



Water-use dynamics of an alien-invaded riparian forest within the Mediterranean climate zone of the Western Cape, South Africa

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Abstract. In South Africa, the invasion of riparian forests by alien trees has the potential to affect the country's limited water resources. Tree water-use measurements have therefore become an important component of recent hydrological studies. It is difficult for South African government initiatives, such as the Working for Water (WfW) alien clearing program, to justify alien tree removal and implement rehabilitation unless hydrological benefits are known. Consequently, water use within a riparian forest along the Buffeljags River in the Western Cape of South Africa was monitored over a 3-year period. The site consisted of an indigenous stand of Western Cape afrotemperate forest adjacent to a large stand of introduced *Acacia mearnsii*. The heat ratio method of the heat pulse velocity sap flow technique was used to measure the sap flow of a selection of indigenous species in the indigenous stand, a selection of *A. mearnsii* trees in the alien stand and two clusters of indigenous species within the alien stand. The indigenous trees in the alien stand at Buffeljags River showed significant intraspecific differences in the daily sap flow rates varying from 15 to 32 L day⁻¹ in summer (sap flow being directly proportional to tree size). In winter (June), this was reduced to only 7 L day⁻¹ when limited energy was available to drive the transpiration process. The water use in the *A. mearnsii* trees showed peaks in transpiration during the months of March 2012, September 2012 and February 2013. These periods had high average temperatures, rainfall and high daily vapor pressure deficits (VPDs – average of 1.26 kPa). The average daily sap flow ranged from 25 to 35 L in summer and approximately 10 L in the winter. The com-

bined accumulated daily sap flow per year for the three *Vepri lanceolata* and three *A. mearnsii* trees was 5700 and 9200 L, respectively, clearly demonstrating the higher water use of the introduced *Acacia* trees during the winter months. After spatially upscaling the findings, it was concluded that, annually, the alien stand used nearly 6 times more water per unit area than the indigenous stand (585 mm a⁻¹ compared to 101 mm a⁻¹). This finding indicates that there would be a gain in groundwater recharge and/or streamflow if the alien species are removed from riparian forests and rehabilitated back to their natural state.

1 Introduction

While extensive research has been undertaken on the water use of terrestrial ecosystems in South Africa, little is known about the water use and growth of trees growing in riparian areas. This knowledge gap, as well as the poor ecological conditions of South African riparian habitats, has led to uncertainty and contention over riparian rehabilitation techniques. The deep fertile soils, with high soil moisture contents associated with riparian areas, make them ideal for plant establishment and growth (Everson et al., 2007). As such, these areas are extremely vulnerable to invasion by pioneer plant species, particularly alien species that have historically been introduced for commercial forestry. Riparian zone vegetation, which can be described as the interface between terrestrial and aquatic ecosystems (Richardson et al., 2005), has

a significant impact on the hydrology of a catchment due to the close proximity of riparian vegetation rooting systems to the water table. Most riparian trees are phreatophytic, meaning they have access to a permanent source of water because their rooting system is within the shallow groundwater.

Through the process of evaporation and transpiration, riparian vegetation influences streamflow rates, groundwater levels and local climates (Richardson et al., 2005). Vegetation along riverbanks filter surface and subsurface water moving laterally through the soil towards the river channel. This helps to maintain channel water quality, by regulating the water temperature (through shading), bank stability and turbidity (through root colonization and surface cover), and traps debris (Askey-Dorin et al., 1999). Riparian vegetation can access a wide range of water sources within the riparian zone, which includes rainfall, soil water, stream water and groundwater (O'Grady et al., 2006). Commercial forestry has been blamed for increasing the green water (water lost by total evaporation) and decreasing the blue water (water in rivers and dams) in areas across South Africa (Jewitt, 2006). Introduced tree species change the natural landscape by altering the stream banks and thereby increasing soil erosion, altering fire regimes, as well as changing the physical and chemical composition of the soil (Joshi et al., 2004; Le Maitre et al., 1996; Tabacchi et al., 2000). For these reasons, invasive alien plants, particularly introduced commercial trees, are considered to be a major threat to biodiversity globally (Reid et al., 2009; Solarz, 2007; Wal et al., 2008). There is a widespread belief in South Africa and globally that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land restoration programs. This is based on observations that indigenous trees are generally slow growing and that growth and water use are broadly linked (Everson et al., 2007; Gush, 2011). However, tree water use is technically difficult and expensive to measure, and so there is scant evidence of low water use by indigenous trees in South Africa. A global review of water-use differences between introduced invasive and indigenous (native) plants at the leaf, plant and ecosystem scales (Cavaleri and Sack, 2010) indicates that invasive plants use up to 136 % more water than the indigenous species at the leaf scale (Baruch and Fernandez, 1993; Dixon et al., 2004; Pratt and Black, 2006). At the plant scale, there is a diverse range in water use ranging from the invasive species using comparatively 100 % less to 150–300 % more water than the indigenous species (Cleverly et al., 1997; Nagler et al., 2003; Kagawa et al., 2009). At the ecosystem scale, studies indicate that invasive species use 189 % more water than indigenous-dominated stands, particularly in tropical moist forests (Nosetto et al., 2005; Yopez et al., 2005; Fritzsche et al., 2006). In the high rainfall areas of South Africa, invasive alien plants growing in riparian areas are estimated to reduce annual streamflow by $523 \times 10^6 \text{ m}^3$ with a predicted annual reduction estimated to be as high as $1314 \times 10^6 \text{ m}^3$ if allowed to reach a fully invaded state (Cullis et al., 2007).

Management of invaded riparian zones can result in hydrological gains disproportionately greater than the catchment area affected, with up to 3 times more streamflow yield than upslope areas (Scott and Lesch, 1996; Scott, 1999).

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

The Buffeljags River site in the Western Cape has been an ecological research site since 2006 (Geldenhuys, ongoing) and forms part of a selective thinning experiment designed to assist Working for Water (WfW) clearing programs. The government-funded WfW program clears catchment areas of invasive alien plants with the aim of restoring hydrological functioning while also providing poverty relief to local communities through job creation (Turpie et al., 2008). The aim of this study was to measure tree water use to quantify the potential hydrological benefit of these forest management practices.

1.1 The study area

The Buffeljags River flows southwards along the Langeberg west mountain range into the Buffeljags Dam. The Buffeljags River study area is at latitude $34^{\circ}00'15'' \text{ S}$ and longitude $20^{\circ}33'58'' \text{ E}$ (Fig. 1), approximately 95–110 m above mean sea level. The research area is within the Western Cape afrotemperate forest type which is characterized by very small forest patches occurring along boulder scree consisting of streams, gorges and mountain slopes (Geldenhuys, 2010). The surrounding vegetation type is south Langeberg sandstone fynbos (Mucina and Rutherford, 2011). The Langeberg Mountains consist of Table Mountain sandstone/quartzite (north of the Buffeljags River) with a ridge of shales to the south of the river. The soils are characterized by structureless sands, a result of previous alluvial deposition. The climate is typical of the Western Cape with

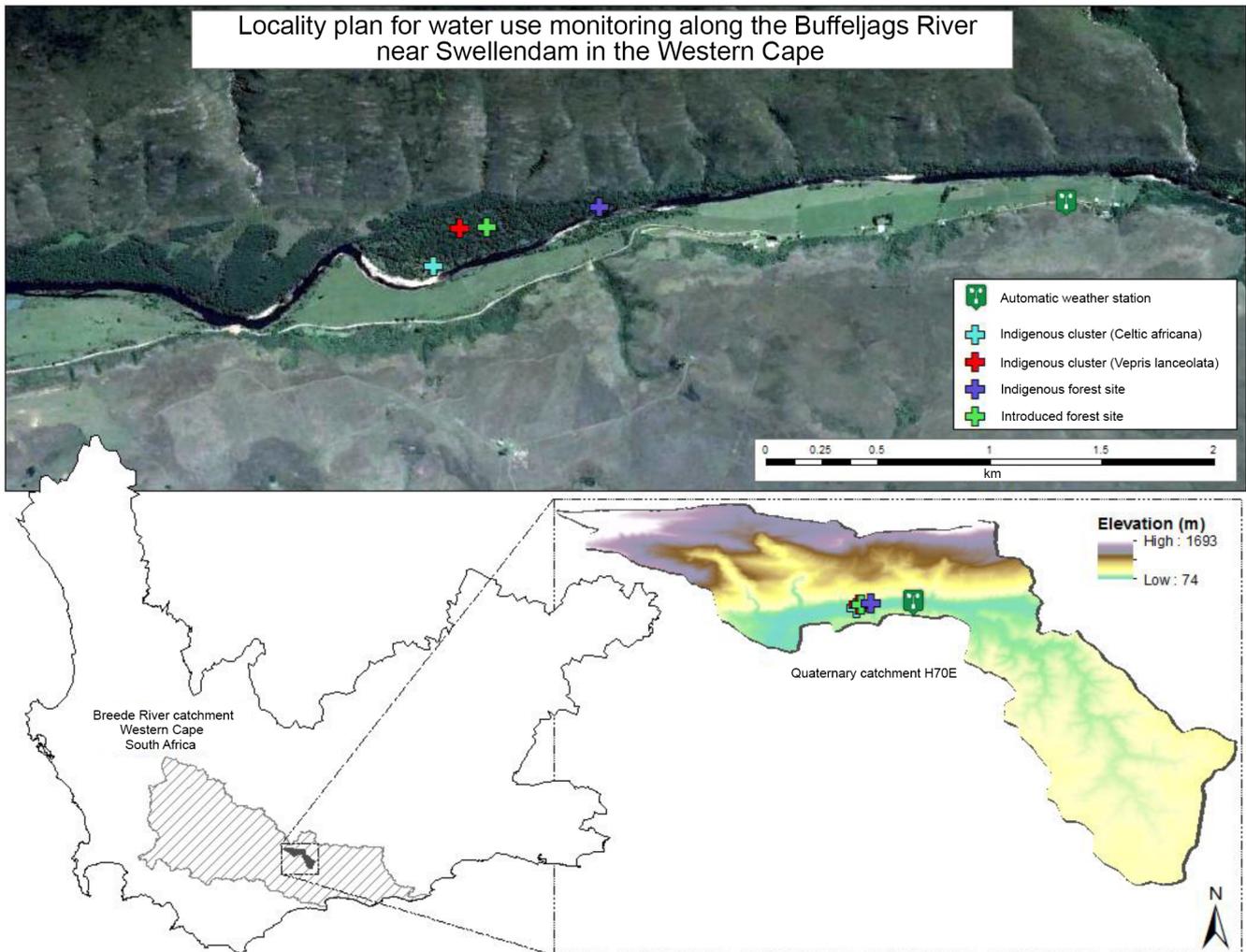


Figure 1. Location of the Buffeljags River research area within the Western Cape, South Africa.

hot summers and cold winters. However, the rainfall is fairly evenly spread throughout the year. The long-term (137-year record) mean annual precipitation (MAP) at Buffeljags River is 636 mm a^{-1} . The daily maximum temperatures range from 17.1°C in July to 27.5°C in January. The mean daily minimum temperature is 15°C in February and 5°C in July. A 99 ha riparian forest occurs along the river with 75 ha of invaded forest (lower reach) and 24 ha of pristine indigenous forest (upper reach) (Fig. 1), comprising of species such as *Celtis africana*, *V. lanceolata*, *Prunus africana*, *Rapanea melanophloeos* and *Afrocarpus* (*Podocarpus falcatus*). The stand height ranges from 3 to 15 m in the indigenous stand and 11 to 17 m in the alien stand. The surrounding vegetation is mountainous fynbos and renosterveld.

Historically, *A. mearnsii* trees were planted for firewood and building material on the nearby farms. Working for Water cleared most of the alien trees which have since grown back over the last 15 years. Currently, the invasion extends approximately 1 km along the river.

1.2 The study sites

Three representative trees within the indigenous stand were instrumented for monitoring sap flow. These trees included an understory tree (*Rothmania capensis*), one medium (*V. lanceolata*) and one large evergreen tree (*V. lanceolata*) that were most common throughout the stand. The leaf area index (LAI) within this stand was 3.6 throughout most of the year with a slight reduction during the winter months. Downstream of this site, within the alien stand (Fig. 1), three *A. mearnsii* trees were instrumented over the 3-year study period. In a similar way, small, medium and large diameter classes were chosen to assist in the upscaling of single-tree transpiration measurements of the *A. mearnsii* trees. The LAI of the *A. mearnsii* stand was 3.1 during the summer months and 2.8 during the winter months. Two indigenous tree clusters within the alien stand were also instrumented. The *V. lanceolata* cluster contained two medium and one large diameter class trees (LAI of 3.4) while the *C. africana* clus-

Table 1. Tree physiology and specific data required for the calculation of sap flow and upscaling.

Indigenous forest site (upper reach)	Diameter (mm)	Size class*	Moisture fraction	Average wounding (mm)	Wood density (m ³ kg ⁻¹)	Representative stem density (stems ha ⁻¹)
<i>Rothmania capensis</i>	125	Small	0.45	2.8	0.59	120
<i>V. lanceolata</i>	134	Medium	0.42	3.7	0.63	65
<i>V. lanceolata</i>	199	Large	0.42	3.4	0.66	24
Introduced/alien forest site (lower reach)						
<i>Acacia mearnsii</i>	121	Small	0.89	3.2	0.54	650
<i>Acacia mearnsii</i>	167	Medium	0.47	3.2	0.73	200
<i>Acacia mearnsii</i>	194	Large	0.71	3.0	0.61	50
Indigenous cluster (lower reach)						
<i>V. lanceolata</i>	166	Medium	0.45	3.2	0.66	65
<i>V. lanceolata</i>	174	Medium	0.45	3.2	0.65	65
<i>V. lanceolata</i>	202	Large	0.47	2.9	0.66	24
Indigenous cluster (lower reach)						
<i>C. africana</i>	319	Large	0.52	6.1	0.71	24
<i>C. africana</i>	422	Large	0.50	6.0	0.71	24

* Note that the stem density was grouped as per size class.

ter contained two large diameter class trees with a LAI of 3.3 in the summer months and 1.8 during the winter months. The LAI provided an indication of the seasonal physiological changes of the trees and the light variations between the sites.

Both the indigenous and introduced alien stands were in a climax state with most of the canopy trees falling into the medium or large size classes. Although there were many smaller trees (excluding trees with a $\varnothing < 5$ mm), these did not contribute significantly to the total transpiration as they were shaded out by the climax trees. An overview of the individual tree characteristics has been provided in Table 1. Variations in stem moisture content were possibly due to the different ages and sizes of the trees measured (variations in sap wood depth and active xylem concentration).

2 Methods

A meteorological station was established on 25 January 2012 at Buffeljags River in a nearby planted *Eragrotis plana* field, 1.6 km from the indigenous site. Rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) was measured at a height of 1.2 m from the ground, with additional measurements at a height of 2 m for air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp and Zonen, Delft, the Netherlands), and wind speed and direction (model 03002, R. M. Young, Tra-

verse city, Michigan, USA). These were measured at a 10 s interval and the appropriate statistical outputs were recorded every hour.

A HPV system using the heat ratio algorithm (Burgess et al., 2001) was set up to monitor long-term sap flow on all of the selected trees over a 3-year period. The instrumentation is described by Clulow et al. (2013) and included a 0.5 s heat source (sap flow trace) in the form of a line heater. A pair of type-T thermocouple probes was used to measure pre- and post-temperatures 5 mm above (downstream) and below (upstream) of the heater probe (Clulow et al., 2013). Hourly measurements (CR1000, Campbell Scientific Inc., Logan, Utah, USA) were captured over the 3-year monitoring period (January 2012 to March 2015). Monthly checks were undertaken to adjust probe depths in order to account for radial stem growth if required.

An assessment of the bark and sapwood depth was undertaken on the selected trees using an increment borer. This assessment assisted in determining the HPV probe insertion depths and the calculation of sapwood area. The heat pulse velocity (V_h – cm h⁻¹) was calculated from

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

where k is the thermal diffusivity of green (fresh) wood, x is the distance (5 mm) above and below the heater (representing upstream and downstream), and v_1 and v_2 (°C) are increases in the downstream and upstream temperatures

(from initial average temperatures), respectively. A thermal diffusivity (k) of $2.5 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ (Marshall, 1958) was used. Wounding or damaged xylem (non-functional) around the thermocouples were accounted for using wound correction coefficients described by Swanson and Whitfield (1981). Sap velocities were then calculated by accounting for wood density and sapwood moisture content as described by Marshall (1958). Finally, sap velocities were converted to tree water use (Q_{tree}) or sap flow (L h^{-1}) by calculating the sum of the products of sap velocity and cross-sectional area for individual symmetrical tree stems (Clulow et al., 2013).

Tree growth was recorded every 2 months throughout the monitoring period by measuring diameter at breast height with a dendrometer, and canopy height was recorded using a VL402 hypsometer (Haglöf, Sweden). Leaf area index (LAI-2200, LI-COR, Lincoln, Nebraska, USA) was measured monthly under each stand. Riparian forests typically have a narrow canopy with limited aerodynamic fetch, which excludes techniques such as eddy covariance and scintillometry being used to support the upscaling of point water-use measurements to stand water-use values. Due to the homogeneous composition of the alien stand and the dominance of *V. lanceolata* and *C. africana* species within the indigenous stand, a methodology was followed based on recent upscaling studies (Ford et al., 2004; Miller et al., 2007). In addition, detailed stem density data were available for the site due to extensive ongoing ecological research (Atsame-Edda, 2014). Medoid (representative of the population) trees were selected for sap flow measurement. This included the most commonly occurring alien and indigenous species (canopy and understorey) and a range of size classes for each species. A species density analysis was undertaken ($\text{Ø} > 50 \text{ mm}$) in replicated 400 m^2 plots per site. A relationship between total tree water use ($Q_{\text{tree}} - \text{L day}^{-1}$) and each representative size and species class was identified. This allowed for the estimation of the stand water flux (Q_{stand}) which was divided by the plot area (400 m^2) in order to obtain comparative units between the indigenous and alien stands ($\text{L day}^{-1} \text{ ha}^{-1}$). These values were then accumulated to annual values so that the effect of alien and indigenous (evergreen and deciduous) stands on the water balance could be quantified throughout a hydrological year.

The *A. mearnsii* site had a thin litter layer consisting mostly of broken branches, bark and leaves compared with the indigenous site which had a thicker litter layer with a large amount of organic matter accumulated from the various tree species and understorey vegetation. Volumetric soil water contents were measured hourly at both the indigenous and alien sites (concurrent to the HPV measurements) with three time domain reflectometry (TDR) probes (Campbell Scientific CS 615) installed horizontally at each site at depths of 0.1, 0.3 and 0.5 m. The TDR probes were connected to spare channels on the CR1000 data logger of the HPV system. With hourly volumetric water content measurements, the response of trees to rainfall events or stressed conditions was

monitored and supported the interpretation of the HPV measurements. An observation borehole was installed at the site to monitor the groundwater recharge as well as to confirm the assumption that all the trees within the riparian forest had direct access to groundwater. Soil samples were taken to determine the distribution of roots, bulk density and soil water content. These samples (taken at various depths throughout the profile) were weighed before and after oven drying to determine the soil characteristics.

3 Results

3.1 Weather conditions during the study period

The mean annual precipitation (MAP) over the 3-year study was significantly higher than the long-term average (636 mm a^{-1}) by $300\text{--}500 \text{ mm a}^{-1}$ (2012 to 2014 being 1017 , 902 and 1127 mm a^{-1} , respectively). The rainfall distribution was variable (lacking a seasonal trend) throughout the 3 years with a mean monthly value of 85 mm a^{-1} (Fig. 2). There were numerous days of high hourly rainfall (to a maximum of 30 mm h^{-1} and 102 mm day^{-1}) demonstrating the prevalence of high-intensity storms at the site (Fig. 3). The solar radiation peaked at $34 \text{ MJ m}^{-2} \text{ day}^{-1}$ following the same seasonal trend to that of the daily minimum and maximum temperatures.

The relative humidity (RH) ranged from 20 to 90 %, with little seasonal trend. During periods of high solar radiation, the vapor pressure deficit was high and correlated to peaks in transpiration rates. An average daily temperature of $22.1 \text{ }^\circ\text{C}$ was recorded at Buffeljags River in the summer months. During these months, daily maximum temperatures occasionally exceeded $40 \text{ }^\circ\text{C}$. During the winter months, the temperatures averaged $12.1 \text{ }^\circ\text{C}$ due to numerous days with low solar radiation, such as during rainfall events and cloudy days, and would likely result in little to no transpiration occurring. The daily reference total evaporation (ET_0), derived from data captured at the meteorological station, averaged approximately 1 mm day^{-1} in the winter period to 4 mm day^{-1} during the summer period. The daily ET_0 peaked at 7.5 mm day^{-1} , which correlated to peaks in measured transpiration.

3.2 Tree water use

For comparative purposes, the water use of similar-sized *V. lanceolata* and *A. mearnsii* trees were compared during the wet and the dry seasons (Figs. 4 and 5). During the summer month of January, the *V. lanceolata* tree water use exhibited seasonal curves indicative of the clear sunny days and high correlation to the solar radiation. The medium-sized *V. lanceolata* ($\text{Ø} 17.4 \text{ cm}$) used an average of 24 L day^{-1} during the summer months (October–March) and an average of 8 L day^{-1} during the winter months (April–September) (Fig. 4). The medium-sized *A. mearnsii* ($\text{Ø} 16.7 \text{ cm}$) used an

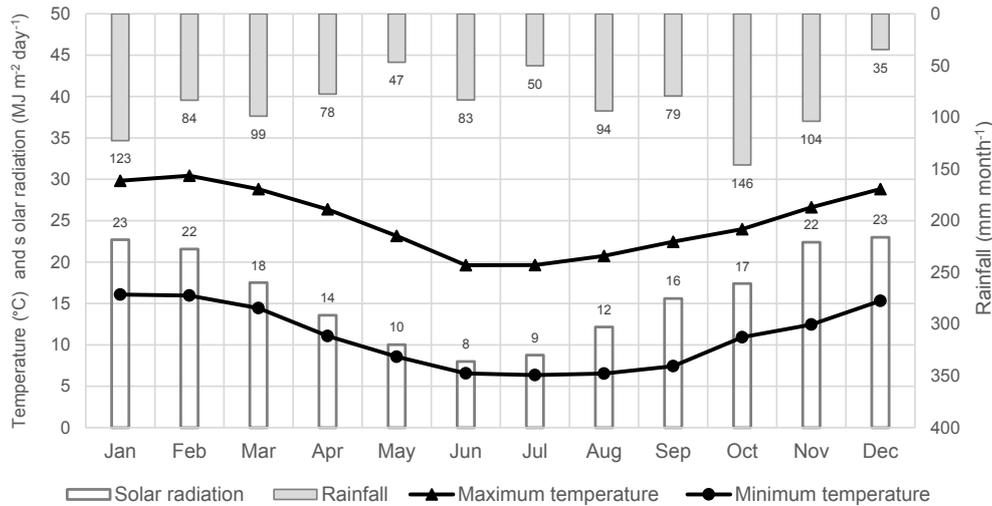


Figure 2. The monthly rainfall, monthly solar radiant density, and average monthly maximum and minimum air temperatures at Buffeljags River averaged over 3 years.

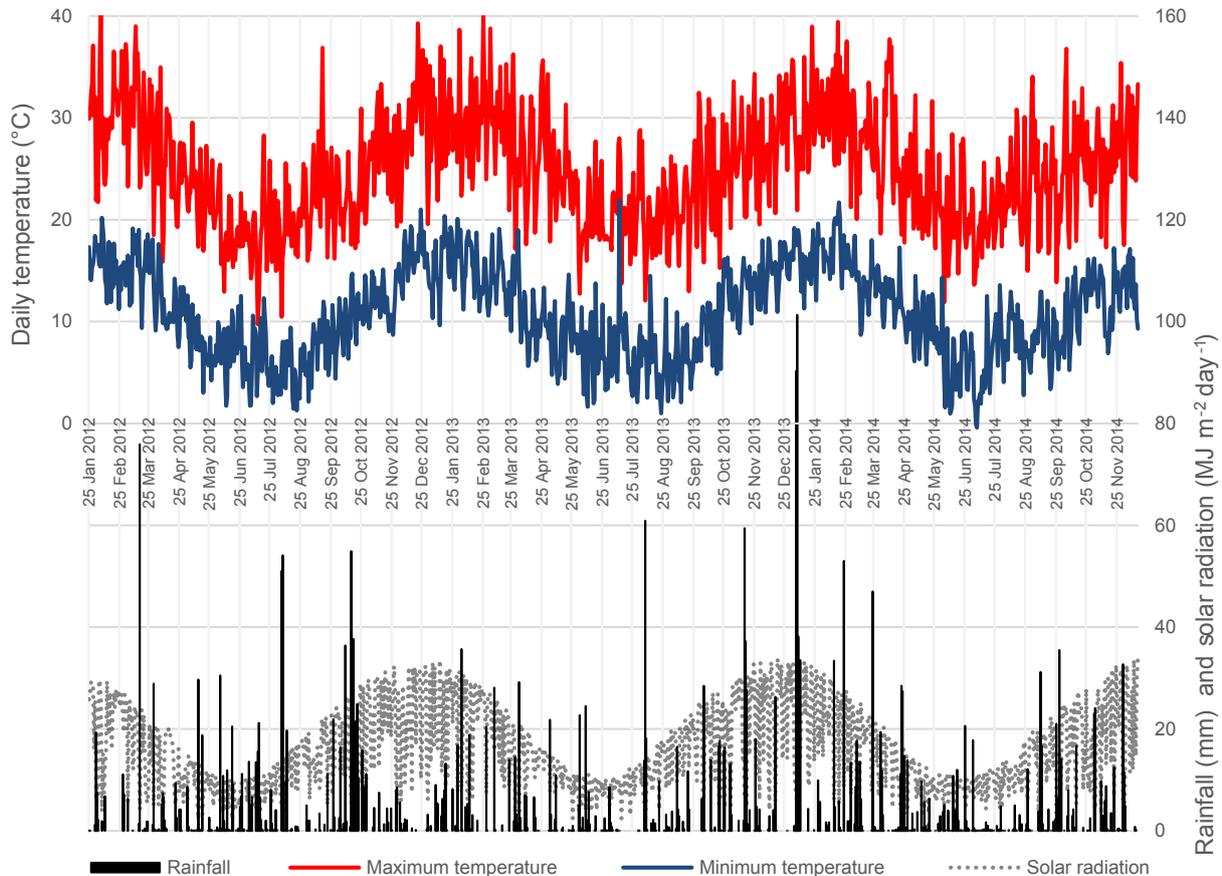


Figure 3. The daily rainfall, solar radiation and maximum and minimum air temperatures at Buffeljags River.

average of 10 L day^{-1} in the winter months, similar to that of the *V. lanceolata*. In the summer months, the *A. mearnsii* used an average of 39 L day^{-1} , significantly higher than the indigenous tree (Fig. 5). During significant rainfall periods

(> 5 mm), there was little to no water use in both trees due to the low evaporative demand and the wet canopy.

Individual whole-tree water use was significantly reduced in winter (May and June) for most of the trees, dropping by

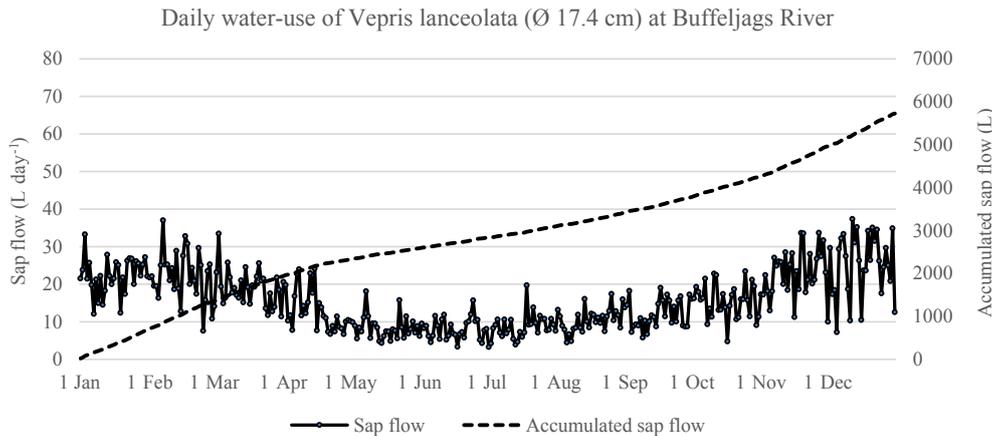


Figure 4. Sap flow (daily and accumulated) from an indigenous *V. lanceolata* in the lower-reach stand at Buffeljags River (January 2012 to March 2015) averaged over 3 years.

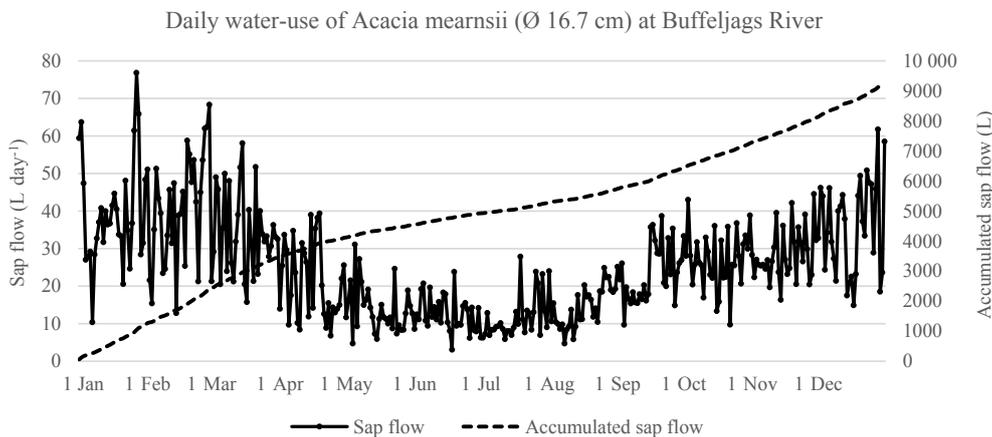


Figure 5. Sap flow (daily and accumulated) from an alien-invasive *Acacia mearnsii* in the lower-reach stand at Buffeljags River (January 2012 to March 2015) averaged over 3 years.

approximately 75 % from the peak water use. This was attributed to fewer daylight hours in the winter months which resulted in reduced available energy at this time of year to drive the transpiration process. From November 2012 to March 2013, all species showed a significant increase in water use during this hot summer period. The water use in the *A. mearnsii* trees showed a distinct peak in transpiration during the months of March 2012, September 2012 and February 2013. During March 2012, the high average temperature (21.5 °C), a 76 mm day⁻¹ rainfall event and high daily vapor pressure deficits (VPDs) (average of 1.26 kPa) contributed to a high atmospheric demand. On cloudless days with a high VPD and high soil water content, the trees would be expected to use more water than during overcast days. The average daily sap flow ranged from 15 L day⁻¹ in the smaller-class tree, 25 L day⁻¹ in the medium-class tree and 39 L day⁻¹ in the large-class tree (Tables 1 and 2).

The daily summer water use of two of the *V. lanceolata* trees (Table 2) in the upper indigenous stand showed high

water use with an average of 19 L day⁻¹ (medium class) and 37 L day⁻¹ (large class). The high water use in the large tree was ascribed to its size and deep rooting system which is presumed to have had easy access to groundwater at this site due to the proximity to the river (10 m horizontal distance). This was verified with the borehole levels and a root analysis at the site. The water level ranged from 3.2 to 4.8 m below ground level at the site where roots were observed to 5 m. The water use of the small understorey tree *R. capensis* had a much lower water use (average of 8 L day⁻¹) which indicated that although the understorey used less water, it still made a significant contribution to the water balance given the abundance of understorey species in the indigenous forest.

The indigenous *C. africana* trees displayed a high water use during the summer period. As this is a deciduous tree, no water was used during leaf fall in winter. The largest *C. africana* tree had a canopy area of 75 m² and was the largest tree at the site. Approximately 37 700 L of water were transpired by this tree annually during the measurement period

Table 2. Sap flow (daily and accumulated) for each species measured at Buffeljags River (January 2012 to March 2015).

Forest type/ location	Species	Diameter (mm)	Daily average summer sap flow (L day ⁻¹)	Daily average winter sap flow (L day ⁻¹)	Annual accumulated sap flow (L a ⁻¹)
Indigenous forest site (upper reach)	<i>V. lanceolata</i>	134	19	7	6534
	<i>V. lanceolata</i>	199	37	6	15 565
	<i>Rothmania capensis</i>	125	11	4	4133
Introduced/alien forest site (lower reach)	<i>Acacia mearnsii</i>	194	25	8	9226
	<i>Acacia mearnsii</i>	121	39	10	5469
	<i>Acacia mearnsii</i>	167	32	9	7207
Indigenous cluster (lower reach)	<i>V. lanceolata</i>	174	14	6	5725
	<i>V. lanceolata</i>	166	24	8	3430
	<i>V. lanceolata</i>	202	39	14	9174
Indigenous cluster (lower reach)	<i>C. africana</i>	319	46	0	19 821
	<i>C. africana</i>	422	95	0	37 769

(Table 2). Given that this species is deciduous, it is important to note that this tree uses a high volume of water in summer when water resources are usually limited.

The indigenous cluster in the alien site had a LAI of 3.4, which was higher than the LAI of 3.1 under the nearby *A. mearnsii* trees. The indigenous trees in the upper-reach indigenous site had an LAI of 3.6. Although the summer water use was higher in the introduced trees, the radial sapwood area was larger in the indigenous trees (up to 413 cm²) than the introduced trees (up to 171 cm²). Trees with the highest sap velocities are therefore not necessarily those with highest whole-tree water use. However, this does indicate that the alien trees are more effective users of water, relative to their sapwood area.

3.3 Soil profile and water content

The volumetric soil water content (VWC) in the alien stand at Buffeljags River was very low, dropping to 7 % during dry periods (Fig. 6). During high rainfall events, the soil VWC exceeded 20 %, showing a rapid but short response to rainfall. This indicates that the soil water moves through the soil profile rapidly with very little water being stored in the profiles, particularly in the lower profile. The soils had a dry bulk density (ρ_b) of 1.58 g cm⁻³, a particle density (ρ_{particle}) of 2.66 g cm⁻³ and a porosity 0.42, typically characteristic of sandy soils. The drying curve, after an isolated event, took on average 22 h from saturation to the expected field capacity (Fig. 6). *A. mearnsii* stands are known to have deep rooting systems, with observations of greater than 8 m in South Africa (Everson et al., 2007). This suggests that, during dry periods, this stand can access water from deeper layers in the soil profile.

In the indigenous stand (Fig. 7), the middle TDR probe (0.3 m) showed the highest water content. During the warmest period (December to April), there was very little

water in the profile (even after rainfall events). This would suggest that the deeper roots from the indigenous species were readily using water below the TDR probe measurement depths as there was no correlation between transpiration and change in VWC. In contrast, the alien stand upper soil profile water content responded to rainfall events, indicating that interception storage (including throughfall and stemflow that contribute to litter catch) played a significant role when comparing these stands. After an isolated rainfall event, the drying period of the soil profile at the indigenous site took much longer (up to 1 week) from its peak to the driest level. The average soil water content at the indigenous stand was 5 %, lower than that of the alien stand, suggesting a difference in root activity given the same soil characteristics.

The VWC at both sites did not respond significantly to rainfall events under 5 mm h⁻¹ except during consecutive events. The average water table depth, measured using an observation borehole, ranged from 5.2 m below the ground surface during the dry season to 3.2 m below the ground surface during the wet season (excluding extreme events). The water table recharge time showed a strong relationship to the soil wetting and drying response time recorded at both sites. In conclusion, both the indigenous and introduced stands are limited by atmospheric energy fluxes rather than water limitations as both stands had root contact with the water table.

3.4 Upscaling tree water use

The results obtained from the research area were used to determine an actual annual water use per unit area for both the invaded alien and pristine indigenous tree stands (Fig. 8). Using the stem density per size class, stands of forest were compared rather than individual trees. LAI and canopy area measurements undertaken indicated a closed canopy. The up-scaled water use for a 3-year average of the *A. mearnsii* stand was 5879 L ha⁻¹ for the small size class, 7639 L ha⁻¹ for the

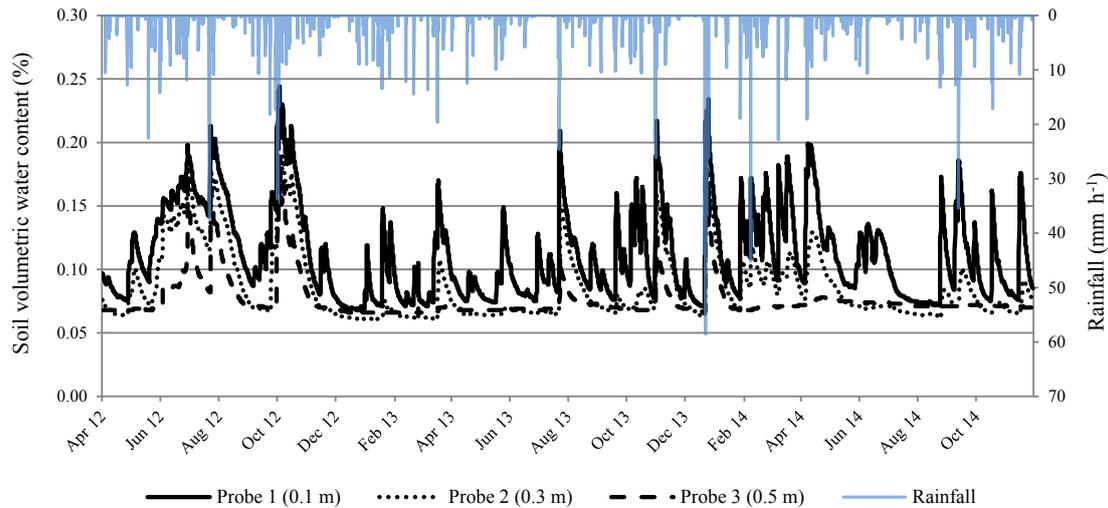


Figure 6. Hourly soil volumetric water content of the lower alien stand and the hourly rainfall at Buffeljags River from April 2012 to October 2014.

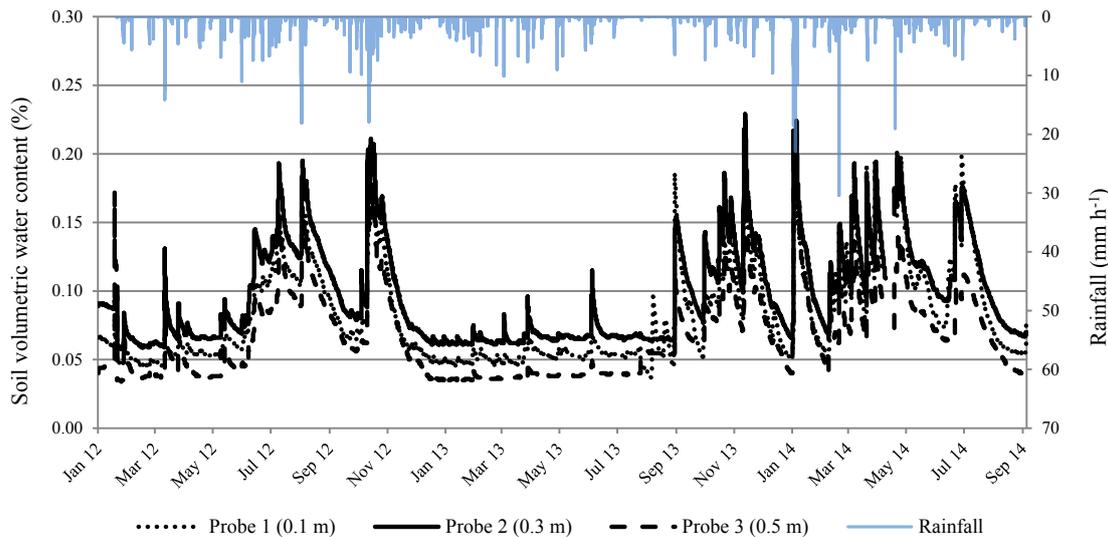


Figure 7. Hourly soil volumetric water content of the upper indigenous stand and the hourly rainfall at Buffeljags River from January 2012 to September 2014.

medium size class and 9981 L ha^{-1} for the large size class. When upscaled for all species and size classes for the 3-year average, the total stand water use was approximately $5.85 \text{ ML ha}^{-1} \text{ a}^{-1}$ (585 mm a^{-1}). This was 57 % of the average annual precipitation recorded during the monitoring period (1021 mm a^{-1}).

The annual water use of the indigenous stand was 1209 L ha^{-1} for the small size class, 6321 L ha^{-1} for the medium size class and 18900 L ha^{-1} for the large size class. The upscaled indigenous stand used $1.01 \text{ ML ha}^{-1} \text{ a}^{-1}$ (101 mm a^{-1}). This was 9.8 % of the average annual precipitation. Based on these results we concluded that the alien stand uses nearly 6 times more water per unit area annually than the indigenous stand. This roughly correlated to the

growth rate of each stand, where the stem breast height diameter increase over the study period (recorded on each tree measured) was 3–8 times faster than similar-sized indigenous trees.

The inter-species and size class water-use variations, particularly within the indigenous stand, highlight the importance of good replications of a representative sample tree species and size classes. These results also highlight that individual indigenous trees, such as the *C. africana*, can use more water than an individual alien *A. mearnsii* tree. An example of this is the largest *C. africana* using 14000 L more water annually than the largest *A. mearnsii*. However, the *C. africana* tree had a much larger diameter and had a large canopy area under which no other trees grew, whereas ap-

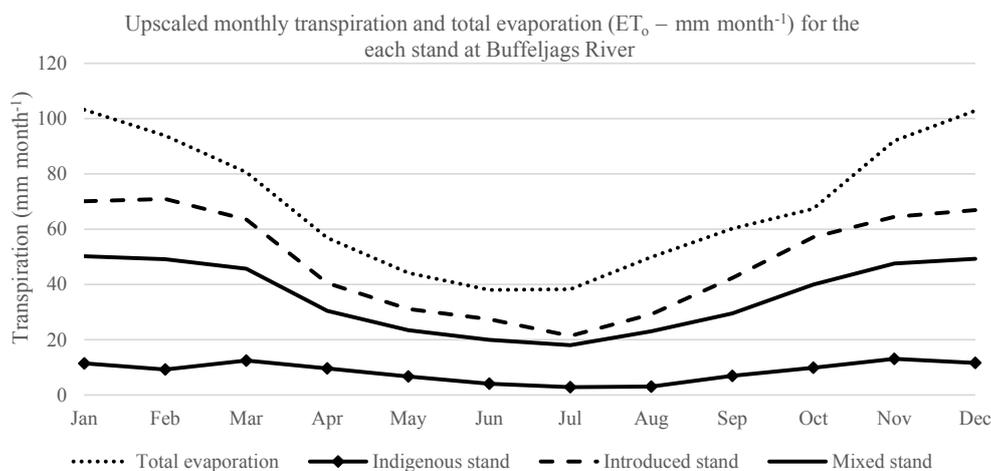


Figure 8. Upscaled monthly transpiration for the indigenous, introduced (*A. mearnsii*) and mixed stands in comparison to reference total evaporation.

proximately 10 medium-sized *A. mearnsii* trees could occupy the same area as this particular tree. The importance of upscaling using representative samples of species and size classes is clearly demonstrated by the study.

4 Discussion and conclusion

There is a widespread belief in South Africa that indigenous tree species, in contrast to introduced tree species, use less water and should be planted more widely in land rehabilitation programs (Olbrich et al., 1996; Dye, 2001; Dye et al., 2008; Everson et al., 2007; Gush and Dye, 2008, 2009; Gush et al., 2015). A review of relevant literature revealed a general paucity of information relevant to both indigenous and introduced tree water use, the methods of replication and the techniques used. Internationally, improved HPV techniques have been used with various vegetation types, and the accuracy of these studies has been validated using gravimetric methods (Granier et al., 2001; Burgess et al., 2001; O'Grady et al., 2006; Steppe et al., 2010; Vandegehuchte and Steppe, 2013). International studies indicate that, at the plant scale, introduced invasive species can use from 100 % less water to between 150 and 300 % more water than indigenous landscapes. Furthermore, there can be a significant disconnect between upscaling plant-scale measurements to an ecosystem scale (Cavaleri and Sack, 2010). In South Africa, the HPV technique has been shown to provide accurate estimates of sap flow in both introduced tree species such as *A. mearnsii* and *Eucalyptus grandis*, and indigenous tree species such as *Podocarpus henkelii* and *C. africana* (Smith and Allen, 1996; Dye, 2001; Dye et al., 2008; Everson et al., 2007). A key recommendation from the literature, which has been emphasized in a recent study by Gush et al. (2015), is that more indigenous tree stand management research is needed in South Africa.

Spatial estimates of evaporation and transpiration are required but are difficult to obtain in remote areas with limited aerodynamic fetch. A large capital and human effort was invested towards this study in order to extend the monitoring period, with a range of species and replicates. This allowed for an accurate comparison of indigenous and introduced tree water use. The Buffeljags River site is unique in that it is one of very few sites within South Africa with an extensive rehabilitation program that aims to assist WfW and similar clearing programs. The results showed that individual tree water use varies depending on size and species. Upscaled comparisons showed that stem density is important to the accurate representation of stand water use. A stand of introduced *A. mearnsii* can use up to 6 times more water annually than a mixed indigenous stand. This finding is significant in that it provides clear evidence to justify the highly expensive clearing programs, which have in the past lacked quantifiable data on the potential hydrological benefits of alien plant clearing. The results also indicate that rehabilitation or clearing programs need to consider the seasonal rainfall variability of a site, as planting of deciduous indigenous trees may provide larger benefits in summer rainfall areas due to no transpiration during periods when water resources are limited.

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

Data availability. Due to the high-frequency data used for this paper, all data with linked figures and tables have been uploaded to the central database at the Centre for Water Resources Research

(CWRR) at the University of KwaZulu-Natal in Pietermaritzburg. The author, Bruce Scott-Shaw, can be contacted for these data at brucecharless@gmail.com.

Competing interests. The authors declare that they have no conflict of interest.

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