WATER USE MEASUREMENTS OF SELECTED WOODLAND TREE SPECIES WITHIN THE KRUGER NATIONAL PARK

M.B. Gush and P.J. Dye
CSIR and University of KwaZulu-Natal, Scottsville

Abstract

There is widespread belief that indigenous trees use less water than exotic trees. However, there is insufficient information on indigenous species to prove or disprove this hypothesis. Furthermore, growth rates of most indigenous tree species are slow when compared to exotic plantation species, rendering them economically unviable from a timber production perspective. However, the quality and value of the ecosystem goods and services that indigenous trees provide may be very high, possibly providing an economically and ecologically attractive alternative land-use option. In an effort to provide some answers to these questions a solicited Water Research Commission Project entitled “The water use in relation to biomass of indigenous tree species in woodland, forest and plantation conditions” was initiated and is currently ongoing. The overall aim of the project is to investigate rates of growth and water use of a selection of indigenous tree production systems, and to make economic and hydrological comparisons to current commercial forestry systems. Comparisons are being conducted for sites spanning a wide rainfall gradient, and savanna vegetation within the Kruger National Park was selected to represent the low rainfall (570mm) end of the rainfall spectrum. This phase of research is taking place in woodlands south of Skukuza, where the Heat Pulse Velocity (HPV) technique is being used to measure sap flow velocities (and ultimately water use) of some commonly occurring tree species.

Tree species selected for water use measurements using the HPV technique were the Red Bushwillow (*Combretum apiculatum*), Marula (*Sclerocarya birrea*) and False Marula (*Lannea schweinfurthii*). Results so far suggest that water use by these indigenous trees is closely correlated to season (soil moisture availability), tree leaf area, and vapour pressure deficits. Transpiration in the *Sclerocarya birrea* and *Lannea schweinfurthii* trees ceases during the dry winter months when they lose their leaves. The *Combretum apiculatum* trees show a similar trend in transpiration rates, however the transition between dry and wet seasons is less pronounced as these trees typically retain a proportion of their leaves throughout the winter months. Additional project objectives still to be investigated include: estimates of aboveground biomass production and the value of utilisable products; suitable modelling frameworks to permit spatial and temporal extrapolation; and potential economic returns from water used by the trees.

1. Introduction

Exotic plantation forestry is a profitable land use in many of the high-rainfall regions of South Africa, but is restricted in certain areas because of the high water use of commercial plantations and their detrimental impact on catchment water yields. There is a widespread belief that indigenous trees may use less water than exotic trees, and consequently produce smaller reductions in catchment water yields. Growth rates of many indigenous species are slow when compared to exotic plantation species, but the quality and value of the wood may be very high, possibly providing an economically attractive alternative land-use option in areas where afforestation with exotic species is curtailed. There is insufficient information on indigenous species to prove or disprove this hypothesis. Research is required to provide growth and water use data for a diverse range of indigenous tree production systems, to permit a comprehensive comparison to current exotic tree plantations.

A direct comparison of the growth and water use of exotic forest plantations and indigenous tree systems is often difficult because of differences in climate. Generally, as rainfall declines and evaporative conditions increase, trees tend to adapt to the more frequent and pronounced soil water deficits with numerous adaptations that include reduction in overall tree density and leaf area index, decreased leaf stomatal conductances and increased root-shoot ratios. Zhang *et al*. (1999) produced a diagram (Figure 1) that served as a useful framework within which appropriate tree systems for this study were selected. They reviewed hydrological data from over 250 catchments from around the world, and found distinct trends in catchment water yield and estimated evapotranspiration (ET) associated with grassland and forest-dominated catchments. In Figure 1, the vertical distance between any plotted point or trend line and the 1:1 line of equality represents the quantity of water not evaporated and therefore leaving the catchment as stream or river flow. Clearly, a change of vegetation from grassland to forest may result in a large increase in total ET, and a corresponding decrease in catchment water yield. Also of significance are the shapes of the forest and grassland / crop trend lines. At the low end of the rainfall gradient, changes in vegetation have relatively little effect on the proportions of ET and catchment water yield, since rainfall is so limiting that any type of vegetation is able to take up and evaporate most of what infiltrates into the soil. The difference in ET between grass and trees increases as MAP increases. The forest curve flattens out at around 1600 mm per year. This is a maximum annual ET that is limited by available energy for evaporation. This can only be exceeded where advected energy is available at a site. Clearly the potential for enhancing catchment water yields through land use change is greatest in high rainfall catchments.

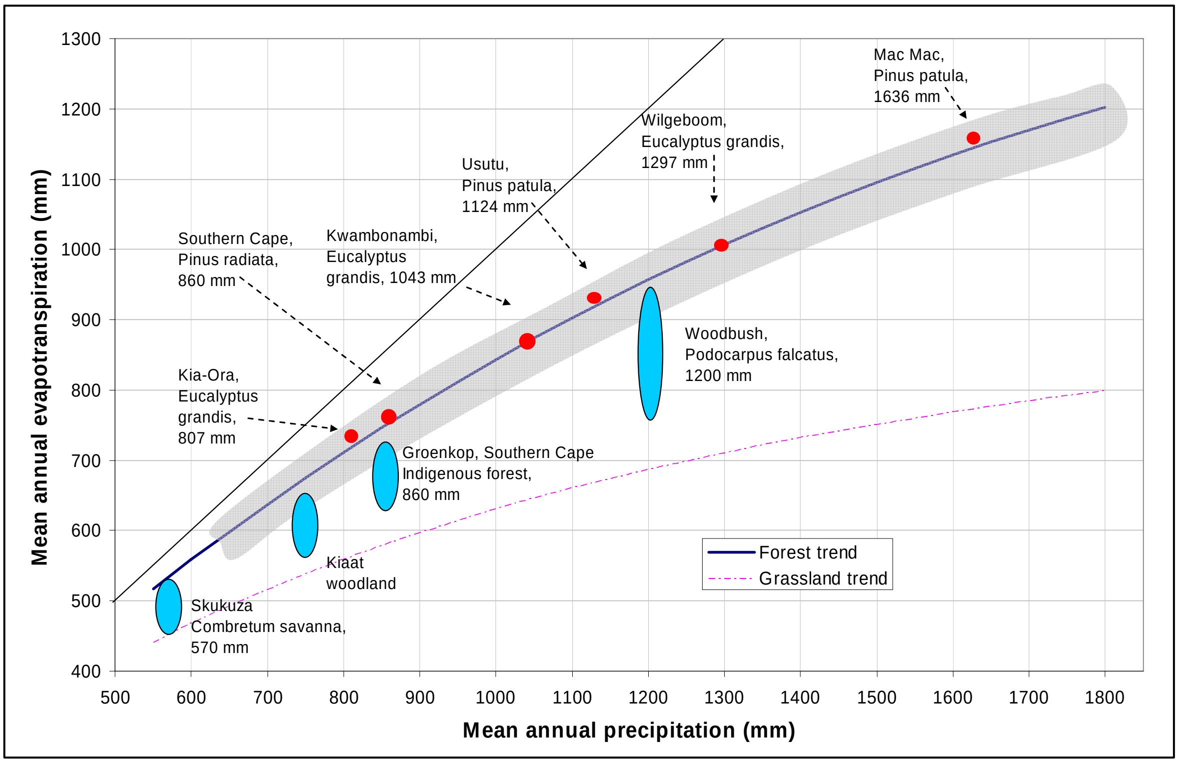

Figure 1. **The relation between mean annual precipitation and mean annual evapotranspiration for different vegetation types. Trend lines indicate the global trends in mean annual evapotranspiration from forested and grassland catchments (Zhang *et al.*, 1999). Filled circles indicate the likely position of forest plantations from which high quality water use and biomass data are available. Oval symbols indicate the likely positions of indigenous forests and savanna woodlands that are being investigated in this project.**

The water use of exotic forest plantations is expected to fall within the shaded forest band shown in Figure 1. Data from South African research catchments supports this assumption. Species grown in forest plantations are selected for fast growth, and therefore typically exhibit high leaf areas, evergreen canopies, high stomatal conductance and deep root systems. Grassland, on the other hand, is a conservative user of water. Above-ground growth is highly seasonal, with peak leaf area often attained for only a short period in mid summer. Root systems are generally shallower than for trees. We expect that the Y-axis position of indigenous tree-dominated systems will lie somewhere within the oval symbols, in-between the forest and grassland trend lines.

Although greatest gains in catchment water yield are possible in high rainfall regions, there are two reasons why it is important to adequately sample tree systems in lower rainfall regions in this project. Firstly, catchments receiving lower MAP are often very large and therefore still have large impacts on streams and rivers. Secondly, a surprisingly high proportion of South African forest plantations occur in areas of relatively low rainfall. It is these areas where alternative tree production systems may be more economically feasible.

The efficiency of water use for biomass production in woodlands and savannas is also a relevant question. Vast areas of South Africa are covered by woodlands that produce essential fuel wood, poles and other products for local consumption. Alternative land use cropping options exist in many of these areas, and the overall efficiency of water use for biomass production, and the net benefit of the water used are important criteria that need to be understood to permit the evaluation of different land use scenarios.

Meeting the above objectives requires, amongst other things:

- The selection of a suitably diverse sample of indigenous tree production systems to illustrate to what extent water use efficiency varies with species, tree age, site conditions and climate, and
- The measurement of whole-year patterns of water use in each system.

The research reported on here describes the measurement of transpiration (i.e. water use, excluding intercepted water) from the tree component of savanna vegetation, using the Heat Pulse Velocity (HPV) technique.

2. Methods and Materials

2.1 Site selection

The study site was selected with a number of objectives in mind. In terms of mean annual precipitation (MAP) it was important that the site represented dry savanna vegetation, as discussed in relation to Figure 1 above, with the occurrence of appropriate tree species. To this end, the choice of locality was greatly facilitated by a decision that the site needed to be close to an existing experiment south of Skukuza in the Kruger National Park, where a flux tower is providing Eddy Covariance data on carbon and water fluxes (Scholes *et al.,* 2001). Data from the flux tower site is yielding information on the total evapotranspiration from trees, grass and bare soil. Motivation to select the site close to this experiment was provided by the desire to estimate what fraction of this total evapotranspiration originates from the trees. Together with tree growth measurements, these data will allow the calculation of water use efficiency (WUE) of the tree component alone, for comparison with other tree production systems.

An additional pragmatic requirement for the selection of an appropriate site was that the selected trees were in close proximity to each other to facilitate wiring. This was necessitated by the presence of a single supplementary power source (solar panels) to which all logging systems needed to be wired. Furthermore, in an effort to increase sample size while minimising equipment costs, multiplexers were utilised to allow a single logger to monitor two separate sites. This introduced a constraint in terms of wiring lengths. A final, albeit non-essential, criterion that aided the selection of the site was the presence of cell-phone reception. This enabled remote data transfer to take place using modems wired to the loggers. A cluster of suitably diverse and closely located trees was located.

The actual site is situated at (25º 01.184’ S, 31º 29.813’ E), and is semi-arid (570mm MAP), and hot (22ºC MAT). It is described as sandveld savanna, and supports broadleaved species, dominated by *Combretum apiculatum* (Scholes *et al.,* 2001). Three tree species that typically occur in the sandveld savanna vegetation type were selected for water use monitoring using the HPV sap flow technique described below. Species selected for measurements were the Red Bushwillow (*Combretum apiculatum),* Marula (*Sclerocarya birrea)* and False Marula (*Lannea schweinfurthii)*. Table 1 gives some details about the selected trees.

Table 1. Sample tree details

Species	Breast height stem circ. (m)	Height (m)	Crown perimeter (m)	Probe sets	LAI 02/09/04	LAI 08/02/05	LAI 17/05/05
S. birrea	1.83	11.79	68.0	12	0.36	1.23	0.37
S. birrea	1.225	11.23	37.8	8	0.31	1.45	0.53
L. schweinfurthii	1.53	10.32	35.5	12	0.23	1.69	0.53
L. schweinfurthii	0.62	7.97	21.4	4	0.50	1.15	0.84
C. apiculatum	0.55	9.44	15.0	4	0.56	1.83	0.80
C. apiculatum	0.344	6.64	8.6	4	0.71	0.97	0.80
C. apiculatum	0.593	7.92	17.5	4	0.58	1.35	0.80

2.2 Instrumentation

Continuous measurements of sap velocities (using the Heat Pulse Velocity technique) and some climatic variables (using automatic weather station sensors) are being conducted at the KNP site. The heat pulse velocity (HPV) technique is an appropriate technique for measurement of sap velocities in trees. The heat ratio method (HRM) of operation applied in the HPV technique is fully described in Burgess *et al.*, (2001). However, the description below is given for the readers benefit, and is drawn largely from that reference.

The heat ratio method measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant below and above a heater probe. In order to achieve this, three parallel holes are accurately drilled (with the help of a drill guide strapped to the tree) into the sapwood (xylem) portion of tree trunks. The upper and lower holes are both situated 5mm from the central hole (above and below, respectively). Copper-constantan thermocouples, wired to a multiplexer or logger, are inserted into the upper and lower holes to a specific depth below the cambium (below-bark insertion depth). A heater probe, wired to a relay control module, is inserted into the central hole.

At a pre-determined time interval (usually hourly), the temperatures in the upper and lower thermocouples are measured and the ratio (upper over lower) is logged. Directly thereafter, the central (heater) probe releases a short (0.5 second) pulse of heat, which diffuses through the adjacent wood and is taken up by the sap moving upwards through the xylem of the tree. As the heat pulse is carried up the tree by the sap, the upper thermocouple begins to warm. Logging of the changing heat ratio commences 60 seconds after the initiation of the heat pulse and is measured continuously (approximately every second, depending on the processing speed of the logger) until 100 seconds after the heat pulse. The average of these ratios is calculated and utilised in subsequent formulae to derive the sap velocity. These formulae are described in Burgess *et al.*, (2001). Further measurements of sapwood area, moisture content and density, as well as the width of wounded (non-functional) xylem around the thermocouples, are used to convert sap velocity to a total sap flow rate for the entire sample tree (Marshall, 1958). These measurements are usually taken at the termination of the experiment due to the destructive sampling required to obtain them. The conversion of sap velocity to sap flow is readily derived as the product of sap velocity and cross-sectional area of conducting sapwood. Gross wood cross-sectional area is calculated from its under-bark radius. Heartwood is discounted by staining the sapwood or by observing the dark colour often associated with heartwood. Where sap velocity is estimated at several radial depths, total sapwood area is divided into concentric annuli delimited by midpoints between measurement depths. In this way, point estimates of sap velocity are weighted according to the amount of conducting sapwood in the annulus they represent (Burgess *et al.*, 2001).

The number of probe sets (2 thermocouples and one heater) utilised per tree is determined arbitrarily by the diameter of the tree, but typically range from 4 to 12. The thermocouples are typically inserted to four different depths, since velocities are highest in the younger xylem near the cambium and slower in the older, deeper xylem. Data loggers are programmed to initiate the heat pulses and record the heat ratio changes in the respective thermocouple sensor pairs. Cellular phone modems connected to the loggers allow remote downloading of data as well as uploading of revised programmes to the logger. In order to minimise battery usage by the modem it is programmed to only switch on for a couple of hours each day during which time remote data transfer operations can be carried out.

Automatic weather station sensors are used to monitor changes in air temperature and relative humidity. Conditions are continuously measured at 10s intervals, and averaged or totalled at hourly intervals. A solar panel is used to charge the batteries that power the system. Protection of equipment against damage by wild animals was pre-requisite and is by means of a “wigwam” of treated gum poles anchored in the ground with the tops wired to the tree above the probes. Weld-mesh fencing stapled to the pole framework excludes animals. The top portion was covered by several layers of shade cloth to reduce the influence of direct sunshine on the thermocouple probes.

3. Results and Discussion

Figure 2 illustrates data collected from the automatic weather station at the site between January 2005 and January 2006. Seasonal changes in temperature and rainfall are evident. Following a relatively dry summer (Jan-Mar ’05) and a typically dry winter, the first significant spring rains (45mm) fell on the 6th of November 2005. These were supplemented by good rains in the ensuing summer months, although the total precipitation for the 2005 calendar year (445mm) was significantly below the long term mean of 570mm. Temperatures were somewhat above the long term mean, with an average for 2005 of 23°C. The highest recorded temperature was 41.4°C on 12 October 2005, and the lowest was 6.3°C on the 11th July 2005.

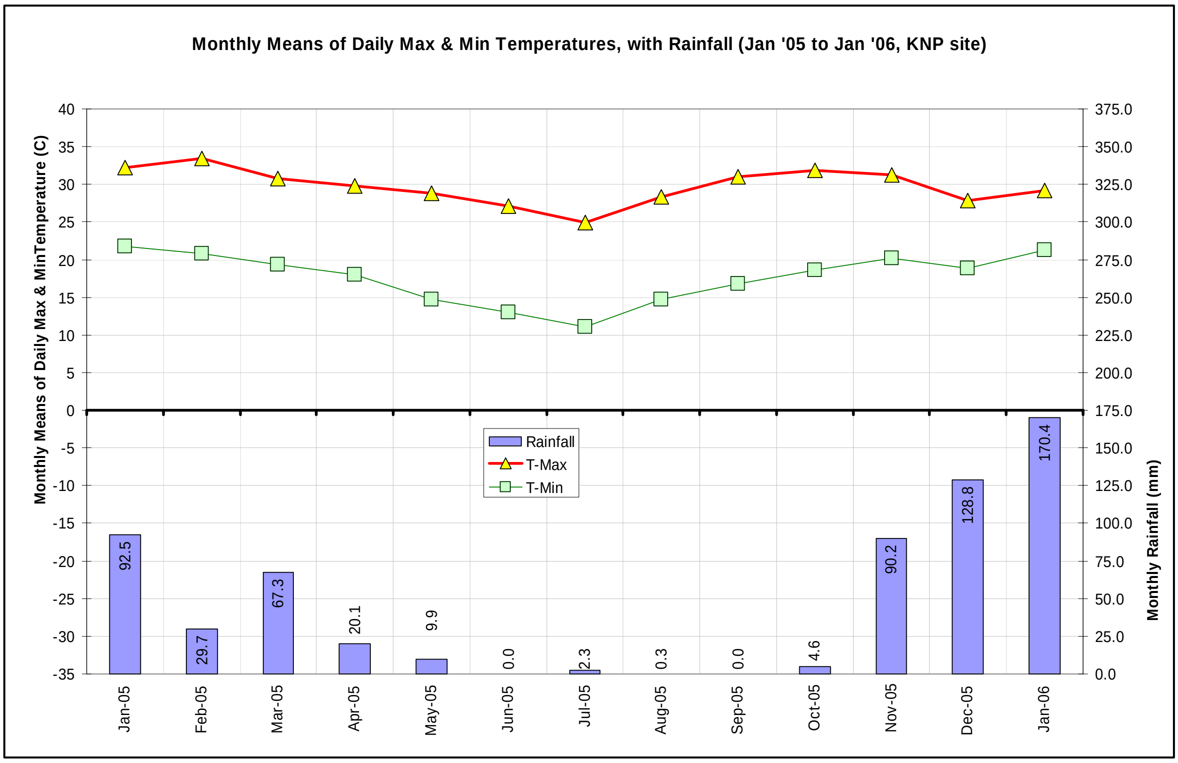

Figure 2. **Monthly means of daily maximum and minimum temperatures, with monthly rainfall, from the KNP site, near Skukuza.**

Sap velocity measurements in the seven sample trees being monitored with the heat pulse velocity technique commenced in September 2004 and continued into the 2005/6 growing season. Monitoring is scheduled to continue until August 2006 at which time the probes will be removed and the necessary supplementary measurements taken (wounds width, sapwood area, moisture content and density). Figures 3, 4 and 5 illustrate hourly sap velocity data (cm/hr) measured in *C. apiculatum, L. schweinfurthii* and *S. birrea* trees respectively. The period encompasses two summer rainfall seasons, and significant rainfall events are illustrated.

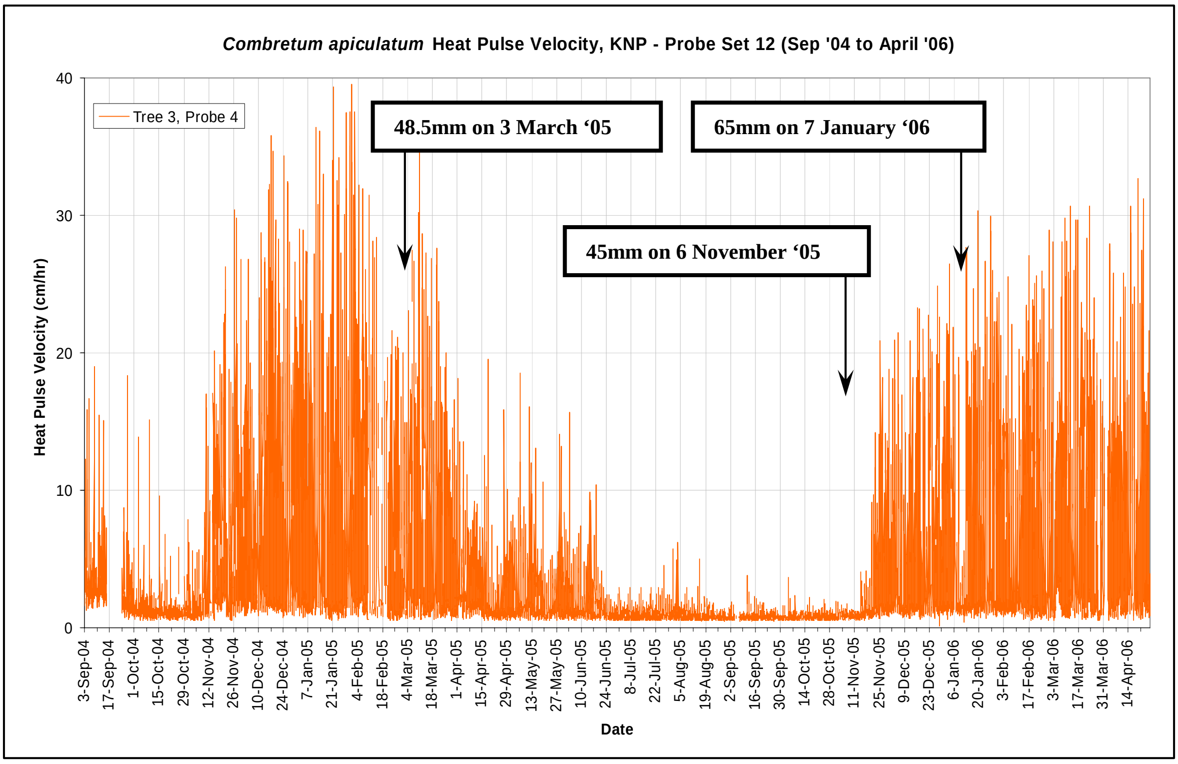

Figure 3. Hourly sap velocity data (cm/hr) collected from a *Combretum apiculatum* tree in the Kruger National Park. Note the influence of significant rainfall events.

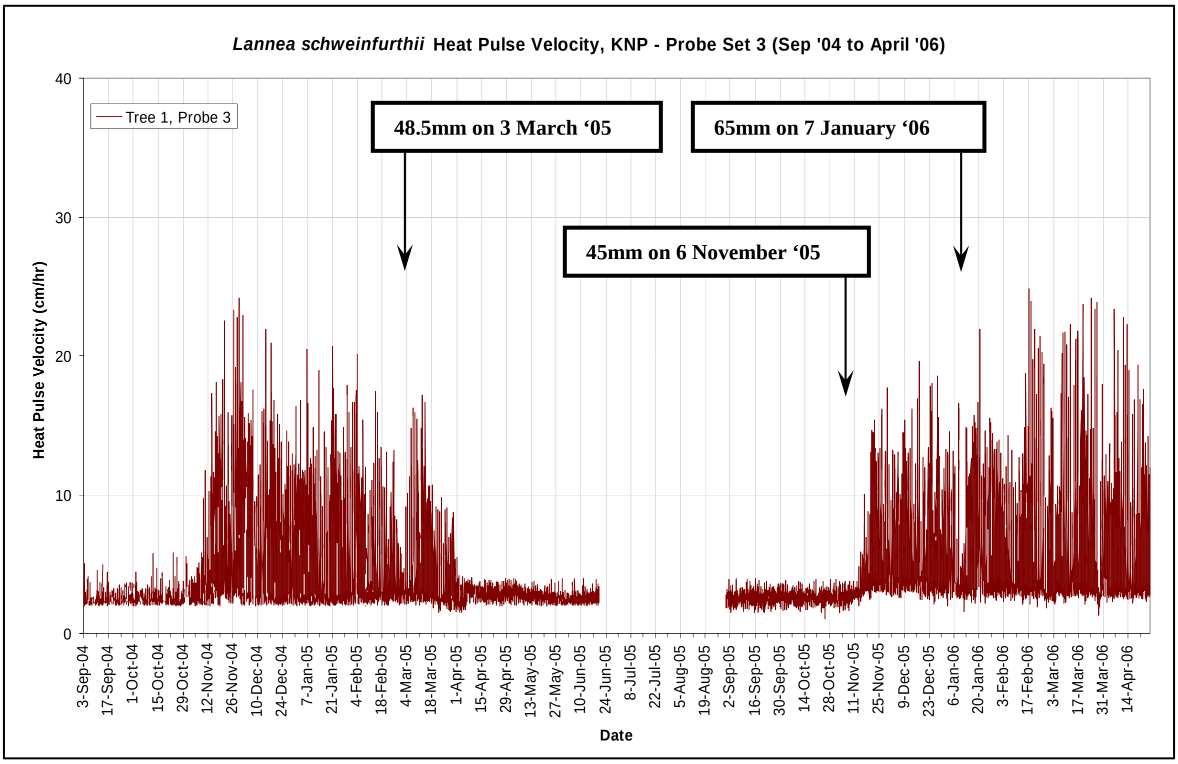

Figure 4. Hourly sap velocity data (cm/hr) collected from a *Lannea schweinfurthii* tree in the Kruger National Park. Note the influence of significant rainfall events.

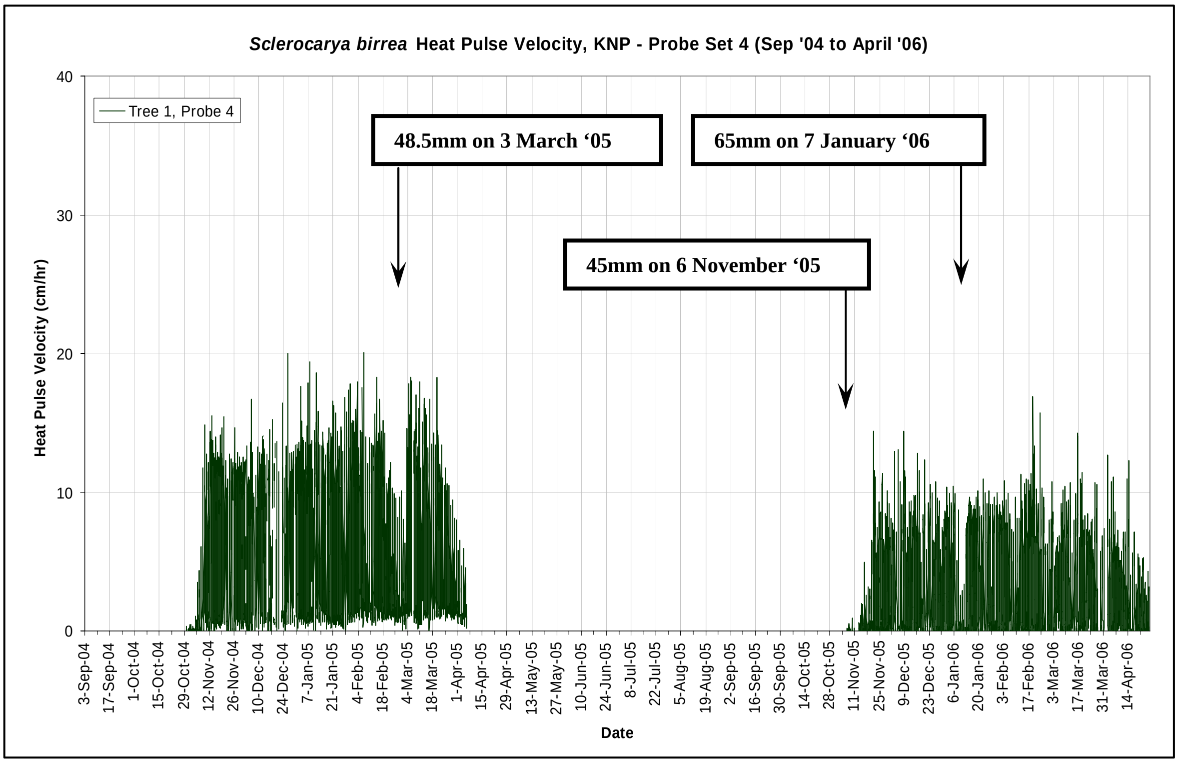

Figure 5. **Hourly sap velocity data (cm/hr) collected from a *Sclerocarya birrea* tree in the Kruger National Park. Note the influence of significant rainfall events.**

From Figures 3, 4 and 5 it is possible to observe the summer peaks in sap velocity, and the decline to the dry winter period. This decline in sap velocity is more gradual in the semi-deciduous *C. apiculatum* tree (Figure 3) as opposed to a more rapid decline evident in the fully deciduous *S. birrea* and *L. schweinfurthii* trees (Figures 4 and 5). The influence of a few large rainfall events on sap velocities is clear. These events served to replenish soil water reserves (e.g. 3 March 2005, and 7 January 2006), in which case the increase in available water was manifested in increased and prolonged sap velocities. The rain that fell on 6 November 2005 broke the dry winter period and sap flow resumed shortly thereafter. Sap velocities in the *S. birrea* and *L. schweinfurthii* trees are lower than in the *C. apiculatum* tree, although this does not necessarily imply a lower water use as the former species have much wider stems (i.e. slower sap velocity but greater sap volume).

The HPV systems for some trees were removed during a field visit between 9 and 20 May 2005. This allowed the equipment to be thoroughly cleaned and stored during the dormant and dry winter period when the trees were leafless and hence not transpiring. The *C. apiculatum* HPV system, however, remained deployed in the field as this species maintains some leaf cover throughout the winter (depending on available water). It was consequently deemed important to record any possible sap flow throughout this season. The removed systems were reinstalled during a short field visit between 22 and 28 September 2005. This entailed a complete re-drilling and installation of all the HPV probe sets and systems for these trees. The advantages of this were that there was an opportunity to replace any previously faulty instrumentation (e.g. heater probes) and also reposition the sap velocity monitoring probes. The latter is useful due to the fact that the final sap flow calculations using this technique are significantly influenced by the insertion depth associated with a particular probe set. These depths are measured extremely accurately at the time of installation; however while the sample tree stem diameter expands with growth the probes tend to remain at their original position (relative to the centre of the stem), so the insertion depths gradually become deeper over time. On the other hand, the pressure of sap or resin from the tree can also sometimes force out the probes from their original positions. It is therefore necessary to periodically remove, re-measure and re-insert the probes to the desired depths. During this visit it was noted that the *S. birrea* and *L. schweinfurthii* trees were just beginning to produce new leaves, so the recommencement of sap velocity monitoring was well timed.

Figure 6 illustrates two important periods of sap velocity monitoring in a large *S. birrea* tree. These include the end of one wet season and the start of the following wet season, but exclude the dry season (no sap flow). The declining trend of daily sap velocities towards the end of the wet season (March / April) and the subsequent resumption of transpiration at the start of the following wet season (November / December) are evident. There are also clear diurnal patterns in the heat pulse velocities, and the data are well correlated with seasonal, daily, and even hourly climatic conditions at the site. It is speculated that seasonal variations in sap velocity are not only correlated to available soil moisture, but also to climatic stimuli such as changes in temperature and daylight length. From field observations it may be deduced that sap flow ceases before all the leaves have dropped from the tree, and only commences after the new flush of spring leaves have been on the tree for over a month. It was noted during the drilling process of probe installation that the bark, of the *S. birrea* trees especially, contained significant quantities of moisture, even during the dry season. This could potentially provide a supplementary source of water during periods of extreme water stress, and would explain why, during extended dry periods, actual reductions in stem circumference have been noted in *S. birrea* trees (R. Scholes, pers. comm.). It is during these periods that the trees would draw from their own “internal” sources of water.

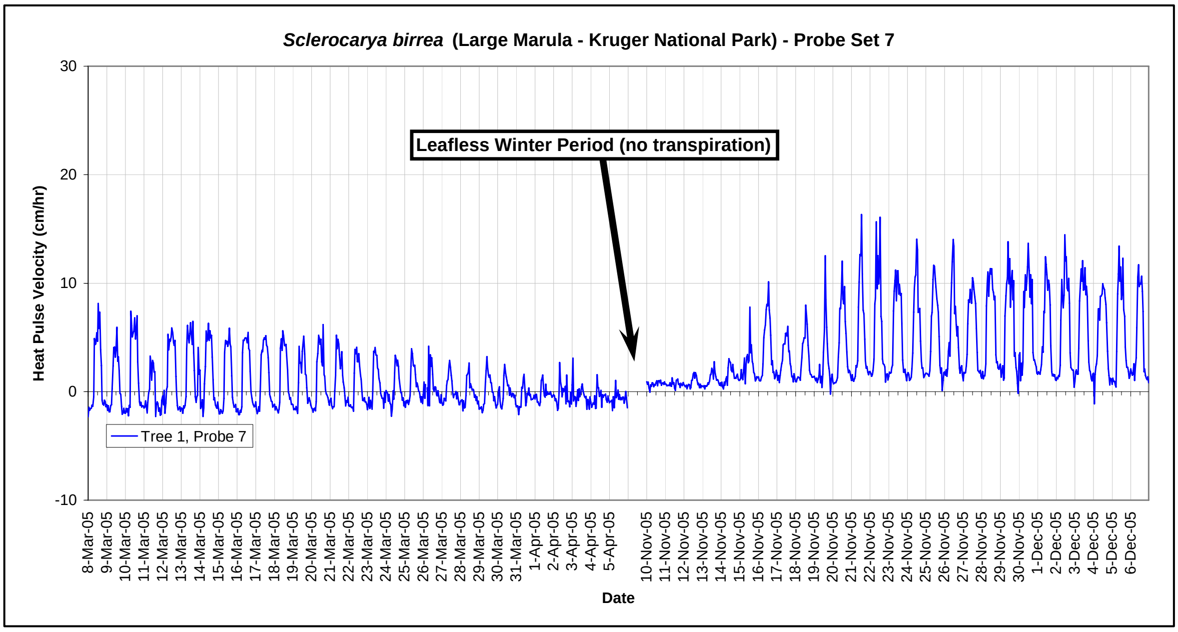

Figure 6. Hourly heat pulse velocity data from a large Marula (*Sclerocarya birrea*) tree in the Kruger National Park. The monitoring period illustrated incorporates the end of the 2004/2005 wet season (March / April 2005), and the start of the 2005/2006 wet season (November / December 2005).

In Figure 7 a 10-day period of sap velocities from a *C. apiculatum* tree is illustrated. The strong correlation between sap velocity and ambient temperature / humidity (vapour pressure deficit) is evident. Differences in heat pulse velocities recorded on clear, warm days (20th to 27th March 2006) and a cool overcast day (28th March 2006) are illustrated. Furthermore, where there are brief drops in temperature and increases in humidity, often associated with a rainfall event, there are corresponding reductions in sap velocity (during the day). The range of sap velocities recorded simultaneously from individual probe sets on any given day is also noteworthy. This reflects the significant differences in sap velocities associated with their relative positions within the sapwood portion of the stem. It is known that sap velocities tend be greater in the outer regions of the sapwood, where cells are young, undamaged and well-connected. This is also the motivation behind inserting HPV thermocouples to different depths within the sapwood. The good correlation between different probe sets, in terms of their diurnal rhythms, greatly facilitates the patching of missing periods of data for any given probe set.

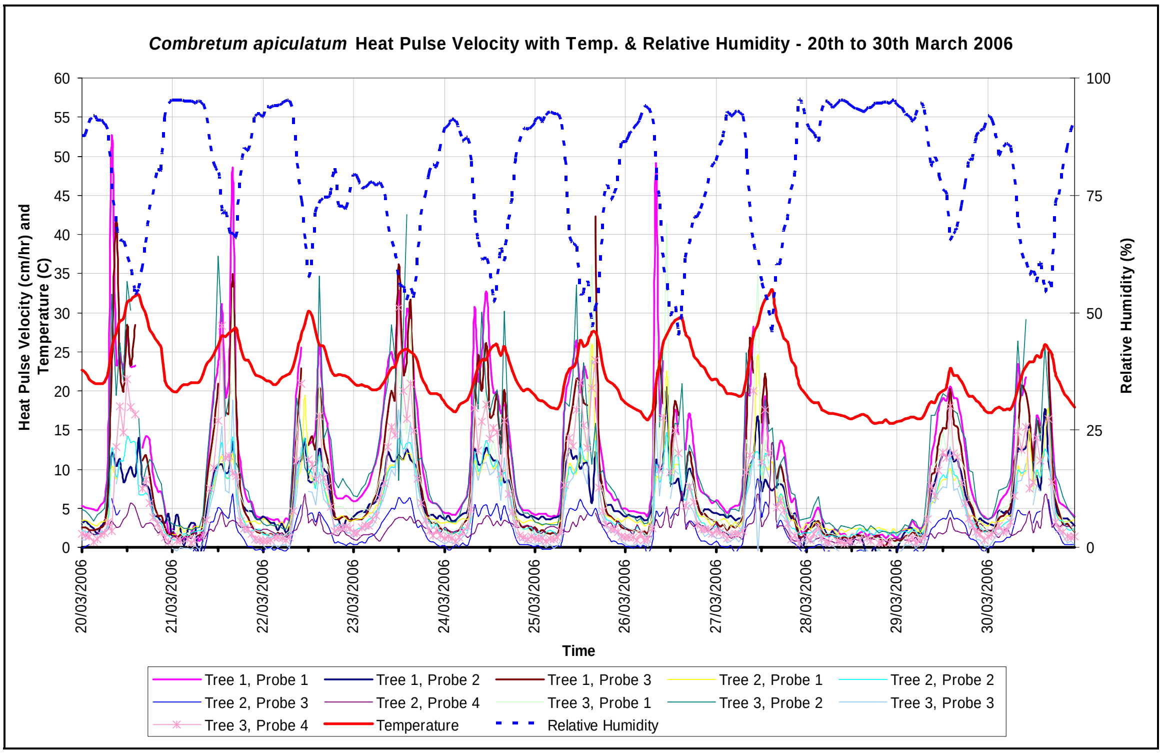

Figure 7. Hourly heat pulse velocity data from a *Combretum apiculatum* tree in the Kruger National Park between the 20th and 30th of March 2006.

4. Conclusions

The heat ratio method of the HPV technique appears to be supplying good quality sap velocity data. Velocities vary somewhat between species due to physiological differences, although overall trends are similar. Influences on sap velocity are noticeable at different time scales, ranging from annual (season / physiology / water stress), to daily (rainfall) and hourly (temperature and RH fluctuations). Results so far suggest that water use by the selected trees is extremely seasonal and closely correlated to moisture availability, tree leaf area, and vapour pressure deficits of the air. Transpiration ceases during the dry winter months when the *Sclerocarya birrea* and *Lannea schweinfurthii* trees lose their leaves. The *Combretum apiculatum* trees show a similar trend in transpiration rates, however the transition between dry and wet seasons is less pronounced as these trees typically retain a proportion of their leaves throughout the winter months.

The data so far are only for sap velocity (cm/hr). The conversion of sap velocity to sap flow is readily derived as the product of sap velocity and cross-sectional area of conducting sapwood. Further measurements of sapwood area, moisture content and density, as well as the width of wounded (non-functional) xylem around the thermocouples, are eventually used to convert sap velocity to a total sap flow rate for the entire sample tree. These measurements will be taken at the termination of the experiment. Supplementary data (from the scintillometry and eddy covariance techniques) will provide integrated tree / grass Et, while this HPV study is yielding tree transpiration only, so it will also be possible to deduce grass and soil evapotranspiration by subtraction.

This work has focused on the water use of a few selected tree species in Sandveld Savanna. The question then is how to eventually scale these measurements up so as to be representative of tree water use in this vegetation type as a whole. It is beyond the means of the project to monitor all the various tree species represented in this land cover, which is why an effort was made to select the most representative species initially. Results from these trees could be combined and weighted to determine a typical water use pattern of the “average tree” within this environment. The next step would then be to determine how many trees occurred per unit area (i.e. what proportion of the landscape is represented by trees alone). On the basis of this analysis it will be possible to have an indication of the water use of the tree component of savanna vegetation.

Acknowledgements

The authors would like to extend their sincere appreciation to the following organisations and individuals:

- The Water Research Commission for initiating and funding this solicited project,
- The greater CSIR project team including Dr. Colin Everson and Mr. Alistair Clulow,
- Scientific Services of the Kruger National Park, for allowing the monitoring of trees in the park,
- Walter Khubeka and the various game guards affiliated with Scientific Services who have provided, respectively, technical support and protection / assistance in the field.

References

BURGESS, S.O., ADAMS, M.A., TURNER, N.C., BEVERLY, C.R, ONG, C.K., KHAN, A.A.H. & BLEBY, T.M. (2001). An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* 21: 589-598.

MARSHALL, D.C. (1958). Measurement of sap flow in conifers by heat transport. *Plant Physiology* 33: 385-396.

SCHOLES, R.J., GUREJA, N., GIANNECCHINNI, M., DOVIE, D., WILSON, B., DAVIDSON, N., PIGGOTT, K., MCLOUGHLIN, C., VAN DER VELDE, K., FREEMAN, A., BRADLEY, S., SMART, R. & NDALA, S. (2001). The environment and vegetation of the flux measurement site near Skukuza, Kruger National Park. *Koedoe* 44(1): 73-83.

ZHANG, L., DAWES, W.R. & WALKER, G.R. (1999). *Predicting the Effect of Vegetation Changes on Catchment Average Water Balance*. Technical Report 99/12, Cooperative Research Centre for Catchment Hydrology, CSIRO, Canberra.