A COMPARISON OF PRODUCTIVE AND NON-PRODUCTIVE GREEN WATER-USE EFFICIENCY OF *PODOCARPUS HENKELII* AND *PINUS PATULA* IN THE KWAZULU-NATAL MIDLANDS

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ABSTRACT

A number of studies undertaken in South Africa to quantify the green water-use (total evaporation) of introduced commercial forestry species have shown conclusively that green water-use from commercial forest plantations is substantially higher than from the original grasslands or fynbos that were replaced by afforestation. Green water can be categorised into productive (transpiration) and non-productive (canopy and litter interception and soil evaporation) fluxes. There is a widespread perception within South Africa that indigenous tree species, in contrast to commercial forestry genera/species, are water-wise and should thus be planted more extensively in view of their more efficient use of water. However, information on the water-use of indigenous trees and forests is scarce and indirect, and the relative contributions of transpiration, canopy interception and litter interception to total evaporation have until now not been investigated in South Africa. To quantify these fluxes, both field measurements and modelling were undertaken. In this study, green water-use by indigenous *Podocarpus henkelii* and an exotic species *Pinus patula* are compared. The results from this study show that the productive green water-use by *P. henkelii* and *P. patula* was 41.0% and 95.9% of gross precipitation respectively over the 18 month period of this study. The non-productive canopy and litter interception by *P. henkelii* accounts for 29.8% and 6.2% respectively, while canopy and litter interception accounted for 22.1% and 10.7% respectively for *P. patula*. The productive green WUE of *P. henkelli* and *P. patula* is 7.14g.mm^{-1} and 25.21g.mm^{-1} respectively, in comparison with the total green WUE of 3.8g.mm^{-1} and 18.8g.mm^{-1}. From a water resources management and planning perspective it is important to consider the total green WUE, but also to have a good understanding of the relative contributions of each component of the green water fluxes so that water abstracted from the soil can be differentiated from the water that does not reach the soil due to losses of canopy and litter interception and does not get lumped as one evaporative loss.

Keywords: Water-use efficiency; *Pododarpus henkelii*; *Pinus patula*; transpiration; rainfall interception

INTRODUCTION

The production of biomass for direct human consumption as food and timber is by far the largest human managed consumer of freshwater on Earth (Falkenmark and Rockström, 2006). The limited supply of indigenous timber means South Africa has a large area of exotic forest plantations that are planted in the wetter regions of the country, covering an area of approximately 1.4 million hectares compared with 0.5 million hectares covered by indigenous forests. The commercial forestry sector contributes approximately 22 billion Rand to the South Africa economy and employs approximately 170 000 people (Chamberlain *et al*., 2005; DAFF, 2010). The “Green Water” concept where all vapour fluxes including transpiration, soil evaporation, canopy interception and litter interception are considered was introduced by Falkenmark (1995) and has since gained prominence as a highly effective way of highlighting the role of evaporation from the landscape (Jewitt, 2006). The consideration of green water flows in formal water resources planning is however proving to be very difficult (Jewitt, 2006), not least because of confusion in terminology.

There have been a number of studies undertaken in South Africa to quantify the green water-use (total evaporation) of introduced commercial forestry species. These studies have shown conclusively that green water-use from commercial forest plantations is substantially higher than from the original grasslands or fynbos that were replaced by afforestation and that this results in reduced streamflows (Blue water) (Dye, 1996; Scott *et al*., 2000). Thus, forest plantations have mostly reduced catchment water yields, and this has resulted in legislation limiting further afforestation in areas where water supplies are already committed. Although the demand for timber is growing strongly, the extent of the national forestry estate is essentially capped to minimise further declines in surface “Blue Water” resources (Dye *et al*., 2008). The production of biomass is a water–dependant process. During photosynthesis, when the stomata are open to take in carbon dioxide, a large amount of water is simultaneously being transpired. While transpiration is considered a productive green water flow as it is responsible for biomass production, it is accompanied by non-productive evaporative losses from the soil, litter and canopy should water be available. Together, these vapour fluxes of transpiration, soil evaporation, and canopy and litter interception constitute the total Green water used in biomass production (Falkenmark and Rockström, 2006).

There is a widespread belief within South Africa that indigenous tree species, in contrast to commercial forestry genera/species including *Pinus* (pine), *Eucalyptus* (gum) and *Acacia mearnsii* (wattle), are “water-wise” and should be planted more widely in view of their perceived more efficient use of water. This perception appears to be based on the observation that indigenous trees are generally slow growers, and the belief that growth rate and water-use are broadly linked. However, tree water-use, and the total evaporation from forests and woodlands, is difficult to measure, and so evidence of low water-use by indigenous trees is scarce and indirect. The most comprehensive study of water-use by indigenous trees in South Africa was undertaken by Dye *et al*., (2008) and largely forms the benchmark against which the results from this study are compared. Typically, water-use efficiency (WUE) studies express water-use in terms of an increase in wood biomass relative to transpiration (i.e. productive Green water-use). In this study, only the stem biomass was considered, and did not included the branches and leaves. From the findings of a study by Dye *et al*., (2008) which considered the productive Green WUE of indigenous species, it was found that the WUE of indigenous species is generally lower than that of commercial forestry species. Dye *et al*., (2008) defined WUE in their study as the increase in stem dry biomass per unit of water transpired. Although transpiration by the indigenous species was generally lower in comparison to more productive commercial species, particularly *Eucalyptus grandis,* the rate of growth was also much slower, and result in a lower WUE. Dye *et al*., (2008) concluded that in general, indigenous trees appear to possess an advantage over commercial species on productive sites in having lower water-use and lower streamflow reduction impact, but not in growth rate. Because Dye *et al*., (2008) based their study on transpiration measurements only, the non-productive component of total evaporation (i.e. interception) was not considered. Because of the scarcity of studies on water-use of indigenous trees and forests the relative contributions of transpiration, canopy interception and litter interception to total evaporation have, until now, not been investigated in South Africa. The aims of this study are therefore:

1. To establish the relative contributions of transpiration, canopy interception and litter interception to total evaporation in an indigenous *P. henkelii* even aged plantation.
2. Determine the productive and non-productive green water-use of *P. henkelii and P. patula*.
3. Calculate the total green WUE of *P. henkelii* and *P. patula*.
4. Compare the total green WUE of *P. henkelii* and *P. patula*.

METHODOLOGY

Continuous sap flow (transpiration) monitoring on an hourly basis was undertaken for both *P. henkelii* and *P. patula* for one year to incorporate seasonal variations and responses to climatic factors. Event-based measurements of canopy and litter interception were recorded for *P. henkelii* as well. Hourly measurements of solar radiation, temperature, relative humidity, wind speed and rainfall complemented these measurements and were used as an input into the Variable Storage Gash canopy interception model and drying curve litter interception model (Bulcock and Jewitt, 2012b), which was used to estimate interception from the *P. patula* stand. The components of productive and non-productive green water used to calculate total green water-use efficiency is shown in **Figure 1**.

INSERT FIGURE 1

Site Description

Two study sites situated 50m apart from each other were selected on the Mondi owned Tetworth estate in Karkloof, near Howick in the KwaZulu-Natal Midlands (S 29° 21' 25.2" and E 30° 11' 49.3", alt. 1148 m.a.s.l). The sites have a mean annual precipitation of 1271 mm (Lynch and Schulze, 2006), most of which falls during the summer months between October and April. The mean annual potential evaporation of the area is high at between 1600-1800 mm (Schulze, 1997), but the FAO-56 short grass reference evaporation (Allen *et al*., 1998) was 1518mm for the period of the study. Mucina and Rutherford (2006) describe the area as southern mistbelt forest. A characteristic of the local rainfall regime is a strong orographic effect, caused by the lifting and convective cooling of the summer south-east winds over the Karkloof mountain range (Dye *et al*., 2008). During the 547 day study period from October 2009 to March 2011, a total of 1635.9mm of rainfall was recorded, of which 346 days had rainfall. Of the 346 rain days, 147 (42%) of them had less than 1mm as shown in **Figure 2**. The first site was a small (<1ha) even aged indigenous *Podocarpus henkelii* planation that was located close to a riparian area, but at an elevation about which the soil would be classified as a true riparian area. *Podocarpus henkelii* are evergreen and have long slender drooping leaves (Palgrave, 2002) which is important when considering the canopy water holding characteristics and canopy interception. Information on past stand management are limited due to changes in ownership of this particular farm, and the trees are of an unknown age. However, by virtue of their size (average tree height of 8m) and stem diameters (DBH: 15-30cm) the trees are estimated to be roughly 40 years old. The trees were hand-planted, but have not been pruned. The planting spacing is somewhat irregular but an average distance between trees (3 m x 3 m) translates into a planting density of approximately 1111 trees per hectare. The second site is a commercial plantation stand of *P. patula* grown for saw timber with a planting density of 816 trees per hectare (3.5m x 3.5m) and is not situated in a riparian zone. They were planted in September 2002, making them approximately 9 years old at the beginning of the study. They have been subjected to limited thinning or pruning since 2003. The soils at both sites are classified as Clovelly, characterised by an orthic A-horizon and a yellow-brown apedal B-horizon with a sandy-clay-loam texture and a depth of more than 1.2m. Both sites have a similar slope of 23% (1:4.1) and 26% (1:3.8) for the *P. patula* and *P. henkelii* stands respectively. The *P. patula* stand is on a south-west (SW) facing slope and the *P. henkelii* is on a south-south-west (SSW) facing slope.

INSERT FIGURE 2

Canopy Interception

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

Litter Interception

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

Canopy and Litter Interception Models

Due to the unavailability of canopy and litter interception data for the *P. patula* stand at the Karkloof site, the “variable storage Gash model” and idealised drying curve models (Bulcock and Jewitt, 2012b) were used to simulate canopy and litter interception respectively for *P. patula*. The model descriptions and verification are detailed in Bulcock and Jewitt (2012b).

Sap Flow Measurements

The Heat Pulse Velocity (HPV) technique is an internationally accepted method for measuring the flow of sap in trees and has received much attention by researchers in recent years, (Smith and Allan, 1996; Gush and Dye, 2009). The HPV technique was used to measure the sapflow/transpiration for both *P. henkelii* and *P. patula*. The HPV technique has been extensively applied in South Africa (Dye & Olbrich, 1993; Dye, 1996; Dye, Soko & Poulter, 1996; Dye *et al.*, 1996; Gush, 2008; Gush & Dye, 2009) on both indigenous tree species and commercial forestry species. The HPV measurements described in this paper are based on the heat ratio method (HRM) described by Burgess *et al*. (2001) because of its ability to accurately measure low rates of sap flow that were expected in the indigenous *P. henkelii* stand. The HRM requires a line-heater to be inserted in the xylem at the vertical midpoint (commonly 5 mm) between two temperature sensors (thermocouples). Heat pulses are used as a tracer, which is carried by the flow of sap up the stem. This allows the velocity of individual heat pulses to be determined by recording the ratio of the increase in temperature measured by the thermocouples (TC's), following the release of a pulse of heat by the line heater. For these measurements TC pairs and heater probes were positioned 80cm up the main stem of each tree, below the first branches. TC's were inserted to four different depths within the sapwood to determine radial variations in sap flow (i.e. each tree contained four TC pairs). The insertion depths of the TC's were calculated after first determining the total sapwood depth for each species, and then spacing the probes evenly throughout. While performing the drilling, a drill guide was strapped to the tree, to ensure that the holes were as close to parallel as possible. CR1000 data loggers connected to AM16/32 multiplexers (Campbell Scientific, Logan, UT) were programmed to initiate the heat pulses and record hourly data from the respective TC pairs.

Heat pulse velocities derived using the HRM were corrected for sapwood wounding caused by the drilling procedure, using wound correction coefficients described by Swanson & Whitfield (1981) based on the wound widths reported in **Table 1**. The corrected heat pulse velocities were then converted to sap flux densities according to the method described by Marshall (1958). Finally, the sap flux densities were converted to whole-tree total sap flow by calculating the sum of the products of sap flux density and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). Hourly sap flow values were recorded from all the trees. Periods of missing data were patched using data from another probe set which is the most highly correlated. The complete record was aggregated into daily, monthly and annual totals. Individual tree sap flow volumes (L.month^{-1}) were scaled up to a hectare using the planting density to also derive sap flow (transpiration) totals in mm-equivalent volumes (Gush *et al*., 2011).

The sap flow and stem diameter increment rates were measured by Gush *et al*., (2011) in two trees at each site (**Table 1**). The study trees were selected after doing an initial survey of the range of stem diameters in the plantations. Based on the findings of the initial survey, trees that fell within the two most prominent stem diameter classes were selected in order to be as representative of the stand as possible with the limited number of samples used. Bark thicknesses of the sample trees were determined by excising bark sections from the stems. Measurements of sapwood depth, required to determine the insertion depths of thermocouple probes for water-use measurements, were obtained using a 5mm inside-diameter increment corer (Haglöf, Sweden). Cores were subsequently analysed for sapwood depth using measurements of the visual distinction between lighter coloured sapwood and darker coloured heartwood. Wood density for the two tree species was determined using mass and volume measurements (Archimedes Principle) on stem-wood samples chiselled from the trees at a height near to where the probes were inserted. Monitoring began on 13 August

2009 and continued until the end of March 2011. The canopy and litter interception monitoring began at the beginning of the wet season in October 2009.

INSERT TABLE 1

Stem Growth Measurements

In addition to sap flow measurements, stem biomass increments surveys were undertaken for both *P. henkelii* and *P. patula*, in order to calculate WUE. Stem volume increment measurements were carried out at the inception of the study on the 13 August 2009 and subsequently a year later on the 12 August 2010 in order to include all seasons in 1-year. Stem circumferences were measured at 1m intervals up the tree, and subsequently converted into volume by assuming that the stem consists of a series of truncated cones with a complete cone on the top (Gush *et al*., 2011). The volumes (V) (m^3) of the individual cones was calculated using Equation 1.

$$V = (\pi . r^2 . h)/3 \qquad [1]$$

Where, r is the radius at the base of the cone (m), and h is the height of each cone (m).The volumes of the truncated cones were calculated using Equation 2.

$$V = [\pi . h(r_1^2 + r_1 r_2 + r_2^2)]/3 \qquad [2]$$

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

The stem volume increments were converted to dry mass using the wood densities determined from samples collected for each species in this study as shown in **Table 1**.

Plant Area Index Measurements

The single-sided plant area index (PAI) (including leaves, branches and twigs) was measured using the LI-COR LAI-2000 plant canopy analyser (LAI-2000, LI-COR, Inc., Lincoln, Nebraska, USA). Ten sets of four readings were taken for each tree. A sunlit canopy was avoided by taking the readings just before sunset when the solar elevation is low (below 45^o). A 45^o view restrictor was used to block the sensor in the field of view of the operator. This procedure was followed for all sites, and the values are shown in **Table 1**.

RESULTS

The results discussed in the subsequent sections are for the period of October 2009 to March 2011 at the *P. henkelii* and *P. patula* stands in Karkloof.

Relative Contributions of Transpiration, Canopy and Litter Interception.

The transpiration recorded in the *P. henkelii* stand shows a relatively consistent rate throughout the year (**Figure 3**) with monthly transpiration varying between 26.8mm and 48.8mm. This may be attributed to the evergreen nature of *P. henkelii*, as well as the lack of seasonal water stress due to the riparian location of the site. Also, *Podocarpus* is a gymnosperm and therefore the xylem consists of tracheids which have a lower conductivity than the vessels of angiosperms. The highest sap flows were recorded during the summer months when leaf area, temperature and available water are high, as well as having longer day lengths. Transpiration accounts for the largest water-use at 41% and 95.9% of the gross precipitation for *P. henkelii* and *P. patula* respectively during the study period (**Table 2 and Table 3**). It is also important to note that the transpiration by the *P. patula* exceeds the total quantity of water that infiltrates into the soil. Therefore, the *P. patula* is reliant on additional water from upslope to recharge the soil water, or else is accessing ground water. *P. henkelii* transpires on average 97.8 L per unit of plant area per year, compared to the 436.9 L per unit of plant area for *P. patula*. Therefore, even though *P. henkelii* has a smaller PAI than *P.*

patula, the exotic *P. patula* transpires on average 4.5 times more per unit of plant area than indigenous *P. henkelii*. Canopy interception is the second highest water-use at 29.8% and 22.1% of gross precipitation for *P. henkelii* and *P. patula* respectively. The highest absolute monthly canopy interception loss for both *P. henkelii* and *P. patula* was recorded in December 2009 at 50.4mm and 37.2mm respectively. The highest canopy interception losses are expected during the summer months when there is the highest rainfall, as well as highest evaporation potential due to the higher temperatures. Conversely, the lowest absolute canopy interception losses are recorded during the winter months when there is very little rainfall, with as little as 3.7mm and 2.7mm being lost to canopy interception in May 2010 for *P. henkelii* and *P. patula* respectively. Litter interception is the lowest evaporative loss, accounting for only 6.2% and 10.7% of gross precipitation for *P. henkelii* and *P. patula* respectively. The small litter interception amount can be attributed to the large number of consecutive rain days, during the rainy summer months, thereby not allowing time for much evaporation to take place. The study site is also situated in a mistbelt, and the presence of mist suppresses evaporation. The trees also have a dense canopy with a PAI of between 3.5 and 4.0 for *P. henkelii* and between 2.3 and 2.5 for *P. patula*, and therefore little solar radiation reaches the litter to aid in evaporation. During the winter months, there is little rainfall, and after canopy interception losses have been accounted for, there is little throughfall to be intercepted by the litter.

INSERT FIGURE 3.

INSERT TABLE 2.

INSERT TABLE 3.

Productive Green Water-Use Efficiency

The stem growth and WUE for the two *P. henkelii* and *P. patula* trees was calculated for the one year period 13 August 2009 to 12 August 2010 (Gush *et al*., 2011) and is summarised in **Table 4** and **Table 5**. The WUE was calculated as the increase in stem wood dry mass relative to transpiration. The WUE was also calculated as a mm-equivalent by considering the planting density of 1111 and 816 stems per hectare for *P. henkelii* and *P. patula* respectively. From **Table 4** and **Table 5** it can be seen that the average productive WUE of the two *P. henkelii* trees is 0.79 g.L^{-1} or 7.14g.mm^{-1} transpired and 2.06g.L^{-1} or 25.21g.mm^{-1} for *P. patula*. Dye *et al*., (2008) found comparable WUE values of 2.40 and 2.50g.L^{-1} for an 8 and 16 year old *P. patula* stand in KwaZulu-Natal respectively. However, WUE values ranged from 1.40 to 4.50g.L^{-1} depending on age and site location. No other WUE studies on *P. henkelii* could be found, but a number of studies on *Podocarpus falcatus* have been done. Dye *et al*., (2008) found the WUE of *P. falcatus* under plantation conditions in Magoebaskloof, Limpopo to be 0.86g.L^{-1} and 1.05 g.L^{-1} in a single tree site in Karkloof, KwaZulu-Natal. In Table 4 and Table 5 the values of annual transpiration are given as 195.0 mm and 559.2 mm for the two *P. henkelii* trees and 803.7 mm and 1311.1 mm for the two *P. patula* trees. This gives a mean for the two species of 378.6 mm and 1057.4 mm for *P. henkelii* and *P. patula* respectively. Despite the difference in the mean transpiration for *P. patula* and *P. henkelii* being large, by performing a one-tailed t-test it is shown to be not statistically significant at the 95% level (p=0.08). However, the difference in WUE between the two species is significant at the 95% level (p = 0.036), assuming that these differences are based on species and not site factors.

INSERT TABLE 4

INSERT TABLE 5

Total Green Water-Use Efficiency

Typically, WUE will be reported as it is calculated above. However, it is important to also consider WUE for the total water-use. Using the average mm-equivalent productive WUE of the two *P. henkelii* and *P. patula* trees of 7.14g.mm^{-1} and 25.21g.mm^{-1} transpired water respectively, as shown in **Table 4** and **Table 5**, the stem mass increment for the period October 2009 to March 2011 can be estimated and therefore, the total WUE was determined as shown in **Table 6**.

INSERT TABLE 6

After calculating the average stem mass increment for the period of October 2009 to March 2011, the total WUE was calculated by multiplying the average productive WUE by the transpiration. In order to calculate the total WUE, the stem mass increment was divided by the sum of all water fluxes (transpiration, canopy and litter interception). When the total WUE is calculated by considering all the water fluxes, the WUE of *P. henkelii* is 3.8g.mm^{-1} as opposed to 7.14g.mm^{-1}, which is a difference of 46.8%. Similarly, the total WUE of *P. patula* is 18.8g.mm^{-1} as opposed to 25.21g.mm^{-1}, which is a difference of 26.2%.

Uncertainties and Potential Sources of Error

One of the limitations of this study is the relatively short study period and it is well documented that annual growth increments are variable from year-to-year. The growth of the tree is largely seasonal, so an annual increment which includes both a summer and winter period may not be accurate in upscaling for just another summer period. The sample size of this study is small and was limited by the availability and cost of equipment. Therefore, the variability of water-use between the trees in the stand could not be well represented.

The canopy interception was not measured in the *P. patula* stand but was modelled using the Variable Storage Gash model (Bulcock and Jewitt, 2012). However, the Variable Storage Gash model was developed and validated in a *P. patula* stand in the KwaZulu-Natal Midland and was found to estimate canopy interception in *P. patula* well.

Stemflow was not measured, so the throughfall values are slightly high and should be taken into consideration when using these results. In a review by Levia and Frost (2003) of stemflow studies of different species and in different locations, it was found that on average stemflow accounted for 5.5% of the gross precipitation. This is similar to the findings of José (2013) whose review of stemflow studies suggests that on average stemflow accounts for less than 5% of gross precipitation. Therefore, if a value of 5% of gross precipitation is used as an estimate of stemflow for *P. patula* and P. *henkelii*, then the throughfall will effectively increase by 81.8mm for the period of this study (i.e. canopy interception decreased by 81.8mm). If this value is used to recalculate the total green WUE, then the total green WUE will increase to 4.1g.mm^{-1} and 19.6g.mm^{-1} for *P. henkelii* and *P. patula* respectively.

The HPV technique is the most common method of measuring sapflow/transpiration and has shown to measure accurately in a variety of hardwood trees. However, Pine trees have a strongly defined ring structure in the sapwood which gives rise to a complex radial pattern of sapflow. In a study by Dye *et al*., (1996) which evaluated the HPV technique in *P. patula*, it was found that the sapflow was overestimated by as much 49% compared to cut tree uptake measurements. However, the sapflow results of this study corresponded well with other studies mentioned previously. It is therefore important to bear these considerations in mind when using the results of this study and it is recommended that a follow-up study is undertaken where the total evaporation is validated using long-term measurement with a scintillometry system or other above-canopy measurement system.

DISCUSSION AND CONCLUSION

Many WUE studies express water-use in terms of an increase in stem wood biomass relative to transpiration (productive Green water-use). While this approach is useful in terms of a physiological water-use, it may be misleading for water resources management and planning, particularly in areas where interception by the canopy and litter are significant as has been shown to be the case in the KwaZulu-Natal Midlands (Bulcock and Jewitt, 2012a). For example, two different crops/trees may have similar productive Green WUE's, but one may have a significantly higher or lower canopy and litter interception than the other resulting in a different total Green WUE. As shown in the results of this research, the difference between productive Green WUE and total green WUE where the non-productive Green water fluxes are included is 46.8% and 26.2% for *P. henkelii* and *P. patula* respectively. Therefore, for the total Green WUE approach to be implemented in more studies, there is a need for sound canopy and litter interception models that make use of readily available data that can be used in cases where interception data are not available.

In terms of productive Green WUE, introduced species such as *P. patula* may be 2-4 times more efficient in their water-use than *P. henkelli*, based on the results of other studies (Olbrich *et al*., 1996; Dye *et al*., 2001; Gush and Dye, 2009; Gush *et al*., 2011), which correspond well with the findings of this study. These previous studies on the WUE of introduced species such as *P. patula* and *E.*

grandis in South Africa show that their WUE can be as high as 4.5g.L^{-1} and 5.5g.L^{-1} respectively. Gush *et al*., (2011) reported a mean WUE from a number of studies for *P. patula* to be 2.5g.L^{-1}, which is consistent with the findings of this study. Gush and Dye (2009) found that the WUE of a number of indigenous tree species including *Trema orientalis*, *Celtis Africana*, *Podocarpus falcatus*, *Ptaeroxylon obliquum*, *Olea eurpaea* subsp. *africana* and *Berchemia zeyheri* to be 0.96, 1.57, 1.04, 1.32, 0.31 and 1.67g.L^{-1} respectively, highlighting that introduced species are generally more water-use efficient than indigenous species. The difference in productive WUE was found to be statistically significant at the 95% level ($p = 0.036$) if it is assumed that the differences are based on species and not site factors. The site factors are however very similar and this is probably a fair assumption. Although the *P. henkelii* site is closer to the riparian area than the *P. patula*, the soil properties at the depth at which the soil profile was classified (1.2m) where the same, While the indigenous *P. henkelii* may not be as water-use efficient as some introduced plantation species, it does have a relatively lower water-use year on year. It was found in this study that *P. patula* transpires on average 4.5 times more per unit of plant area than *P. henkelii*. This large difference may be attributed to a number of physiological factors. Firstly, the stomatal conductance in *Pinus* is larger than in *Podocarpus*. Rolando (2008) measured maximum stomatal conductance in *P. patula* to be 150 mmol.m^{-2}.s^{-1} and Saugier *et al*., (1997) measured a maximum stomatal conductance of 124 mmol.m^{-2}.s^{-1} in *Pinus banksiana*. In comparison, Dye *et al*., (2008) measured a maximum stomatal conductance of 32.1 mmol.m^{-2}.s^{-1} in

Podocarpus falcatus. Secondly, Baldocchi *et al*., (1987) found that canopy transpiration and canopy photosynthesis were strongly coupled. Myers *et al*., (1999) reported net photosynthetic rates of between 5.24 and 6.47 mmol.m^{-2}.s^{-1} for *Pinus taeda*. In comparison, rates of between 2.34 and 3.88 mmol.m^{-2}.s^{-1} for *P. falcatus* were reported by Dye *et al*., (2008) depending on photosynthetically active radiation (PAR). As a result of the much higher transpiration rates by *P. patula*, the water-use by the *P. patula* exceeds the amount of rainfall reaching the soil. Conversely, the *P. henkelii* uses less water than that which drains to the soil and therefore has less impact on the water resources. This is important from a water resources management perspective, where the harvesting of timber is of secondary importance, as the indigenous species may have a lower annual reduction in streamflow than introduced plantation species. It must however be stressed that *P. henkelii* cannot be used to characterise the water-use for all indigenous species, as not all indigenous species will necessarily have a lower water-use than commercial forestry species. *P. henkelii* is a gymnosperm with a tracheid dominated xylem, and so the sapflow is slow. From a hydrological or water management point of view, a potential application of low water-use indigenous species such as *P. henkelii* could be to plant them in riparian areas within commercially afforested areas as is the case at the site of this study. Many of the narrow riparian areas of grassland that remain after commercial afforestation are heavily infested with alien invasive species due to the difficultly in managing them. As it is dangerous to perform bi-annual burns within the plantation, it may be a viable land-use option to plant indigenous trees species in these areas due to their low water-use (Gush *et al*., 2011). However, when considering the impact of planting trees within a riparian area, the productive and non-productive Green water-use should be considered, as it is the total Green water-use that will ultimately determine the streamflow reduction as well as the water resource management and planning decision.

While it is the total Green water that needs to be considered from a water resources management and planning perspective, one cannot lose sight of the importance of considering the individual components of productive and non-productive green water. The non-productive components of total evaporation have been referred to by some as “white water” (Savenije, 2004), highlighting that hydrologically it is problematic to lump these two components together and that there needs to be clear recognition that these components need to be considered separately in hydrological process studies. Failure to have a sound conceptual understanding of the individual components that make up total Green water flows may lead to modelling efforts being compromised (Jewitt, 2006). This point is emphasised by Savenije (2004) who states that the “common mistake of lumping interception with transpiration leads to an over-dimensioning of the soil moisture stock”. Therefore, this paper highlights the importance of considering the individual components of both productive and non-productive Green water flows, and in particular, the role that interception plays in the hydrological cycle and that from a water resources management and planning point of view, the total Green WUE needs to be considered. However, it is still vitally important to understand the productive water-use efficiency for the optimisation of future water, food and timber requirements.

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FIGURES

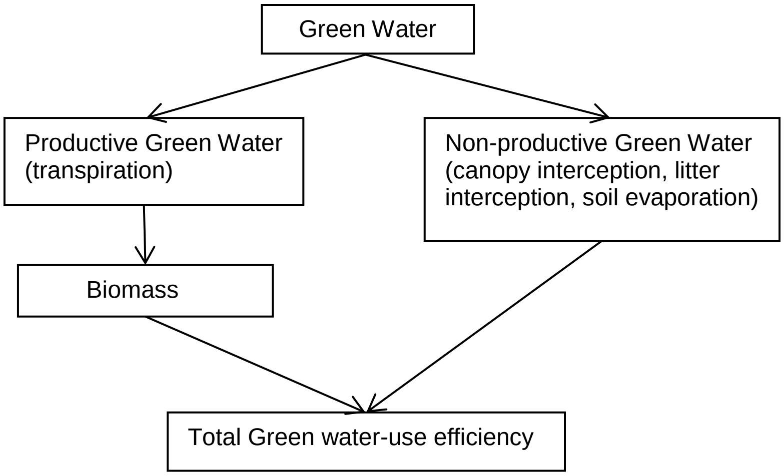

Figure 1. Schematic showing the components of productive and non-productive green water used to calculate total green water-use efficiency.

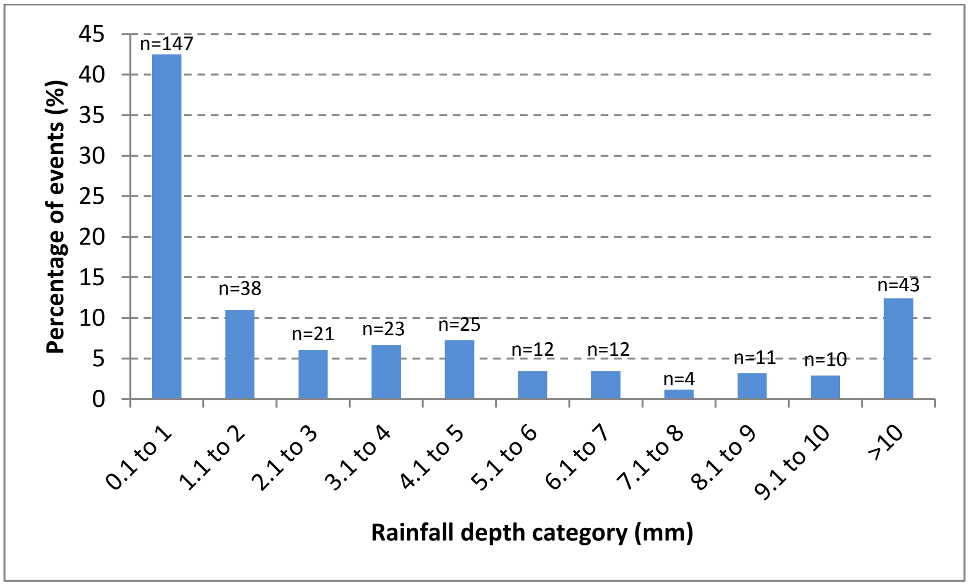

Figure 2. Percentage of rainfall events per rainfall depth category for the period October 2009 to March 2011

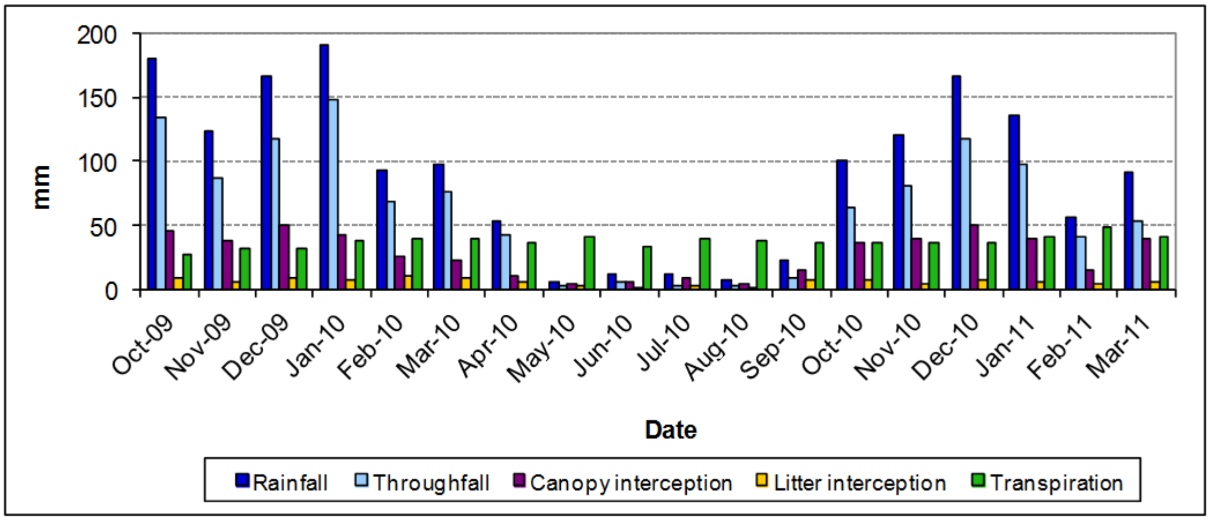

Figure 3. Measured contributions of rainfall, throughfall, canopy interception, litter interception and transpiration for the period October 2009 to March 2011 for *P. henkelii*.

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Table 1. Sample tree details as of 12 August 2010.

Tree	Diameter at Breast height (mm)	Tree height (m)	PAI	Sapwood depth (mm)	Wound width (mm)	Bark width (mm)	Wood density ($g.cm^{-3}$)	Mean litter thickness (mm)
P.henkelii 1	140	6.34	3.5	55	3	7	0.468	52
P.henkelii 2	230	7.33	4.0	95	3	7	0.468	52
P. patula 1	200	8.77	2.3	85	4	10	0.380	151
P. patula 2	240	10.79	2.5	100	4	10	0.380	151

Table 2. Monthly contributions and totals of rainfall, throughfall, canopy interception, litter interception and transpiration measured for the period October 2009 to March 2011 for *P. henkelii*.

Date	Rainfall (mm)	Throughfall (mm)	Observed canopy interception (mm)	Observed litter interception (mm)	Water drained to soil (mm)	Transpiration (mm) *P. henkelii*
Oct-09	179.6	134.5	45.1	8.9	125.6	26.8
Nov-09	123.6	86.2	37.4	5.2	81.0	32.2
Dec-09	167.2	116.8	50.4	9.0	107.8	32.3
Jan-10	190.6	148.8	41.8	7.3	141.5	37.2
Feb-10	93.1	68.0	25.1	9.9	58.1	39.0
Mar-10	98.3	76.3	22.0	9.2	67.1	39.1
Apr-10	53	42.5	10.5	6.2	36.3	36.2
May-10	6.1	2.4	3.7	1.9	0.5	40.3
Jun-10	11.6	5.7	5.9	1.5	4.2	33.8
Jul-10	11.5	3.3	8.2	2.0	1.3	39.0
Aug-10	7.6	2.7	4.9	1.0	1.7	38.3
Sep-10	22.1	8.2	14.9	7.0	1.2	36.2
Oct-10	100.4	63.7	36.7	7.9	55.8	36.2
Nov-10	120.2	80.7	39.5	3.6	77.1	36.7
Dec-10	166.4	116.9	49.5	7.3	109.6	36.0
Jan-11	135.9	97.1	38.8	5.3	91.8	41.3
Feb-11	56.6	41.5	15.1	3.5	38.0	48.8
Mar-11	92.1	53.4	38.7	5.1	48.3	40.8
Total (mm)	1635.9	1148.8	488.1	101.8	1047.0	670.3
Percentage of rainfall (%)		70.2	29.8	6.2	64.0	41.0

Table3. Monthly contributions and totals of rainfall, throughfall, modelled canopy interception, modelled litter interception and transpiration for the period October 2009 to March 2011 for *P. patula*.

Date	Rainfall (mm)	Throughfall (mm)	Modelled canopy interception (mm)	Modelled litter interception (mm)	Water drained to soil (mm)	Transpiration (mm) *P. patula*
Oct-09	179.6	146.3	33.3	17.3	129	66.0
Nov-09	123.6	96.0	27.6	10.2	85.8	73.5
Dec-09	167.2	130.0	37.2	17.4	112.6	82.7
Jan-10	190.6	159.7	30.9	14.2	145.5	94.3
Feb-10	93.1	74.6	18.5	9.2	65.4	124.2
Mar-10	98.3	82.1	16.2	10.8	71.3	113.6
Apr-10	53	45.2	7.8	12.0	33.2	93.9
May-10	6.1	3.4	2.7	1.7	1.7	104.2
Jun-10	11.6	7.2	4.4	2.9	4.3	67.3
Jul-10	11.5	5.4	6.1	3.9	1.5	62.5
Aug-10	7.6	4.0	3.6	1.9	2.1	79.6
Sep-10	22.1	11.1	11.0	9.5	1.6	74.8
Oct-10	100.4	73.3	27.1	15.3	58	71.7
Nov-10	120.2	90.8	29.2	7.0	83.8	79.6
Dec-10	166.4	129.9	36.5	14.1	115.8	76.7
Jan-11	135.9	107.3	28.6	10.3	97	94.7
Feb-11	56.6	45.5	11.1	6.9	38.6	109.4
Mar-11	92.1	63.5	28.6	9.9	53.6	101.1
Total (mm)	1635.9	1275.3	360.4	174.5	1100.8	1569.8
Percentage of rainfall (%)		77.9	22.1	10.7	67.3	95.9

Table 4. Summary of productive WUE data for *P. henkelii* trees as calculated from a mass-based ratio of biomass increment relative to productive green water-use for the one year period 13 August 2009 to 12 August 2010.

Tree	1yr water-use (L)	1yr water-use (mm)	Stem Volume increment (m^3)	Wood Density (g.cm^{-3})	Stem mass increment (g)	WUE (g stem wood.L transpired water^{-1})	WUE (g stem wood.mm transpired water^{-1})
P. henkelii 1	1755	195.0	0.00215	0.468	1006.2	0.5733	5.16
P. henkelii 2	5033	559.2	0.01088	0.468	5091.8	1.0117	9.11
Average	**3394**	**378.6**	**0.00652**	**0.468**	**3049.0**	**0.7925**	**7.14**

Table 5. Summary of productive WUE data for *P. patula* trees as calculated from a mass-based ratio of biomass increment relative to productive green water-use for the one year period 13 August 2009 to 12 August 2010.

Tree	1yr water-use (L)	1yr water-use (mm)	Stem Volume increment (m^3)	Wood Density (g.cm^{-3})	Stem mass increment (g)	WUE (g stem wood.L transpired water^{-1})	WUE (g stem wood.mm transpired water^{-1})
P. patula 1	9849	803.7	0.05157	0.380	19596.6	1.9897	24.23
P. patula 2	16067	1311.1	0.09035	0.380	34333.0	2.1369	26.19
Average	**12958**	**1057.4**	**0.07096**	**0.380**	**26964.8**	**2.0633**	**25.21**

Table 6. Summary of WUE data for *P. henkelii* and *P. patula* trees as calculated from a mass-based ratio of biomass increment relative to total green water-use for the period October 2009 to March 2011.

Tree	Average productive WUE (g.mm transpired^{-1})	Transpiration (mm)	Stem mass increment (g)	Canopy interception (mm)	Litter interception (mm)	Total Green water (mm)	Total Green WUE (g.mm total green water^{-1})
P. henkelii	7.14	670.3	4785.9	488.1	101.8	1260.2	3.8
P. patula	25.21	1569.8	39574.7	360.4	174.5	2104.7	18.8