The annual pattern of sap flow in two *Eucalyptus* species established in the vicinity of gold mine tailings dams in central South Africa

Peter Dye[1 *], Alistair Clulow[2], Eric Prinsloo[3], Vivek Naiken[4] and Isabel Weiersbye[1]

[1]Ecological Engineering and Phytotechnology Programme
Restoration and Conservation Biology Research Group
School of Animal, Plant and Environmental Sciences
University of the Witwatersrand, P. Bag 3, WITS 2050
Johannesburg, South Africa

[2]School of Bioresources Engineering and Environmental Hydrology,
University of KwaZulu-Natal, P. Bag X01, Scottsville 3209, Pietermaritzburg,
South Africa

[3]CSIR, Built Environment, P.O. Box 320, Stellenbosch 7599, South Africa

[4]CSIR, Natural Resources and the Environment, C/O Agrometeorology,
University of KwaZulu-Natal, P. Bag X01, Scottsville 3209, Pietermaritzburg,
South Africa

* Corresponding Author, e-mail: pdye@mweb.co.za;

Abstract

Several hundred mine tailings dams occur in the Witwatersrand Basin Goldfields in central South Africa. Seepage of acid mine drainage (AMD) from these unlined structures is widespread, and a variety of contaminants is released into soil and groundwater. The "Mine Woodlands Programme" is aimed at evaluating the use of high-density tree stands over surrounding contaminant plumes to limit the spread of contaminants through hydraulic control of groundwater and enhanced uptake or immobilization of contaminants. The annual pattern of hourly sap flow in four contiguous *Eucalyptus dunnii* trees (aged three years) was followed over a full year in a species trial situated near Carltonville. The annual pattern of hourly sap flow was also recorded in four contiguous sample trees (aged four years) of the clonal hybrid *E. grandis x camaldulensis* (*E. GxC*) at another trial near Orkney. Both species showed high sap flow rates close to reference evaporation rates in response to summer rains. Both showed greatly reduced sap flow rates during the latter half of the dry winter season. Sap flow rates only recovered after the arrival of the first spring rains. Annual sap flow (*E. dunnii* 673 mm; *E. GxC* 767 mm) was similar to the recorded annual rainfall at each site (*E. dunnii* 629 mm; *E. GxC* 795 mm), and was substantially lower than total annual reference evaporation (*E. dunnii* 1 273 mm; *E. GxC* 1 330 mm). We conclude that the roots of both species are not yet deep enough to

access the AMD-influenced groundwater which lies at depths of 14 and 10 m below the ground at the Carltonville and Orkney sites, respectively. Despite prolonged water deficits, both species survived well and maintained sufficient vigour to permit the quick recovery of high transpiration rates in the following summer. This is essential to hasten root growth and improve the chance of contact with groundwater plumes.

Keywords: *Eucalyptus dunnii*, *Eucalyptus GxC*, sap flow, mine tailings dams, South Africa, groundwater

Introduction

Mine tailings dams in the Witwatersrand Basin Goldfields (WBG) in central South Africa number several hundred and, together with “footprints” remaining after removal and reprocessing of tailings material, occupy a combined area of 400-500 km^2 (Rösner et al., 2001). These extensive deposits release contaminated water (acid mine drainage) from their wet cores, and a fraction of this passes beneath the perimeter toe drains to spread through the surrounding soils and shallow aquifers. Plumes of such mine water are identified by contaminants such as sulphates, chlorides and dissolved heavy metals, and their concentrations may exceed health standards. There is an urgent need to find an affordable and sustainable solution to this problem, since significant seepage is expected to continue over many decades into the future. Many of the mines in the WBG are heading for closure and require evidence of effective long-term control of water contamination before closure certificates can be granted by regulatory authorities.

The Mine Woodlands Project was initiated in 2001 by AnglogoldAshanti and the University of the Witwatersrand, with the aim of investigating the role that trees can play in confining AMD to the vicinity of the tailings storage facilities (TSFs). The surroundings of most TSFs in the WBG are largely grassland, and much local and global evidence exists to show that annual evapotranspiration (ET) may be substantially increased by establishing trees (Bosch and Hewlett, 1982; Zhang et al., 1999; Farley et al., 2005) where sufficient water is available to the trees. Such an increase in ET is expected to reduce soil water contents and increase the depth to groundwater, reducing saturated flow of AMD towards streams and rivers.

Since the WBG region is climatically unsuited for commercial forestry, little prior knowledge of survival, growth and water-use exists for tree species. It was necessary, therefore, to establish species trials to assess rates of growth and water-use of a wide variety of tree species under the relatively harsh environmental conditions surrounding TSFs. Access to groundwater to supplement low rainfall is a crucial requirement for the long-term survival of such tree plantations and their effectiveness in slowing the spread of plumes. A selection of tree species drawn from a total of 48 indigenous species and 10 exotic species was planted in trials situated in three mining districts (Carltonville, Orkney/Klerksdorp and Welkom), at sites that lie down-slope of tailings dams. Early field evaluation of the various species showed that the six species of *Eucalyptus* outperformed all other species in terms of stem diameter, tree height and above-ground biomass. In view of evidence of widespread deep rooting among a wide variety of tree species (Canadell et al., 1996), sap flow studies were initiated to determine to what extent the stands of young trees were limited to soil water originating as rainfall, and whether there was any evidence that they were already utilizing groundwater, or stored water in unsaturated subsoil horizons.

The objective of this study was to measure the annual sap flow in the best-performing *Eucalyptus* species in each of two site-species trials (West Wits in the Carltonville district, and Vaal River in the Orkney/Klerksdorp district), to evaluate their access to soil and groundwater, and their potential to increase evapotranspiration and alter site water balances at a relatively early age in their growth cycle.

Materials and methods

West Wits site-species trial (Carltonville)

This trial (26^{o} $26^{/}$ $22.42^{//}$ S, 27^{o} $20^{/}$ $41.21^{//}$ E, Figure 1) is situated in the Carltonville district. It lies below a large complex of TSFs at an altitude of 1590 metres above mean sea level (m.a.m.s.l.), and mean annual rainfall at the nearby Blyvooruitsig weather station (0474684-W) is 704 mm. The soil consists of a deep (>120 cm) Hutton soil form (Lillieburn family; Soil Classification Working Group, 1991) derived from a highly weathered diabase sill (GeoCon, 2001), with clay textured apedal soils. In the FAO system, the equivalent soil classification is a Rhodic Ferralsol. The depth to the water table in a nearby borehole (MB42) was found to be 14.89 and 13.89 metres below ground level on 2 February 2007 and 12 July 2007, respectively. The main contaminant in this groundwater plume is SO_4 at 436 mg L^{-1}, with total dissolved solids at 1 275 mg L^{-1}, an estimated EC of 1 314 μS cm^{-1} (Hubert and Wolkersdorfer, 2015) and a measured pH of 7.0 (Unpublished data, AGA).

The species *Eucalyptus dunnii* was selected for sap flow measurement in this trial, as it exhibited dense canopies and good diameter and height growth. The trial was planted in January 2004 at a tree spacing of 2.5 by 3 m (1 333 trees per hectare). The trees were thus three years old at the start of the sap flow measurement period in January 2007. Plots comprise a grid of nine by seven rows of trees. Four sample trees forming a square near the centre of the plot were selected on the basis of their relatively good size, well-developed canopy and absence of stem defects.

Vaal River Mispah site-species trial (Orkney)

This trial (26^{o} 59$^{/}$ 19.19$^{//}$ S, 26^{o} 46$^{'}$ 35.28$^{//}$ E, Figure 1) is located in the Orkney/Klerksdorp district and lies below the Mispah TSF. The altitude of the trial site is 1 320 m.a.m.s.l., and the mean annual rainfall at a nearby weather station (Klerksdorp TNK; 0436294-W) is 572 mm. The soil consists of very deep (>200 cm) sandy clay loam to sandy loam textured Hutton (Hayfield family; Soil Classification Working Group, 1991) derived from highly weathered, largely chert-free, Malmani formation dolomite. In the FAO system, the equivalent soil classification is a Rhodic Ferralsol. Two boreholes (VRM51 and VRM58) situated close to the trial margins revealed a water table at 10.8 and 9.9 metres below ground level respectively in January 2007. Mean pH (7.3), SO_4 (1 367 mg L^{-1}), TDS (2 653 mg L^{-1}) and an estimated EC of 2 735 µS cm^{-1} (Hubert and Wolkersdorfer, 2015) characterized the plume at these boreholes.

Plots in this trial again comprised a grid of nine by seven trees. All trees were planted in January 2003 at a planned spacing of 2.5 by 3 m (1 333 trees per hectare). By January 2007 (age 4) a *Eucalyptus* hybrid clone (*Eucalyptus grandis* x *camaldulensis*, GxC) had demonstrated relatively good stem and height growth and had developed a dense and continuous canopy. Four healthy single-stemmed trees forming a square near the centre of the plot were selected for sap flow measurement. A subsequent check showed that spacing was wider than planned, with each tree occupying 9.9 m^2 (1 010 trees per hectare).

Sap flow measurements

The heat ratio version of the heat pulse velocity technique (Burgess et al., 2001) was used to simultaneously record hourly sap flow rates in the four sample trees at each site, from 30 January 2007 to 28 January 2008. Sets of three probes (two thermocouple (TC) probes and a line heater probe) were implanted radially into the sapwood at four positions around each tree stem, spaced approximately 90^{O} from each other. The 60 mm-long line heaters were made from 1.8 mm outside-diameter stainless steel tubing, enclosing a constantan filament. TC probes were situated parallel to, and 5 mm above and below, the line heater. These probes (consisting of type T copper-constantan thermocouples embedded in 2 mm outside-diameter PTFE tubing) were inserted into the upper and lower holes to a specific depth below the cambium. All drilling was performed with the drill bit projecting through a 30 mm steel drill guide firmly strapped to the tree, to ensure that the holes were as close to parallel as possible. In each tree, the TC probes were inserted to four different depths to sample the radial variation in sap flux density. These depths were fixed at 9, 16, 23 and 30 mm below the surface of the bark, with the mean bark thickness being estimated as 5 mm. To account for radial stem growth in these fast-growing trees, TC probes were repositioned to their correct depths on 5/6 September 2007. Probes were connected to CR10X data loggers via AM16/32 multiplexers (Campbell Scientific, Logan, UT). The logger was programmed to initiate a heat pulse every hour, and to record pre-pulse and post-pulse temperatures (Burgess et al., 2001). Raw data were downloaded remotely using cellular phone modems. Heat pulse velocity (HPV) was calculated using the heat ratio method (Burgess et al., 2001). These readings were corrected for wound widths (measured from 12.5 mm diameter radial cores extracted from the stems at the conclusion of measurements) using wound-correction coefficients described by Swanson and Whitfield (1981). These in turn were converted to sap flux density (Marshall, 1958), using sapwood density and sapwood moisture fractions recorded for *Eucalyptus* GxC clones reported by Dye et al. (2004). From these sap flux densities, whole-tree sap flow was calculated by summing the product of sap flux density and cross-sectional area for four different sapwood annuli centred on each TC measurement depth.

All hourly uncorrected HPV data were checked to identify missing or suspect readings. These were patched using correlations to other probe sets in the same tree. Where these were unavailable or poorly correlated, missing or poor values for a single hour were estimated as the mean of values recorded just before and just after, to preserve the daily trend of hourly readings. A 5-hour moving average was calculated to smooth the daily curve and reduce the influence of occasional spikes in HPV. Where the probes were not exactly parallel, a non-zero value was recorded under conditions of no-flow. These were evaluated by plotting daily means of values recorded from 01:00 to 03:00, and used to decide on a mean correction to be applied to the entire data set. Finally, on days with too much suspect or missing hourly data, daily sap flows for a sample of days just prior to, or following the period in question were expressed as a fraction of daily reference evaporation (Allen et al., 1998). The mean fraction was then used to estimate missing daily sap flow from the calculated daily reference evaporation. Daily reference evaporation was calculated using hourly temperature and relative humidity data recorded with a Vaisala CS500 air temperature and relative humidity sensor mounted in a radiation shield and fixed in the upper canopy of a neighbouring tree at a height of approximately 2 m above the ground. Solar radiation and wind speed were recorded at an automatic weather station (26^{o} 57’ 46.68” S; 26^{o} 42’ 56.89” E) situated 6.54 km from the Vaal River Mispah trial.

Results

West Wits trial (E. dunnii)

The annual pattern of daily sap flow (mean of four trees) is shown in Figure 2, and is compared to calculated daily reference evaporation. A declining trend in both is evident from January until June 2007 as day length and evaporative demand of the air decline. Sap flow rates are distinctly less than reference evaporation rates over this period. After the mid-year solstice, the trend in reference evaporation rates increases strongly, but sap flow rates remain low until the start of significant rains in October when they rapidly increase again. The advent of rains is accompanied by increased cloudiness, decreased solar radiation, reduced temperatures and increased atmospheric humidity (Figure 3), causing reference evaporation to decline sharply (Figure 2). The sap flow increase at this time shows a greater response to the availability of soil water than to evaporative conditions. Further periods of low sap flow occur in November and January, and are correlated to episodes of high humidity, lower temperatures and low solar radiation. Total annual sap flow (mean of four trees) amounts to 673 mm (Table 1). This is considerably less than the total reference evaporation of 1 273 mm calculated over the same period at this site.

Vaal river trial (E. GxC)

Figure 4 illustrates the annual pattern of daily sap flow in relation to reference evaporation and daily rainfall. From the start until the beginning of May, sap flow is similar to reference evaporation rates, both declining in response to shorter days and lowered evaporative demand. In early June, the two diverge as dry winter weather sets in. Sap flow remains below the reference evaporation level until early October. It was observed in early September that the majority of leaves had died and turned brown. At this point, significant spring rains occurred, causing new leaves to develop, and sap flows to increase steadily towards their mid-summer peak. The spring rains also caused an abrupt decline in reference evaporation, due to a sudden drop in temperature and solar radiation, and rise in relative humidity of the air (Figure 5). A period of low daily sap flows in January 2008 (Figure 4) also corresponds with conditions of cloud and rain associated with reduced solar radiation and raised atmospheric humidity. Total sap flow (mean of four trees) over the year amounted to 767 mm (Table 1), which is considerably less than the total annual reference evaporation of 1 330 mm calculated over the same period.

Discussion

The effectiveness of trees in intercepting mine seepage water in saturated zones adjacent to TSFs is expected to depend on the speed and efficiency with which their roots are able to gain contact with, and absorb this groundwater. Until this occurs, the trees will be largely reliant on stored soil water, and water-use will be broadly constrained by rainfall and any available soil water storage carried over from previous years.

The *E. dunnii* and *E. GxC* trees at the two site-species trials demonstrated relatively fast growth and well-developed canopies by age three and four, respectively, and the purpose of this study was to quantify their annual sap flow to gauge their access to mine-affected groundwater at this early stage in the rotation. The water tables at these sites are estimated to lie at depths of approximately 14 and 10 metres below ground level, respectively. Previous research in a well-drained, granite-derived and highly permeable deep soil in

Mpumalanga province demonstrated that four-year-old *E. grandis* trees were able to source more than half of their annual water requirement from depths below 8 m (Dye et al., 1997). Data from *Eucalyptus* forests and stands elsewhere confirm that trees of this genus are capable of very deep rooting (Kimber, 1974), often displaying a dimorphic root structure to maximize access to nutrients near the surface, as well as to groundwater from deep subsoil strata (Jacobs, 1955).

The sap flow patterns at both sites revealed that severe stress occurred during the winter of 2007. This stress was corroborated by field observations in early September 2007 of severe leaf mortality in the *E. GxC* trees at Vaal River. Annual sap flow was shown to comprise approximately half of reference evaporation at both sites, with both these rates diverging sharply after the winter solstice. Annual sap flow at both sites was similar to total rainfall falling over the same period. The timing of the precipitous decline in sap flow rate in the mid-to late dry season, the quick recovery after the first significant rainfall, and the relatively low groundwater EC all point to low water availability as the main cause. We infer that the roots are not yet in contact with the water table.

Despite this finding, growth and canopy development of the two species was rapid, and has clearly demonstrated that they are drought resistant and capable of a quick recovery after rainfall resumes. A similar rapid recovery in transpiration rates after a rainfall event preceded by a period of drought stress has been reported in *E. grandis* trees in Zululand (Dye, 2000). This resilience to drought is viewed as a very important attribute, since a high degree of vigour is necessary to ensure survival and promote rapid growth of the root system in the early stages of the growth cycle.

Sap flow monitoring has been successful in illustrating the annual pattern of transpiration by the trees. Comparison to simultaneous weather data and calculated reference evaporation has also been useful in highlighting the relative influence of evaporative conditions of the atmosphere on daily sap flow under different conditions and times of year. It has confirmed that the difference between actual transpiration and reference annual evaporation (~700 mm versus ~1 300 mm) in young *Eucalyptus* stands is largely caused by dry season drought stress, and that a higher water-use rate should be attainable by trees with sufficient all-year water availability. Further research is required to monitor dry season water-use over the entire range of trial sites and tree species. The purpose will be to identify those species showing the earliest and most sustained rates of winter-time transpiration rates, and the sites that are most conducive to establishing woodlands for the control of contaminated mine seepage water.

Conclusions

We conclude that during the critical early years in their growth cycle when rootings depths are still relatively shallow, both species are able to survive long dry seasons without access to supplementary groundwater, and maintain sufficient vigour to resume strong growth and high sap flow rates in the following summer. This physiological resilience is viewed as extremely important to promote deepening of the root systems so that the trees can eventually tap into the groundwater plumes to reduce the spread of contaminated water.

Acknowledgements

This study forms part of the Ecological Engineering and Phytotechnology Programme at the University of the Witwatersrand, Johannesburg and the Environmental Management Department of Anglogold Ashanti Limited, South Africa. We are grateful to the Department of Trade and Industry (THRIP) and the National Research Foundation of South Africa for support of the Mine Woodlands Project. Mr B. Oageng provided valuable support in the field. The South African Weather Service is thanked for supplying some of the weather data.

References

Allen RG, Pereira LS, Raes, D, Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - *FAO Irrigation and Drainage Paper 56.* FAO - Food and Agriculture Organization of the United Nations Rome, Italy. 315 pp.

Bosch JM, Hewlett, JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3-23.

Burgess SSO, Adams MA, Turner NC, Beverly CR, Ong CK, Khan AAH, Bleby TM. 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* 21: 589-598.

Canadell J, Jackson RB, Ehleringer JB, Mooney HA, Sala OE, Schulze, E-D. 1996. Maximum rooting depth of vegetation types at the global scale. *Oecologia* 108: 583-595.

Dye PJ. 2000. Water-use efficiency in South African *Eucalyptus* plantations: A review. *Southern African Forestry Journal* No. 189: 17-26.

Dye PJ, Poulter AG, Soko S, Maphanga D. 1997. The determination of the relationship between transpiration rate and declining available water for

Eucalyptus grandis. *WRC Report No. 441/1/97*, Water Research Commission, Pretoria, South Africa.

Dye PJ, Jacobs S, Drew D. 2004. Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *Forest Ecology and Management* 193: 197-218.

Farley KA, Jobbagy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy, *Global Change Biology* 11: 1565-1576.

GeoCon 2001. Regional geohydrological assessment to determine the status and impact of groundwater pollution at the Anglo Gold West Wits operations. Report GC/R/01/10/10, Southern Africa Geoconsultants, Pretoria, South Africa.

Hubert E, Wolkersdorfer C. 2015. Establishing a conversion factor between electrical conductivity and total dissolved solids in South African mine waters. *Water SA* [on-line] 41: 490-500.

Jacobs, MR. 1955. *Growth habits of the eucalypts*. Commonwealth Government Printer, Canberra.

Kimber PC. 1974. The root system of Jarrah (*Eucalyptus marginata*). *Research Paper No. 10*, Forests Department of Western Australia, Perth, 5 pp.

Marshall DC. 1958. Measurement of sap flow in conifers by heat transport. *Plant Physiology* 33: 385-396.

Rösner T, Boer R, Reyneke R, Aucamp P, Vermaak J. 2001. A preliminary assessment of pollution contained in the unsaturated and saturated zone beneath reclaimed gold-mine residue deposits., *Report No. 797/1/01*, Water Research Commission, Pretoria, South Africa.

Soil Classification Working Group. 1991. *Soil classification – a taxonomic system for South Africa*. *Memoirs of the Agricultural Natural Resources of South Africa No. 15.* Department of Agricultural Development, Pretoria, South Africa.

Swanson RH, Whitfield DWA. 1981. A numerical analysis of heat pulse velocity theory and practice. *Journal of Experimental Botany* 32: 221-239.

Zhang L, Dawes, WR, Walker GR. 1999. Predicting the effect of vegetation changes on catchment average water balance. *CSIRO Technical Report 99/12*, CRC for Catchment Hydrology, CSIRO, Canberra, Australia.

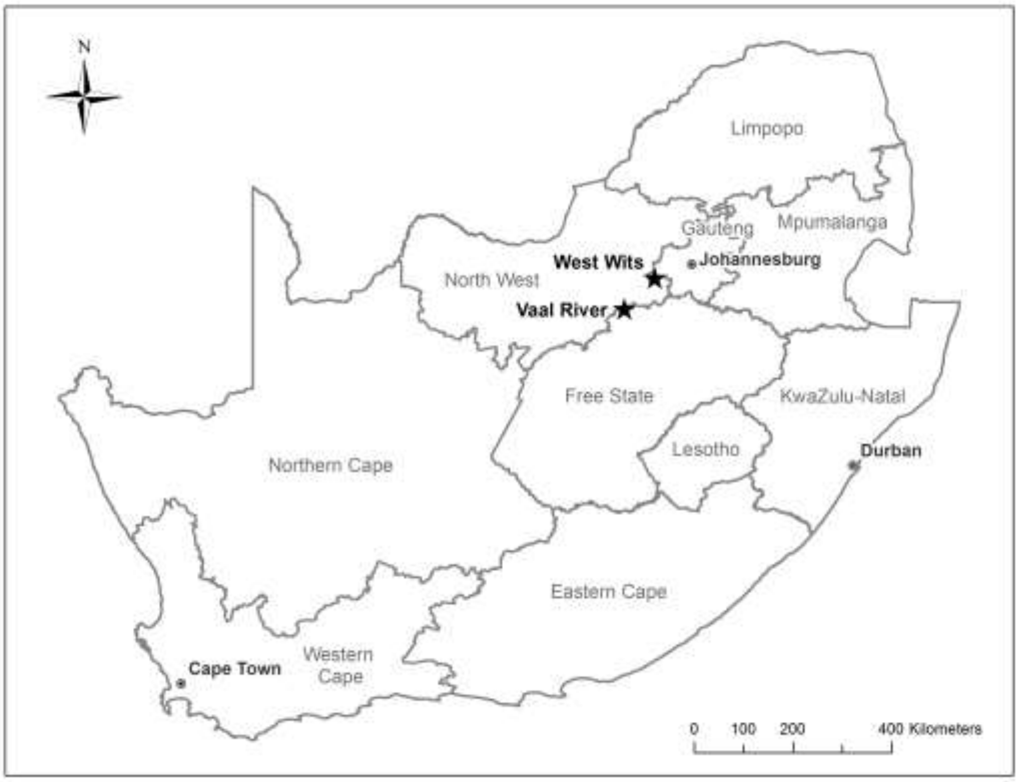

Figure 1. The location of West Wits and Vaal River trial sites.

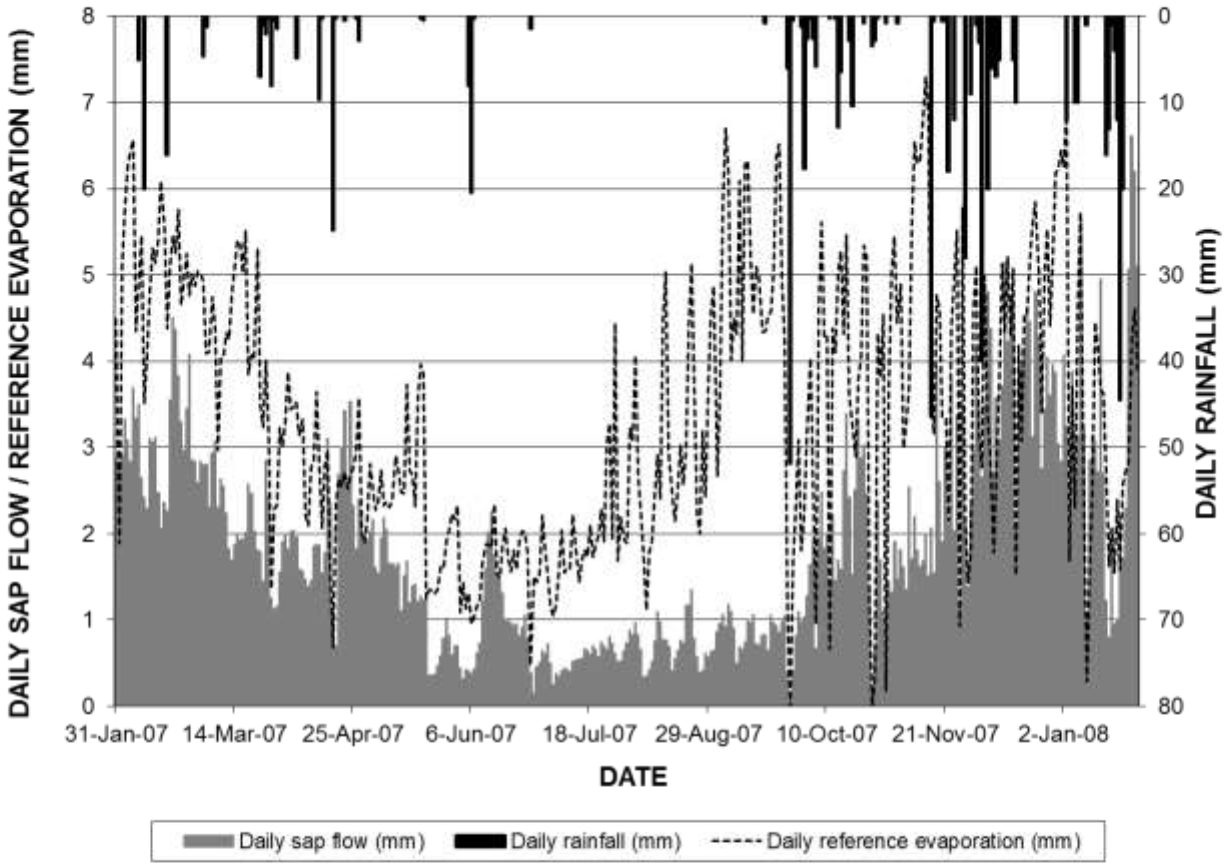

Figure 2. The pattern of mean daily sap flow in four *E. dunnii* trees shown in relation to reference evaporation (mm) and daily rainfall (mm).

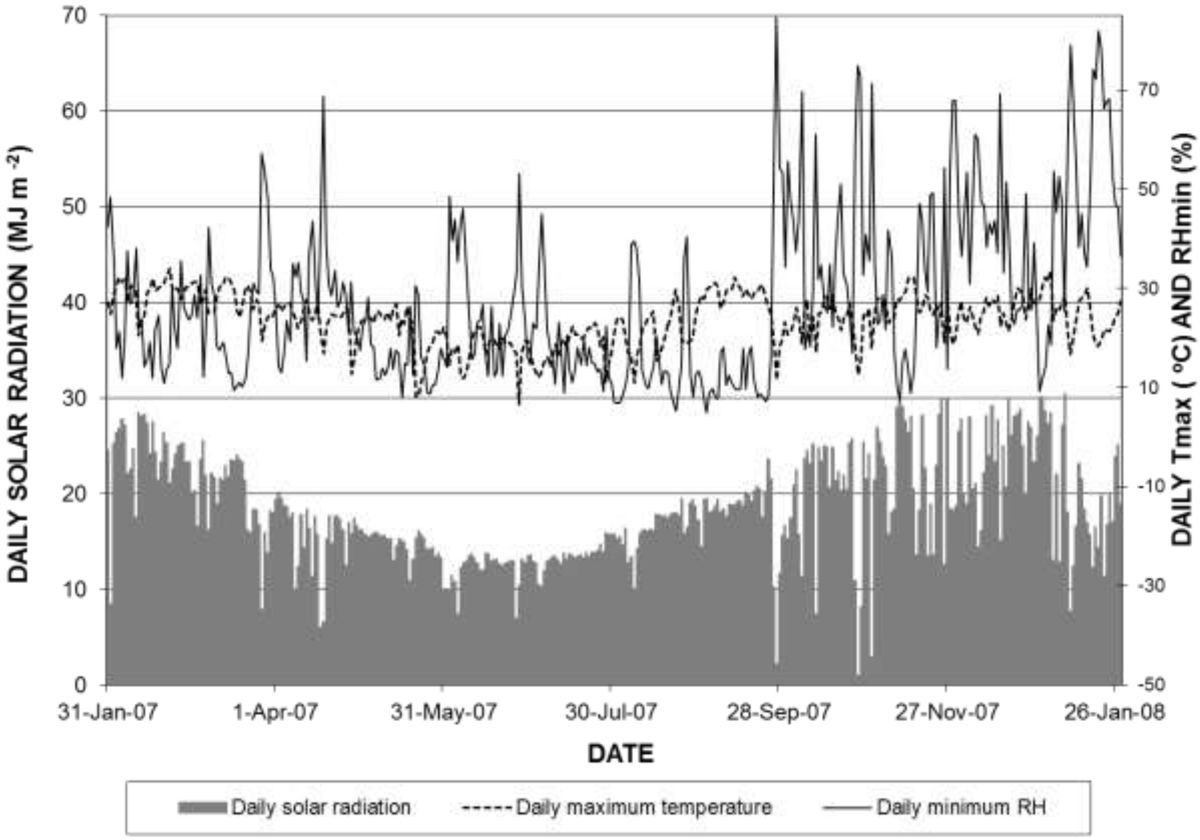

Figure 3. The annual pattern of solar radiation (MJ m^{-2}) recorded at the Vaal River weather station. Daily maximum temperature (Tmax) and daily minimum relative humidity (RHmin) recorded within the West Wits *E. dunnii* plot are also shown.

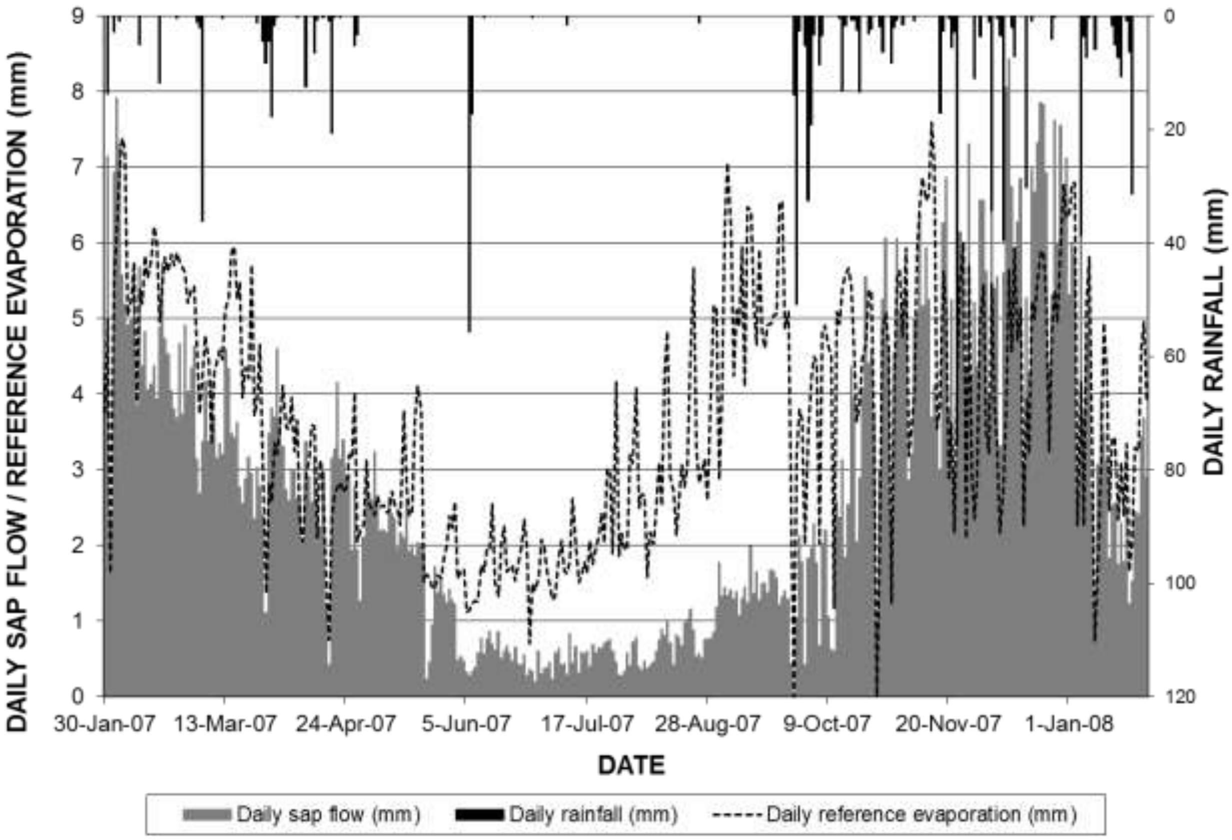

Figure 4. The pattern of mean daily sap flow in four *E. GxC* trees shown in relation to reference evaporation (mm) and daily rainfall (mm).

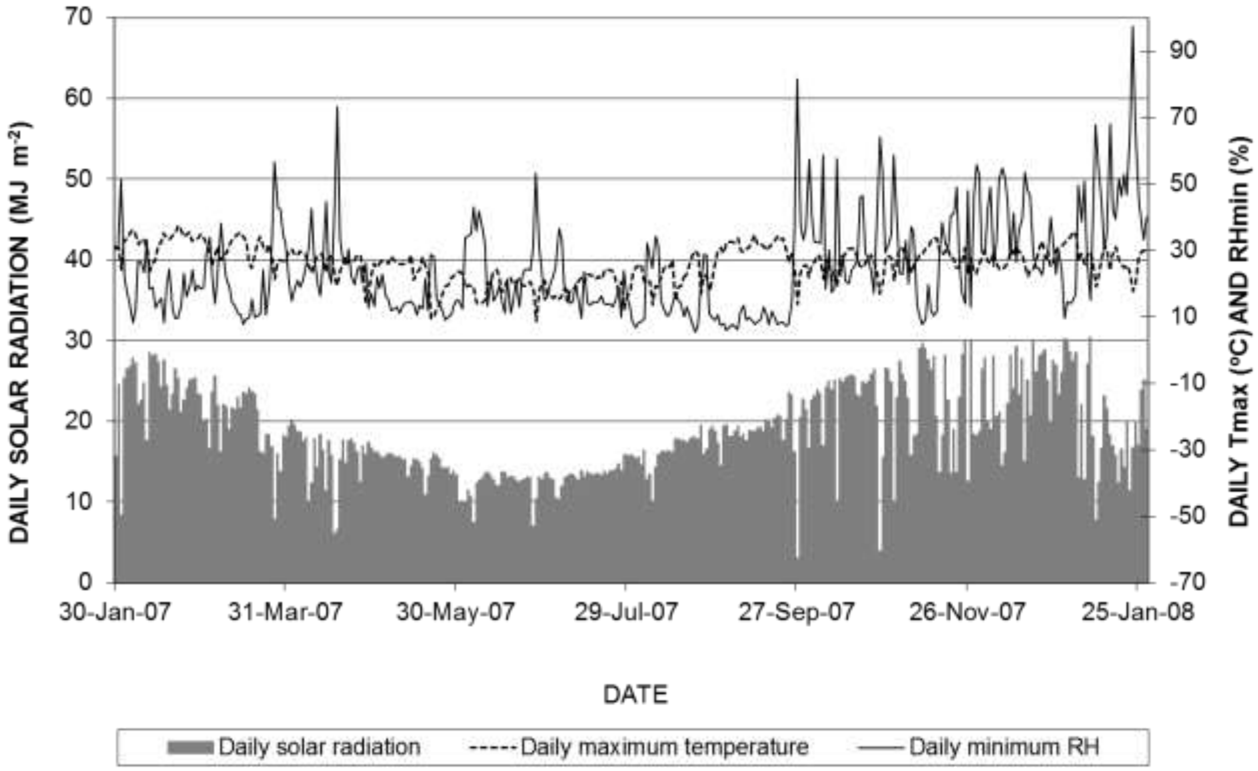

Figure 5. The annual pattern of solar radiation (MJ m^{-2}) recorded at the Vaal River weather station. Daily maximum temperature (Tmax) and daily minimum relative humidity (RHmin) recorded within the Vaal River Mispah *E. GxC* plot are also shown.

Table 1. Description of planting date, tree espacement, tree dimensions and total sap flow recorded in the two *Eucalyptus* plots over the monitoring period from January 2007 to January 2008.

	West Wits Trial (*E. dunnii*)				Vaal River trial (*E. GxC*)			
	Tree 1	Tree 2	Tree 3	Tree 4	Tree 1	Tree 2	Tree 3	Tree 4
Date planted	Jan 2004				Jan 2003			
DBH at start (Jan 2007) cm	11.8	11.5	9.2	9.8	9.9	11.3	12.9	12.0
DBH at end (Jan 2008) cm	14.1	13.7	11.0	12.1	11.1	13.3	14.7	13.2
Estimated % of green leaves on 5 September 2007					10	50	60	85
Annual sap flow (l)	7873	4474	2611	4680	3931	8045	8501	5799
Tree spacing (m^2 $tree^{-1}$)	7.3				9.9			
Annual sap flow (mean of 4 trees) (mm)	673				767			
Annual ref ET (mm)	1273				1330			

Annual rainfall (mm)	629	795