et al.*, 2014). Lake Sibhya has seen a 4 m drop in water levels from 2001 to 2010 (Smithers *et al.*, 2017). The major cause of this decrease was due to below average rainfall being received over the period 2001 to 2011, although nearly 1.4 m of the drop in the lake level can be attributed to the impact of afforestation which began in the catchment in the 1990's (Smithers *et al.*, 2017). Therefore, it is vital to understand how the water use of fast-growing introduced species used in forestry plantations, as well as the expanded woody cover of indigenous species, have changed, in comparison to the original Maputaland woody grassland vegetation mosaic. This information can be used to assist decision makers and local communities in the decision-making process, when determining the best land use practices for the area (Everson *et al.*, 2011).

1.2 Hypothesis

The introduced species used in plantations will use more water than the indigenous tree species, and both the indigenous and introduced tree species will use more water than the grasslands.

1.3 Aim

The aim of this research was to determine the water use of the dominant land uses (vegetation systems) and tree species in the Vasi Pan area at two spatial scales of observation.

1.4 Objectives

The objectives ~~It was the aim~~ of this study were:

- i) to determine the individual tree water use of dominant indigenous species and plantation species, using sap flow measurement techniques;
- ii) to determine the water use of the dominant land uses (vegetation systems) in the Vasi Pan area, using the eddy covariance technique;
- iii) to calculate reference evaporation, using the FOA56 Penman-Monteith model; and
- iv) to derive crop coefficient for the dominant land uses (vegetation systems) monitored during the study.

2. LITERATURE REVIEW

2.1 Understanding the Fundamental Concepts of Evapotranspiration

Evapotranspiration (ET) forms an integral part of the hydrological cycle and is vitally important for understanding its role in this complex system, when determining water management practices. The term evapotranspiration describes water loss from the earth's surface to the atmosphere, by the combined processes of evaporation, with water originating from a wide range of sources, such as open water bodies, bare soil and intercepted canopy water, and transportation from vegetation and other living surfaces containing moisture (Li *et al.*, 2009; Verstraeten *et al.*, 2008, Fisher *et al.*, 2017). There are several factors affecting ET and different types of ET are measured, using a variety of methods. It is therefore important to understand the theoretical foundation of ET.

2.1.1 Theoretical foundation

Evapotranspiration over land is comprised of three individual components, including evaporation from the soil, transpiration by plants and evaporation from the water intercepted by the plant canopy and litter layer (Kool *et al.*, 2014). Transpiration relates to plant productivity, while evaporation does not directly contribute to plant production (Kool *et al.*, 2014). The process of ET is governed by the heat and energy exchanges occurring at the earth's surface, and it is limited and controlled by the availability of energy, as well as the water and pressure gradient between the evaporating surface and the atmosphere (Hemakumara *et al.*, 2003; Mutiga *et al.*, 2010).

Evaporation is the physical process of transferring water, stored in a variety of sources, to the atmosphere. Transpiration is a bio-physical process, in which water is evaporated from the vascular system of plants through the leaf stomata, which is controlled by the opening and closing of guard cells (Verstraeten *et al.*, 2008). The process of ET represents mass and energy fluxes and evaporation can be quantified by using water or energy balance equations. These equations are considered to be conservation equations, where the components of evaporation are calculated as a residual of the budget of a set system (Kool *et al.*, 2014). The outcome of the equations is impacted by the size and time-scale of the set system. The water balance equation is the sum of the inputs and the outputs (Kool *et al.*, 2014), which can be seen in the equation below:

$$ET = P + I + R + D + \Delta S \quad (2.1)$$

where P is precipitation, I is irrigation, R is runoff, D is drainage and ΔS is the change in soil water storage. This is a practical tool for estimating ET on a large scale (Hillel, 1998).

The shortened energy balance equation is commonly used in evaporation studies (Drexler *et al.*, 2004) to describe the partitioning of energy at the earth's surface (Clulow *et al.*, 2015)

$$R_n = LE + H + G \quad (2.2)$$

where R_n is net radiation, H is sensible heat flux, G is soil heat flux and LE is the latent heat flux. Incoming solar radiation drives the energy balance of a system. The shortened energy balance equation does not account for energy associated with the photosynthesis, respiration and that which is stored in a plant's canopy. These components are considered small in comparison to the others (Thom, 1975).

2.1.2 Types of evapotranspiration

Three types of ET are measured, namely, potential, reference and actual evapotranspiration (Abouali *et al.*, 2013; Li *et al.*, 2009). The concept of potential evapotranspiration (ET_p) was introduced by Penman (1948). It provides an estimate of the total capacity of the energy available to evaporate water from the vegetation cover into the atmosphere, which is unlimited by the water and nutrient supply and is in a state of full physiological activity (Allen *et al.*, 1998; Abouali *et al.*, 2013; Irmak and Haman, 2003). Reference evapotranspiration (ET_o) is the amount of water evaporated from a reference crop (commonly short grass) under the prevailing meteorological conditions (Abouali *et al.*, 2013; Verstraeten *et al.*, 2008). Actual evapotranspiration (ET_a) is the real or actual state of water use in a system and ET_a is the most accurate measurement for determining the role of ET in the hydrological cycle. However, it can be difficult to measure, as direct measures of ET_a over a large spatial and temporal scale, as in field monitoring, can be costly (Mutiga *et al.*, 2010).

2.1.3 Factors affecting evapotranspiration

As previously mentioned, the process of ET is governed by the heat and energy exchanges occurring at the earth's surface, and it is limited and controlled by the availability of energy, water and the pressure gradient between the evaporating surface and the atmosphere (Mutiga *et*

al., 2010, Fisher *et al.*, 2017). There are a number of factors that affect the rate of ET, including solar radiation, wind speed, vapour pressure deficit, stomatal conductance, leaf area index and air temperature (Li *et al.*, 2009), and there are basic meteorological and plant factors that affect plant water uptake. An increase in solar radiation increases the atmospheric water demand. This creates a greater vapour pressure gradient between the atmosphere and the evaporative surface, resulting in increased evapotranspiration rates (Verstraeten *et al.*, 2008). An increase in atmospheric temperature has the same effect on the ET rate. This is because, for every 10 °C increase in temperature, the atmosphere can hold double the amount of water (Verstraeten *et al.*, 2008). A high atmospheric relative humidity causes a less steep potential gradient and this lowers the transpiration rate (Li *et al.*, 2009; Verstraeten *et al.*, 2008). Greater wind velocities cause an increase in transpiration because they reduce the boundary layer thickness, and the relative humidity in the boundary layer is considered to be 100 % (Verstraeten *et al.*, 2008). Plant factors can affect the water uptake and transpiration rate. The root depth can affect water uptake, as deeper roots have the potential to access groundwater. Transpiration is regulated by the stomata in the leaves. Stomatal conductance is mostly affected by light and moisture levels (Verstraeten *et al.*, 2008). The leaf area index is the ratio of the plant leaf area to the leaf area projected on a field (Verstraeten *et al.*, 2008). Therefore, a larger leaf area index on a whole plant results in a higher transpiration rate (Li *et al.*, 2009; Verstraeten *et al.*, 2008), if not water limited.

2.1.4 Importance of evapotranspiration

The energy transport system and water cycle in the biosphere, atmosphere and hydrosphere are controlled and governed by the role of ET in the system's dynamics. Evapotranspiration is therefore of great importance for understanding the role it plays in hydrology, meteorology (Miralles *et al.*, 2014; Vergopolan and Fisher, 2016) and agriculture (Allen *et al.*, 1998; 2011) in predicting and estimating regional-scale surface runoff and groundwater (Li *et al.*, 2009). Globally, 60 % of the average precipitation is accounted for by the mean land surface ET (Li *et al.*, 2009). This statistic indicates that reliable ET estimates are important, when determining water management practices relating to the prediction of natural hazards, such as floods, droughts (Anderson *et al.*, 2013; Otkin *et al.*, 2016) and climate change (Dai *et al.*, 2004; Sheffield *et al.*, 2012; Greve *et al.*, 2014; Prudhomme *et al.*, 2014; Mao *et al.*, 2015). Land surface ET is considered to be a vital component in water cycle modelling. However, little is known about this component of the hydrological cycle, compared to its other aspects. Research

that aims to improve ET measurements, at various scales, is of utmost importance for improving the accuracy of hydrological models.

2.2 A Brief Review of Evapotranspiration Measurement Techniques

A number of methodologies have been developed to measure ET, or components of ET, such as transpiration, soil evaporation and interception, which occur at a variety of spatial scales, from single plants to entire watersheds (Wilson *et al.*, 2000). These estimates of ET can be used to understand plant water use. The methodologies used to assess ET are of a complex nature, because ET has spatial and temporal dimensions and it is essential to account for the interactions between them (Bastiaanssen *et al.*, 1998; Verstraeten *et al.*, 2008). Spatial variation in ET can be attributed to the changes in plant water availability, soil water content, vegetation type and coverage, as well as soil types across a landscape (Makkeasorn *et al.*, 2006; Verstraeten *et al.*, 2008). ET is a hydrological process that is reliant on meteorology and climate, and this accounts for its spatial and temporal variability (Verstraeten *et al.*, 2008). As previously mentioned, ET is the “process whereby water is transferred from the soil and/or the vegetation layer to the atmosphere” (Kalma *et al.*, 2008). This physical process has three requirements, namely, a source of water, a source of energy and a vapour sink. On a physical basis, the methods for assessing evaporation have been broadly classified as mass budget methods, energy budget methods (equation (2.1)) and methods based on the measurement of mean profiles and atmospheric turbulence (Kalma *et al.*, 2008).

The selection of a specific method for research is reliant on the location of the research, the physical characteristics of the vegetation to be measured and the time and funding available for undertaking the research (Scott-Shaw *et al.*, 2016). The common methods that are used to estimate or measure vegetation water use are sap flow measurement, micrometeorological methods, modelling approaches and remote sensing. Each method has a number of advantages and disadvantages, which can be dependent on the site characteristics and requirements (Scott-Shaw *et al.*, 2016). These different methods of estimating ET can be categorized further, according to the scale of observation. The estimation of ET can be measured at the scale of an individual plant (sap flow), at a landscape scale (eddy correlation, scintillometry) and at a regional scale (remote sensing e.g. the Surface Energy Balance System (SEBS)) (Shuttleworth, 2008; Verstraeten *et al.*, 2008) (Table 2.1).

2.2.1 *Level of observation: individual plant*

Measuring the *in situ* sap flow in the xylem has been used for decades to study plant water relations in individual plants (Swanson, 1994). Sap flow measurements are used to estimate the transpiration rate of plants. Models are used to scale up transpiration measurements in order to represent the evapotranspiration rates of whole fields or canopies, including soil evaporation (Kool *et al.*, 2014). The original techniques involved tracers of sap flow in the roots and stems, by using dyes (James and Baker, 1933; Kramer, 1940). However, these methods involved cutting the plant and therefore an alternative method was first used by Huber in 1932, using heat as a non-invasive tracer to measure sap flow. Over the years, the use of heat pulse methods has evolved and been refined, and current techniques are now largely based on the conduction and convection of heat in the xylem tissue (Burgess *et al.*, 2001; Vandegehuchte and Steppe, 2013). These thermometric techniques are classified into three broad categories. The first technique is where the movement of a short heat pulse is traced in the sap stream. The second technique uses a controlled heat source, where heat that is moving away from the source is measured. The third, and least common, technique involves an empirical relationship that relates heat dissipation to sap flow (Burgess *et al.*, 2001). These measurement techniques can be categorized as the heat pulse, heat balance and constant heat methods (Kool *et al.*, 2014). There are a number of methods within each category and the four most commonly-used methods are briefly discussed below. Several variations on the discussed methods do exist in the literature; however, for the sake of brevity, they are not included here.

2.2.1.1 Heat pulse methods

Curves indicating a temperature response, after a short pulse of heat from a probe is placed in the stem, can be used in heat pulse methods to quantify and calculate sap flow. It is assumed that the time delay of the temperature rise is proportional to the sap flow velocity (Kool *et al.*, 2014). The instrumentation of the heat pulse method is simple and the system has low power requirements, making it a commonly-used method (Burgess *et al.*, 2001). Of these methods, the compensation heat pulse method (CHPM) has been the most extensively used method in numerous fields of study, such as hydrology, forestry and agriculture (Edwards *et al.*, 1997). However, the development of the heat ratio method (HRM) by Burgess *et al.* (2001), which has certain advantages and overcomes some of CHPM shortcomings, has gained popularity.

The theoretical construction for converting the heat pulse velocity (V_h), measured by CHPM into quantifiable sap flow rates, is well developed and has been reviewed, in detail, in papers such as by Swanson and Whitefield (1981) and Smith and Allen (1996). In brief, the CHPM requires two probes containing thermocouples to be inserted to equal depths into the sap-wood. The temperature probes are placed asymmetrically above and below, at a fixed distance from the line heater, which is placed at the midpoint of the temperature probes. The heat pulse moves through the sap stream via convection. The time it takes for the heat pulse to travel from the midpoint to the temperature probes is recorded and indicates the sap flow velocity (Bleby *et al.*, 2004; Burgess *et al.*, 2001). The heat-pulse velocity is calculated by using the equation below (Burgess *et al.*, 2001):

$$V_h = \frac{x_d + x_u}{2t_0} 3600 \quad (2.3)$$

where V_h is heat-pulse velocity ($\text{cm}\cdot\text{h}^{-1}$), t_0 is the time taken for the upstream and downstream probes to reach thermal equilibration after the release of a heat pulse, x_d and x_u are the distances (cm) of the temperature thermocouples upstream and downstream from the heater probe. Because x_u is located on the opposite side of the heater probe, in relation to x_d , it is assigned a negative value.

An advantage of the CHPM is that it is independent of thermal diffusivity; however, due to the way the equation was developed, the length of the heat pulses impacts the measured V_h . The underestimation of V_h increases as the pulse length increases (Vandegheuchte and Steppe, 2012). One of the greatest limitations of the CHPM is that it overestimates the low and zero rates of sap flow (Becker, 1998). This is because the heat pulse may dissipate before reaching the measurement point, during periods of low flow. This will cause temperature sensors to record equal temperatures, because the temperatures will have returned to their original value (Burgess *et al.*, 2001). The development of the HRM allows one to determine the sap flow direction and to measure the low flow rates accurately.

The HRM developed by Burgess (2001) has a similar set up to the CHPM; however, the temperature probes are set at equal distances, downstream and upstream from a line heater. Unlike the CHPM, which measures V_h as the distance travelled over time, the HRM measures the ratio of the increase in temperature at equidistant points, following the release of the heat

pulse (Bleby *et al.*, 2004; Burgess *et al.*, 2001). Calculations for heat pulse velocity are based on Marshall (1958):

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) 3600, \quad (2.4)$$

Where k is the thermal diffusivity of green (fresh) wood ($2.5 \times 10^{-3} \text{ cm}^2 \cdot \text{s}^{-1}$), x is the distance (cm) between the heater and each temperature probe, and v_1 and v_2 are the increase in temperature (from the initial temperatures) at equidistant points downstream and upstream, respectively, x cm from the heater. By knowing the sapwood basal area, one can convert sap flow velocities into transpiration rates (Verstraeten *et al.*, 2008). When scaling up sap flow measurements to tree level, the tree characteristics, such as stem diameter and height, must be known.

The accuracy of data from heat pulse techniques are very sensitive to the inaccurate placement of the probes, therefore one must correct for probe misalignment. Once the probes have been removed, an assessment of the probe misalignment can be carried out. Metal pins are placed in each hole and the measurements of the spacing and angle of the protruding ends of the metal pins are taken. Simple trigonometry can be used to calculate the placement of the thermocouple probes within the sapwood (Hatton *et al.*, 1995). When correcting for probe misplacement in the HRM, one uses the method detailed by Burgess *et al.* (2001), which is based on the correction of measurements, using an empirical test of zero bias. The baseline V_h , which corresponds to zero sap flow, was measured after the completion of the experiment, by cutting the tree stems and continuing to measure sap flow for several hours afterwards. When using *in situ* sap flow measurement techniques, one must correct for wounding.

When installing the probes, the drilling of holes into the xylem tissue can cause considerable mechanical damage and disrupt sap flow pathways. Corrections are therefore necessary to account for wounding. This can be done by using algebraic equations and is represented by equation 2.5 for CHPM (Swanson and Whitfield, 1974):

$$V_C = a + bv_h + cv_h^2, \quad (2.5)$$

where, v_c is the corrected heat pulse velocity, v_h is heat pulse velocity (equation (2.3) and $a-c$ are correction coefficients specific to wound size that are generated using a finite-difference numerical model.

This is also represented by equation 2.6 for HPV (Burgess *et al.*, 2001):

$$V_c = bv_h + cv_h^2 + dv_h^3 \quad (2.6)$$

where, v_c is the corrected heat pulse velocity, v_h is heat pulse velocity (equation (2.3) and $b-d$ are the correction coefficients specific to the size of the wound (x), which was developed from a new numerical model developed by Burgess *et al.* (2001).

The HRM has proven that it can provide relatively accurate measurements of the reverse and low flows. However, this method has been proven to be limited in its ability to measure high sap flux densities ($>45.\text{cm}^3.\text{cm}^{-2}.\text{h}^{-1}$) (Blelby *et al.*, 2008, Vandegehuchte and Steppe, 2013). In South Africa, the HRM has been proven to be accurate for measuring the water use of alien invasive species, such as *Acacia mearnsii*, and indigenous tree species, such as *Podocarpus henkelii* (Dye *et al.*, 2001; Everson *et al.*, 2007; Dye *et al.*, 2008, Scott-Shaw *et al.*, 2016). Limited research is available on the use of the HRM measure of ET in indigenous woody monocots, such as palm species, which form part of the natural vegetation in the study area. The available research focuses on agricultural crop species (Madurapperuma *et al.*, 2009). Heat pulse methods provide an approach for estimating individual tree water use and are an alternative for measuring forest/woodland transpiration in complex heterogeneous terrain (Scott-Shaw *et al.*, 2016).

2.2.1.2 Heat balance method

Heat balance methods can be used to measure the mass flow of water, which pertains to the energy budget of energy input into the stem and the ensuing energy losses (Kool *et al.*, 2014). Of the heat balance methods, the Stem Steady State heat energy balance (SSS) technique is well developed and commonly used. The SSS technique (Sakuratani, 1984), can be used to estimate sap flow by calculating the heat balance for a portion of the stem that is supplied by a continuous and known amount of heat. The amount of heat conducted in the sapwood is calculated as the difference between the amount of heat released and the sum of the conductive heat lost (Grime

and Sinclair, 1999; Scott-Shaw *et al.*, 2016). The SSS method consists of an insulated collar on an area that has been smoothed around the stem. This insulated collar provides a constant and continuous source of heat that is applied over the total circumference of the stem that is encircled by the heater, in order to create a steady state condition. To maintain a steady state condition, foam insulation and weather shields are placed around the collar and they are extended above and below it. This minimizes the effect of external heating and cooling on the measurements, such as that of the wind and solar irradiation, on the measurements (Savage *et al.*, 2000). A comprehensive description of the methods for calculating sap flow, using the SSS technique, can be found in Savage *et al.* (2000). By applying a constant source of energy, one must account for heat energy flux according to the conservation of energy. The components of heat energy flux may be conducted vertically upward, downward or radially outwards through the stem, and heat is stored in the plant limb. These are assumed to be the components of energy loss. The heat component that is transported in sap can be calculated using (Savage *et al.*, 2000):

$$E_{sap} = E_{heater} - E_{axial} - E_{radial} - E_{storage} \quad (2.7)$$

Sap flow ($\text{kg}\cdot\text{s}^{-1}$) can be determined from a quotient of the sap convection energy component ($\text{J}\cdot\text{s}^{-1}$) and the product of sap specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) and the temperature difference above and below the heater (Savage *et al.*, 2000). The sapwood basal area is used to convert sap velocities into transpiration rates (Verstraeten *et al.*, 2008).

The advantages of this method is that it is non-invasive, it can be used on both woody and herbaceous plants, as well as multi-stemmed plants, it provides a symmetrical representation of the sapwood area and it is easy to install (Scott-Shaw *et al.*, 2016). Some of the disadvantages of the SSS technique are that the equipment has a high power requirement, the size of the collars can limit the measurements being taken on larger trees and, during high sap flow conditions, sap flow measurements are overestimated (Scott-Shaw *et al.*, 2016, Jarman *et al.*, 2009)

2.2.1.3 Constant heat method

Constant heat methods quantify sap flow velocity from a constant heat source, based on temperature dissipation. These sap flow values are then scaled up to calculate transpiration for the plant (Kool *et al.*, 2014). A commonly-used constant heat method that is used and widely applied is a thermal dissipation (TD) probe. This is because it has a high level of accuracy, it has a simple set up, it is reliable, and it comes at a relatively low cost (Lu *et al.*, 2004). This

method was developed by Granier (1985; 1987), who based his work on the findings of Vieweg and Ziegler (1960). The TD method is an empirical method that uses heat dissipation to measure the sap flux density in trees. It enables one to estimate low, average and high sap flux densities, but it requires zero flow conditions for the calculations. The set-up for the TD method requires two probes to be inserted radially into the stem, with the upper probes containing a line heat source. The upper probe is supplied with a constant electric voltage, providing a constant current through the heater, and the difference between the two probes is monitored (Lu *et al.*, 2004). The method relates the temperature difference between the probes to sap flux density (SFD) ($\text{m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). Heat dissipates more rapidly when sap flux density increases. This is based on an experimental regression for three species (*Pseudotsuga menziesii* and *Pinus nigra* and *Quercus pedunculata*) (Vandegehuchte and Steppe, 2013). This leads to issues with the underestimation of the SFD, when one compares estimates with values that are calculated from other methods. Therefore, the original equation was corrected (Vandegehuchte and Steppe, 2013) :

$$\Delta T_{sw} = \frac{\Delta T - b\Delta T_m}{a} \quad (2.8)$$

with ΔT_{sw} being the corrected temperature difference for the portion of the heated probe within the conductive sapwood, ΔT_m is the temperature difference for the portion of the probe in the inactive xylem (assumed to be equal to ΔT_0), and a and b is the proportion of the length of the heated probe in contact with the sapwood and inactive xylem, respectively. However, this correction technique requires an accurate estimation of the position of the boundaries between the active and inactive xylem covered by the probe, and this requires destructive measurement techniques.

For the accurate estimation of the SFD, species-specific calibrations are necessary to determine the empirical relationship between the measured temperature ratio and the SFD (Vandegehuchte and Steppe, 2013). The TD method calculations are dependent on zero flow occurring; however, in practice, zero flow is not reached because of the water uptake for vegetative and reproductive growth, as well as the replenishment of the internal water storage during the night (Zweifel and Häsler, 2001). High wind speeds, in combination with high water vapour pressure deficits, can also cause night-time water loss (Snyder *et al.*, 2003).

2.2.2 Level of observation: Landscape

The point measurements of ET, at the scale of individual plants, only measure transpiration, but it is important to consider the input from soil and canopy evaporation, when determining total ET (Verstraeten *et al.*, 2008). Landscape measurements allow for ET to be measured over a greater scale and they consider combined evaporation and transpiration inputs. Landscape measurements also have the advantage of being able to obtain ET data from a heterogeneous landscape and add value for the improvement of hydrological models (Kool *et al.*, 2014).

2.2.2.1 Eddy Covariance method

The eddy covariance method (EC), which was developed by Brutsaert (1982), is a technique that was established to determine evaporation, using the very high frequency measurements (10-20 Hz) of water vapour and CO₂ above a canopy. Above aerodynamically rough vegetation, eddies of air can be important drivers of gas exchange; therefore, frequent measurements can indicate gas concentrations within these eddies (Dye *et al.*, 2008). The EC system is reliant on the shortened energy balance approach and requires estimates of all the components of the energy balance equation (Gush *et al.*, 2015). The EC method is a standard and direct measurement for measuring evaporation rates in real time. This method is governed by equation 2.9 for turbulent exchange (Brutsaert, 1982):

$$ET = p_a \overline{wq}, \quad (2.9)$$

where ET is in kg.m⁻².s⁻¹, p_a is the air density, w is the vertical wind velocity, q is the specific humidity and the over bar indicates the mean value of a suitable period.

The system requires a sonic anemometer, to measure 3-D wind-speed, and an open- or closed-path gas analyser, which can be used to measure the water vapour concentration. The area upwind of the instrument is represented in the measurements, and can be influenced by factors such as wind speed, instrument height and atmospheric stability (Kool *et al.*, 2014).

The EC method is most suited for tall canopies, because the accuracy of the measurements increases, as a result of the increase in turbulence as one moves higher. This method needs a surface that is homogenous, with few disruptions between the instrument height and the surface. One of the advantages of this method is that it represents a large area, ranging from a few

hundred meters to several kilometres, and can take continuous measurements (Wilson *et al.*, 2001). This technique provides a high temporal resolution and great spatial scales for ET estimates, which highlight the vital link between the hydrological and biochemical processes (Scott-Shaw *et al.*, 2016). The disadvantages of the EC method include the fact that it has a limited use in areas with complex terrain and low turbulent periods can cause difficulties in data interpretation.

2.2.2.2 Scintillometry

Scintillometry is a technique that has been developed relatively recently, where measurements are based on the physical principle of the propagation statistics of electromagnetic waves through a turbulent atmosphere (Verstraeten *et al.*, 2008). It uses the theoretical relationship between latent and sensible heat flux and atmospheric scintillation, which is caused by temperature and humidity fluctuations and which is measured by a beam of electromagnetic radiation (Shuttleworth, 2008). The technique measures the path-averaged structure parameter of the refractive index in the air (C_n^2) and is discussed, in detail, by Savage (2009). The small fluctuations in the C_n^2 are caused by small temperature and humidity fluctuations and these turbulence effects are known as scintillations (Dye *et al.*, 2008, Verstraeten *et al.*, 2008). The system consists of an infrared light source that is beamed from transmitters towards receiver devices that are accurately aligned. The infrared beam is affected (attenuated) by temperature fluctuations. The method allows for the calculation of the mean surface sensible heat flux along the light path, together with data on wind speed, air pressure and air temperature. The evaporation rate is equated to latent heat fractions and can be derived from simple energy balance equations (Dye *et al.*, 2008). Scintillometry, using Large Aperture Scintillometers (LAS), is able to provide evaporation estimates over a spatial area of up to 5 km (LAS) and 10 km (XLAS). Other advantages of the scintillometry method are that the instruments are portable, data processing is relatively uncomplicated and the simple design gives reliable results (Dye *et al.*, 2008). Some disadvantages of the scintillometry method include the fact that the direction of sensible heat flux cannot be distinguished without further estimates of atmospheric stability, and highly turbulent conditions cause more severe scattering, when the method is based on the weak scattering of the scintillometry beam (Jarman *et al.*, 2009).

2.2.3 *Level of observation: Regional*

At the larger geographical scale of observation, it is important to consider how the landscape varies over both the temporal and spatial scales. Field measurements provide limited accuracy,

when modelling large geographical (regional) scales, because they provide ET estimates over a small-scale homogenous area, whereas at a large-scale, the land surface is more heterogeneous (Su, 2002; Jarman *et al.*, 2009; Li *et al.*, 2009). The advances in satellite-based remote sensing provide cost-effective methods for mapping regional patterns of ET at large geographical scales (Li *et al.*, 2009).

The use of remote sensing techniques for estimating total evaporation has been improving since they were first introduced in the 1980's. Remote sensing techniques allow one to capture hydro-meteorological data at a large-scale, including relatively inaccessible areas, and they provide time series data, due to the periodic updating of information (Su, 2002; Jarman *et al.*, 2009; Li *et al.*, 2009; Bastiaanssen *et al.*, 2012). There are numerous remote sensing techniques that utilize satellite earth observation data to estimate ET. These techniques can be categorized into the following four broad classes (Courault *et al.*, 2005): (a) empirical direct methods, which integrate satellite earth observation data directly into semi-empirical models; (b) deterministic methods, which are based on Vegetation-Atmospheric Transfer models to determine the different components of the energy budget; (c) vegetation index methods, which employ satellite earth observation data to calculate a reduction factor, for example, the crop coefficient; and (d) techniques based on the parameterisation of the energy balance, by combining empirical relationships with physical modules to estimate ET. Numerous models fall within each class, and one that is of particular interest, as it has been commonly utilized land water use studies, is the Surface Energy Balance System (SEBS) (Li *et al.*, 2009; Su, 2002; Verstraeten *et al.*, 2008).

The SEBS model was developed by Su (2002) and is a satellite-based technique for estimating ET at a variety of scales, land uses and climates (Jarman *et al.*, 2009; Mengistu *et al.*, 2014). It is open-source software that is available from the Integrated Land and Water Information System (ILWIS), which makes it easily accessible. The SEBS model uses remote sensing and meteorological data to determine the turbulent fluxes within the atmosphere or the evaporative fraction at both local and regional scale. The model tools integrate the meteorological and satellite earth observation data to provide an estimate of daily ET (Su 2002). The model tools are used to determine the roughness length of heat transfer, land surface physical parameters and the evaporative fraction (Su, 2002). When calculating daily ET, it is assumed that the evaporative fraction remains constant throughout the day. This calculation is derived from numerous equations, based on a number of parameters that have previously been mentioned. A

detailed account of all the equations can be found in Su (2002). Below is the derived equation from the SEBS model to estimate daily ET (Su, 2002):

$$E_{daily} = 8.64 \times 10^7 \times \Lambda_0^{24} \times \left(\frac{Rn_{24} - G_0}{\lambda p_w} \right) \quad (2.10)$$

where, E_{daily} is daily ET, Λ_0^{24} is the daily evaporation fraction, Rn_{24} is the daily net radiation, p_w is the density of water, and λ is the latent heat of vaporization.

The disadvantages of the SEBS model are that the evaporative fraction is assumed to be constant, when calculating daily ET, there are many parameters needed to run the model and it requires dry and wetland data to determine sensible heat flux (Verstraeten *et al.*, 2008). One of the advantages of the SEBS model is that it calculates spatially represented ET estimates, which account for the heterogeneity of the land surface over increasing geographic scales (Su, 2002). For the SEBS model no prior knowledge of turbulent fluxes is needed, it is an open source software and is therefore, easily accessible and the user interface is relatively simple to use. Therefore, the SEBS model has the potential to be widely used in the decision-making and planning process (Verstraeten *et al.*, 2008).

Each of the techniques for estimating ET has its own set of advantages and disadvantages (Table 2.1). The choice of which technique to use is dependent on the study at hand and it also depends on the vegetation type (e.g. grasslands are more suited to energy balance techniques) and the available budget for equipment. The use of these methods is important for this research, as accurate water use estimates are vital for gaining an understanding of the hydrological impact of a specific plant species or vegetation type (Everson *et al.*, 2011).

Table 2.1: Summary of ET techniques at varying scales of observation

Scale	Technique	Method	Description	Advantages	Disadvantages
Individual plant	Compensation heat pulse method	Heat pulse	<i>In situ</i> measurement of sap flow monitoring the rate of movement of a heat pulse	Independent of thermal diffusivity	Overestimation of low, zero and reverse rate of flow; unable to determine sap flow direction
	Heat ratio method	Heat pulse	<i>In situ</i> measuring of the rate of movement of a heat pulse using a ratio calculation to determine heat pulse velocity in sap flow	Able to determine sap flow direction and measure low flow rates accurately	Measurements sensitive to probe misalignments and wounding; limited in measuring high flux densities
	Stem steady state energy balance	Heat balance	Estimate sap flow by calculating heat balance for a portion of the stem which is supplied a constant heat from an external source surrounding the stem	Non-invasive; simple installation, accurate transpiration estimates; useable for irregular shaped plants	High power requirement; over estimates high sap flow conditions; collar size limits ability to monitor large trees
	Thermal dissipation	Constant heat	An empirical method using heat dissipation from a constant source of heat to measure sap flux density in trees	Estimates high, low and zero sap flow events; reliable and accurate data	Requires zero flow for calculations
Landscape	Eddy covariance	Energy balance	High frequency measurements of water vapour and CO ₂ above a canopy to determine ET	Measurements for a large area, continuous and direct measurements in real time	Limited use in complex terrain; low turbulent period hinder data interpretation
	Scintillometry	Energy balance	Uses the theoretical relationship between latent and sensible heat flux and atmospheric scintillation measured by a beam of electromagnetic radiation	Portable and simple design; range of several kilometres	Inaccurate in high turbulent conditions; unable to determine direction of sensible heat flux
Regional	Remote sensing	Energy/ mass balance	Utilises remote sensing imagery and meteorological data to determine atmospheric turbulent fluxes	Large scale ET estimates; cost effective; monitor inaccessible area; spatial representative	Temporal and spatial resolution is limited by available satellite imagery

2.3 Evapotranspiration Modelling Techniques

There are several evaporation models that can be used to determine the ET_a of a vegetation type. Each model considers the climatic variables of an area. Certain models are more suited to modelling the ET_a for certain surfaces, therefore it is important to choose the correct model for the study area. Two of the most commonly-used evapotranspiration models are the FAO56 Penman–Monteith model and the Priestley-Taylor model.

2.3.1 FAO56 Penman-Monteith reference evaporation

The FAO56 Penman-Monteith model is used to calculate reference evaporation (ET_o) and has taken several years to develop. The model is based on the original Penman evaporation model (Penman, 1948), which assumed that the earth's surface lacked any control over evaporation, for example, a wet surface or open water situation. This model was then extended by Monteith (1965) to include the effects of the surface and aerodynamic resistance functions applicable to vegetated surfaces (Clulow *et al.*, 2015). This model became known as the Penman-Monteith model. The additions to the model increased the accuracy of the results; however, it was highly data-intensive (Mao *et al.*, 2002; Drexler *et al.*, 2004; Clulow *et al.*, 2015). Therefore, the model was standardised into a form known as the FOA56 Penman-Monteith model, by the Food and Agricultural Organisation in Irrigation and Drainage Paper No.56 (Allen *et al.*, 1998). The model has been widely applied internationally, as it calculates ET_o from weather variables measured at most standard weather station systems, at both hourly and daily intervals. The recommended FAO56 Penman-Monteith equation for estimating daily ET_o (mm. day^{-1}) (Allen *et al.*, 1998) may be written as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2.11)$$

where R_n is the net radiation at the crop surface ($\text{MJ.m}^{-2}.\text{day}^{-1}$), G is the soil heat flux density ($\text{MJ.m}^{-2}.\text{day}^{-1}$), T is the air temperature at a height of 2 m ($^{\circ}\text{C}$), u_2 is the wind speed at a 2 m height (m.s^{-1}), $e_s - e_a$ saturation vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve ($\text{kPa.}^{\circ}\text{C}^{-1}$), and is γ the psychrometric constant ($\text{kPa.}^{\circ}\text{C}^{-1}$).

According to Allen *et al.* (1998), a reference crop can be defined as a “hypothetical crop with an assumed height of 0.12 m, having a surface resistance of 70 s.m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered”. The ET_a of a nearby crop can be calculated by adjusting the ET_o by a crop coefficient of (K_c):

$$ET_a = ET_o \cdot K_c \quad (2.12)$$

where the crop is not water stressed. K_c values have been compiled for different vegetation types at different stages in crop development (Allen *et al.*, 1998; Allen *et al.*, 2000; Irmak *et al.*, 2005; Allen *et al.*, 2006).

K_c values have been incorporated as an input into several hydrological and crop-growth models, such as CANEGRO (Inman-Bamber, 1991), ACRU (Schulze, 1995), SWB (Annandale *et al.*, 2003) and SAP-WAT (van Heerden *et al.*, 2009), amongst others. The estimation of crop coefficients is most suitable for uniform agricultural crops and limited research has been conducted using crop coefficients for natural heterogenous vegetation types (Clulow *et al.*, 2012).

2.3.2 Priestley-Taylor potential evaporation

The Priestley-Taylor equation (Priestley and Taylor, 1972) is a simplified version of the Penman model, for specific conditions. It allows for potential evaporation to be calculated in terms of energy fluxes (McMahon *et al.*, 2013). This is because the evaporation potential of air moving over a short, well-watered canopy will eventually reach an equilibrium, causing the effect of aerodynamic resistance to become negligible. Irradiation will dominate and the rate of evaporation will be equal to ET_p (Clulow *et al.*, 2015):

$$ET_p = \frac{\alpha}{L_v} \cdot \frac{\Delta}{\Delta + \gamma} \quad (2.13)$$

where α is a constant, L_v is the specific latent heat of the vaporisation of water (2.45 M.J.kg^{-1}), Δ is the slope of the saturation water vapour pressure versus T_{air} , and γ is the psycho-metric constant.

The Priestley–Taylor model is appropriate for estimating the evaporation of open water areas and wetlands (Price, 1992; Souch *et al.*, 1996; Mao *et al.*, 2002), but it has also been used in numerous studies over other surfaces, such as forests (Shuttleworth and Calder, 1979), cropped surfaces (Davies and Allen, 1973; Utset *et al.*, 2004), pastures (Sumner and Jacobs, 2005) and even soil water limited conditions in forest clear-cuts (Flint and Childs, 1991), with varied success and deviations from the originally proposed estimate for α of 1.26 (Clulow *et al.*, 2015).

2.4 Forestry as a Land Use in South Africa

The rainfall is not evenly distributed throughout South Africa. High rainfall catchments cover a mere 14 % of South Africa's land, but their contribution to the streamflow is vital, producing 53 % of South Africa's mean annual streamflow and 70 % of the country's mean annual low flow (Scott *et al.*, 2000). These catchments are major contributors to South Africa's water resources. Plantations of introduced species are planted over large portions of these high rainfall regions. Forestry, as a land use, covers approximately 1 % of South Africa's land (DAFF, 2017) and makes a valued socio-economic contribution to the country (Chamberlain *et al.*, 2005). Of the land used in forestry, 40.1 % occurs in Mpumalanga, 39.9 % in KwaZulu Natal, 11.6 % in the Eastern Cape, 4 % in Limpopo, and 3.9 % in the Western Cape (DAFF, 2017). In 2013, the South African forestry industry had sales of R20 billion and employed 170 000 workers (Godsmark, 2014). South Africa's commercial forestry plantations are predominantly introduced trees, comprising of 50.6 % pine, 41.8 % eucalyptus, 7.2 % wattle and 0.4 % other, and covering a total of 1 224 456 ha in 2015 (a decrease of 110 000 ha since 2013) (DAFF, 2017).

The South African forestry industry consists of intensively-managed monoculture plantation systems of introduced species. The effect that these systems have on catchment yield has been well documented, both locally and internationally (Bosch and Hewlett 1982; Gush *et al.* 2002; Bruijnzeel *et al.* 2005; Jackson *et al.* 2005; Dye and Versfeld 2007; Scott and Prinsloo 2008; Vanclay, 2009; Mapeto *et al.*, 2017). The introduced tree species used in South African plantations are tall, evergreen, deep-rooted species, which have been genetically improved, for faster growth. They have replaced the natural vegetation, which is often shallow-rooted grasslands and shrubs (Dye and Versfeld, 2007). The physiological differences between the plantations and original vegetation have resulted in an increased total evaporation rate (le Maitre *et al.*, 2015), as well as the ability of plantations species to access soil water reserves in drier months (van Dijk and Keenan, 2007). This indicates that forestry reduces the availability

of water in the catchments. It is for this reason that forestry has been identified as a streamflow reduction activity (SFRA) in the National Water Act (Act 36 of 1998), with the new legislation requiring a licence to practice forestry. SFRA can be defined as “any dryland land use practice that reduces the yield of water (with reference to the yield from natural veld in an undisturbed condition) from that land to downstream users” (Steyl, 1997). The licencing system is an attempt to regulate national forestry activities, particularly in water-scarce catchments, to minimize the effect that forestry has on the natural water resources and reserves, despite the strong demand for wood (Dye *et al.*, 2008). This legislation has resulted in a significant reduction in the afforestation rate over the past two decades (Mapeto *et al.*, 2017). Although commercial forestry benefits the economy, it is widely acknowledged that this form of land use has a significant negative hydrological and environmental impact, at a catchment scale (Dye and Jarman, 2004, le Maitre *et al.*, 2002, Marais and Wannenburg, 2008, de Wit *et al.*, 2002; Mapeto *et al.*, 2017).

2.4.1 The impacts of forestry on the environment

There are many environmental impacts associated with the forestry practices in South Africa, of which the best understood and most widely accepted are their impact on water resources (Versfeld, 1996). Forestry reduces streamflow, which affects the availability of water for other users within a catchment. The National Water Act (Act 36 of 1999) bases the licencing system upon the significant effect of forestry, by identifying it as an SFRA. However, the impact of forestry is far greater than just its impact on water quantity.

The other associated impacts of forestry include the change in water quality, its influence on the groundwater, its impact on the soil, its social impacts and its threat to the biodiversity. Mature trees intercept more precipitation and have greater rates of transpiration. This reduces the total annual runoff, which impacts the water yields in a catchment (Johnson, 1998; Mwendera, 1994). Commercial forestry plantations are a source of non-point source pollution in the water resources (Lesch, 1995). The water quality in streams and rivers is affected by the increasing nutrient input, the increased sediment loads, and the higher concentrations of dissolved salts (Kruger and Everard, 1997). The establishment of plantations impacts the soils, by physically disturbing the soil and altering its properties (Kruger and Everard, 1997). The clearing of natural vegetation, such as grasslands and scrub-bushland habitats, for the introduction of forestry species can affect the properties and functioning of an ecosystem (Richardson, 1998). It alters the vegetation structure, plant diversity, and it displaces the

indigenous flora and fauna of the area (Olbrich *et al.*, 1997). In water-limited environments, invasion by introduced forestry species has the potential to worsen the effects of drought and to impact the water balance of the ecosystems (Dzikiti *et al.*, 2013; Swaffer and Holland, 2015). An issue with forestry plantations of introduced species, is their potential to invade the surrounding natural vegetation and to impact downstream water users and aquatic systems, due to their increased water use. A study by Dzikiti *et al.* (2016) in the Western Cape compared the water use of an invasive *Eucalyptus camaldulensis* stand and the indigenous vegetation after clearing, using remote sensing techniques (SEBAL). *Eucalyptus camaldulensis* used substantially more water than the stand of cleared vegetation. Clearing invasive *E. camaldulensis* stands has the potential to save 2.0 ± 0.3 ML per hectare. Forestry can impact the groundwater levels through direct abstraction by tree root systems, or by impacting the rate of recharge of percolating water to the groundwater table (Jewitt, 2005). Although the development of forestry in an area can have a number of social benefits, such as employment opportunities, there are a number of social costs associated with changes in land use, including the loss of access to water, land and other resources (DWAF, 1997).

Plantations of introduced forestry species have a significant impact on South Africa's water resources, therefore it has been proposed that indigenous forest species should be used in addition to conventional plantation-based systems (Dye *et al.*, 2008; Gush and Dye 2009). These proposals are based, in part, on the assumption that the slow growth rate of indigenous species (Stapleton, 1955; van Daalen, 1991) correlates with a lower water use (Gush and Dye 2009; Wise *et al.*, 2011). However, this claim is relatively unsubstantiated, as information on indigenous trees and forests water use is indirect and scarce (Gush *et al.*, 2015). The need for change in land use practices is more evident, as there is a growing concern that global climatic fluctuations, characterised by extreme dry periods (Warburton and Schulze, 2006) will impact the already limited water resources.

2.4.2 Water use: introduced vs indigenous tree species

Understanding the differences in water use between introduced and indigenous tree species is important for determining suitable land use practices and assisting the rehabilitation of degraded land. South Africa's forestry industry is dominated by plantations of introduced species, including eucalyptus, pine and wattle, which have been established on land that was previously natural vegetation, such as fynbos or seasonally dormant grassland.

Forestry is not evenly distributed across South Africa, but it is more common in the relatively wet areas of the country (Dye, 2013), with the majority of forestry plantations occurring in Mpumalanga and KwaZulu-Natal. The impact that plantations have on catchment yields is well documented in many areas of South Africa, but there is limited research in this field of study for the Maputaland Coastal Plains in northern KwaZulu-Natal, which provides a unique hydrological setting, as the system is largely reliant on ground-water input. A reduction in the number of fires, because of the introduction of forestry, as well as the expansion of human settlements, has seen this woody grassland vegetation mosaic, which is characteristic of Maputaland, becoming more woody in recent years, increasing the pressure on the water resources.

Table 2.2 provides a summary of the plant water use research that has been conducted on the Maputaland Coastal Plains. It indicates that limited research has been conducted in this area, particularly ground-based ET_a measurements of the indigenous vegetation systems in the area. At present, the water use of only a few vegetation types (peat swamp forest, dune forest, subtropical peatland and dryland grassland) have been monitored in the work of Clulow *et al.* (2012; 2013). Dye *et al.* (1997) found that the water use of three eucalyptus spp. clones varied greatly and is dependent on site quality differences, such as soils, water availability and nutrients. This indicates that the complex and heterogeneous nature of the area limits the reliability of results when conditions are varied in the specific study site. Accurate ET_a measurements of both the introduced and indigenous species are vital for understanding the effect of the current land use activities on the catchment's water resources. The outcomes of research in this area could be important for determining land rehabilitation strategies and alternative economic activities that would best suit this water-scarce landscape.

Table 2.2 Summary of plant water use studies conducted in the Maputaland Coastal Plains, KZN

Reference	Location	Technique	Species	Outcome
Dye <i>et al.</i>, 1997	kwaMbonambi District of Zululand, KZN	Sap flow (HPV)	Three eucalyptus clones (GC15, TAGS and GT529) (12 trees)	Analysis of the water use efficiency (WUE) and total sap flow indicated that each clone species consumes varied amounts of water. WUE varies with soil water availability and site quality.
Dye <i>et al.</i>, 2004	Bushlands and kwaMbonambi District of Zululand, KZN	3-PG process-based forestry model	12 stands of <i>Eucalyptus grandis</i> × <i>camaldulensis</i> hybrid clones	Annual tree growth predicted by the model, and daily ranges of sap flow, were compared to field measurements. It was concluded that the model can realistically simulate growth and water use over a wide range of rotation age and growth conditions
Brites, 2013	Nyalazi plantation located on the western shores of Lake St. Lucia, Zululand, KZN	17 years of piezometers and deeper boreholes data at 21 sites.	<i>Pinus elliottii</i> and <i>Eucalyptus grandis</i> × <i>camaldulensis</i>	Pine plantations had a minor effect on the groundwater environment, while the Eucalyptus species had a significant impact, lowering the groundwater table between 10 and 16 metres over a period of 13 years within the plantation area.
Clulow <i>et al.</i>, 2012	Coastal wetland in Maputaland, KZN	Surface renewal method, eddy covariance	Mfabeni Mire (subtropical peatland) and Embomveni Dune (dryland grassland)	ET was lower than expected, despite the available water and high average wind speeds. ET was suppressed by the inflow of humid air and comparatively low leaf area index of the wetland vegetation. Wetlands are not necessarily high water users.

Clulow et al., 2013	Eastern Shores area of the iSimangaliso Wetland Park, Maputaland, KZN	Sap flow (HPV)	Peat Swamp forest (PWS): <i>Syzygium cordatum</i> and <i>Shirakiopsis elliptica</i> Dune forest: <i>Mimusops caffra</i> , <i>Eugenia natalitia</i> and <i>Drypetes natalensis</i>	Soil water limited tree water use 64% of the time over the measurement period at the dune forest. The water use of <i>Shirakiopsis elliptica</i> was highly seasonal, while <i>Syzygium cordatum</i> was not influenced by seasonal rainfall variations.
Scott-Shaw et al., 2016	Maputaland Coastal Plains, KZN	Sap flow (HPV and SSS)	<i>Phoenix reclinata</i> , <i>Eucllyptus grandis</i> , <i>pinus elliotii</i>	General finding was that indigenous trees have a more conservative water use than introduced plantation species. The <i>Phoenix reclinata</i> is one of the highest consumers of water of indigenous species.
Clulow et al., 2015	Nkazana Peat Swamp Forest Eastern Shores area of the iSimangaliso Wetland Park, Maputaland, KZN	EC, Sap flow (HPV)	Subtropical swamp peat forest <i>Syzygium cordatum</i> and <i>Shirakiopsis elliptica</i>	Extended periodic EC measurements, using long-term sap flow data. Accurate monthly crop coefficients were calculated. Gained further understanding of the microclimate within a subtropical peat forest and derived a model for estimating long-term ET _a over heterogenous landscapes.

2.5 Conclusion and Discussion

The literature shows that accurate measurements of ET are crucial for improving and implementing water resource management practices. Detailed data of actual ET for the landscape will improve hydrological modelling, it will assist in water resource planning and allocation and it will help to predict natural disasters, such as floods and droughts. However, there is a lack of reliable ET data in many areas of South Africa. From ET estimates, one can determine the water use of vegetation. Water use studies have focused on the major effects of the forestry industry. Water use data is available for introduced tree species growing in monospecific plantations. Data for the water use of indigenous trees is lacking, although a few studies have researched the viability of certain tree species for use in plantations. Other studies, as reviewed in Table 2.2, indicate that water use research has been conducted on only a few indigenous species. There are limited or no data on important indigenous species and, therefore, water use studies at varying scales are needed across the country, to improve our knowledge base on indigenous tree water use. It is important to understand the water use of natural landscapes, particularly in forests that have been invaded by introduced species from nearby plantations. The measurement of a heterogeneous landscape can be difficult and shows varying results. Understanding the water use dynamics in a mixed landscape, where different tree species are competing for water, is important when considering best land use practices for the area. There is a need to monitor the ET of indigenous and introduced tree species that grow in the same stand, at both point and landscape scales. This will provide further insight into the water use of natural vegetation systems.

3. STUDY SITE

The Vasi Pan area is located between Lake Sibhya and Kosi Bay in Northern Zululand (Figure 3.1) and is approximately 68 m above sea level. The area is in the greater Isimangaliso Wetland Park and falls within the Quaternary Catchment W70A and Quinary Catchment 5525. The Maputaland Coastal Plain makes for an interesting study area because it has a unique hydrological system that is largely dependent on groundwater for the supply of water (Scott-Shaw *et al.*, 2016). The area has a distinct dry season, from May to August, and most of the precipitation occurs in the summer months. The mean annual precipitation presented in previous studies was between 750 and 800 mm and the average monthly temperature ranges from 28.8 °C in summer to 14.7 °C in winter (Scott-Shaw *et al.*, 2016).

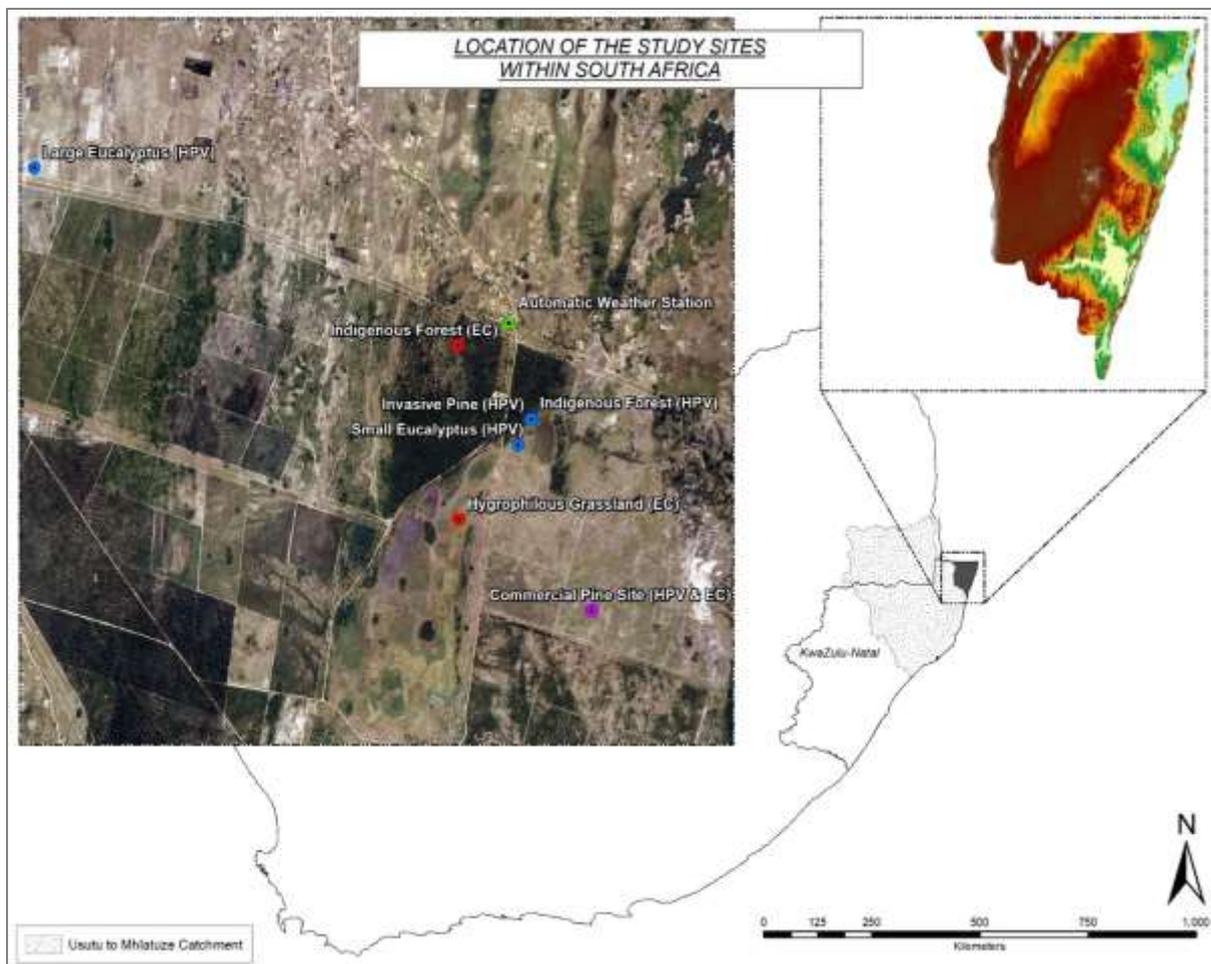


Figure 3.1 The location of the study site (Vasi Pan) within South Africa

The Vasi Pan area lies in the Indian Ocean Coastal Belt Biome and is classified as the Maputaland Coastal Belt (Mucina and Rutherford, 2006; Scott-Shaw and Escott, 2011). The natural landscape varies between densely forested areas that are interspersed with dry

grasslands, which are predominately palm veld, hygrophilous grasslands and thicket (Scott-Shaw *et al.*, 2016). The distribution of the vegetation is determined by the topography of the landscape. The Vasi Pan area is a relatively flat area, consisting of small dune crests, slacks and depressions (Figure 3.2). The vegetation on the dune crests consists of forests and dry, sandy grasslands, while hygrophilous grasslands and wetlands are present in the slacks and depressions (Starke, pers com., 2016). These small changes in elevation make for an interesting and diverse landscape. The soils indicate that there is high precipitation and leaching, with deep tertiary sands and Pliocene/Miocene beds overlying cretaceous mudstone (Everson *et al.*, 2015). The soils in the area are generally perceived to be infertile and they have low agricultural potential, therefore Sappi introduced pine plantations to the area in the 1960's.

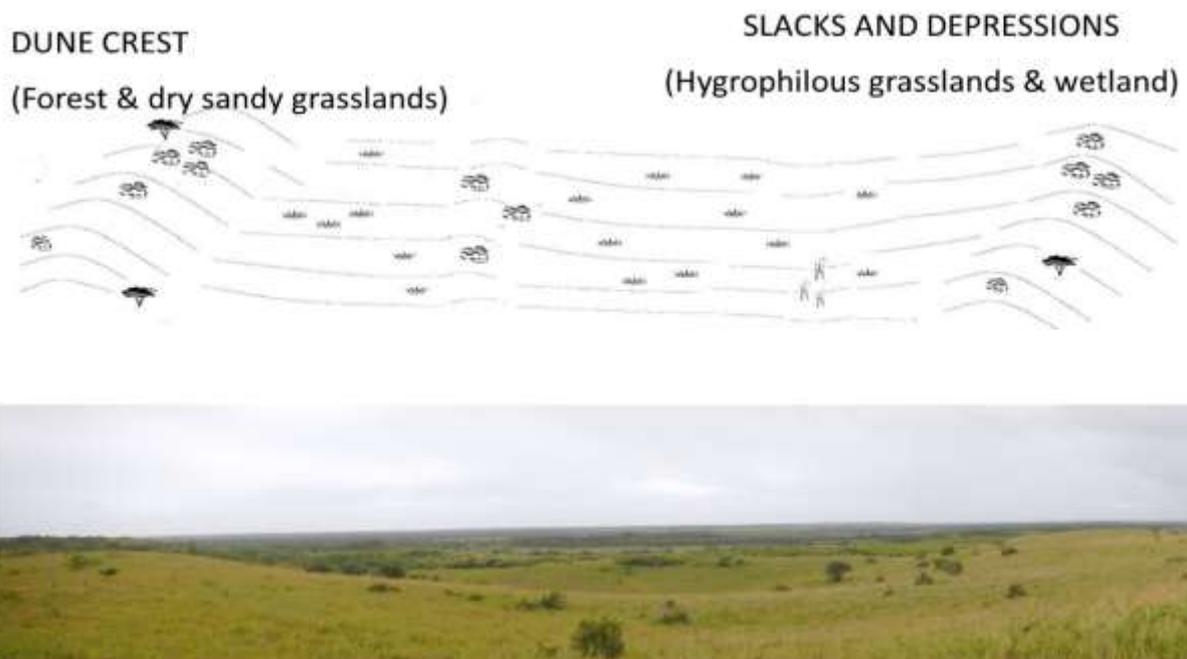


Figure 3.2 The effect of the landscape topography on vegetation distribution in the Vasi area (Starke, unpublished, WRC presentation, 2017)

The pine plantations were later replaced with eucalyptus trees, as they were found to grow better in the area. The Sappi plantation land was transferred to the Nygonyma Trust. The SA Forestry Magazine (2014) reported that the land transfer was the largest land reform project in the history of South African forestry. The land was subsequently leased by the Trust to the Department of Agriculture, Forestry and Fisheries (DAFF) and they are currently known as the Manzengwenya plantations (Scott-Shaw *et al.*, 2016). There are illegal woodlots in the area

that are owned by the local community members. The forestry industry is a large source of income and work for the surrounding local communities.

The introduction of forestry to the area has altered the vegetation structure of the surrounding landscape and has potentially had an impact on the water resources in this water-scarce area. The historical imagery from 1942 and 1959 (Figure 3.3) before the introduction of plantations to the area, shows that indigenous forest was not present in the Vasi Pan area, but that the Maputaland woody grassland (CB2) (Mucina and Rutherford, 2006) was present and consisted of grassland, with intermittent bush clumps. The exclusion of fire in the area, because of

forestry, allowed for an increased growth in woody species, therefore altering the vegetation structure of the area (Figure 3.3).

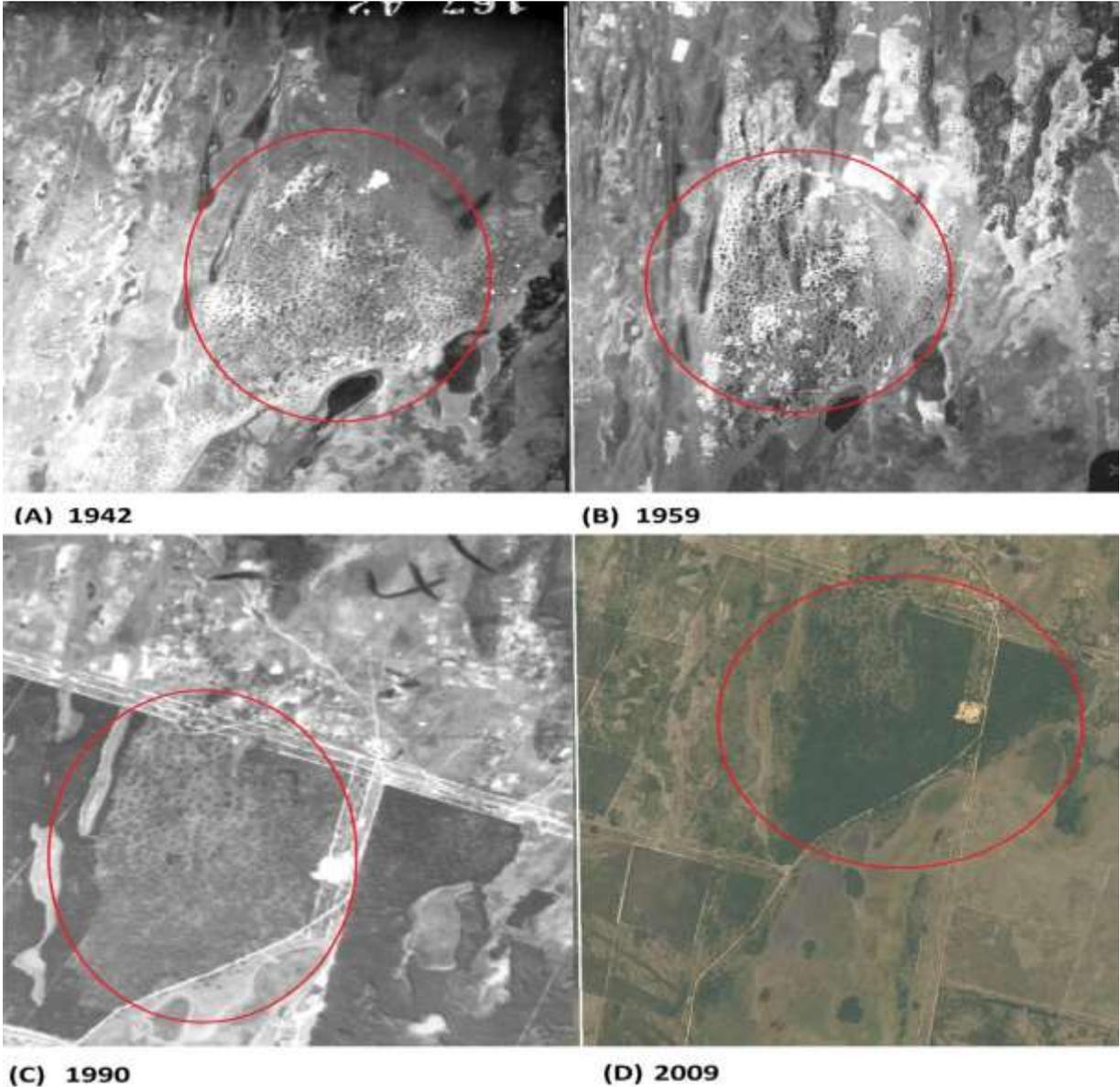


Figure 3.3 The change in vegetation structure from 1942 until 2009 in the Vasi Pan area (Scott-Shaw *et al.*, 2016)

4. MATERIALS AND METHODS

The methodological approach to this study used various ET measurement techniques, at varying scales of observation, to assess the different land uses' water use in the Vasi Pan area. ET measurements were conducted at the level of the individual trees, using sap flow measurements, and at a landscape level, using the eddy covariance system. This approach improved the accuracy of the data, created links between the data, validated findings, and identified trends and deviations within the results.

4.1 Meteorological Station

Meteorological data were required as input in the study, when performing calculations to determine total evapotranspiration. These data were obtained from the automatic weather station (AWS) located at the Isibusiso Esihle Education Centre near the Vasi Pan, which was set up on 20 November 2014. The station was placed on a flat uniform grassland area to meet the requirements of the FAO 56 reference evaporation (ET_o) calculations (Allen *et al.*, 1998). A Campbell Scientific CR200 datalogger recorded the air temperature (CS500, Vaisala Inc., Helsinki, Finland), the relative humidity (CS500, Vaisala Inc., Helsinki, Finland), the wind speed and direction (Model 03002, R.M. Young, Traverse City, Michigan, USA), the solar radiation (LI 200, LI-COR, Lincoln, Nebraska, USA) at 2 m and the rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) at 1.2 m. Data from the station were downloaded at regular six-week intervals during site visits.

There was an issue with the rain gauge from July 2016 to February 2017. The values recorded in these months were unrealistically high. Attempts were made to fix the rain gauge by rewiring and replacing the data logger; however, these were unsuccessful. A new rain gauge was installed in February 2017, which solved the problem. The erroneous data was corrected by using the relationship between the overlapping data from nearby weather stations and the project's AWS near Vasi Pan.

4.2 Individual Tree Water Use Monitoring

In situ measurements of sap flow in the xylem can be used to determine an individual tree's water use. Sap flow measurements provide an estimate of the tree's transpiration rate. The detailed ground-based data are critical for the accuracy of the hydrological models and for understanding the impact that tree species have on the available water resources.

4.2.1 Site selection for long term monitoring of individual tree sap flow

Four sites were selected for the long-term monitoring of individual tree sap flow, using the heat ratio method (HRM). A vegetation survey undertaken in the Vasi area by A. Starke, identified common indigenous tree species in the area (Starke, pers com., 2016). This research assisted in the selection of the indigenous tree species for monitoring. The species used in local plantations were also selected for monitoring. The selected sites consisted of a range of dominant land uses in the area (Figure 4.1).



Figure 4.1 Land uses selected for HPV monitoring: a) large eucalyptus stand (5-year-old); b) mixed indigenous forest invaded by pine; c) small eucalyptus stand (2-year-old); and d) commercial pine stand

4.2.1.1 Indigenous forest site

The indigenous forest site was a mixed species indigenous forest, in which several of the identified common species were present (Figure 4.1b). This site was located on the edge of Vasi Pan North (Figure 3.1). The four tree species that were chosen for long-term sap flow monitoring were *Albizia adiathifolia* (Flat Crown), *Sclerocroton integerrimus* (Duikerberry), *Apodytes dimidiata* (White-pear) and *Trema orientalis* (Pigeonwood) (Table 4.1). The sap flow data from each tree provided an insight into the water use of indigenous tree species growing in competition with one another.

4.2.1.2 Invasive pine site

The invasive pine site was located on the fringe of a mixed indigenous forest (Figure 4.1b). At this site, four pine trees (*Pinus elliottii*) were selected for long-term monitoring (Table 4.1). The trees selected for monitoring were on the fringe of the indigenous forest, in close proximity to the indigenous trees being monitored. The data provided an indication of water use differences between introduced and indigenous species, when growing in competition with one another.

4.2.1.3 Large eucalyptus site

In consultation with the local community and the Isibusiso Esihle Education Centre, access was granted to monitor a five-year old eucalyptus hybrid woodlot that is owned by a local community member (Figure 4.1a). The large eucalyptus stand was in a dry and sandy grassland area north of the Vasi Pan (Figure 3.1)

The three trees that were selected for long-term monitoring provided a representation of varying diameter sizes within the woodlot (Table 4.1). The diameter size was determined by measuring the diameter of 30 trees within the woodlot. The measured diameters were sorted into three frequency distribution classes (low, middle, high). The mean diameter size for each frequency distribution class was calculated. HPV sensors were installed in trees with a similar diameter to the mean diameter for each frequency distribution class, to provide a range of sap flow data for trees representing the various size classes.

4.2.1.4 Small eucalyptus site

A stand of two-year old eucalyptus trees were selected for long term tree monitoring of sap flow (Figure 4.1c). This stand was located on the edge of Vasi North (Figure 3.1) and close to the Vasi wetland boundary. At the start of the monitoring, many of the trees were too small for the instrumentation, therefore, three trees that were large enough for the placement of probes in the trunk, with diameters of 7-9 cm, were selected. This site provided an understanding of the water use of the young introduced eucalyptus trees when planted in the wetland fringe.

4.2.1.5 Commercial pine stand

A well-established pine plantation (Figure 4.1d) near the Vasi Pan was selected for the long-term monitoring of sap flow (Figure 3.1). This site was installed late in the study (June 2017) as it was decided that it would be beneficial to have simultaneous measurements of sap flow and ET_a , measured by the eddy covariance system, in the commercial pine stand. Three trees, representing various size classes, were selected for installation (Table 4.1). The tree size was

needed for installation was determined by using the same method as previously described for the large eucalyptus trees. Pine plantations are a common land use in the area, therefore, the water use data obtained from this site are vital for understanding the impact of pine plantations on the available water resources.

It was preferable to monitor multiple trees for each species for the replication of data, particularly for the indigenous tree species, to reduce intra-specific sampling variability and to provide a range of size classes. However, the number of long-term monitoring sites was limited by the large capital costs of the monitoring equipment, high maintenance requirements and issues with regards to the security of equipment.

Table 4.1 Vasi Pan HPV sites installation information: species physiology, HPV probe and CS616 insertion depths

Site	Tree No. and Species	Height (m)	Diameter (cm)	HPV Probe Depths (cm)	CS 616 Depth (m)	Comment
Indigenous forest	1. <i>Albizia adianthifolia</i> (Flatcrown)*	4.7	11.6	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8	Measurements started with HRM and SSS window period in 2015
	2. <i>Sclerocroton integerrimus</i> (Duikerberry)	5.1	9.6			
	3. <i>Trema orientalis</i> (Pigeonwood)	6	13.7			Started 14/07/2016
	4. <i>Apodytes dimidiata</i> (White-pear)	5.4	11.2			
Invasive Pine	5. <i>Pinus elliottii</i>	5.9	14.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5		Measurements started with HRM and SSS window period in 2015
	6. <i>Pinus elliottii</i>	5.7	14.6			
	7. <i>Pinus elliottii</i>	4.6	13.7			
	8. <i>Pinus elliottii</i>	5.3	11.2			
Large eucalyptus	9. <i>Eucalyptus grandis</i>	16.2	15.5	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8	Started 14/06/2016
	10. <i>Eucalyptus grandis</i>	15.2	11.3			
	11. <i>Eucalyptus grandis</i>	16.1	8.6			
Small eucalyptus	12. <i>Eucalyptus grandis</i>	12	8.1	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	N/A	Started 01/08/2016
	13. <i>Eucalyptus grandis</i>	10	9			
	14. <i>Eucalyptus grandis</i>	10.6	7.9			
Commercial pine stand	15. <i>Pinus elliottii</i>	11.2	16.6	Probe 1: 1 Probe 2: 2 Probe 3: 3 Probe 4: 4	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8	Started 30/05/2017
	16. <i>Pinus elliottii</i>	10.4	14.1			
	17. <i>Pinus elliottii</i>	15.6	17.6			

4.2.2 Installation of the Heat Pulse Velocity System

Heat pulse velocity systems were installed at five sites, following the principles of the heat ratio measurements, as detailed in Burgess *et al.* (2001). A total of 17 trees were instrumented with HPV sensors for long-term monitoring in the Vasi Pan area. The sapwood depth was assessed, using an increment borer, to determine the depth to which the HPV probes were to be inserted (Figure 4.2a). These depths varied, according to the depth of the sapwood, and were located to

represent four different concentric rings of the sapwood area, for scaling to the water use of the whole tree (Table 4.1), as sap flow velocities can vary radially across the xylem (Wullschlegel and King, 2000).

The HPV system consisted of an 18-gauge hypodermic needle, with a 1 cm wound heater of constantan wire at the distal end. The needle with the heater was 1.8 mm in diameter and 35 mm long. The needle heater was inserted into a 2.5 mm outside diameter brass tube, which was inserted into the sapwood area. The thermocouples, made of type T copper-constantan, were embedded in PTFE tubing (outside diameter 2 mm) and were equidistant (5 mm) from the central needle heater. They were inserted to the predetermined depths per calculated sapwood area. A single tree installation consisted of four pairs of probes (with each pair consisting of a needle heater and an upper and lower thermocouple), which were inserted radially to varying depths in the tree stem (Figure 4.2b).



Figure 4.2 Heat pulse velocity installation setup at Vasi Pan: a) assessment of sapwood depth using an incremental borer; b) temperature thermocouples placed equidistance above and below the needle heater; and c) metal fence to prevent disturbance from cattle and filler foam placed around probes to provide insulation.

The system was controlled and data were collected, using a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) connected to an AM 16/32b multiplexer (Campbell Scientific Inc., Logan, Utah, USA). This system was programmed to measure the hourly sap flow velocity.

The selected trees were monitored over a 12-month period, from July 2016 to July 2017, which allowed for an understanding of the seasonal variations in a tree's water use. To ensure that the data were not affected by outside variables, such as, incoming solar radiation or heat loss, insulation foam was placed around the line heater and temperature probes, which also assisted in holding the probes in place. A metal fence was erected around each tree to prevent any disturbance by cattle (Figure 4.2c).

4.2.3 Analysis of Heat Pulse Velocity data

The HPV data were screened to identify periods of missing data or periods of data showing unrealistically high spikes or low negative values, which is termed 'noisy' data. Noisy data is data that does not follow the trends of the other probes, and/or does not follow any logical relation to the preceding or following values, or environmental changes (Dye *et al.*, 2008). These data are, therefore, considered to be faulty. When patching periods of missing or noisy data for one probe within a tree, good quality data from neighbouring probes in the same tree were used to patch the data. The probe with the highest correlation to the probe being patched was identified through correctional analysis. A simple linear regression was used to patch the data from the functional probe. In some instances, data for all probes in a tree were missing or noisy. In these cases, data from adjacent trees of the same species were used to correlate and patch the affected periods of data. When whole trees were found to have long periods of missing or noisy data, it was best to patch the data with weather station data that were recorded at the same frequency as the HPV data. A correlation between good quality HPV data, before and after bad data, was used to preserve the seasonal variability. ET_o , which was derived by using the Penman-Monteith equation, was used to patch the missing/noisy data. Sap flow is directly related to the availability of energy and therefore, atmospheric conditions, unless energy is not the limiting factor but rather the availability of water. This gives confidence in the accuracy of this technique for in-filling data.

Once the data patching process is complete, it is essential to confirm the "zero flux" value. This value refers to the times of the day when sap flow/transpiration is expected to be zero. It is expected that the lowest values in the diurnal HPV trends will stabilize at around zero; however, a slight misalignment in the position of the thermocouples probes in a tree, cause this not to be the case (Dye *et al.*, 2008). To correct the data, it is necessary to apply an offset to the data, in order to align the lowest values with zero. This offset was calculated by averaging the values from 22h00 to 2h00 each night and applying the offset to the following day.

The raw HPV data were converted to whole-tree sap flow rates in litres, using the following procedures. The area of non-functional xylem (wounding) around the thermocouples was accounted for by using wound coefficient that are described by Burgess *et al.* (2001).

$$V_c = bv_h + cv_h^2 + dv_h^3, \quad (4.1)$$

$$b = 6.6155x^2 + 3.332x + 0.9236$$

$$c = -0.149x^2 + 0.0381x - 0.0036$$

$$d = 0.0335x^2 - 0.0095x + 0.0008$$

where, v_c is the corrected heat pulse velocity, v_h is sap flow velocity and b - d are the correction coefficients specific to the size of the wound (x). To ensure the accuracy of sap flow measurements, there is a need to calibrate sap flow systems for each new species monitored. This is because the theory underpinning HPV measurements assumes a thermally homogenous sapwood.

Following the procedure described by Marshall (1958), sap flux densities were calculated by accounting for moisture content and wood density. The conversion of sap flux density to sap flow was calculated as a product of sap flux density and the cross-sectional area of conducting sapwood (Dye *et al.*, 2008). Sap flow ($L.h^{-1}$) was calculated as the sum of the products of sap flux densities and the cross-sectional area for individual tree stem annuli. Following the work of Dye *et al.* (2008) and Clulow *et al.* (2013), sap flow was assumed to equate to the tree transpiration and tree water-use. Daily water use ($L.day^{-1}$) was calculated for each site as an average of the individual trees that were monitored.

4.2.4 Monitoring of volumetric water content

Soil water content probes were placed at each site to measure the hourly volumetric water content (VMC). These measurements coincided with the hourly sap flow measurements of the HPV systems. At each site, a pit was dug and three Campbell Scientific CS 616 probes, connected to channels on the CR1000 datalogger, were inserted horizontally at a 0.2, 0.4 and 0.8 m, respectively, to ensure the soil water profile was monitored. Each site had similar soils of a deep uniform, sandy profile. The VMC measurements assisted in the interpretation of the

tree water use data, supporting the findings with regards to the response of trees to dry and wet periods.

There was an issue with the logger program with regards to data storage and unfortunately, only a week's worth of data was stored on the memory card. The soil water content data for each site was incomplete, and therefore, data analysis was limited.

4.2.5 *Tree physiology measurements*

To interpret the tree water use data, tree physiology variables, such as growth measurements, leaf area index, wood density and moisture content, were measured.

4.2.5.1 Tree growth measurements

The height and diameter of the trees installed with HPV systems were measured pre- and post-study, to provide tree growth increment data. Growth measurements were taken for the plantation species on each field visit (approximately every six weeks). Replicated measurements for the indigenous tree species were not possible, due to the lack of available plants near the setup HPV system. The diameter of 30 trees from each stand in the small eucalyptus, large eucalyptus and pine plantations were recorded three times during the monitoring period. The remoteness of the monitoring site made it difficult to record growth measurements at more frequent and regular intervals.

4.2.5.2 Leaf Area Index measurements

The Leaf Area Index (LAI) can be defined as “one half of the total surface area of green leaves per unit of ground area” (Woodgate *et al.*, 2015). Only “one half” is considered, since stomata are generally confined to the lower (abaxial) leaf surface. LAI measurements are important for understanding the vegetation structure and functioning in a varying climate. The measurements are directly related to tree water use, as it is directly related to rate of photosynthesis and evapotranspiration of the canopy (Running, 1984; Running and Coughlan, 1988; Woodgate *et al.*, 2015). Ground-based LAI readings (LAI 2200, LI-COR Inc., Lincoln, Nebraska, USA) were taken at all the sites during each site visit. A measurement sequence of five above the canopy readings, and then 10 below the canopy readings, were replicated three times at each site.

4.2.5.3 Assessment of tree wood density, moisture content and wounding width

At the end of the monitoring period, measurements of woody density, the moisture content and width of wounded (non-functional) xylem around the thermocouple were recorded, and used to convert heat pulse velocity to sap flux density (Marshall, 1958). The width of wounding was assessed by removing a sample surrounding the thermocouples and line heater, and measuring the width of damaged xylem (Figure 4.3). Three wood samples were extracted from each tree species, using a chisel (Figure 4.3). The samples were sealed in air-tight bags and analysed in the laboratory for density and moisture fraction.

Wood density was calculated as the oven-dry mass per unit of the green volume, which was determined by the samples' displacement in water (Malan, 2005). The samples were placed in containers and immersed in water for 30 minutes; they were then used to determine the weight of the displaced water. The container was placed on a scale and a pin was used to fully submerge the wood in the water, without touching the sides of the container, and the subsequent weight of displacement was recorded. The weight of displacement is equal to the green volume of the wood. The samples were placed in an oven at 105 °C for 24 hours, providing a constant mass. The moisture content of the under bark was determined by using the wet mass of the wood, taken before its immersion in water, as well as the oven-dried mass. Table 4.2 summarises the data obtained from these samples.

Table 4.2 Tree specific data required for the calculation of sap flow

Trees species	Wood density (cm ³ g ⁻¹)	Moisture fraction	Average wounding (mm)
<i>Albizia adianthifolia</i> (Flatcrown)	0.6	0.9	6.0
<i>Sclerocroton integerrimus</i> (Duikerberry)	0.6	0.9	6.0
<i>Apodytes dimidiata</i> (White-pear)	0.6	0.9	6.0
<i>Trema orientalis</i> (Pigeonwood)	0.6	0.9	6.0
<i>Pinus elliottii</i>	0.5	0.4	6.0
<i>Eucalyptus grandis</i>	0.7	0.8	6.0



Figure 4.3 Assessment of wood density and wounding widths required for the calculation of sap flow

4.3 Water Use Monitoring of Locally Dominant Land Uses

When determining the water use of different land uses in an area, it is important to measure all components of evapotranspiration accurately. The use of eddy covariance systems provides detailed transpiration and evaporation data over heterogeneous and homogeneous landscapes.

4.3.1 Selection of Eddy Covariance monitoring sites

Three sites were selected for monitoring the total evapotranspiration (ET_a) of the selected plant communities, using an eddy covariance system. Two EC systems were available for use in this study. One system was attached to a permanent lattice mast, which was left on site to collect continuous data, while the other was a portable EC system on a trailer, which could easily be moved from site to site, to monitor short window periods. The length of the monitoring periods by the portable EC systems was limited by the battery life and the cost of equipment security, as local guards were employed to ensure that the equipment remained undisturbed.

The sites selected for monitoring are represented of the dominant land uses in the area. The natural vegetation in the area is grassland; however, this has changed over time, with the exclusion of fire leading to the increased density of indigenous forests and the introduction of forestry to the area since 1960. The lattice mast was placed in an indigenous forest with a canopy height of 4 m (Figure 3.1). The site was well-hidden and, therefore, the EC system was left to continuously collect data from the date of its installation in December 2016 until July 2017. This provided an insight into the seasonal changes of the forest’s total evapotranspiration. The sites selected for monitoring, using the portable trailer EC system, were a Vasi Pan hygrophilous grassland and a commercial pine stand (Figure 3.1). The monitoring window for each site was approximately two to three weeks (Table 4.3). The Vasi Pan hygrophilous grasslands provided a reference landscape to compare how the changes in land use differed according to the water use, as opposed to the previous natural landscape. This provided insight into how land use changes in the Vasi area have affected water resources.

Table 4.3 Eddy Covariance monitoring periods (days), where useable data was obtained, for the selected land uses in the Vasi area

EC Sites	2016					2017					
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Indigenous forest					12	31	30	10	30	7	
Commercial pine stand									30	31	12
Hygrophilous grassland		8	14		14	22	10	7			

4.3.2 Installation of Eddy Covariance systems in the field

The EC technique was chosen to measure the total ET over the mixed species stand and over grasslands. To do this, an extended Open Path Eddy Covariance system (OPEC) was used to ensure that all the necessary components were measured (Figure 4.4). Both EC systems used in the study had a fetch of 100 m and were fitted with the following: (a) a net radiometer (NR-Lite), which measured net radiation; (b) Soil Heat Flux plates (HFP01 non-self-calibrating), which measured spatially averaged soil heat flux; (c) averaging soil thermocouple probes (TCAV-L), which provided the average temperature of the top 60–80 mm of soil; (d) soil water content probes (CS616), which measured the volumetric water content in the soil; and (e) a

IRGASON (Campbell) or a Campbell Scientific EC150 system, which measured the fluxes of carbon dioxide and water vapour. The systems were controlled by CR3000 loggers, which were programmed with the EasyFlux™-DL program. This program reduces the post-processing time, as fully-corrected fluxes are processed by the datalogger.

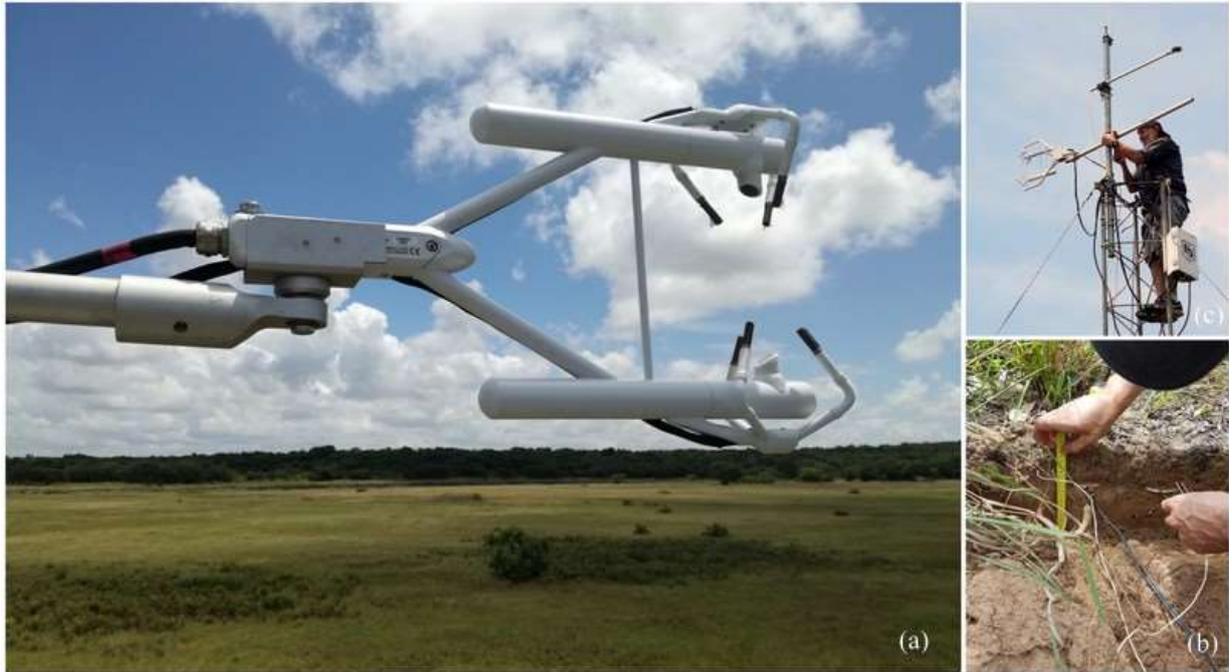


Figure 4.4 Equipment installation of the EC system in Vasi Pan. a) IRGASON (Campbell Scientific) placed on the mobile EC system in the hygrophilous grassland; b) placement of Soil Heat flux plates and Soil Thermocouple probes; and c) installation of EC150 CO₂ and H₂O open path gas analyser on the lattice mast in the indigenous forest

A suitable site was found, which represented the local indigenous forest, and a Webb Industries lattice mast was erected (Figure 4.5c). At this site, an EC150 Campbell Scientific EC system was installed at 6 m, which was 2 m above the forest canopy. The system and the previously-mentioned additional system components were installed, following the instructions provided in the Campbell Scientific EasyFlux™-DL manual (Campbell Scientific, 2016)

The mobile EC system was mounted on a trailer (Figure 4.5) to facilitate the rapid deployment and acquisition of total evapotranspiration (ET_a) data from various land uses. The land uses chosen for monitoring were a commercial pine stand and Vasi Pan hygrophilous grassland. The trailer was fitted with a Clark WT8 pneumatic mast that was capable of being extended to 21 m, using an air compressor. In the pine stand, the mast was set to a height of 14.6 m and to a height of 4 m in the hygrophilous grassland. The system mounted on the mast consists of a Campbell Scientific IRGASON system, which fully integrates the open-path gas analyser and sonic anemometer. This system has been specially designed to increase the accuracy of flux measurements. The system simultaneously measured the absolute CO_2 and water vapour, air temperature, barometric pressure, three-dimensional wind speed and sonic air temperature.



Figure 4.5 Selected EC monitoring sites: a) trailer system in the hygrophilous grasslands; b) trailer system monitoring a commercial pine stand; and c) permanent lattice mast in indigenous forest

4.3.3 Processing and analysis of Eddy Covariance data

The Easy FluxTM-DL software, developed by Campbell Scientific, was installed on the data loggers of the EC systems. It is a CRBasic program that enabled the CR3000 data logger to collect fully corrected fluxes of CO_2 , latent heat (H_2O), sensible heat, ground surface heat flux and momentum. Site-specific variables were entered into the program at the start of monitoring.

to ensure that the energy fluxes were processed correctly. The program processes the EC data using commonly-used corrections in the scientific literature.

The main correction procedures and algorithms implemented into the program from the EasyFlux manual are listed below:

- i) Despiking and filter 10 Hz data, using sonic and gas analyser diagnostic codes and signal strength and measurement output range thresholds,
- ii) Coordinate rotations, with an option to use the double rotation method (Tanner and Thurtell, 1969), or the planar fit method (Wilczak *et al.*, 2001),
- iii) Lag CO₂ and H₂O measurements against sonic wind measurements for maximization of CO₂ and H₂O fluxes (Horst and Lenschow 2009; Foken *et al.* 2012), with additional constraints to ensure lags are physically possible,
- iv) Frequency corrections, using commonly-used cospectra (Moore, 1986; van Dijk, 2002; Moncrieff *et al.*, 1997) and transfer functions of block averaging (Kaimal and Finnigan, 1989), line/volume averaging (Moore, 1986; Moncrieff *et al.* 1997; Foken *et al.* 2012; van Dijk 2002), time constants (Montgomery, 1947; Shapland *et al.*, 2014; Geankoplis, 1993), and sensor separation (Horst and Lenschow, 2009; Foken *et al.*, 2012),
- v) A modified SND correction (Schotanus *et al.*, 1983) to derive sensible heat flux from sonic sensible heat flux, following the implementation, as outlined in van Dijk (2002). In addition, fully corrected real sensible heat flux, computed from fine-wire thermometry, may be provided,
- vi) Correction for air density changes, using WPL equations (Webb *et al.*, 1980),
- vii) Data quality qualifications, based on steady state conditions, surface layer turbulence characteristics and wind directions, following Foken *et al.* (2012); and
- viii) The calculation of energy closure based on energy balance measurements and corrected sensible and latent heat fluxes.

The energy flux data was visually checked for outliers. Latent energy (LE) fluxes were converted from W.m² to mm and were summed per day. A monthly Bowen ratio was calculated at a daily time interval for each site. The Bowen ratio is defined as (Bowen, 1926):

$$\beta = \frac{H}{le}$$

for a specific period. It provided an indication on the dominance of LE or H and showed a change in the distribution and weighting of the energy balance components within and between the sites (Clulow *et al.*, 2015).

Monthly crop coefficients (K_c) were calculated by using ET_a from the EC systems and ET_o from the AWS (calculated using the FAO56 Penman-Monteith equation). K_c was calculated at an hourly interval, when $R_n > 0$ and $ET_a > 0.1 \text{ mm}\cdot\text{hr}^{-1}$ (Clulow *et al.*, 2015), and summed to daily totals, as recommended by Irmak *et al.* (2005). An average of the daily total provided a monthly K_c value.

5. RESULTS

5.1 Meteorological Data

The mean annual precipitation observed in the Vasi Pan area since 1914 is between 750 mm and 800 mm (Scott-Shaw *et al.*, 2016). There was a high variation in the mean annual precipitation, with some years receiving as little as 427 mm and as much as 1689 mm in a hydrological year (Scott-Shaw *et al.*, 2016).

As previously mentioned (Section 4.1), there was an error in the rainfall data, where recorded values were unrealistically high. Although, attempts were made to correct the data, there was still some uncertainty in the values from July 2016 to February 2017. This was evident as the sum of total rainfall for November and January 2016 exceeded the historical mean annual precipitation for the area, with unrealistically high values, despite attempts to correct the data (Figure 5.1). However, seasonal trends in rainfall could still be observed.

The Vasi Pan area has a distinct dry and wet season. The wet season begins in September, with peak rainfall occurring in summer from November to January (Figure 5.1). The frequency and size of rainfall events decreases from February, with very little rain falling in the winter period (June to August).

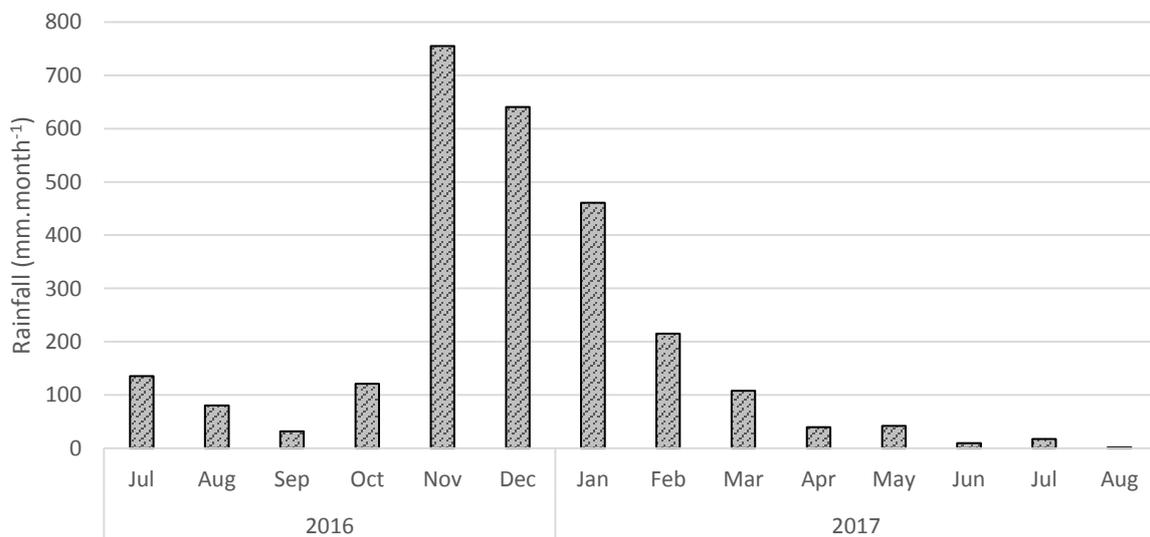


Figure 5.1 Total monthly rainfall occurring at Vasi Pan

There were seasonal differences in solar radiation, with a summer peak of 604 MJ in January 2017 and a winter peak of 420 MJ in August 2016 (Figure 5.2). Solar radiation varied, due to cloud cover, with higher solar radiation occurring on clear days. It is important to note the influence that cloud cover has on solar radiation, as a trees sap flow response to energy is well documented (Landsberg and Waring, 1997; Meiresonne *et al.*, 1999; Granier *et al.*, 2001; Williams *et al.*, 2001; Wullschleger *et al.*, 2001; Meinzer *et al.*, 2004)

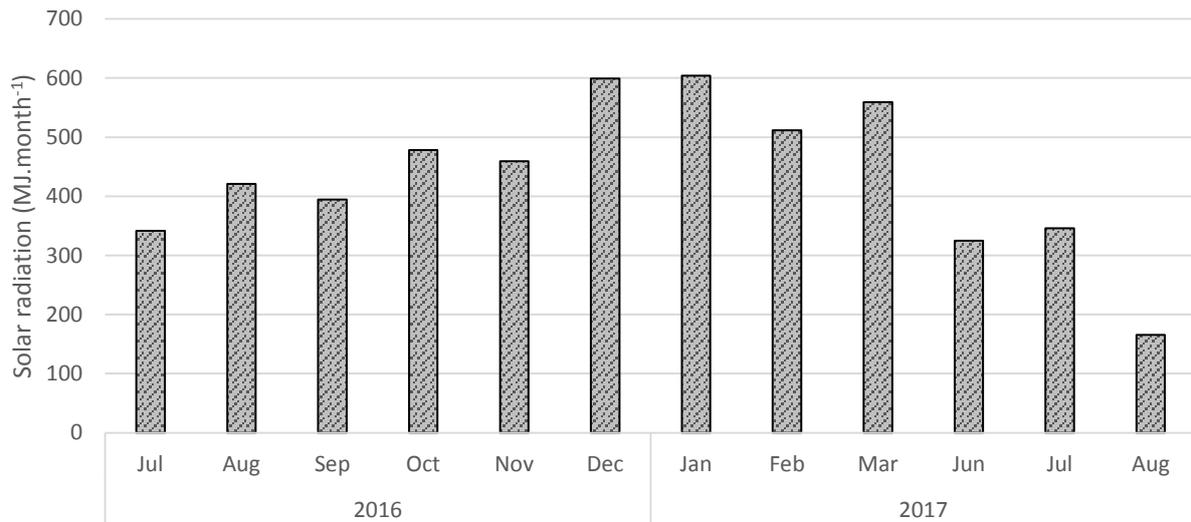


Figure 5.2 Total monthly solar radiation observed at Vasi Pan

The warm Mozambique current from the north has a warming influence on the Maputaland coastal areas. The Vasi Pan area has a subtropical climate, experiencing hot summers and mild winters. There were small differences in the daily and seasonal maximum and minimum air temperatures. Summer temperatures were hot, with air temperatures frequently exceeding 30 °C, while winters were mild, with maximum temperatures averaging 25.6 °C (Figure 5.3). The average daily minimum temperatures were 22.4 °C in summer and 14.7 °C in winter.

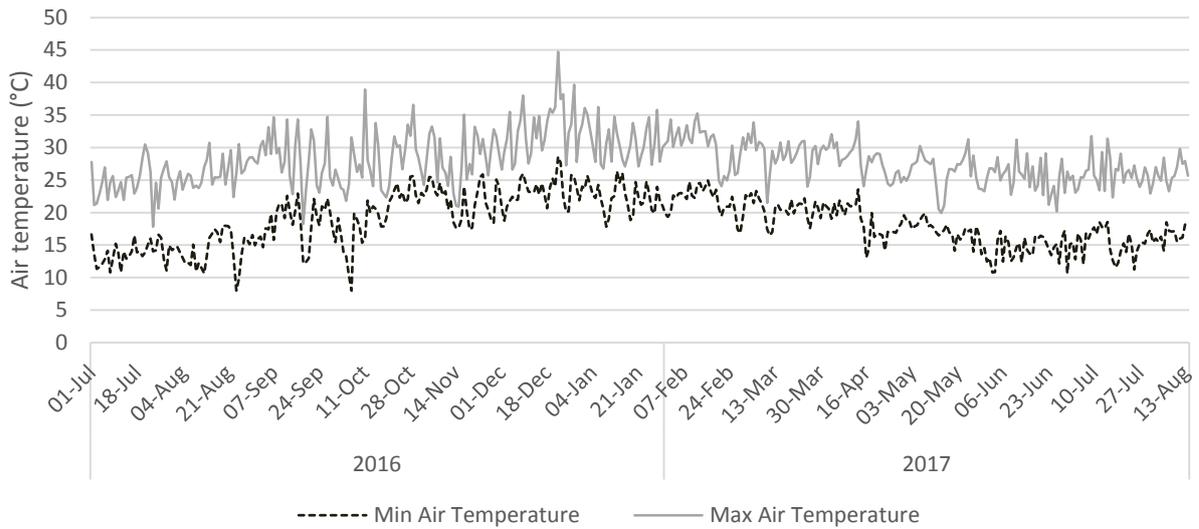


Figure 5.3 Maximum and minimum air temperature observed at Vasi Pan

Vapour pressure deficit (VPD) was recorded from November 2016 to July 2017; however, data for the month of January 2017 was unavailable as there was an issue with the data logger. The average monthly daytime VPD was low (0.8 kPa), which generally indicates a low atmospheric evaporative demand (Figure 5.4). The Vasi Pan area has a humid subtropical climate, which accounts for the low VPD values. Maximum daily VPD occurred at midday and peak VPD was lower in the summer months (November to February) than in the winter months (June to July), as summer was more humid.

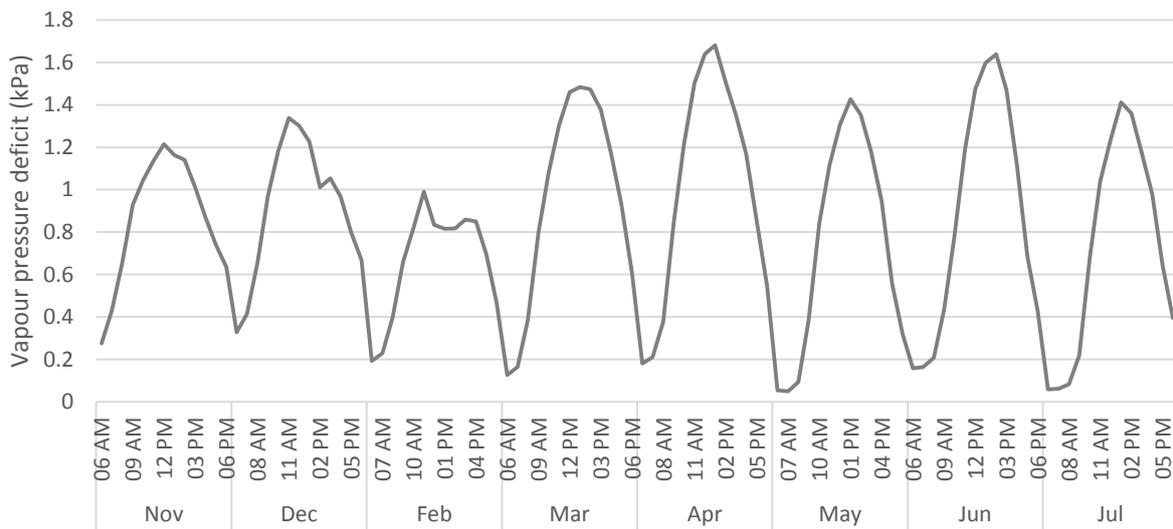


Figure 5.4 Monthly daytime ($R_n > 0$) vapour pressure deficit measured in the Vasi Pan area

The soils in the Vasi Pan area had a deep, uniform sandy profile and held little water. The VMC was generally low, between 2 and 13 % (Figure 5.5), due to the low water retention properties

of sandy soils. After rain, the VMC for all three probes rapidly increased and steadily decreased during the subsequent period of no rainfall, as the water drained quickly through the soil.

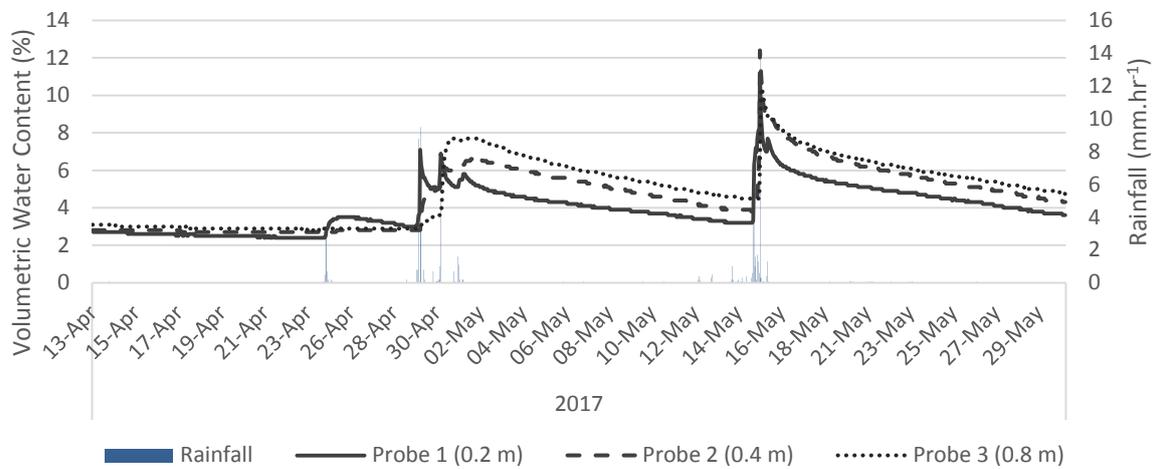


Figure 5.5 Hourly volumetric water content measured at the indigenous forest site

5.2 Individual Tree Water Use Derived from Sap Flow Measurements

Sap flow data for the indigenous forest site were recorded from late July 2016 to early August 2017, providing an insight into the annual seasonal variability of indigenous tree water use. The Duikerberry (*Sclerocroton integerrimus*) had the highest mean daily water use (8.7 L.day^{-1}) of the indigenous species monitored, then the White-pear (*Apodytes dimidiata*) (7.7 L.day^{-1}) and Flatcrown (*Albizia adianthifolia*) (6.2 L.day^{-1}). Unfortunately, the Pigeonwood (*Trema orientalis*) only gave a week's worth of good data and was therefore not included in the study. The water use data from the individual indigenous spp. followed similar trends which allowed for the daily water use of each species to be represented as an average for all three trees (Figure 5.6).

The indigenous trees are semi-deciduous in winter, accounting for the low daily water use of $\sim 2 \text{ L.day}^{-1}$ from July 2016 to late September 2016 (Figure 5.6). The start of the wet season in spring (October 2016) and the flush of new leaves on the trees coincided with increased daily water use, as transpiration resumed ($6\text{-}14 \text{ L.day}^{-1}$). Peak water use occurred during summer (December 2016), when daily water use reached a maximum of 15.3 L.day^{-1} .

The water use of indigenous trees was low during rainfall events in summer. For example, in mid-February, water use declined from $\sim 14 \text{ L.day}^{-1}$ to $\sim 4 \text{ L.day}^{-1}$, coinciding with a decrease in

solar radiation from $\sim 25 \text{ MJ.day}^{-1}$ to $\sim 11 \text{ MJ.day}^{-1}$, due to the high cloud cover (Figure 5.6). Thus, during the summer wet periods, the transpiration of the trees was energy dependent.

From March to July, there was a steady decline in radiation from $\sim 20 \text{ MJ.day}^{-1}$ to $< 10 \text{ MJ.day}^{-1}$, as solar altitudes declined with the onset of winter (Figure 5.6). Following two weeks of no rainfall, the water use of indigenous trees increased from 7 L.day^{-1} to 12 L.day^{-1} , in response to the small rainfall event (0.5 mm.day^{-1}) on 15 April 2017 (Figure 5.6). This was despite the continued decline in radiation during this period, indicating water-limited transpiration.

The daily water use in winter 2017 steadily decreased from early June, from $\sim 11 \text{ L.day}^{-1}$ to $\sim 5 \text{ L.day}^{-1}$. This decline coincided with the start of the dry season and the loss of some leaves from the trees. During the winter months, when the trees were inactive (June to late September), the daily water use was not noticeably affected by rain or changes in solar radiation (Figure 5.6). From the results, it was evident that water use of indigenous trees responded to the seasonal variability in the trees' physiology. However, in the trees' active growing season, their water use was limited by the rainfall and available energy, depending on the prevailing climatic conditions.

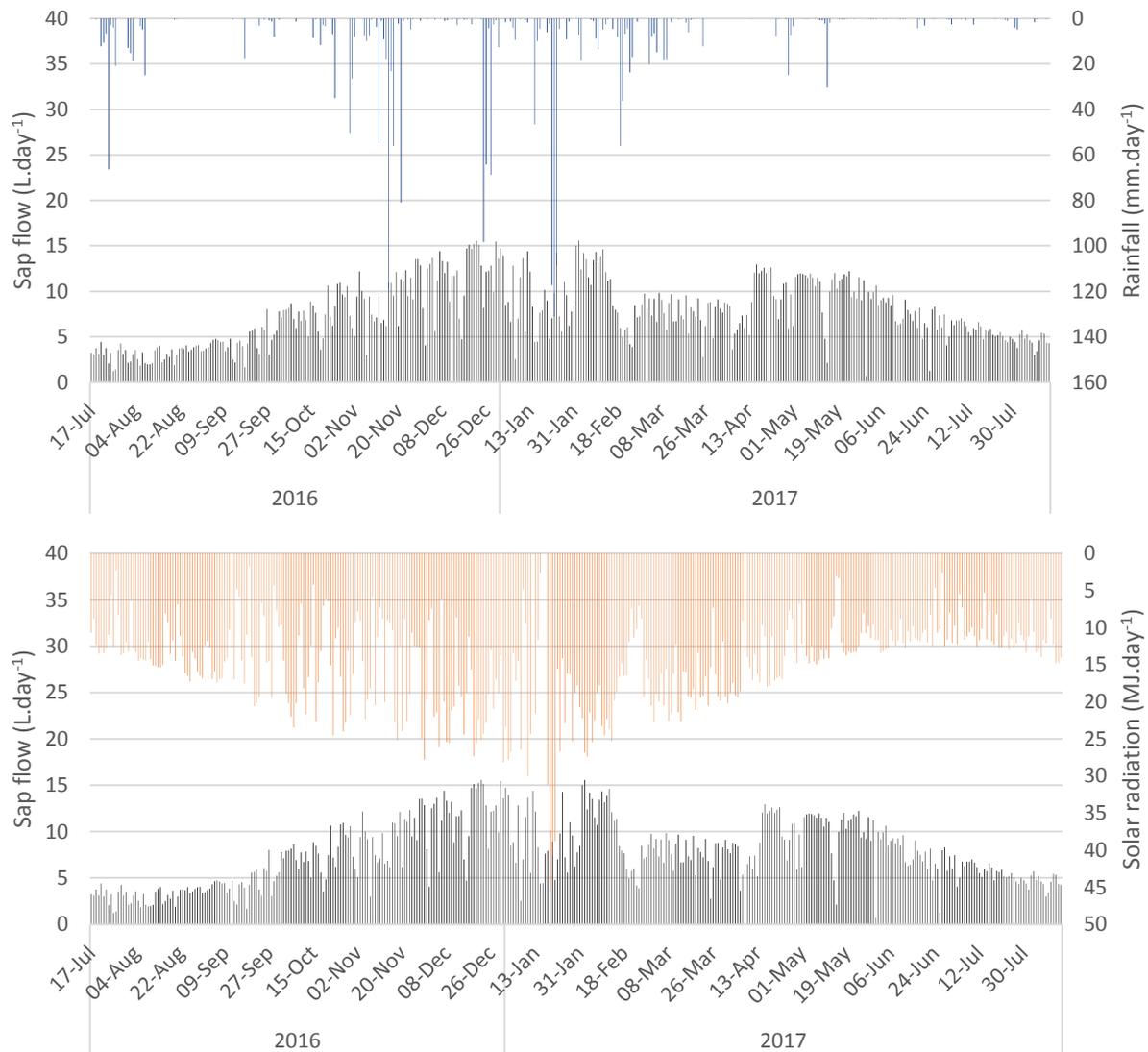


Figure 5.6 Mean daily water use ($L.day^{-1}$) of the indigenous forest spp. (average diameter 11.5 cm) monitored were located within a mixed indigenous forest on the fridge of Vasi Pan North compared with daily rainfall ($mm.day^{-1}$) and solar radiation ($MJ.day^{-1}$)

Sap flow data for the invasive pine site were collected from late July 2016 to early August 2017. The total daily water use for the invasive pine site, shown in Figure 5.7, was an average of the four pine trees monitored.

In the 2016 winter months (July to October), daily water use reached a low of $<2 L.day^{-1}$ and a maximum of $11.2 L.day^{-1}$ (Figure 5.7). This variation in daily water use was in response to the

rainfall. For example, daily sap flow rapidly increased from $\sim 2 \text{ L.day}^{-1}$ to $\sim 11 \text{ L.day}^{-1}$, in response to a five-day rainfall event in late July. During the subsequent five-week dry period, the daily water use steadily decreased from $\sim 9 \text{ L.day}^{-1}$ to below 1.5 L.day^{-1} (Figure 5.7). It took approximately three weeks, from the time of the last rainfall, for the water use values to return to values similar to those before the rainfall event (i.e. $\sim 2 \text{ L.day}^{-1}$). This pattern in daily water use was repeated during small rainfall events in late September 2016. Solar radiation over this period continued to steadily increase by $\sim 10 \text{ MJ day}^{-1}$ from 17 July to 31 October 2016. However, the daily water use showed no response to the increased solar radiation. This implied that the water use of the invasive pine trees was limited by water availability.

In the wet summer period (November 2016 to February 2017), rainfall occurred regularly and the invasive pine trees had access to a more stable supply of water. Daily summer water use reached a maximum of 21.2 L.day^{-1} , with an average of 5.8 L.day^{-1} . As water availability was not limiting during this wet period, the availability of energy became a limiting factor that affected the transpiration rates. This was evident from the 14 February to 25 February 2017 (Figure 5.7), when a drop in solar radiation ($\sim 25 \text{ MJ.day}^{-1}$ to $\sim 8 \text{ MJ.day}^{-1}$) coincided with a decrease in the daily water use ($\sim 10 \text{ L.day}^{-1}$ to $<5 \text{ L.day}^{-1}$).

The results showed that the daily water use of the invasive pine trees was largely dependent on water availability, providing a possible indication that the invasive pine trees were obtaining water predominantly from the vadose zone. This also implied that the pine trees at the indigenous site were not in regular contact with the groundwater table, as the water use was close to zero in the dry periods, despite being evergreen.

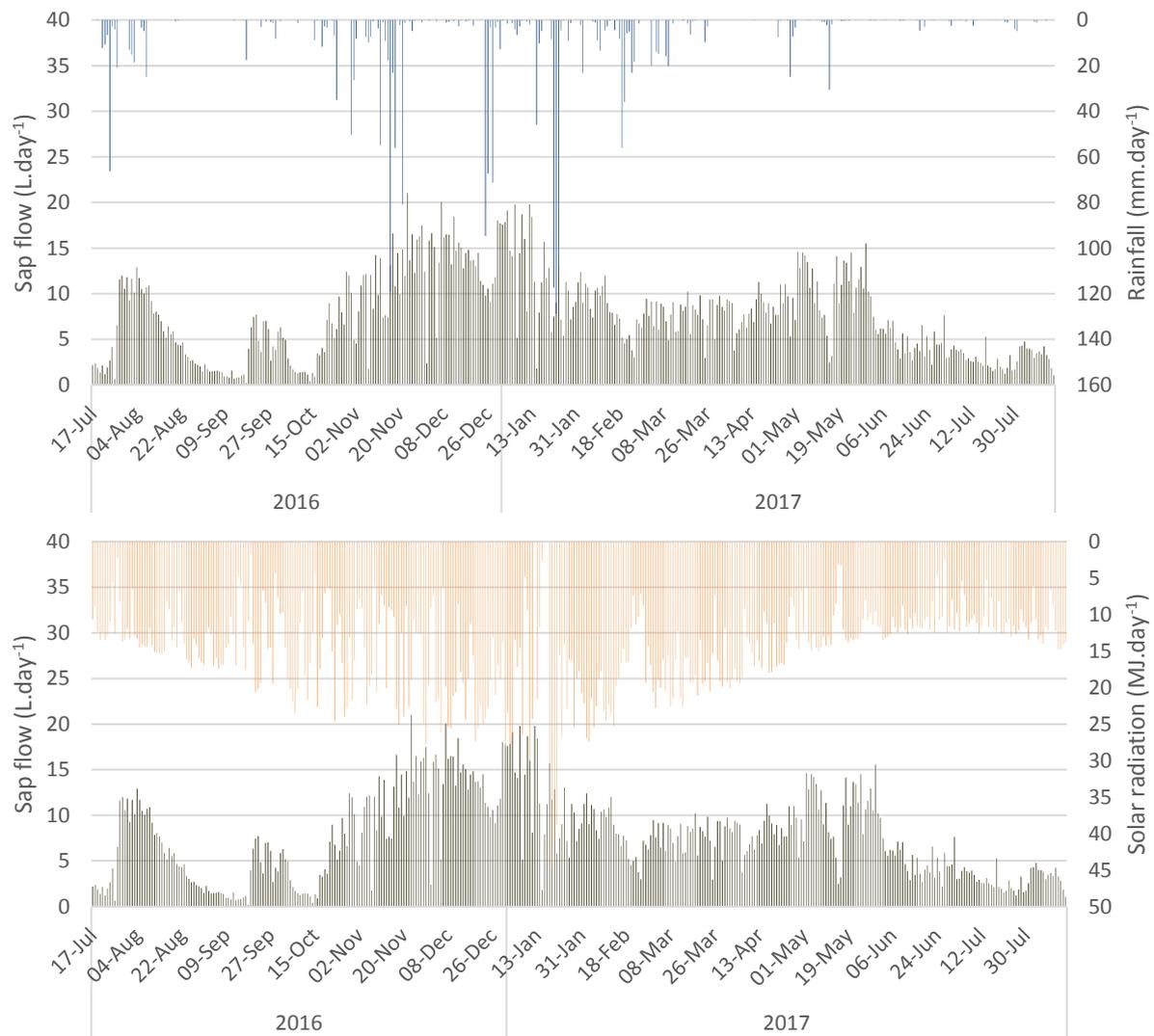


Figure 5.7 Mean daily water use (L.day⁻¹) of the invasive pine trees (average diameter 13.4 cm) monitored were located within a mixed indigenous forest on the fridge of Vasi Pan North compared with daily rainfall (mm.day⁻¹) and solar radiation (MJ.day⁻¹)

Due to the shortage of sap flow equipment, monitoring at the commercial pine stand was restricted to a short period from June 2017 to mid-August 2017. This corresponded to the dry winter season. During this period, the average daily water use was 5.3 L.day⁻¹, with a maximum of 12.7 L.day⁻¹ and minimum of 3.4 L.day⁻¹ (Figure 5.8).

The daily water use of commercial pine trees did not show any consistent trends in response to rain or solar radiation. Solar radiation remained low (<12 MJ.day⁻¹), with little daily variation. In addition, the daily rainfall events over this time were small (<5 mm.day⁻¹) and infrequent, which is expected in the dry winter period. These factors may account for the lack of response

from the trees, in terms of their daily water use. A longer monitoring period was needed to determine the effects of these climatic variables on the seasonal water use of commercial pine trees.

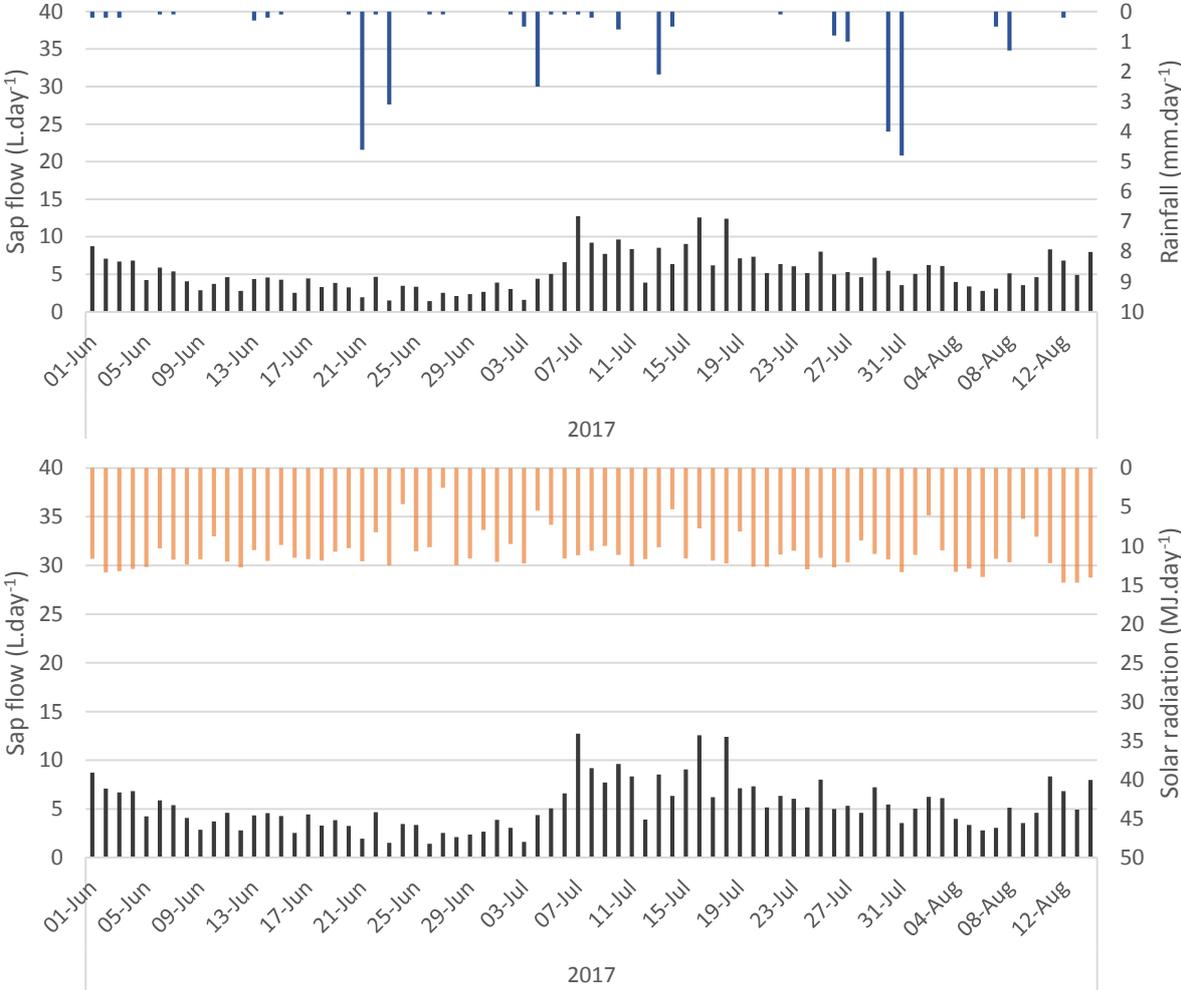


Figure 5.8 Mean daily water use (L.day⁻¹) of the pine trees (average diameter 16 cm) monitored were located in a commercial pine stand compared with daily rainfall

Water use at the small eucalyptus stand (2-year-old) was monitored from the beginning of the wet season in September 2016 to the dry season in August 2017. The daily water use (Figure 5.9) was calculated as an average of three trees.

The daily water use was high during the wet months (Figure 5.9), with a maximum of 35.3 L.day⁻¹ and an average of 19.2 L.day⁻¹ (November 2016 to February 2017). During the wet period, the daily water use responded to changes in solar radiation. For example, from 8-9

November 2016, a decrease in solar radiation (20.0 to 9.3 MJ.day⁻¹) coincided with a decrease in daily water use (18.4 to 9.5 L.day⁻¹).

The daily water use of the small eucalyptus trees decreased from the end of the wet summer season (March 2017) into the winter season. This decrease was in response to a decline in solar radiation, with the onset of winter. During the dry winter season, the average daily water use was 8.0 L.day⁻¹ (June- July 2017) and the trees' water use did not respond to rainfall events. The lack of response to infrequent rainfall events and the high average water use during the dry season, indicated that the water use of the small eucalyptus trees was limited by available energy and not by water availability. The small eucalyptus trees were not reliant on rain, but were potentially obtaining the water they used for transpiration from the shallow groundwater zone, as the trees were planted on the fringe of a wetland (Vasi Pan North).

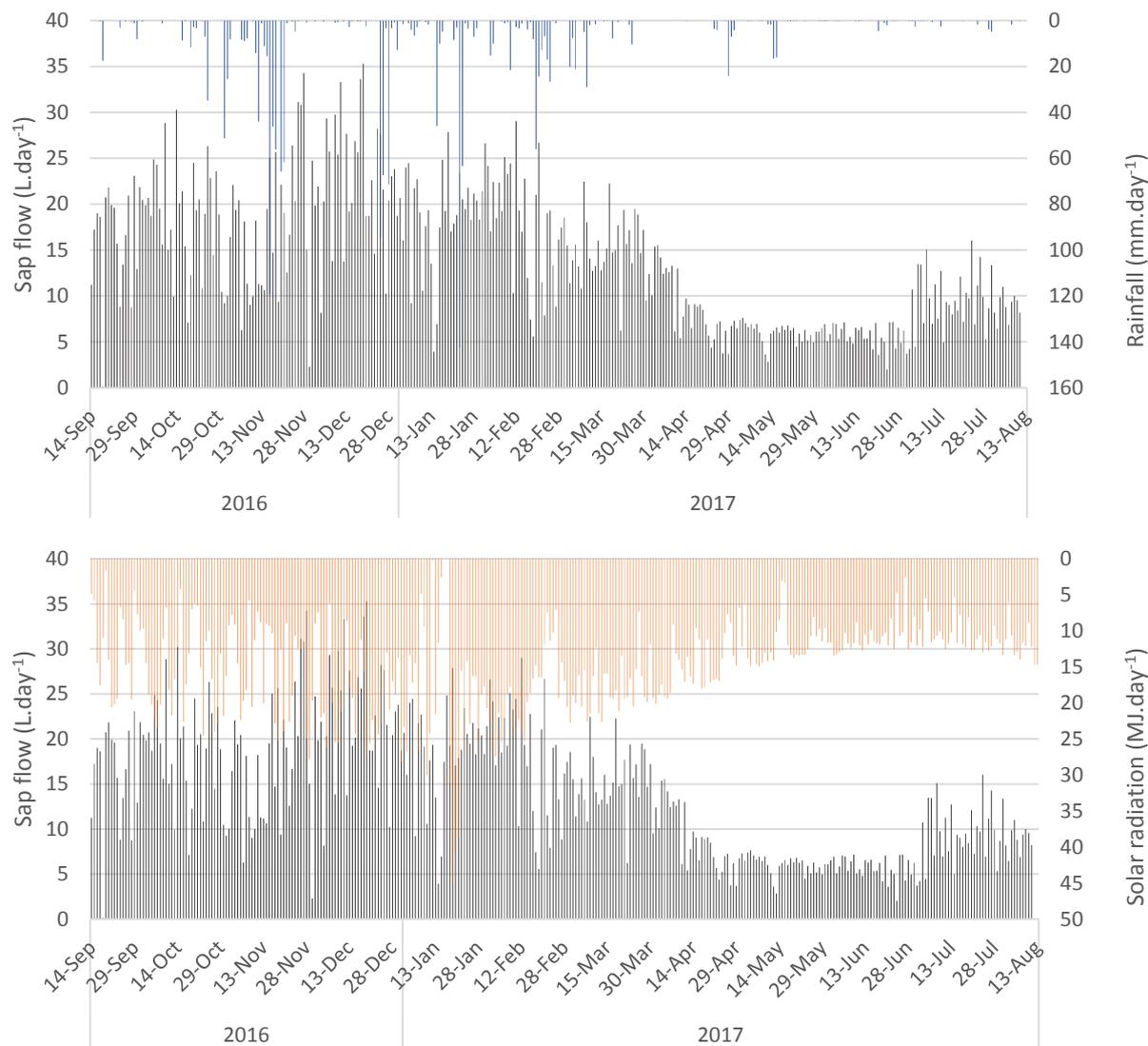


Figure 5.9 Mean daily water use (L.day⁻¹) of the small eucalyptus trees (average diameter 8.3 cm) monitored were located on the edge of Vasi Pan North compared with daily rainfall (mm.day⁻¹) and solar radiation (MJ.day⁻¹)

The large eucalyptus trees (5-year-old) were monitored from the wet season (November 2016) into the dry season (August 2017). Daily water use during the wet season was high, with an average of 18.0 L.day⁻¹ (November 2016 to February 2017) and a maximum of 35.0 L.day⁻¹ (Figure 5.10) During the wet season, when rainfall occurred frequently, daily water use responded to changes in solar radiation, decreasing as the solar radiation decreased.

Four weeks with no rainfall, from the 25 March to 25 April, resulted in the daily water use of large eucalyptus trees decreasing from 26.4 to 7.8 L.day⁻¹ (Figure 5.10). Their water use increased from ~4 to ~12 L.day⁻¹ after two large rainfall events (>20 mm) in May. During the

dry season (June to August 2017), average water use remained low (4.8 L.day⁻¹), as restricted water supply and solar radiation limited transpiration (Figure 5.10). The water use of the large eucalyptus trees in summer was therefore limited by water availability. This relationship between soil water availability and tree water use indicated that the large eucalyptus trees relied on rain as their primary source of water.

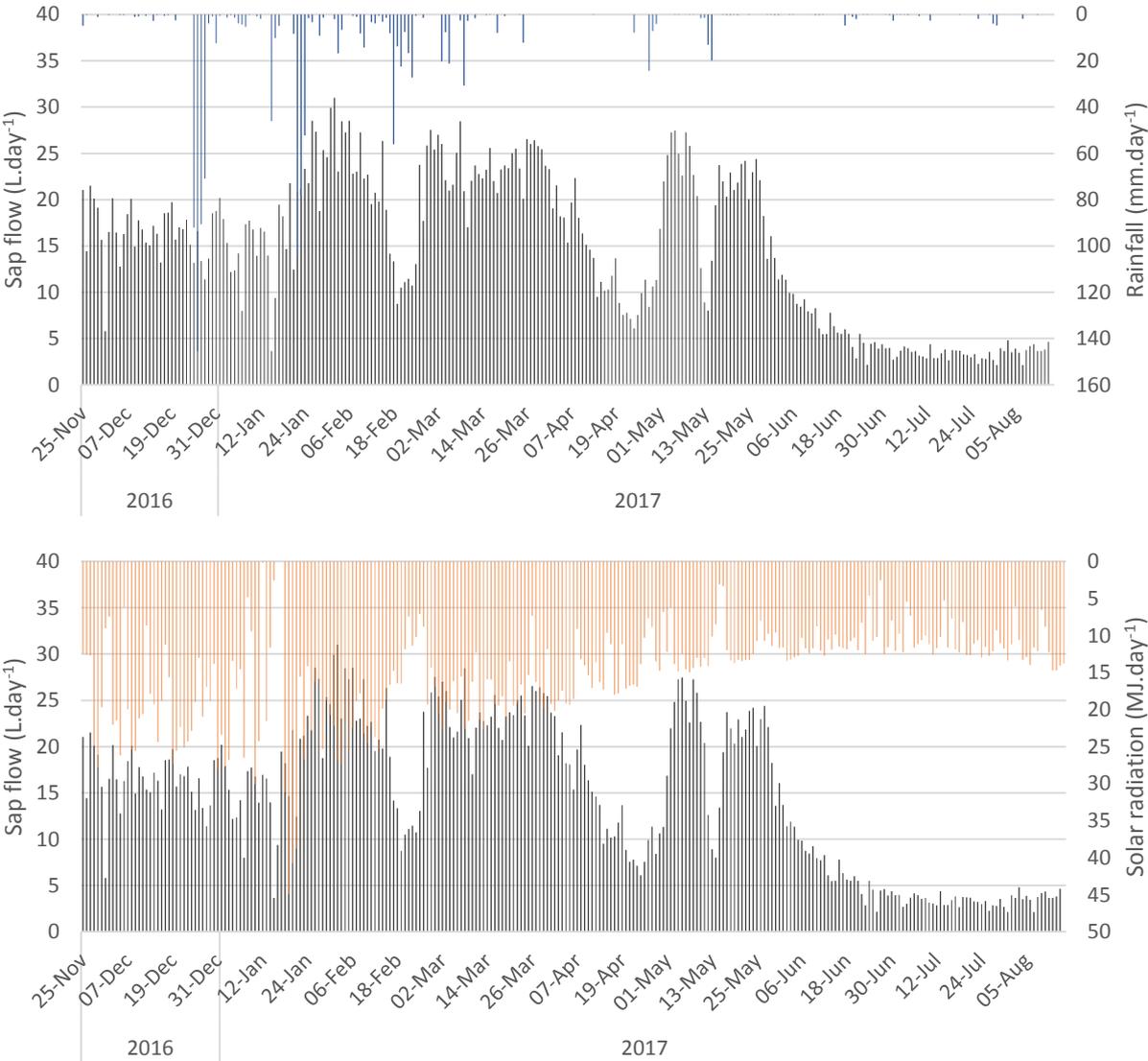


Figure 5.10 Mean daily water use (L.day⁻¹) of the large eucalyptus trees (average diameter 11.8 cm) monitored compared with daily rainfall (mm.day⁻¹) and solar radiation (MJ.day⁻¹)

The monthly water use of the monitored trees varied seasonally, with more water being used in the wet summer months than in the dry winter months (Figure 5.11). The large eucalyptus trees

used the most water per month in March 2017 (735.1 L), while the indigenous trees used the least water per month in July 2016 (46.7 L). The length of the monitoring period for the selected species varied according to the installation date, therefore, cumulative water use was not

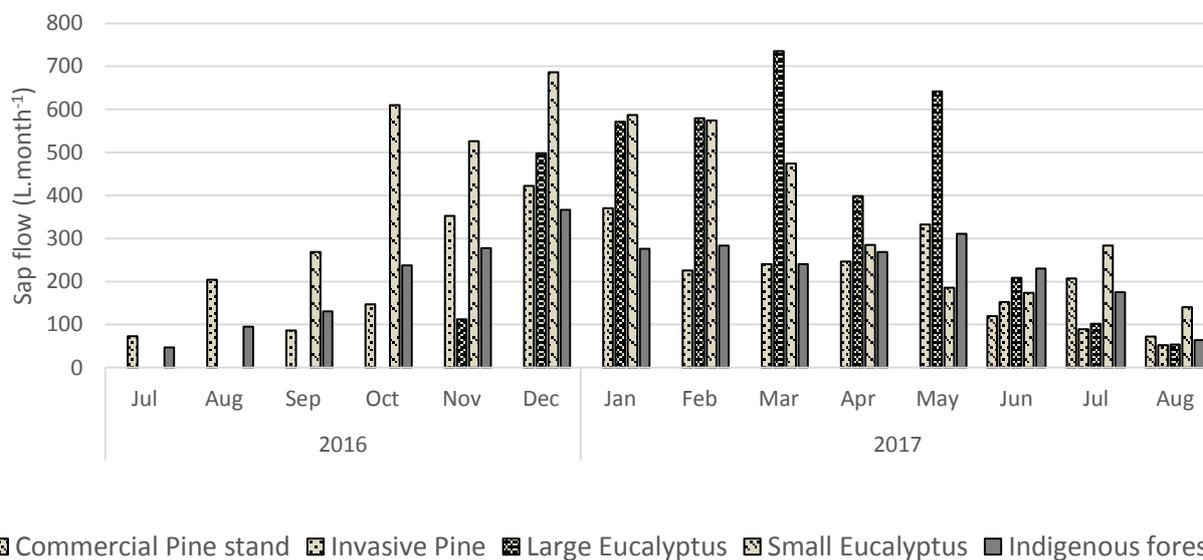


Figure 5.11 Total monthly water of the tree spp. monitored around the Vasi Pan area

calculated, as the results would not be comparable between species.

The average daily water use, for all the tree spp. monitored, was higher in summer than in winter (Table 5.1). In summer, the average daily water used was highest for the small eucalyptus (19.2 L.day⁻¹) and lowest for indigenous trees (10.0 L.day⁻¹). The large and small eucalyptus trees used substantially more water per day (~ 8.0 L.day⁻¹) than the pine and indigenous trees.

In winter, all the tree spp. monitored used significantly less water per day than in summer. The average daily water used was highest for the small eucalyptus trees (8.0 L.day⁻¹), and lowest for the invasive pine trees (4.7 L.day⁻¹) in winter (Table 5.1). The average daily water uses were similar for the commercial and invasive pine sites, the indigenous forest site, and the large eucalyptus site (Table 5.1). However, at the small eucalyptus site, the trees used ~ 3 L.day⁻¹ more water than the trees at the other sites in winter. The difference between the large and small eucalyptus winter average water use is of particular interest, as their water use averages were similar in summer.

The average daily water use of the large and small eucalyptus trees was similar in summer, with a difference of only 1.2 L.day⁻¹ (Table 5.1). However, throughout the winter, the difference in their average daily water use was far greater (3.2 L.day⁻¹), with the small eucalyptus using more water. This difference in daily water use was because the transpiration rates of the large eucalyptus trees are water-limited, while the small eucalyptus trees were energy-limited. The small eucalyptus trees were planted on the fringe of the Vasi North wetland, where the groundwater table was shallow and the trees could easily access the water during times of low rainfall. The large eucalyptus trees were planted on dry grasslands and the groundwater table was deeper, therefore the large eucalyptus trees were reliant on rainfall as their main source of water.

Table 5.1 The average daily water use for the tree spp. monitored in the Vasi Pan area during summer and winter

	Average tree diameter (cm)	Average water use (L.day ⁻¹)	
		Wet summer (Nov-Feb)	Dry winter (June-Aug)
Indigenous forest	11.5	10.0 2	4.7
Commercial pine stand	16.0	na	5.3
Invasive pine stand	13.4	11.4	4.7
Large eucalyptus	11.8	18.0	4.8
Small eucalyptus	8.4	19.3	8.0

5.3 Landscape water use

The recorded LE and H values for the hygrophilous grassland were found to be unrealistically high (Figure 5.12a). For example, the values for LE and H often exceeded or equalled R_n (Figure 5.12a), Therefore, there was a lack of energy balance closure (i.e. $R_n - LE - H - G \neq 0$). Because of the errors in measurement of LE and H, the EC data obtained for the hygrophilous grassland were excluded from this study. This error in measurement was due to an incorrect input of site parameters in the data logger program.

Energy fluxes for the commercial pine stand were recorded over the 2017 dry season and the data followed the expected energy balance relationship, where LE and H were less than R_n (Figure 5.12b). During the monitoring period, LE peaked at 10 am (~100 W.m²) and was lower than H, which peaked at midday (~200-300 W.m²). The LE peaking at 10 am indicated that there was stomatal closure to control water loss as VPD increased during the day. The average

monthly Bowen ration was >1 , indicating that H dominated the energy balance (Figure 5.12b) in winter. The average Bowen ratio increased from June (1.3) to August 2017 (2.7), indicating that less energy was available or used to evaporate water.

Energy fluxes for the indigenous forest were measured from the end of summer (February 2017) to mid-winter (July 2017). The noticeable dips in R_n , for the months of February, June and July, were due to cloud cover (Figure 5.12c). The balance of energy between two of the three components shifted during the monitoring period. G remained low (<50), while the partitioning of energy between LE and H varied (Figure 5.12c). For the months of February, March, May, and June, LE dominated the energy balance, with an average Bowen ratio of < 1 . During these months, more of the available energy was being used for the evaporation of water. The average monthly Bowen ratio was close to one for April (0.97) and July (1.1), indicating that the available energy was being equally partitioned between evaporating water (LE) and heating up the atmosphere above the soil (H).

The energy balance closure, calculated from the direct hourly energy flux daytime values, was poor for each land use (indigenous forest 43.8 %; commercial pine stand 66.1 %). These discrepancies may be a result of an overestimation of LE and/or H, an underestimation of the available energy ($R_n - G$) and unaccounted energy, such as advection or storage in the canopy biomass.

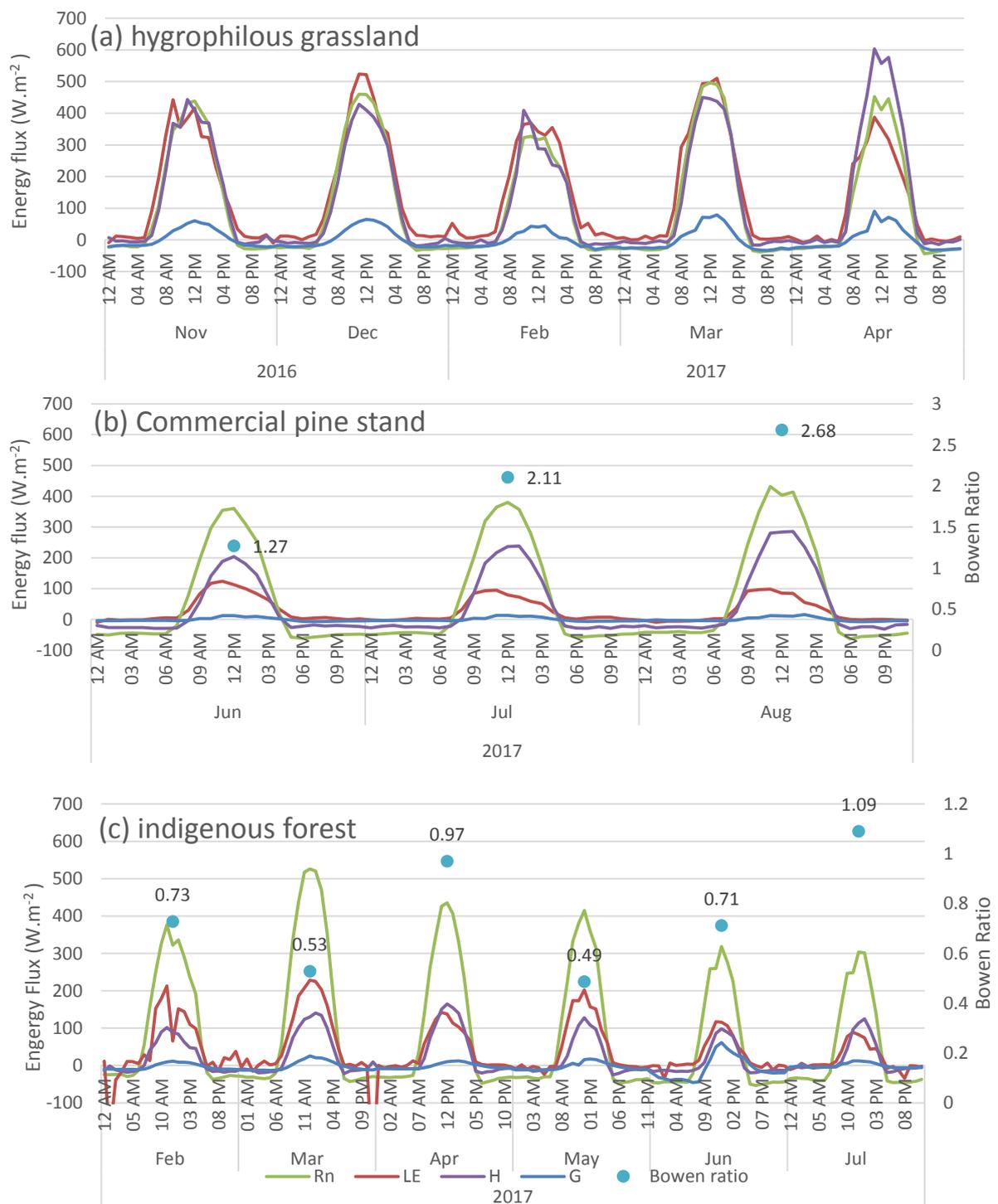


Figure 5.12 Average hourly energy fluxes and average monthly Bowen ratio measured at the chosen land uses (a-c)

Commercial pine stands were identified as a dominant land use in the Vasi area and a 12-year-old stand was identified for monitoring sap flow and ET_a monitoring, using an EC system, during the dry winter period of 2017 (June to mid-Aug). The ET_a peaked in late July

(2.1 mm.day⁻¹) and, during this period, the average ET_a was low (1.1 mm.day⁻¹), as rainfall and solar radiation were limiting (Figure 5.13). The ET_a measurements indicated that the trees were conservative water users in winter, despite the presence of a shallow groundwater table.

There was a significant difference in the ET_a and transpiration (t-test, $p < 0.0005$) measured during the monitoring period. The average transpiration (1.8 mm.day⁻¹) was greater than the average ET_a (1.1 mm.day⁻¹) (Figure 5.13). This result was unexpected, as transpiration should be less than ET_a. This is because the HPV technique only measures transpiration, while the EC system included other sources of evaporation, such as the plant sub-canopy and bare soil (ET_a). The results indicated that HPV measurement systems were potentially over-estimating the sap flow or the EC system was underestimating ET_a.

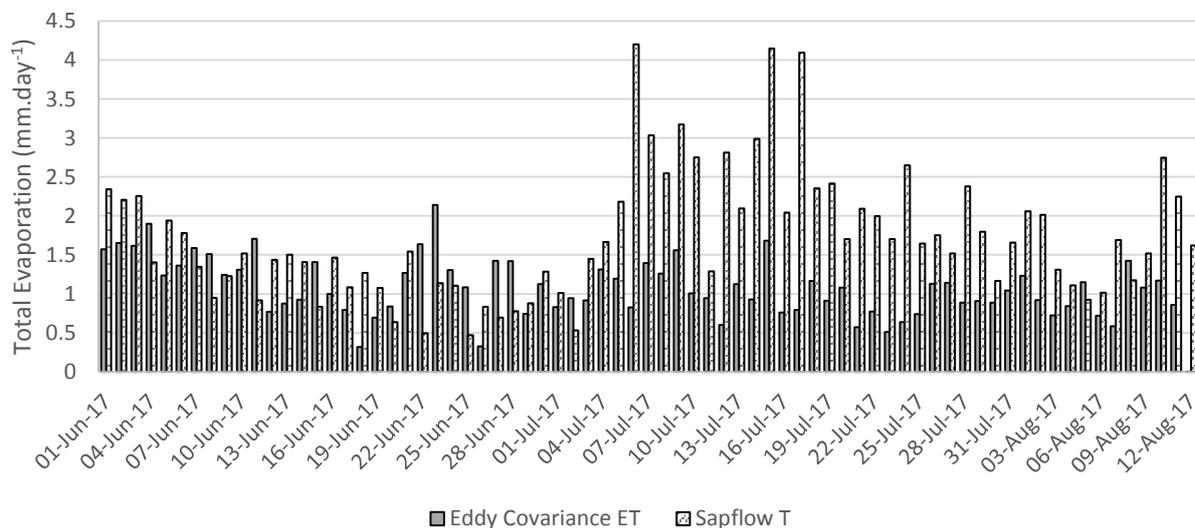


Figure 5.13 Daily total evaporation of the commercial pine stand measured using EC and sap flow techniques

The ET_a from the indigenous forest was monitored from the wet period in February 2017 to the dry period of July 2017. The daily ET_a steadily decreased over the monitoring period, with a maximum ET_a of 3.7 mm.day⁻¹ occurring in February 2017 (Figure 5.14). The average ET_a showed distinct seasonal decreases every two months, as the radiation and rainfall decreased from February to March (2.6 mm.day⁻¹), April to May (1.5 mm.day⁻¹) and June to July (1.0 mm.day⁻¹). This indicated that the total evaporation of the indigenous trees was responding to the seasonal changes in climate and tree phenology.

From June to July 2017, simultaneous measurements of ET_a were taken in the indigenous forest and the commercial pine stand. The average daily water use for the commercial pine stand ($1.5 \text{ mm}\cdot\text{day}^{-1}$) was higher than the average recorded for the indigenous forest ($1.0 \text{ mm}\cdot\text{day}^{-1}$) (Figure 5.14). Although the commercial pine stand used slightly more water than the indigenous forest, both forest types were conservative water users in winter.

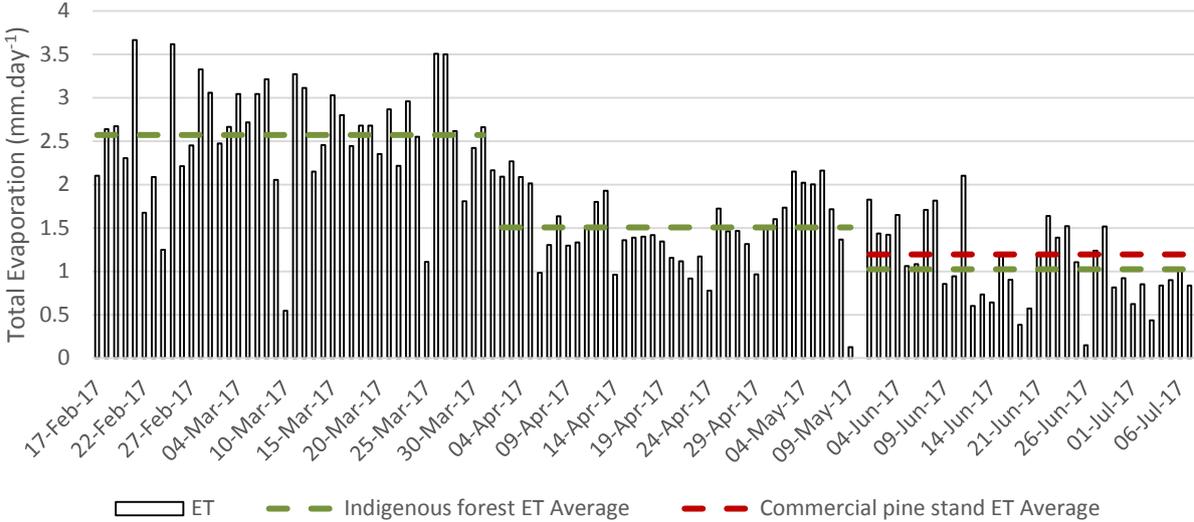


Figure 5.14 Daily total evaporation measured above the indigenous forest

The monthly K_c values calculated for the indigenous forest and commercial pine stand followed the same trends as the HPV and EC data. For the indigenous site the K_c was highest in February 2017 (0.9) and the lowest in July 2017 (0.4). High K_c values are typical when the vegetation is actively transpiring, which is associated with high incoming solar radiation and water availability. These conditions were present during the summer months in the Vasi Pan area. The K_c values decreased from February to July 2017; however, an increase from April (0.5) to May (0.69) was due to the late rains that occurred in May. In the commercial pine stand, K_c was the highest in June (0.6) and the lowest in August (0.3). The values decreased monthly during the dry season. The K_c for June and July were similar for the commercial pine stand and the indigenous forest, with values of ~ 0.5 .

The K_c values in winter were generally much lower than one, indicating that the ET_a was much less than the ET_o . In summer, the values were just less than one, indicating that ET_a was nearly equal to ET_o (evaporative demand).

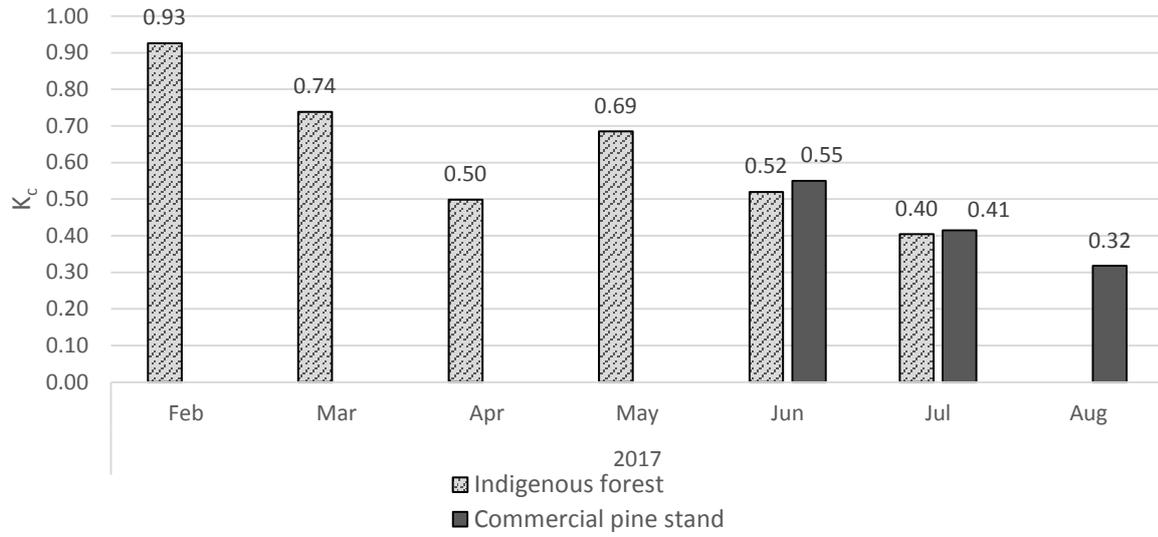


Figure 5.15 Monthly crop coefficient (K_c) for the selected land uses in the Vasi Pan area

6. DISCUSSION AND CONCLUSIONS

An objective of this study was to determine the water use of dominant indigenous and plantation species in the Vasi Pan area. The sap flow and EC data provided an indication of the seasonal water use of the selected species (Table 4.1) and comparisons with simultaneous weather data has helped to highlight the relative influence of climatic conditions on the daily sap flow.

The water use of the pine trees (*Pinus elliottii*) varied seasonally, with the pines trees using less water in the dry season. The timing of the decline in water use, the rapid recovery after significant rainfall, and the presence of a relatively shallow groundwater table, inferred that the water use of the pine trees was dependant on the available water from rain. In South Africa, several studies have reported sap flow data for *Pinus spp*; however, no comparable study on the water use of *Pinus elliottii* in the Zululand region was found. A study measuring the water use of invasive pines in riparian zones in the Western Cape showed similar trends in water use (Dzikiti *et al.*, 2013). The results from this study, and that of Dzikiti *et al.* (2013), showed a substantial decline in water use in the dry periods, despite the presence of shallow groundwater. This was because most pine species are isohydric, which means that they close their stomata, as soil and atmospheric conditions become dry, to maintain a relatively constant leaf water potential (Klien *et al.*, 2011; Lagergren and Lindroth, 2002). The pine trees growing in the Vasi Pan area are isohydric, as the LE peaked at 10 am in winter before maximum net radiation and air temperatures were reached, indicating stomatal closure.

The discrepancies between ET_a and transpiration measurements in the commercial pine stand highlighted potential errors in values obtained from the EC and HPV monitoring techniques. As previously mentioned in the section 5.3, one would expect data obtained from the EC system (ET_a) to be greater than values obtained from HPV techniques (transpiration). To determine the accuracy of the data obtained from each measurement technique, calibration is needed. However, this is a laborious process and resources for this study were limited. The overestimation of transpiration may be due to a large wounding width of 6 mm, which would substantially increase measurements. This wound width was beyond the range tested by Burgess *et al.* (2001) when he developed his numerical solution. Therefore, it is important to consider whether the equation holds linear for wound widths beyond the tested range. This is an important area for future research.

The average daily water use for pine trees (~16 years-old, diameter 14 cm) growing in the Vasi Pan area was ~11 L.day⁻¹ in summer and ~5 L.day⁻¹ in winter. These values are significantly lower than values recorded in previous studies undertaken in summer rainfall areas throughout South Africa (Dye *et al.*, 2001; Gush *et al.*, 2011). The daily average water use of *Pinus patula* trees, located in Karkloof, KZN midlands, were found to be ~50-100 L.day⁻¹ in summer and ~25-30 L.day⁻¹ in winter (Dye *et al.*, 2001; Gush *et al.*, 2011). This difference in water use can be attributed to the differences in soil water holding capacity between the two regions. The pine trees in the KZN midlands are planted on shale and sandstone soils, which have a greater water holding capacity than the sandy soils located in the Vasi Pan area.

The semi-deciduous nature of the monitored indigenous species accounts for the seasonal variation in water use. The trends in daily water use conformed to the patterns from other single-tree water use studies in South African indigenous tree production systems (Gush and Dye, 2009; Gush 2011; Mapeto *et al.*, 2017). Similar results were found in a moist southern Cape forest, as ET_a varied from season to season (Dye *et al.*, 2008). The seasonal variation in transpiration rates is an adaptation that allows the trees to survive in conditions with limited soil water storage and regular dry periods. A comparable study by Clulow *et al.* (2013) measuring the water use of indigenous species growing in a dune forest in Zululand, found that the indigenous species used ~25 L.day⁻¹ in summer, which was considerably higher than the values recorded in this study (~10 L.day⁻¹).

The water use of the small (2-year-old, diameter 8.3 cm) and large eucalyptus (5-year-old, diameter 11.8 cm) (*Eucalyptus grandis*) trees monitored in the Vasi Pan area were lower than the values recorded in a previous study monitoring eucalyptus spp. in Zululand (Dye *et al.*, 1997). Dye *et al.* (1997) measured the water use of three eucalyptus hybrids (6- to 8-year-old) growing on sandy soils in Kwambonambi, Zululand. Their daily water use peaked between 50-70 L.day⁻¹ in mid-summer, which was far greater than the peak summer rates recorded at Vasi Pan (25-35 L.day⁻¹). The sap flow rates exhibited a similar seasonal trend in both studies, with peak water use in summer, due to longer day lengths and frequent rains, while water use decreased in winter, due to a reduction in solar radiation and soil water deficits. A strategy of eucalyptus trees to avoid drought conditions is stomatal closure, this maintains leaf water potential above a critical threshold (Lange *et al.*, 1971; Schulze *et al.*, 1986; Tyree *et al.*, 1988). The large eucalyptus in the Vasi Pan area and eucalyptus trees in Kwambonambi, showed a similar rapid recovery in transpiration rates after a rainfall event, preceded by a period of

drought. This indicated that the water use of the eucalyptus trees in both studies, was generally affected by extended periods of soil water deficits. From these results, one can infer that the roots of the large eucalyptus trees in the Vasi Pan area were not in contact with the groundwater table.

The small eucalyptus trees were planted on the edge of Vasi Pan North, where the groundwater level was shallow. The decrease in water use of the small eucalyptus trees over the seasons was not due to soil water deficits, but due to the seasonal decrease in solar radiation. Their winter water use was $\sim 3.5 \text{ L.day}^{-1}$ higher than the other trees monitored in the study. Dye *et al.* (1996) conducted a study on 3- and 9-year-old *E. grandis* trees to determine the relationship between water use and soil water availability. Plastic sheeting was placed on the ground to prevent soil water recharge. The trees showed no decline in water use in response to increased soil water deficits. Dye *et al.* (1996) attributed this to the ability of 3-year-old eucalyptus trees to abstract water from depths of 8 m, while 9-year-old eucalyptus trees can obtain water from deeper, as live roots have been found at up to 28 m below the surface (Dye *et al.*, 1996). The lack of response to decreased water availability by the small eucalyptus was because their roots were in contact with the water table during dry periods and could maintain transpiration rates by accessing water stored in the soil water profile.

Apart from the small eucalyptus trees planted on the edge of Vasi Pan North, the results showed that the water use of the other trees monitored were limited by water availability, indicating that their roots were not in contact with the groundwater table. Water levels of the nearby Lake Sibhya have dropped by almost 4 m from 2001 to 2010, this is in response to the area receiving below average rainfall over the period of 2001 to 2011 (Smithers *et al.*, 2017). Lake Sibhya water levels can be used as a proxy interpreting groundwater levels in the area, therefore, one can infer that groundwater levels have dropped in recent years. The lowering of the groundwater table in recent years may account for the trees, particularly the deep rooted large eucalyptus trees, not abstracting water from the groundwater table during prolonged dry periods.

The average summer and winter water use of the indigenous and pine trees were similar in this study (Table 5.1). This contrasts with the previous studies which found that daily water use was significantly greater for the pine trees than the indigenous spp. (Gush and Dye, 2009; Gush *et al.*, 2011). Results from a study by Gush *et al.* (2011) in Karkloof, KZN midlands showed that in peak summer *P. patula* trees used more water per day ($50\text{-}100 \text{ L.day}^{-1}$) than indigenous

Podocarpus henkelii trees (10-20 L.day⁻¹). In this study, the eucalyptus trees used more water per day than the indigenous and pine trees. Numerous studies throughout South Africa monitoring various pine, eucalyptus and indigenous tree species have shown that the water use of indigenous trees is lower than the water use of pine and eucalyptus trees (Figure 2.1) (Olbrich *et al.*, 1996; Dye *et al.*, 2001; Gush *et al.*, 2011; Gush *et al.*, 2015). In this study, the water use of the indigenous trees was low, as was the water use of the pine trees.

6.1 Challenges

The greatest challenge in the monitoring of ET in Vasi Pan, Zululand, was the remoteness of the site and the high maintenance requirements of the ET monitoring equipment. The remoteness of the site made equipment maintenance and regular fieldtrips difficult. Often, damaged and faulty equipment could not be not fixed immediately, as spares were not readily available in the field. Equipment failure, due to theft of batteries and solar panels, was an issue. Permanent guards were employed, but this became too expensive.

6.2 Conclusion and Recommendations

There is an ever-growing demand for water, therefore, it is important that water resource managers implement improved management procedures and policies correctly and efficiently (Jarman *et al.*, 2009). For this to happen, it is important to obtain accurate ground-based measurements of ET.

Along the Maputaland Coastal Plain, commercial plantations, increased agricultural activities and the expansion of human settlements have reduced the natural impact of fire in the historical grassland areas and they have resulted in increased woody vegetation systems. These activities have impacted the ground and surface water in the region (Rawlins, 1991; Kelbe and Germishuyse; 2010; Vaeret *et al.*, 2009; Kelbe *et al.*, 2014, Smithers *et al.*, 2017). Therefore, it was vital to understand how the water use in the area has changed due to the introduction of fast-growing species in forestry plantations, as well as the expanded woody cover of indigenous species, in comparison to the original Maputaland woody grassland vegetation mosaic. This information can be used to assist water resource managers and local communities in the decision-making process, when determining the best land use practices for the area (Everson *et al.*, 2011).

It was concluded from the long-term HPV results, that tree water use was affected by climatic variables and soil water retention properties. The VPD in the area was low throughout the year, due to the proximity of the site to the coast. This affected transpiration rates as there was little atmospheric demand to drive transpiration. The sandy soils present at the sites had low water retention properties and therefore, held little water in the soil water profile and drained quickly after rainfall events. During the wet summer months, when the water supply was not limited, the transpiration rates were affected by solar radiation, and on cloudy days, transpiration rates decreased for all species. In the dry winter months, the water use of the large eucalyptus and pine trees was limited by water availability, indicating that trees close their stomata during extended dry periods to maintain a relatively constant leaf water potential to survive (Klien *et al.*, 2011; Lagergren and Lindroth, 2002). The water use of the indigenous trees was seasonal, as they are semi-deciduous and reduce their water use with the onset of the dry season. The small eucalyptus site was energy-limited and transpiration rates decreased in response to a decrease in solar radiation. The small eucalyptus trees were planted on the edge of the Vasi Pan North wetland, where the groundwater is shallow. Therefore, it was concluded that the small eucalyptus trees were potentially accessing water from the groundwater table. To assist in verifying these results, soil water content probes need to be placed at the site to determine the interaction between tree water use and soil water content and additional information from the installation of boreholes would be beneficial.

The ET_a measured in the indigenous forest site, using the EC system, indicated that the indigenous forest's water use followed the same seasonal trend as found in the HPV data, with ET_a peaking in the wet summer and decreasing with the onset of the dry season. The transpiration values at the commercial pine stand were greater than the ET_a values; therefore, the EC system was potentially underestimating the ET_a at the commercial pine stand or HPV methods were overestimating transpiration rates. The error in measurement in the energy fluxes of the hygrophilous grassland site, was unfortunate, as it would have provided a reference value for the natural vegetation system of the area. The altered/ introduced vegetation systems could have been compared with the historical natural vegetation systems, providing insight as to whether these changes in vegetation have affected water resources in the area.

In conclusion, the water use of the tree species that were monitored in this study was low, in comparison to previous studies in South Africa. In terms of the management of forestry in the

area, this study has shown the planting of pine species is preferable over the planting of eucalyptus species, because on average the pines trees used less water than the eucalyptus trees. The daily water use of the trees was limited by water availability, except for the small eucalyptus stand, which was energy-limited. Further research is needed to determine whether the small eucalyptus trees are accessing water from deeper in the soil water profile during the dry season. The placement of plantations, in relation to groundwater levels and wetland boundaries can determine whether the trees will be energy- or water-limited. It is critical for water resource managers to choose the placement of new plantation stands with careful consideration. This is to ensure that the new stands are not within wetland boundaries, as this will determine to what effect the stand has on groundwater resources. There is a need for accurate delineation of wetlands in the area and improved groundwater modelling to assist in the decision-making process.

To improve the findings of this study, it would be beneficial to extend monitoring period in the field, particularly for species where the monitoring period was less than a year or lacked data for both the wet and the dry season. The EC system should be placed in the commercial pine stand during summer, and an attempt should be made to obtain accurate ET_a measurements in the hygrophilous grassland. The analysis of soil water content is important to consider when interpreting sap flow data. Future studies need to ensure that soil water content probes are placed at each HPV site, as this will assist in clarifying the relationship between water content in the top layer of soil and tree water use.

The extent of extraction of water by trees from the groundwater and the impact of afforestation has been a source of uncertainty in models used in the Zululand area. The inclusion of the transpiration and ET_a data, collected in this study, into future modelling exercises will be important for improving the accuracy of the models in the Zululand area. Accurate modelling of this unique groundwater based system will be a key resource used by decision-makers to assist them in the management of this water-stressed catchment. Another tool to be considered, which may assist decision-makers, is the use of the SEBS model to provide insight at a larger scale of ET for the various land used in the area which were not monitored in this study. The SEBS model would provide further evidence as to the differences in water use between the various land uses in the area.

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8. APPENDIX

Table 8.1 Growth measurements of 30 trees eucalyptus taken in the large eucalyptus stand

Tree	Diameter (cm)		Diameter Growth (cm)
	24 Nov 2016	15 Aug 2017	
1	11.8	13.3	1.5
2	11.8	13.0	1.1
3	12.6	13.2	0.6
4	16.1	17.0	0.9
5	11.1	11.8	0.7
6	10.4	10.9	0.5
7	13.3	14.6	1.3
8	21.1	27.2	6.1
9	6.9	7.6	0.7
10	10.3	10.8	0.5
11	13.1	14.0	0.9
12	15.1	16.7	1.6
13	8.8	9.7	0.9
14	6.6	7.1	0.5
15	20.2	20.6	0.4
16	6.1	7.4	1.3
17	9.9	11.1	1.15
18	4.1	5.5	1.4
19	9.8	10.4	0.6
20	10.6	11.7	1.1
21	14.4	15.9	1.5
22	9.4	9.5	0.1
23	11.5	12.1	0.6
24	13.4	15.2	1.8
25	16.4	17.6	1.2
26	14.6	16.1	1.5
27	3.6	4.7	1.1

28	15.6	16.8	1.2
29	18.3	20.0	1.7
30	18.1	19.2	1.1
Average	12.17	13.4	1.2

Table 8.2 Growth measurements of 30 trees eucalyptus taken in the small eucalyptus stand

Tree	Diameter (cm)		Diameter growth (cm)
	20-Jan-17	15-Aug	
1	8.0	10.9	2.9
2	6.2	9.1	2.9
3	8.1	10.9	2.8
4	5.7	8.5	2.8
5	5.1	8.3	3.2
6	4.9	8.0	3.1
7	5.4	8.8	3.4
8	4.6	7.8	3.2
9	5.5	9.0	3.5
10	5.7	8.5	2.8
11	6.0	9.1	3.2
12	4.6	7.7	3.1
13	5.4	8.9	3.5
14	4.0	7.0	3.0
15	3.0	5.5	2.5
16	6.2	9.3	3.1
17	6.7	9.7	3.0
18	8.3	11.7	3.3
19	7.2	10.0	2.8
20	6.4	8.7	2.4
21	7.4	10.0	2.7
22	5.2	7.5	2.3
23	6.1	8.9	2.7
24	7.7	10.5	2.8

25	8.0	10.8	2.9
26	6.9	9.52	2.6
27	6.6	8.9	2.4
28	8.4	11.4	3.0
29	8.0	11.0	3.0
30	8.9	11.4	2.5
Average	6.3	9.2	2.9