Water-Use in Relation to Biomass of Indigenous Tree Species in Woodland, Forest and/or Plantation Conditions

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Report to the Water Research Commission

by

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EXECUTIVE SUMMARY

1. Background

Large areas of commercial forest plantations occur in the wetter regions of South Africa. Covering approximately 1.4 million hectares, they contribute considerably to the economy and employment. However, research has shown conclusively that evapotranspiration (ET) from these plantations is substantially higher than from the original grasslands or fynbos that were replaced by afforestation. Thus, forest plantations have reduced catchment water yields in most areas and this has resulted in water legislation limiting further afforestation in areas where water resources are already committed. The demand for wood is growing strongly, yet the expansion of the national forestry estate is curtailed by legislation in order to minimise further declines in catchment water yields.

South Africa contains a wealth of plant species numbering more than 24 000, of which approximately 1 070 species are indigenous trees belonging to 370 genera and 97 families. There is a widespread perception within South Africa that indigenous tree species, in contrast to the exotic pines, gums and wattle, are water-wise and deserve to be planted more widely in view of their more efficient use of water. This perception appears to be based on the observation that indigenous trees are generally slow growers and the belief that growth and water-use are broadly linked. However, tree water-use, and the total ET from forests and woodlands, is technically difficult to measure and so evidence of low water-use by indigenous trees is scarce and indirect.

The overall aim of this Water Research Commission (WRC) solicited research project, which was co-funded by Working for Water (WfW, DWAF), was to investigate rates of growth and water-use by a wide selection of indigenous tree production systems and to make economic and hydrological comparisons to current commercial forestry systems. More specific aims were listed as follows:
1. Determine the patterns of water-use for stands of selected indigenous tree species of different age classes
2. Determine the rates of above-ground biomass increase
3. Compare results with existing information for currently grown commercial trees
4. Incorporate the data in a modelling framework for temporal and spatial extrapolation.

In view of the potentially broad scope of this project, the reference group provided the following guidelines:

- Measurements of transpiration / evapotranspiration from indigenous trees should be a priority since very little past data were available due to significant technological barriers. Historically this has been the greatest hurdle to improving our understanding of the water use efficiency (WUE) of indigenous trees.

- Modelling of the water-use of indigenous trees should form a very important component of this project. Models are required to provide a framework for understanding the environmental and biological controls on transpiration / ET from tree canopies and permit extrapolation of water-use predictions over time and over larger spatial scales.

- The WUE of indigenous and exotic forest systems should be based on the utilisable wood produced by these systems. A review of potential benefits from indigenous trees conducted at the start of this project reported on the diverse benefits (fruits, traditional medicine, ferns, ecosystem services, recreational and tourism benefits, etc.) that have been exploited from indigenous tree systems in South Africa, but a complete analysis of all of these could not be accommodated within one project.

- The economic benefits of land-use systems based on indigenous species of trees should be described.

There are various definitions of WUE encountered in the scientific literature and it is important to clarify the definition adopted in this report and the units adopted. This study has focussed on biomass production in trees, with the underlying purpose of evaluating the economic potential of wood production from different forms of forestry based on indigenous tree species. It was natural therefore to describe growth and WUE in

terms of the above-ground utilizable fraction of the total tree biomass and to ignore below-ground biomass. In the case of commercial forest plantations and natural forests, the relevant measure of above-ground biomass fraction to use is the utilizable stem, which excludes the butt that remains after felling, but includes the entire stem up to a thin-end point (often defined by a diameter of 7 cm, Bredenkamp, 2000). In the case of savanna vegetation, it is more relevant to consider the biomass of both stem and branches of trees. These are often not clearly distinguishable. In this environment, wood from both stems and branches is used for fuelwood, poles or for carving. The total above-ground woody biomass is therefore a more meaningful measure of utilizable biomass production than stem biomass alone.

Two measures of water-use are adopted in this report. The micrometeorological systems (Eddy Covariance, Bowen Ratio, Surface Renewal, Scintillometry) measure the total evaporation (evapotranspiration) from an entire stand or patch of trees. This measure of water-use is particularly valuable for assessments of the hydrological impact of an entire plantation or forest. Results are most meaningfully reported in units of mm, since they can be readily compared to rainfall. Measurements of sap flow within individual sample trees were recorded at various sites and compared to data collected in the course of past sap flow studies of *Eucalyptus* and pine trees. Hourly or daily sap flow data are described in litres per day. However, where cumulative annual sap flows are presented, this is expressed in more convenient units of tonnes (also equal to cubic metres) of sap flow per tree or per hectare. The value of such sap flow measurements is that they permit more focussed comparisons of water-use across species and are more directly linked to the structure and physiology of the tree and the evaporative conditions of the atmosphere. It is estimated that tree transpiration comprises 80-90% of total evapotranspiration in most South African forest environments. The balance is accounted for by evaporation from wet canopies, and from understorey plants, the forest litter layer and the soil surface.

WUE is expressed primarily in terms of mass of wood produced per mass of water transpired (per tree) or evapotranspired (per stand). However, volumetric units are also used where it is useful to compare results to volume-based growth and WUE data that are widely used in the forestry industry.

2 Measurements of WUE in diverse indigenous tree production systems

Much of the research effort for this project went into field studies of the growth and water-use of trees in a southern Cape indigenous evergreen forest, a plantation of indigenous *Podocarpus falcatus* in Magoebaskloof and a sandveld savanna southwest of Skukuza in the Kruger National Park. These study sites were selected for their diversity of trees species, structural attributes, growing conditions and responses to environmental limitations, in order to examine the problems of water-use measurement and biophysical modelling challenges, as well as to demonstrate the range of tree growth rates and WUE variation under very different environmental conditions.

2.1 Southern Cape evergreen forest

Measurements of ET from the Groenkop indigenous forest, located outside the town of George in the southern Cape, were obtained over 18 days falling within three different seasons of the year. Three micrometeorological techniques (Scintillometry, Eddy Covariance, Bowen Ratio) were deployed, in order to compare the quality of data from each system. The spatially-averaged scintillometer data (based on estimates of sensible heat along a 3 km transect) were selected as being the most appropriate for estimating long-term ET from the forest.

Three different simulation models were evaluated for predicting daily ET over Groenkop forest. The FAO reference equation was shown to generally underestimate ET under high evaporative conditions and to overestimate under low evaporative conditions. This is attributed to the assumption of a constant surface resistance. The Penman-Monteith (P-M) equation with a sub-model accounting for variable canopy conductance was found to give the best match of predicted to observed daily ET. The more complex WAVES process-based model simulated growth and water-use processes in much more detail, but the successful

parameterisation of the many model parameters was a significant challenge. Despite considerable efforts devoted to this task, the WAVES output revealed an overestimation of daily ET under conditions of low evaporative demand which could not be corrected. We concluded that the P-M model currently provides the best prediction of daily ET from indigenous evergreen forests, especially if they are not subject to significant soil water deficits through the year.

The Penman-Monteith equation was used to simulate forest ET over a period of 20 years, using input weather data recorded at the Saasveld weather station. Mean annual volume growth increment of utilizable stem was estimated from long-term monitoring data in permanent sample plots located within a portion of Groenkop. This was calculated to be 4.2 m³ ha⁻¹ yr⁻¹. Table 4.6 summarises the calculations of WUE for Groenkop forest.

Table I *A summary of WUE (expressed as m^3 utilizable stem wood per m^3 ET, as well as g of utilisable stem wood per kg ET) estimated for the Groenkop forest.*

Annual volume increment (m³ ha⁻¹)	Annual ET (m³ ha⁻¹)	WUE (m³ m⁻³)	Estimated mean wood density (kg m⁻³)	WUE (g kg⁻¹)
4.2	9330	0.00045	600	0.276

2.2 Indigenous *Podocarpus falcatus* plantation, Magoebaskloof, Limpopo

Whole-stand ET rates were recorded from a plantation of indigenous *Podocarpus falcatus* in De Hoek plantation, Magoebaskloof, Limpopo province. Measurements were performed in September 2005, February 2006 and August 2006. ET data were gathered on 23 complete days using three micrometeorological systems (In Situ Eddy Covariance (EC) system, RM Young EC system and a surface renewal system). Hourly sap flow data were continuously recorded over a full year in five sample *P. falcatus* trees selected to represent five size classes of trees at the site. The hourly heat pulse velocity (HPV) data were converted to daily sap flow rates and summed over 12 months to provide an estimate of whole-stand tree transpiration. Comparison to the whole-stand total ET showed that the contribution of tree transpiration was seasonally variable and much less than the ET from the understorey canopy during the summer and autumn measurement periods. Despite the proximity of the site to a stream channel, soil water availability was a major limitation to the rate of transpiration from the trees. Available data illustrated the great complexity of such sites, where both understorey and tree overstorey need to be modelled separately to simulate different growth cycles, responses to changing soil water availability, and green leaf area trends, in order to predict whole-stand patterns of ET through the year.

A very simple model based on the FAO reference evaporation equation was used to estimate year-long ET from the site. Growth survey data recorded for the entire trial was used to estimate mean annual stem volume increment. Table II summarises the major components of the mean water balance used to estimate mean WUE for the site.

Table II *A summary of the mean annual water balance and tree WUE estimated for the P. falcatus plantation, Magoebaskloof.*

Mean annual rainfall (mm)	1 001
Mean annual reference ET (mm)	1 299*
Mean annual stand ET (mm)	~702*
Mean annual tree transpiration (mm)	222*
Mean annual volume growth increment (m³ ha⁻¹)	4.07
WUE (m³ wood m⁻³ ET from stand)	0.00057
WUE (m³ wood m⁻³ TR from trees)	0.00183
Wood density (kg m⁻³)	470
WUE (g wood kg⁻¹ ET from stand)	0.268
WUE (g wood kg⁻¹ TR from trees)	0.860

*Estimated over one year, but assumed to be similar to the long-term mean

2.3 Sandveld savanna, Kruger National Park, Mpumalanga

A large aperture scintillometer (LAS) was used to record total ET above predominantly Sandveld savanna at the site southwest of Skukuza in the Kruger National Park. These measurements were performed in Spring (August 2004), Summer (February 2005) and Autumn (May 2005) to cover different phases of the growing season. The HPV technique was used to continuously monitor the annual pattern of hourly sap flow in seven sample trees representing three species (*Combretum apiculatum*, *Sclerocarya birrea* and *Lannea schweinfurthii*). HPV data collection was extended to cover the 2004/5 and 2005/6 growing seasons. Sap flow data from all three species showed the importance of rainfall distribution, as well as leaf area dynamics, in governing the pattern of tree transpiration. The fraction of ground area covered by the canopies of trees and shrubs was estimated to be approximately 70% from an aerial image of the area. Sap flow in the sample trees was expressed relative to canopy area, and scaled-up to estimate the contribution of tree transpiration towards total ET in this landscape. Mean annual transpiration from trees/shrubs (Table III) amounted to 149.7 mm and 150.0 mm in 2004/5 and 2005/6, respectively, comprising 24.2% of rainfall in 2004/5 and 23.3% in 2005/6. Mean annual wood production was estimated from a simulation by the CENTURY model that was previously parameterized and run for this vegetation type. Weather data from the weather station at Skukuza was used for the period 1960 to 1999, and for a further five years from a research site close to the scintillometer transect. The result of a 43-year simulation showed mean wood production (stems and branches) to be 297 kg ha^{-1} yr^{-1}.

Table III *A summary of the mean annual water balance and tree WUE estimated for the Sandveld savanna, Kruger National Park.*

Total mean annual ET (mm)*	621
Total transpiration (trees and grass) (mm)	354
Tree transpiration (mm)	150
Wood annual volume increment (m^3 ha^{-1})**	0.424
WUE (m^3 wood m^{-3} ET from stand)	0.000068
WUE (m^3 wood m^{-3} TR from trees)	0.000283
Wood density (kg m^{-3})	700
WUE (g wood kg^{-1} ET from stand)	0.0476
WUE (g wood kg^{-1} TR from trees)	0.1981

* ET assumed equal to MAP
**Wood volume increment applies to the sum of both stem and branches

3. Modelling lessons

Experience gained in modelling water-use by the three indigenous tree systems revealed very different model requirements. Evergreen indigenous forest in the southern Cape represented the simplest modelling situation, with a dense evergreen canopy, a reasonably constant LAI, and no significant water stress. The forest could be treated as one big leaf, without the need to distinguish overstorey from understorey plants. The relatively simple P-M model is sufficient to describe such forests, provided that canopy conductance is modelled realistically.

The *Podocarpus falcatus* plantation system proved to be complex, with varying fractions of total ET originating from the tree and understorey canopies. To a large extent, this was attributed to pronounced seasonal changes in green leaf area of the understorey vegetation. Soil water availability from this riparian site, with soils associated with periodically high levels of soil water, was surprisingly shown to be a significant factor limiting transpiration from the trees. A model applicable to such sites needs to simulate ET separately for the overstorey and understorey layers, and be able to follow changes in soil water availability and green leaf dynamics, especially of the understorey plants. Plantation weeds are routinely slashed at intervals in managed plantations, so the effects of such management interventions also need to be simulated.

The savanna vegetation was probably the most difficult to simulate realistically, in view of the strong influence of leaf area dynamics, fast changes in soil water availability over the growing season, and a high degree of spatial variation in tree density and species composition. The CENTURY model was difficult to parameterise

successfully for savanna, and this was attributed to the large number of parameters, and insufficient locally-relevant information with which to describe processes and validate output. The monthly time-step of the model version we used appeared to be too coarse to adequately describe the rapid changes in water balance and growth dynamics.

Choice of model is complex because of the large number of models available to the researcher, and lack of clarity on their strengths and weaknesses. As an aid in selecting the most appropriate model for a particular forest, woodland, savanna or plantation, we offer a list of model attributes which, from a review of literature and from experience in this project, may be necessary for achieving realistic simulations. This list should prove useful in matching simulation needs to an appropriate model.

4. Comparative WUE data from commercial forest species

An important requirement of this project was the comparison of growth and water-use rates recorded from the various indigenous forest and woodland systems, to those of commercial forestry species. This involved two separate studies:

- A 3-PG model simulation of a hypothetical stand of *Pinus radiata* at a site in the southern Cape, with which to compare to the Groenkop forest WUE
- A review of available published information on the WUE of commercial forest trees (mainly *Eucalyptus* species)

4.1 *P. radiata* simulations using the 3-PG model

Pinus radiata is the most appropriate forestry species to compare to indigenous forests in the Southern Cape, since it is the dominant commercial timber species in the region. The growth and physiology of this species is comparatively well known, and much information is available in the scientific literature. This literature was reviewed by the project team. Yield tables for this species in the southern Cape were used to portray typical growth rates for this species. A typical saw-timber rotation was simulated, assuming a medium-quality site (2), a rotation length of 28 years, and a planting density of 1 111 stems per hectare. The 3-PG model is widely used for simulating forest plantations, and has been evaluated for use in South African pine plantations.

Species parameter values finally adopted for the *Pinus radiata* simulations are shown in appendix 7. These resulted in a good match between simulated and reference trends (based on the yield tables) for mean diameter at breast height (DBH) and cumulative stand volume. Model simulations were then run for the period 1971 to 1994, using input weather data from the Saasveld weather station. Tree growth was simulated from age four until harvest age. Two scenarios were simulated. In the first, it was assumed that soil water originated solely from rainfall falling on the site, with no additional source of water entering the soil profile. In the second scenario, it was assumed that soil water was augmented by additional water originating from lateral drainage to the site from upslope areas, or from fog-drip. The reason for the two scenarios is that soil water augmentation in the Groenkop forest is suspected (see Chapter 3). It is not known whether *P. radiata* plantations would thrive under the same site conditions, especially in light of the known preference of this species for well-drained soils (Schutz, 1993). Consequently, WUE is estimated for both scenarios. For scenario 1, available water capacity (AWC) was set at 250 mm. For scenario 2, AWC was set at 750 mm, to ensure that no soil water deficits were allowed to build up and limit the growth and water-use of the trees.

Table IV summarises the simulated outputs used in the calculation of WUE for both scenarios. There is little difference in the final growth yields, cumulative ET, and WUE between the two scenarios, indicating that the distribution of rainfall and soil water storage capacity in this low-evaporation environment is sufficient for the trees to avoid significant drought stress and reduction in transpiration and growth rates. Thus, simulated WUE by trees growing in a typically well-drained *P. radiata* site may be compared to WUE by the Groenkop forest.

Table IV *Output from a 3-PG simulation of growth, water-use and WUE of southern Cape* Pinus radiata *undertaken for two soil water availability scenarios.*

	Scenario 1 (rainfall only)	Scenario 2 (rainfall plus in-flow)
Cumulative rainfall (mm)	18 400	18 400
Cumulative ET (mm)	17 223	17 915
Cumulative stem volume (m^3 ha^{-1})	345	363
WUE (m^3 stem wood m^{-3} ET from stand)	0.0020	0.0020
Wood density (kg m^{-3})	400	400
WUE (g stem wood kg^{-1} ET from stand)	0.801	0.810

4.2 Review of single-tree WUE reported for South African plantation trees

In contrast to ET measurement systems, sap flow measurement systems have been available to South African forest scientists for many years, and numerous *Eucalyptus* spp. and *Pinus patula* WUE studies have been performed in diverse plantation forests and districts (KwaMbonambi, Kruisfontein, Witklip, Mkuzi, Frankfort, Legogote). In these investigations, tree diameters and heights of sample trees were measured 12 months apart or occasionally at longer intervals. Sap flow was measured directly in the sample trees using the HPV technique. Total 12-month sap flow was then compared to the annual growth increment. Figure I illustrates the range in WUE (t stem mass t^{-1} transpiration) recorded at the various sites. Variability in WUE increases with increasing annual stem growth increment, and this may reflect poorer sampling of the larger sapwood area by the heat pulse probes. Figure II illustrates the numeric range of WUE (g stem mass per kg water transpired) recorded at all sites.
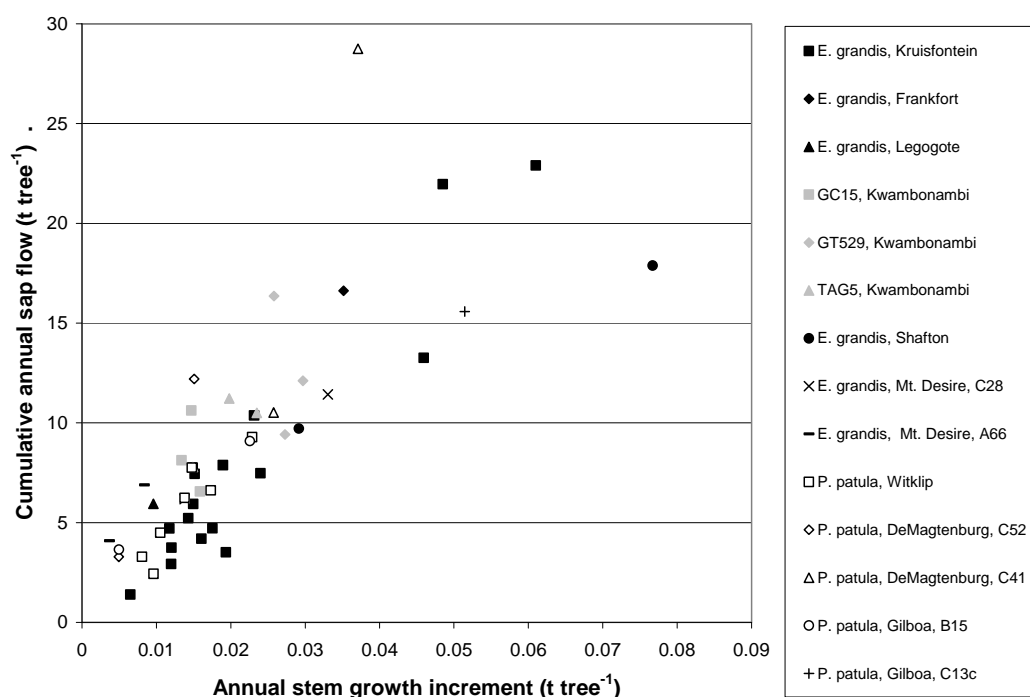
Figure I *The relation between annual stem growth increment and cumulative annual sap flow recorded in plantation-grown* Eucalyptus *and* Pinus *trees of various ages at 14 sites in KwaZulu-Natal and Mpumalanga.*
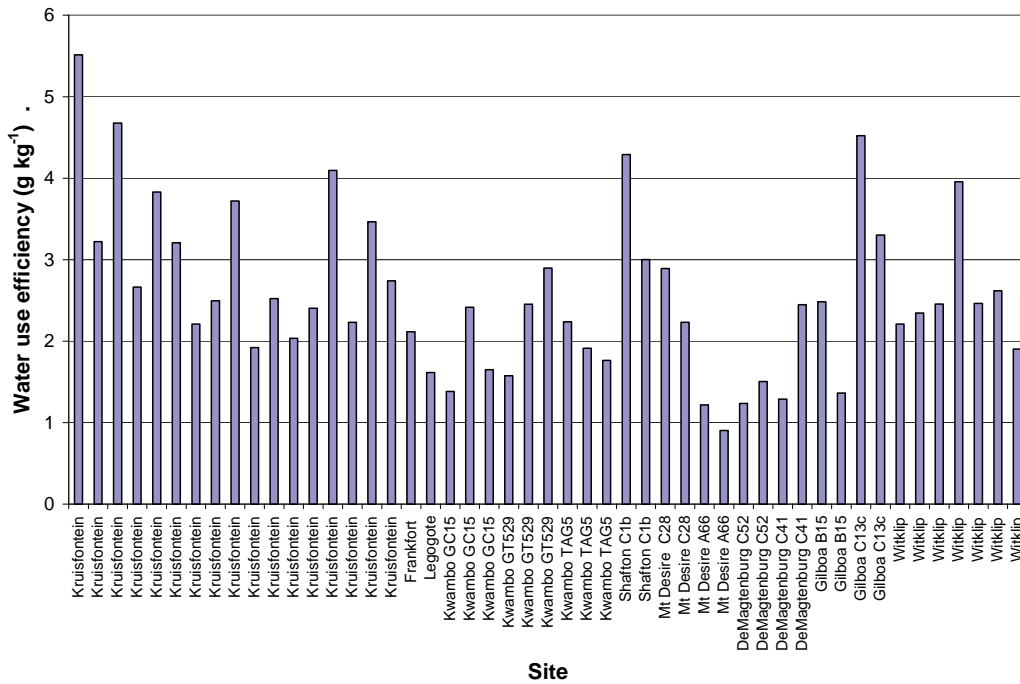
Figure II *WUE (g of utilizable stem mass per kg of water transpired) recorded in a variety of* E. grandis *and*
P. patula *trees at locations in Mpumalanga and KwaZulu-Natal.*

5. A comparison of the economic and biophysical WUE of indigenous and commercial forests in South Africa.

A chapter is devoted to exploring the use of biophysical and economic criteria for measuring the water-use efficiencies of indigenous and exotic trees in South Africa. The biophysical measure for WUE was estimated as the volume of harvested wood (timber, paper and pulp, fuelwood) per cubic meter of water. Two economic measures for WUE were estimated: 1) the present value of net returns (NPV) from the sale of harvested wood per cubic meter of water (volumetric NPV); and 2) the levelised NPV from the sale of harvested wood per cubic meter of water (levelised volumetric NPV). Numerous indigenous and exotic forests and plantations under a range of management regimes and along a rainfall gradient were investigated. Some of the main findings of the research are summarised below, along with their implications for management, policy and future research.

Firstly, the ranking of each forest/plantation in terms of its WUE varies depending on the criterion used to measure WUE. For example, based on the biophysical measure of WUE, the exotic plantations outperform the indigenous species for all the levels of mean annual precipitation tested. However, when an economic measure for WUE is used, the afro-temperate forest and the Yellowwood plantation compare reasonably favourably with the exotic plantations. In fact, when using the levelised volumetric NPV criterion, the afro-temperate forest ranks higher than all the systems investigated except one of the *Eucalyptus* plantations (Figure III). The improved performance of these systems based on economic criteria is because these systems have relatively low costs (are not intensively managed) and have substantially larger product prices. The afro-temperate forest outperforms the Yellowwood plantation because it is a mature system in equilibrium and super-mature trees are harvested annually, whereas the plantation only generates positive economic returns after 40 years. These findings reinforce the argument for conserving existing mature indigenous forests under sustainable-use management regimes.
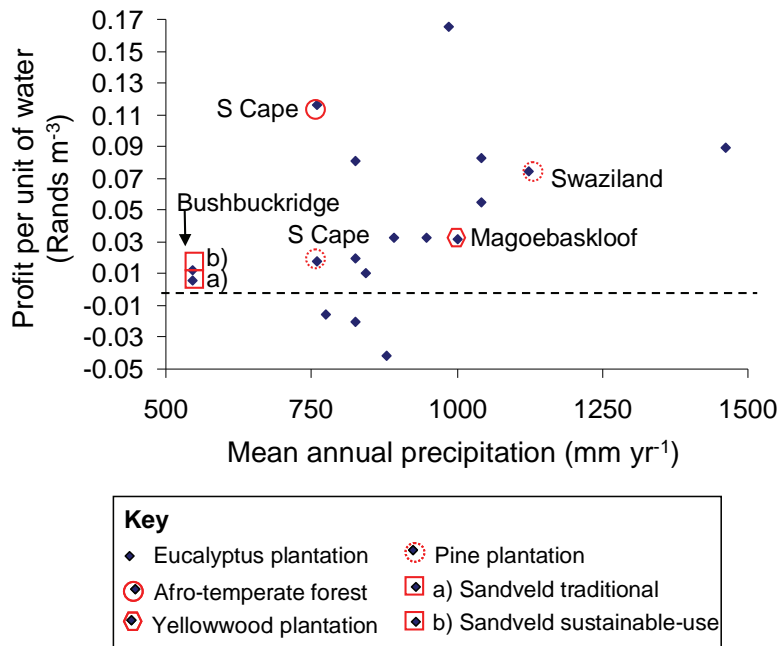
Figure III *The relationship between economic water-use efficiency (levelised Net Present Value per cubic meter of water) and mean annual precipitation along a rainfall gradient in South Africa*

Secondly, the levelised volumetric NPV gives a more accurate reflection of the relative economic WUE of the different systems than the un-levelised volumetric NPV. This is because the former method takes account of the effects of discounting on the present values of costs and benefits experienced at different times over a planning horizon. Levelising benefits and costs in this way ensures that systems with large upfront costs and long rotations – typical of stands of indigenous trees – can be compared with shorter-rotation plantations and not unfairly selected against. For example, it was found in this study that the estimated economic WUE increases by 45% and 133% when 15-year and 40-year NPVs are levelised. Evaluating tree-production systems in this way may promote their adoption more widely.

It is emphasized that the analyses performed are severely constrained by the lack of available data, and many assumptions are made. Also, the lack of economic data and the many assumptions that had to be made requires that a sensitivity analysis of some of the key variables be undertaken. This, however, could not be undertaken in this project.

6. A comparison of the WUE of six indigenous species of trees

The purpose of this phase of work was to gain a broader perspective of the WUE of a diverse selection of indigenous trees yielding potentially useful wood, and to improve our assessment of the potential economic value and hydrological impact of indigenous species grown in plantations. There is much evidence from many sources to suggest that indigenous trees generally grow far slower than commercial forestry species that are selected and bred for fast above-ground growth. To some extent, this may reflect the fact that many indigenous trees are found in established forests, where slow growth rates are at least partly caused by a high degree of competition from other trees and understorey plants, sub-optimal site conditions, and the fact that dominant trees tend to be old and therefore slow-growing. In the context of this project, it was important to examine the potential of various indigenous species for the production of useful timber, and to examine how their rates of growth and water-use compared to those of commercial plantation species.

Species were selected that:

- produce potentially valuable timber
- represent early and late successional phases of forest development
- include both fast and slow-growing species
- include evergreen and deciduous species
- occur in relatively wet and dry sites
- were relatively young
- possessed well-formed canopies
- were well exposed to sunlight.

The last three conditions were set to mimic conditions associated with the early phase of rapid growth in plantation conditions before competition and mean annual increments (MAI) peak, and before growth rates begin to slow. It was also considered important to avoid variable shading effects caused by surrounding trees. A sample tree of each species was selected for WUE measurement. *Berchemia zeyheri* and *Olea europaea* subsp. *africana* were located in the Weenen Game Reserve, while *Podocarpus falcatus*, *Pteroxylon obliquum* and *Celtis africana* were situated at the foot of the Karkloof range north of Howick. A *Trema orientalis* tree was situated in Winterskloof west of Pietermaritzburg. The HPV technique was used in each tree to record hourly sap flow rates over a full 12-month period. Stem and branch dimensions were recorded at fixed heights at the start of the monitoring period, and again at the end to permit whole-tree volume growth increments to be recorded. Data are presented in Table V. Figure IV illustrates the WUE calculated for each species, and is shown in relation to the trend described for commercial forestry species.

Table V   *Summary of WUE data for selected indigenous tree species, as calculated from a mass-based ratio of biomass increment over water-use.*

Species	1-yr Water-use (kg)	Ave. Wood Density (g cm⁻³)	Stem Mass Increment (g)	Total Mass Increment (g)	Water-use Efficiency (g stem wood / kg water transpired)	Water-use Efficiency (g total wood / kg water transpired)
Trema orientalis	8089.45	0.422	7775.7	10653.6	0.9612	1.3170
Celtis africana	8395.87	0.605	13222.1	22925.6	1.5748	2.7306
Podocarpus falcatus	6570.9	0.468	6860.6	8477.3	1.0441	1.2901
Ptaeroxylon oblilquum	4406.97	0.716	5811.7	8600.0	1.3188	1.9514
Berchemia zeyheri	6102.88	0.807	10215.5	12266.5	1.6739	2.0099
Olea europaea subsp. *africana*	5222.75	0.916	1634.2	5381.5	0.3129	1.0304
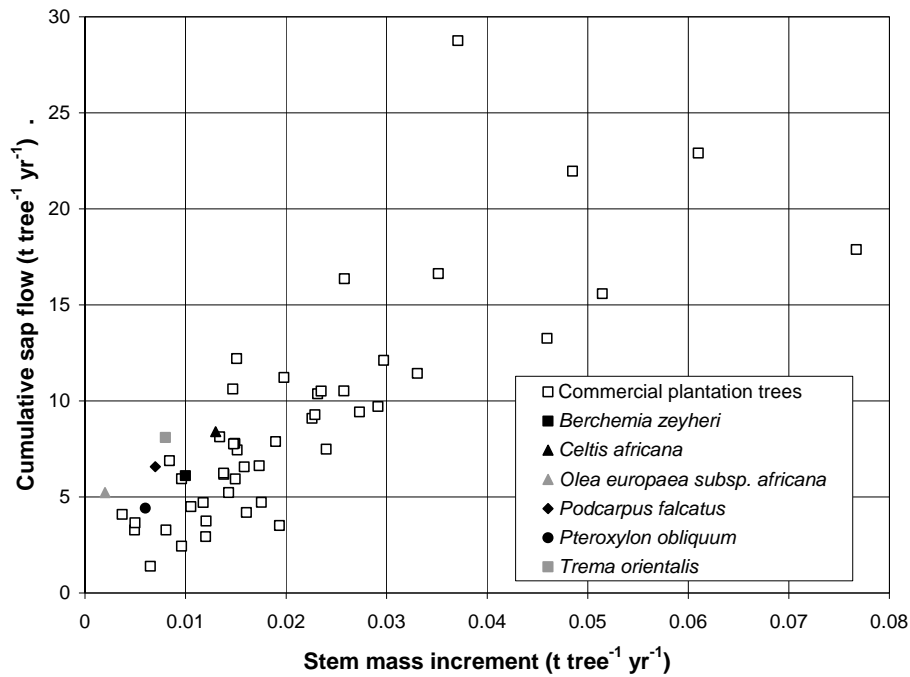
Figure IV   *A comparison of WUE measured in six indigenous species of trees, shown in relation to WUE recorded in a wide range of commercial forest trees.*

The results confirmed the slow stem growth rates that appear to be typical of indigenous tree species. In comparison to commercial forest species, the indigenous species exhibited relatively high sap flow, resulting in low WUE. However, it is clear from Figure IV that tree water-use remains considerably below that of more productive commercial species, implying that plantations of indigenous trees may remain relatively low water-users and therefore be suitable for establishment in areas where commercial forestry species are prohibited.

Many additional measurements of the structure and physiology of the sample trees were performed, and these will be described in a PhD thesis for Mark Gush that is scheduled for completion by the end of 2008.

7. Conclusions

This project has created significant opportunities for the testing of advanced micrometeorological systems under South African conditions, and much of the experience gained has been captured in a WRC report by Jarmain *et al.*, 2009. Specialist skills required to operate these systems have been developed across a wider group of researchers and students. These developments have opened up possibilities for direct measurement of WUE over a variety of forests, woodlands, savannas and plantations, and will undoubtedly improve the efficiency of water resource management.

Several models were used to gain insights into growth and evaporation processes, and for extrapolating daily ET from limited periods of measurement to whole years or longer. Different models were found to be required for different sites and species. Modelling experience during the course of the project has led to improved recognition of the important features of different forests, and the advantages and disadvantages of various models.

Economic analyses have clearly shown that volume growth is not the major criterion affecting the economic viability of forests. Timber value may be far higher for certain indigenous hardwood species than for commercial forest species. Low management costs also play a role in increasing the economic viability of new forms of forestry based on indigenous species. When the many additional benefits from indigenous

forests, woodlands, savanna and plantations are taken into account (e.g. traditional medicine, fruits, recreation and tourism), their economic viability is likely to be further enhanced.

Although the WUE of indigenous species of trees does not appear to be any higher than for commercial forest species (in fact it appears to be generally lower), transpiration remains relatively low in comparison to the more productive commercial species, particularly *Eucalyptus grandis*. Results therefore confirm the belief that indigenous species in general appear to possess an advantage over commercial species in productive sites in their lower water-use and lower streamflow reduction impact.

8. Future research

In view of the optimistic assessment for developing economically feasible new forms of forestry based on indigenous species, it is suggested that further research is warranted to establish a firmer knowledge base from which to assess the potential for such systems in different regions of the country, and in different social and economic contexts.

Four future research tasks are proposed:

- Evaluate the commercial value of wood from a comprehensive range of tree species with potential suitability for woodlot/plantation establishment in different regions of South Africa. The focus need not necessarily be limited to wood production, but could include other valuable products such as bark for traditional medicine and fruits. The outcome would be a short-list of species to consider for further evaluation.

- Broaden our knowledge of growth and water-use (WUE) over a larger number of potentially useful species (identified on the short-list) and over a much wider range of site conditions. This work is likely to remain largely based on studies of single trees (due to the scarcity of even-aged plantations of indigenous species), but where possible, trees growing in such stands should be compared to open-grown trees of the same species and age to estimate the effects of a high degree of competition from neighbouring trees. As before, measurements of stem annual growth increments and annual sap flow will be required to estimate whole-tree WUE. Sample trees will need to be systematically selected from a number of sites that cover major rainfall, temperature and soil fertility gradients over the potential forestry range. Site quality plays a large role in determining the productivity of commercial forests and the same is expected for indigenous trees.

- Investigate the possible economic profitability of indigenous plantations, especially in a rural social and economic context. This will permit setting target levels of growth rate and ET required for economic viability and acceptable hydrological impact. The value and marketing costs of wood and other potentially valuable products would need to be investigated.

- Continue the search for rapid screening criteria that may be used to conveniently identify site conditions required by each species to permit economically sustainable productivity. There are numerous possible rapid measures that could prove useful in indicating potential growth and water-use. Some of the more obvious include the following:
  - Growth ring analyses to establish mean growth rates over time
  - An index correlating short-term sap flow rates at different times of the year to annual cumulative sap flow
  - Measurements of leaf/branch/stem carbon isotope ratios to indicate whole-tree WUE
  - The use of leaf % nitrogen to indicate leaf photosynthetic capacity
  - Measurements of growth efficiency (ratio of wood production to leaf area index) as an index of vigour
  - The use of xylem anatomical structure to infer hydraulic architecture and water-use.

These would need to be measured on some or all of the trees used for WUE measurement to ensure wide applicability over a full range of growing conditions.

It is hoped that the research described in this report will further stimulate investigation of new forms of forestry based on indigenous tree species that are both economically viable and compatible with the need to minimize ET from land covers to conserve catchment water yields.

Glossary of acronyms and abbreviations

3-PG	Model (Physiological Principles in Predicting Growth)
A_{max}	Maximum assimilation rate
A-pan	A pan evaporation
AWC	Available water capacity
AWS	Automatic weather station
B	Equation parameter
BR	Bowen ratio
C	Centigrade
CENTURY	Model
cm	Centimetre
C:N	Ratio of carbon to nitrogen
C_n^2	Structure parameter of the refractive index of air
CO_2	Carbon dioxide
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
D	Air vapour pressure deficit
DBH	Diameter at breast height
e_a	Actual vapour pressure
EAI	Equivalent annual income
EC	Eddy Covariance system
e_s	Saturation vapour pressure
ET	Evapotranspiration
ET_0	Reference evapotranspiration
FAO	Food and Agriculture Organization
G	Soil heat flux density
g	grams
g_s	Stomatal conductance
g_{smax}	Maximum stomatal conductance
g_c	Canopy conductance
g_{cmax}	Maximum canopy conductance
GPP	Gross primary production
GPS	Geographic positioning system
H	Sensible heat flux
h	Height
H_2O	Water
ha	Hectare
hh	Household
HPV	Heat pulse velocity
Hz	Hertz
ICFR	Institute for Commercial Forest Research
IRGA	Infra-red gas analyser
IRM	Integrated rate methodology
I_s	Water stress index
Kg	Kilogram
Km	Kilometre
KNP	Kruger National Park
kPa	Kilopascals
LAI	Leaf area index
LAS	Large aperture scintillometer
LE	Latent heat
m	Metre
m^3	Cubic metre
MAI	Mean annual increment
MAMSL	Metres above mean sea level
MAP	Mean annual precipitation
MAT	Mean annual temperature
mm	Millimetres
mol	mole
MPa	Megapascals
MTO	Mountain to Ocean
n	Refractive index of air
NPP	Net primary production
NPV	Net present value
OB	Over-bark
PAR	Photosynthetically active radiation
PET	Potential evapotranspiration
PhD	Doctor of Philosophy
P-M	Penman-Monteith
PMS	Plant Moisture Stress
R	Global solar radiation
RMY	RM Young Sonic Anemometer
r	Radius
R_0	Equation parameter
R^2	Coefficient of determination
R_n	Net radiation
R&D	Research and development
RH	Relative humidity
s	Second
SCH	Senility criteria harvesting
SR	Surface renewal technique
SVAT	Soil Vegetation Atmosphere Transfer
SVP	Saturation vapour pressure
T	Mean daily air temperature
t	tonne
T_i	Air temperature index
T_{max}	Maximum daily temperature
T_{min}	Minimum daily temperature
TOPOG	Model
TR	Transpiration
U_2	Wind speed
UKZN	University of KwaZulu-Natal
V	Volume
VPD	Vapour pressure deficit
WAVES	Model (Water, Vegetation, Energy and Solutes)
WRC	Water Research Commission
WUE	Water-use efficiency
Yr	Year

1. INTRODUCTION

Large areas of exotic forest plantations occur in the wetter regions of South Africa. Covering approximately 1.4 million hectares, they contribute considerably to the economy, and to employment (Chamberlain *et al.*, 2005). Research has shown conclusively that evapotranspiration (ET) from these plantations is substantially higher than from the original grasslands or fynbos that were replaced by afforestation (Scott *et al.*, 2000; Dye, 1996). Thus, forest plantations have mostly reduced catchment water yields, and this has resulted in legislation limiting further afforestation in areas where water supplies are already committed. The demand for wood is growing strongly, yet the extent of the national forestry estate is essentially capped to minimise further declines in surface water resources.

South Africa contains a wealth of plant species numbering more than 24 000 (Gibbs Russell, 1984), of which approximately 1 070 species are indigenous trees belonging to 370 genera and 97 families (von Breitenbach, 1990). There is a widespread perception within South Africa that indigenous tree species, in contrast to pines, gums and wattle, are water-wise and deserve to be planted more widely in view of their more efficient use of water. This perception appears to be based on the observation that indigenous trees are generally slow growers, and the belief that growth rate and water-use are broadly linked. However, tree water-use, and the total ET from forests and woodlands, is difficult to measure, and so evidence of low water-use by indigenous trees is scarce and indirect. Versfeld and Warren (2002) raised some interesting ideas about whether indigenous species of trees could be planted in areas closed or unsuited to standard exotic forest species, to provide an income from valuable hardwood, while having a minimal impact on catchment water balances. At a WRC-funded scoping meeting held in 2002, such ideas were debated, and it was agreed that the topic of water-use efficiency (WUE) in indigenous trees should be further investigated. The measurement of water-use by trees and forests was recognized as a particular gap in our knowledge, and which therefore needed to form an important part of the new WUE research project.

2. PROJECT AIMS, RESEARCH STRATEGY AND REPORT STRUCTURE

2.1 Project aims

The overall aim of this WRC-funded project was to investigate rates of growth and water-use by a wide selection of indigenous tree production systems, and to make hydrological and economic comparisons to current commercial forestry systems. More specific aims were listed as follows:

1. Determine the pattern of water-use for stands of selected indigenous tree species of different age classes
2. Determine the rate of above-ground biomass increase
3. Compare results with existing information for currently grown commercial trees
4. Incorporate the data in a modelling framework for temporal and spatial extrapolation.

In view of the potentially broad scope of this project, the reference group provided the following guidelines:

- Select a sufficiently diverse sample of indigenous tree production systems to illustrate to what extent water-use efficiency varies with species, tree age, site conditions and climate.
- Measure whole-year patterns of water-use in each system.
- Estimate rates of above-ground biomass production, and the value of utilisable products.
- Identify suitable modelling frameworks to permit spatial and temporal extrapolation.
- Analyse economic returns from water used by the forests/trees.
- Compare with existing information for commercial forest plantations.

2.2 Research strategy

The reference group agreed at the outset that:
- Measurements of transpiration / evapotranspiration from indigenous trees should be a priority, since very little past data were available due to significant technological barriers. Historically, this has been the greatest hurdle to improving our understanding of the WUE of indigenous trees. This project afforded an important opportunity to evaluate relatively new ET measurement systems. These techniques and the data they provided are described in detail, since it was considered important to highlight their strengths and weaknesses, and also establish the credibility of the data.
- Modelling of the water-use of indigenous trees was viewed as a very important component of this project. Models are required to provide a framework for understanding the environmental and biological controls on transpiration / ET from tree canopies, and permit extrapolation of water-use predictions over time and over larger spatial scales. Recently developed micrometeorological systems that were deployed in this project are characterized by great technical complexity and high cost, and require a high degree of supervision by researchers. It was therefore not possible to run them continuously over a full year at the experimental sites, and data had to be collected during several "window periods" (generally 7-10 days) in different seasons of the year. Models are required to account for the daily and seasonal variation in water-use, and then to extrapolate predictions over a full year and also describe year-to-year variations. Models are also essential for extrapolating to different sites and forests, where important tree water-use determinants such as tree density, leaf area index and soil water availability may be different. The three indigenous tree systems researched in this project differed greatly in site conditions and in the structure and physiology of the trees, and provided a useful opportunity to investigate the performance of different models over a range of natural forest, tree plantation and savanna ecosystems.

- The WUE of indigenous and exotic forest systems should be based on the utilisable wood produced by these systems. Gush and Dye (2004) reported on the diverse benefits (fruits, traditional medicine, ferns, ecosystem services, recreational and tourism benefits, etc.) that have been exploited from indigenous tree systems in South Africa, but a complete analysis of all of these could not be accommodated within one project.
- The economic benefits of land-use systems based on indigenous species of trees should be described.

2.3   Structure of report

The major research effort went into detailed studies of the growth and water-use of trees in a southern Cape indigenous evergreen forest (Chapter 3), a plantation of indigenous *Podocarpus falcatus* in Magoebaskloof (Chapter 4), and a sandveld savanna southwest of Skukuza in the Kruger National Park (Chapter 5). These study sites were selected for their diversity of trees and growing conditions, in order to examine the problems of water-use measurement and biophysical modelling challenges, as well as demonstrate the range of tree growth rates and WUE variation under very different environmental conditions. Chapter 6 reviews available data on the WUE of commercial forest plantations. The purpose of this chapter is to provide a comparison to the WUE data measured for the three indigenous tree systems. Chapter 7 offers some insights into the selection and use of models for simulating water-use by different tree-dominated vegetation types. Chapter 8 comprises a comparison of the economic and biophysical WUE of indigenous and commercial forests in South Africa. Chapter 9 describes a further phase of research that involved a detailed comparison of individual indigenous trees belonging to six different species. The purpose of this work was to gain a broader perspective of the WUE of a diverse selection of indigenous trees yielding potentially useful wood, and to improve our assessment of the potential economic value and hydrological impact of indigenous species grown in plantations. Chapter 10 contains a general discussion of results and summarises major conclusions drawn from the study.

2.4   Definition of water-use efficiency and choice of units

A wide range of units were necessarily used to portray the data on growth, water-use and WUE (Table 2.1). This was necessary because of:
- the diversity of tree-based systems investigated in this study
- the variety of water-use measurement systems used
- the range of time period over which data are expressed
- the need to use units that are familiar to foresters
- the preference for avoiding large numbers in graphs and text.

This study has focussed on biomass production in trees, with the underlying purpose of evaluating the economic potential of wood production from new forms of forestry based on indigenous tree species. It was natural therefore to describe growth and WUE in terms of the above-ground utilizable fraction of the total tree biomass, and to ignore below-ground biomass. In the case of commercial forest plantations and natural forests, the relevant measure of above-ground biomass fraction to use is the utilizable stem, which excludes the butt that remains after felling, but includes the entire stem up to a thin-end point (often defined by a diameter of 7 cm, Bredenkamp, 2000). In the case of savanna vegetation, it is more relevant to consider the biomass of both stem and branches of trees. These are often not clearly distinguishable. In this environment, wood from both stems and branches is used for fuelwood, poles or for carving. The total above-ground woody biomass is therefore a more meaningful measure of utilizable biomass production than stem biomass alone.

The productivity of commercial forest plantations has traditionally been measured in terms of volume of timber per hectare, and so much of the comparative data from commercial forest plantations is originally expressed in this unit. Some graphs in this report portray tree growth in units of volume, since this is more easily compared to commercial plantation productivity figures available in the forestry literature. However, much of

the recent literature on WUE reports results in units of g of wood per kg of water used. This makes sense when, as in this study, species with different wood densities are compared. Tree growth and WUE results are therefore also expressed in units of mass.

Two measures of water-use are adopted in this report. The micrometeorological systems (Eddy Covariance, Bowen Ratio, Surface Renewal, and Scintillometry) measure the total evaporation (evapotranspiration) from an entire stand or patch of trees. This measure of water-use is particularly valuable for assessments of the hydrological impact of an entire plantation or forest. Results are most meaningfully reported in units of mm, since they can be readily compared to rainfall. They are generally expressed on a daily, monthly or annual time period.

Measurements of sap flow within individual sample trees were recorded at the Magoebaskloof and Sandveld savanna sites, as well as in the six indigenous species studied at Winterskloof, Karkloof and Weenen. These sap flow rates were compared to data collected in the course of past sap flow studies of *Eucalyptus* and pine trees. Hourly or daily sap flow data are described in litres per day. However, where cumulative annual sap flows are presented, this is expressed in more convenient units of tonnes (also equal to cubic metres) of sap flow per tree or per hectare. The value of such sap flow measurements is that they permit more focussed comparisons of water-use across species, and are more directly linked to the structure and physiology of the tree, and the evaporative conditions of the atmosphere. It is estimated that tree transpiration comprises 80-90% of total evapotranspiration in most South African forest environments. The balance is accounted for by evaporation from wet canopies, and from understorey plants, the forest litter layer and the soil surface.

Finally, WUE is expressed in both volumetric and mass terms as shown in Table 2.1. When applicable to a single tree, water-use is that quantity that is transpired, whereas at a whole-stand scale, water-use is equated to total evapotranspiration.

Table 2.1   A summary of units used in describing growth, water-use and water-use efficiency of trees in this report.

Process	Units	Definition	Scale
Tree growth			
Volume	$m^3\ ha^{-1}$	m^3 of utilizable stem (or stem+branch) volume	Stand
	$m^3\ tree^{-1}$	per ha or per tree	Tree
Mass	$t\ ha^{-1}$	Tonnes of utilizable stem (or stem+branch)	Stand
	$t\ tree^{-1}$	mass per ha or per tree (accounting for wood density)	Tree
Water-use			
Transpiration / sap flow	$t\ ha^{-1}$ or $m^3\ ha^{-1}$	Tonnes or m^3 water transpired per ha or per	Stand
	$t\ tree^{-1}$ or $m^3\ tree^{-1}$	tree over a year	Tree
	$l\ tree^{-1}\ day^{-1}$	Litres per tree per day	Tree
Evapotranspiration	mm	mm equivalent depth of total evapotranspiration	Stand
Water-use efficiency			
	$m^3\ m^{-3}$	m^3 utilizable wood per m^3 water transpired	Tree
	$m^3\ m^{-3}$	m^3 utilizable wood per m^3 water evapotranspired	Stand
	$g\ kg^{-1}$	g utilizable wood per kg water transpired	Tree
	$g\ kg^{-1}$	g utilizable wood per kg water evapotranspired	Stand

3. EVERGREEN INDIGENOUS MIXED FOREST, GROENKOP FOREST, SOUTHERN CAPE

The evergreen indigenous mixed forests of the southern Cape occupy approximately 60 000 ha (Geldenhuys, 1991), and represent a highly valuable asset to the region, not only because of the valuable timber that is abstracted from sections of the forest, but also for their recreational value and importance to the tourism industry in the region.

3.1 Description of site

The Groenkop forest is situated outside the town of George. It borders to the north-east of the Saasveld campus of the Nelson Mandela Metropolitan University. A 40 ha block in the north-central portion of the forest (compartments B6d, B5c and B5d) is reserved for research purposes (see Figure 3.22, later in this chapter), and many studies have been conducted there over the years (Geldenhuys, 1998). Consequently, much is known of the species composition, population dynamics, litterfall rates, vertical microclimate gradients, rainfall interception, soil structure, and other relevant features of the forest. A selection of uncited references to papers with relevance to this forest is provided in Appendix 1.

The forest is predominantly underlain by Table Mountain sandstone, which commonly includes bands of conglomerate and shale. The area receives rainfall throughout the year, but most falls between September and April. Mean annual precipitation is believed to be 860 mm. Mean daily temperatures range from 23.8 ºC in February to 18.2 ºC in August. Mean minimum temperature ranges from 19.7 ºC in February to 8.9 ºC in August. Strong dry and warm berg winds occasionally blow from the north during winter and may fan intense and destructive fires.

The forest appears to be approaching an ecological equilibrium, supporting a high standing biomass, and exhibiting a low mean annual volume increment (~ 4.2 m^3 ha^{-1} yr^{-1}) (Geldenhuys, 2005). Species composition is relatively stable, and a closed, high canopy is formed by the dominant, mature trees. Mean canopy height is estimated to be approximately 24 m. The overstorey canopy is seldom dense, and contains numerous gaps that allow sunlight to penetrate to the understorey vegetation. The leaf area index (area of leaf per unit area of ground) is judged by the authors to be roughly 2 for the overstorey, and 2 or more for the understorey. The distribution of stem size shows a strong inverse J-shaped skew, with many smaller suppressed trees dominated by relatively few larger trees that intercept the major proportion of sunlight and show fastest diameter growth. Most of the forest (including the research block) is classified by Geldenhuys (1993) as *Podocarpus latifolius – Curtisia dentata – Burchellia bubalina* platform forest. A total of 87 tree species have been recorded in the Groenkop forest. The species composition has been comprehensively described (Van Laar & Lewark 1973; Geldenhuys, 1993; Geldenhuys, 1998). The forest is extensive and reasonably flat, and therefore suitable for the use of micrometeorological techniques for measuring ET.

3.2 Evapotranspiration measurement

The start of this project coincided with the purchase by the CSIR of two new micrometeorological systems for measuring ET. This project therefore afforded a good opportunity to test the new systems under field conditions, and compare the results from the different systems. Three ET measurement systems (Eddy Covariance, Scintillometer, and Bowen Ratio) were deployed in the forest. Three 2-week field trips took place in different seasons of the year, resulting in 18 complete days of data.

3.2.1 Eddy Covariance technique

The theory behind this technique is described in Appendix 2. A telescopic mast was erected in a forest clearing (Figure 3.1, 3.2) to minimise problems with the supporting stays snagging on branches. The sensors

were attached to near the top of the 30 m mast (Figure 3.3, 3.4) which projected approximately 6 m above the forest canopy (Figure 3.5).

Figure 3.1   The forest clearing in which the mast with Eddy Covariance sensors was erected.

Figure 3.2   The telescopic mast ready for extension to its full height.

Figure 3.3   The Eddy Covariance sensors attached to the top of the telescopic mast.

Figure 3.4   The fully extended mast showing supporting stays and instruments mounted on a cross-arm near the top.

Figure 3.5   A distant view of the fully extended mast projecting above the forest canopy.

3.2.2   Bowen ratio (BR) technique.

The theory of this technique is also described in Appendix 2. This system requires air temperature and humidity to be recorded at two heights above a canopy. These sensors were attached to the telescopic mast only during the last of the three field campaigns, to provide greater perspective on the reliability of BR data.

3.2.3   Scintillometry technique.

The large aperture scintillometer (LAS) system is also described in Appendix 2. It was used to measure ET along a 3.2 km transect (see Figure 3.6) that passed over the Groenkop experimental block (Figure 3.7). The scintillometry technique allows measurement of sensible heat flux along a transect, and requires information on the remaining energy balance terms in order to estimate latent heat and evaporation. Soil heat flux is a minor component of the energy balance in such forests, but was nevertheless measured in the vicinity of the mast in the experimental block. Solar radiation was measured at an automatic weather station (Figure 3.8) situated on the northern edge of the forest, close to the scintillometer transmitter. Net radiation was measured at the top of the telescopic mast, and positioned over the forest canopy. Wind speed is also an important variable used in the analysis of the scintillometer data. Data from the weather station anemometer were used for this purpose. This instrument was mounted at a broadly similar height to the scintillometer beam.
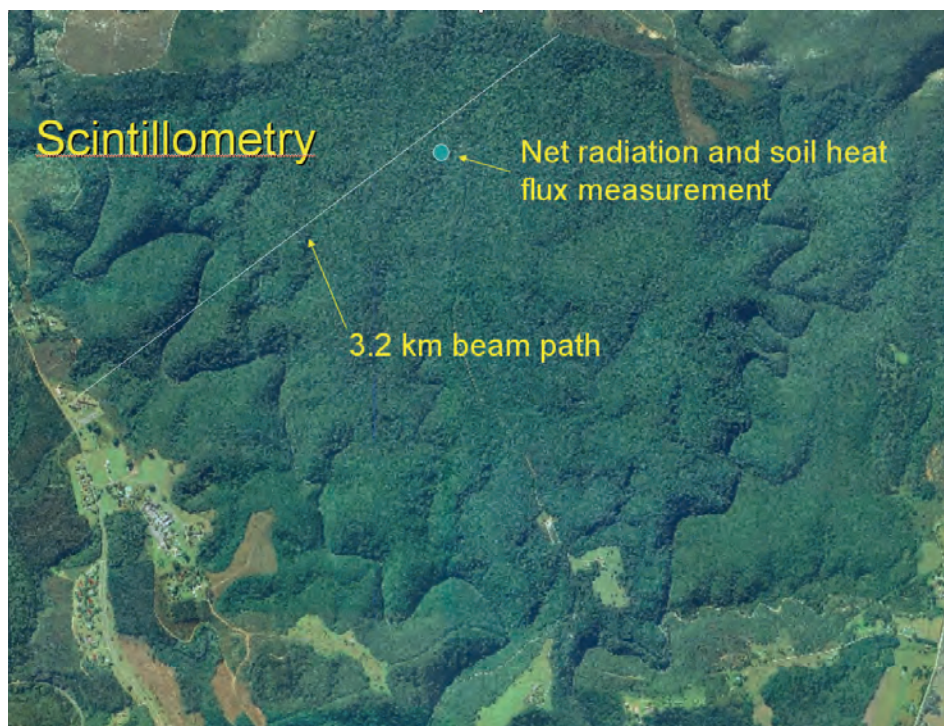
Figure 3.6   An aerial photograph of the vicinity of Saasveld campus showing the location of the scintillometer path, and the site in the experimental block where net radiation and soil heat flux measurements were performed. The Eddy Covariance and Bowen ratio systems were installed at the same location.

Figure 3.7   The LAS transmitter positioned on the upper edge of Groenkop forest and pointing towards the LAS receiver in the distant building (Research block, North campus).

Figure 3.8   An automatic weather station erected behind the LAS transmitter on the edge of the Groenkop forest.

3.2.4   Choice of ET data

Comparison of the three data sets revealed a satisfactory degree of correspondence (Figure 3.9). However, the data obtained through scintillometry were judged to be the best for modelling purposes, since it reflected average evaporative conditions over the 3 km transect, and consequently displayed a smooth rise and fall in the daily pattern of sensible and latent heat fluxes, and an absence of midday spikes that appears to be a particular feature of BR data. Furthermore, data were available over all three sample periods, and contained no periods of missing data. Both the Eddy Covariance and Bowen ratio techniques produce data that were more variable, since they were based on measured small water vapour and temperature gradients over aerodynamically turbulent tree canopies at a single point in the forest.

Figure 3.9/...

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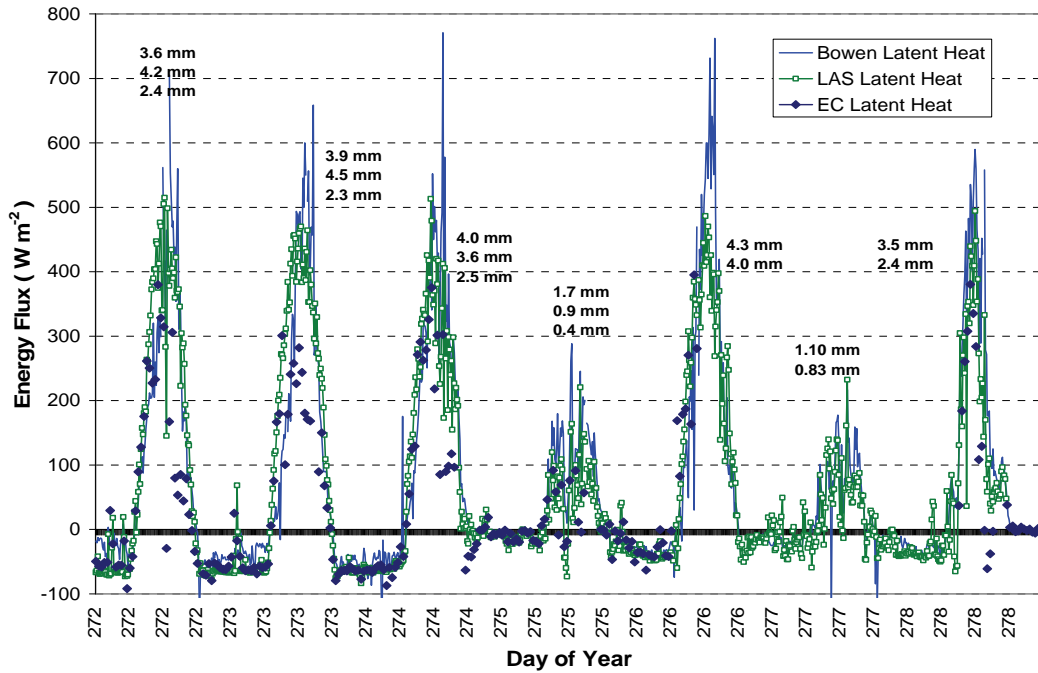
Figure 3.9   A comparison of latent heat estimates derived from the scintillometer (LAS), Eddy Covariance (EC) and the Bowen Ratio analysis during the third field visit.

3.2.5   Description of scintillometer field data

The scintillometer data collected during the February 2004 field campaign are shown in Figure 3.10.
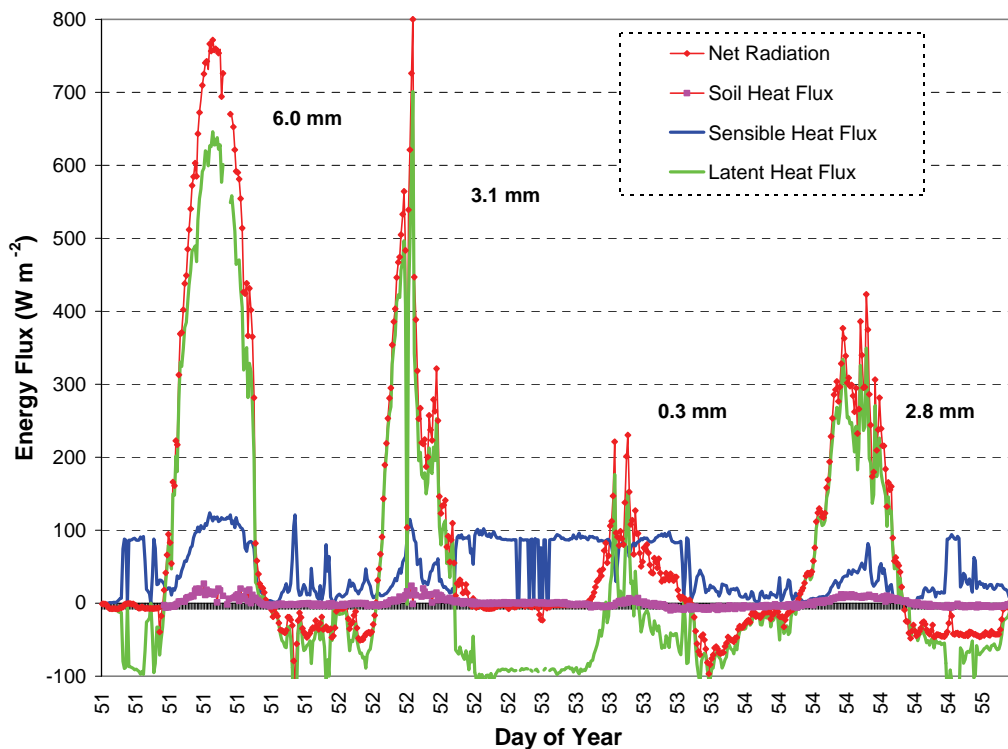
Figure 3.10   Energy balance components estimated for the Groenkop forest in February 2004.

Cloudless weather occurred on day 51, causing a smooth rise and fall in net radiation. The scintillometer estimated a similarly smooth pattern of sensible heat, peaking at less than 120 W m^{-2}. Soil heat flux was very small, peaking at less than 20 W m^{-2}. Assuming that latent heat accounted for the balance of net radiation, daily evaporation on this day was calculated to be 6.0 mm. An approaching low pressure front caused day 52

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and 53 to be cloudy and wet, greatly reducing daily evaporation rates. A partial clearing of the weather occurred on day 54, but further frontal systems brought extended rainfall in the following days.

Figure 3.11 illustrates the energy balance components recorded during the June 2004 field campaign.
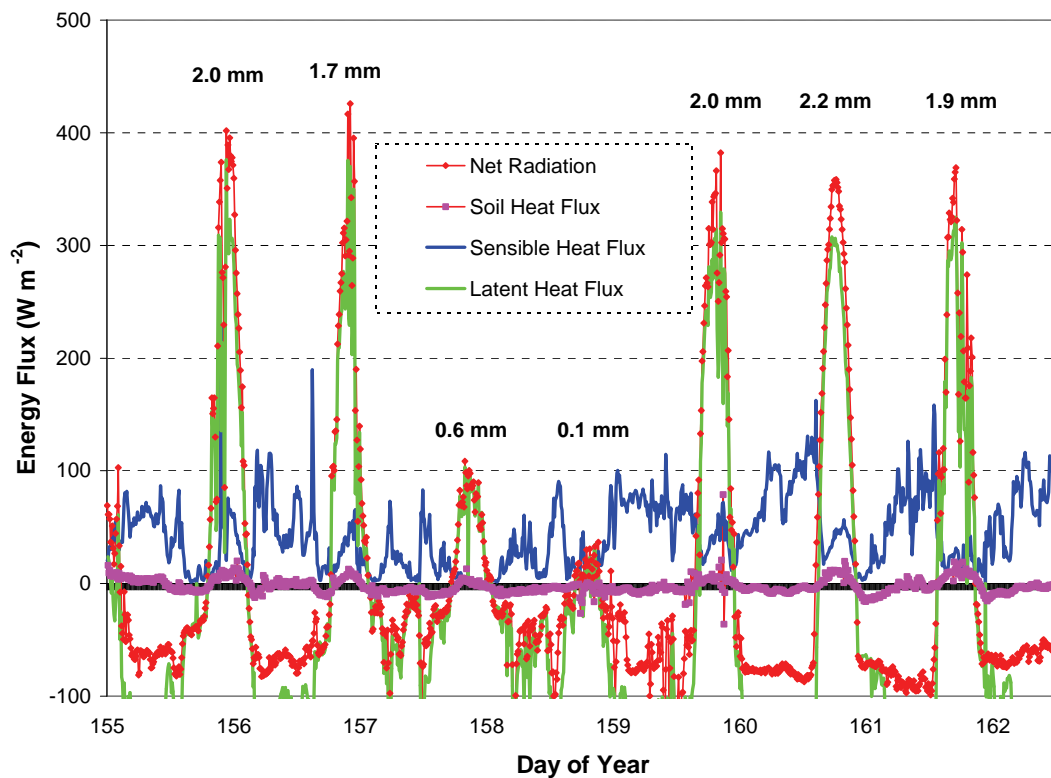
Figure 3.11 Energy balance components estimated for the Groenkop forest in June 2004.

Two days of fine to partly cloudy berg wind weather were experienced before the first two cold fronts of the winter passed over the southern Cape. Due to shorter day lengths and lower solar elevations, net radiation peaked at just over 400 W m^{-2}. A significant daytime sensible heat flux was again recorded on dry days, while soil heat flux at the forest floor was again very low. Latent heat fluxes indicate that daily evaporation at this time of year averages 2 mm.

Figure 3.12 shows the energy balance data collected during the September/October field campaign. Variable Spring weather was experienced during this period. Sensible heat on clear days peaked at around 300 W m^{-2}, leading to latent heat estimates of around 500 W m^{-2}, and daily evapotranspiration estimates of approximately 4 mm. Cloudy and humid conditions were experienced on two of the days, leading to much reduced daily ET.
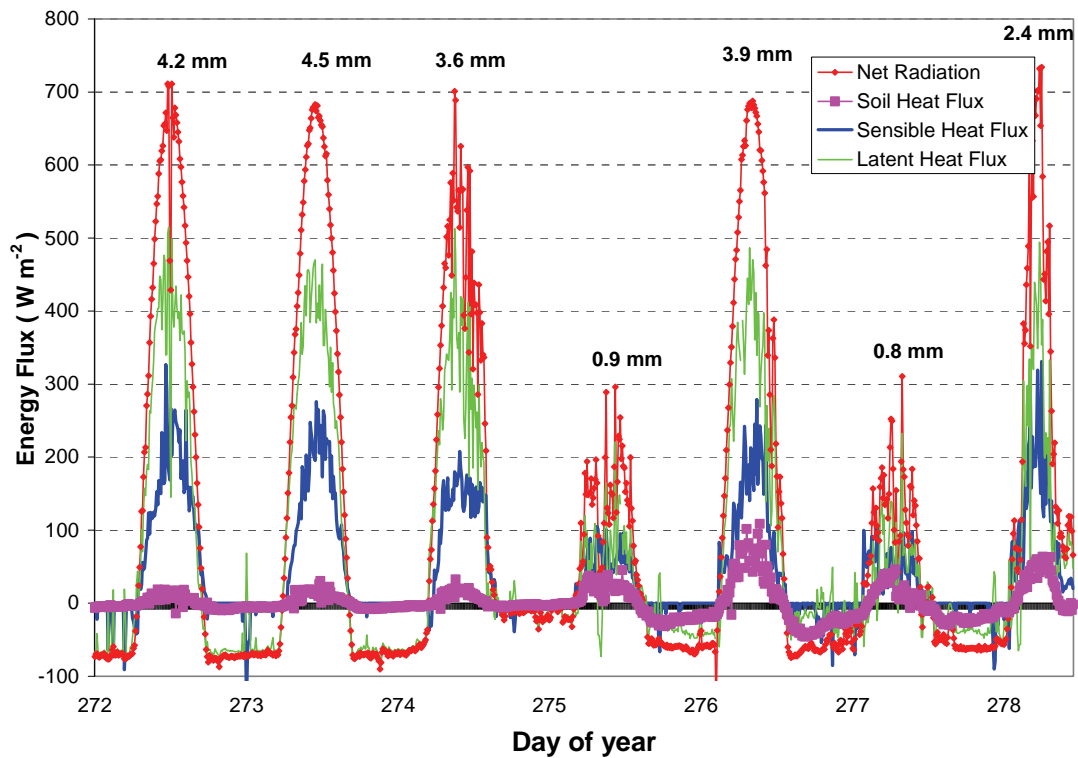
Figure 3.12   Energy balance components estimated for the Groenkop forest from 28 September to 4 October 2004.

3.3   Evapotranspiration modelling

A total of 18 complete days of scintillometer data were recorded over the three field campaigns (Figure 3.13). A wide range of evaporative conditions were encountered on these days, ranging from sunny and warm with dry berg winds, to days with wet, overcast and cool conditions. The sample days are therefore considered to be a reasonable reflection of the range of meteorological conditions experienced by the forest.
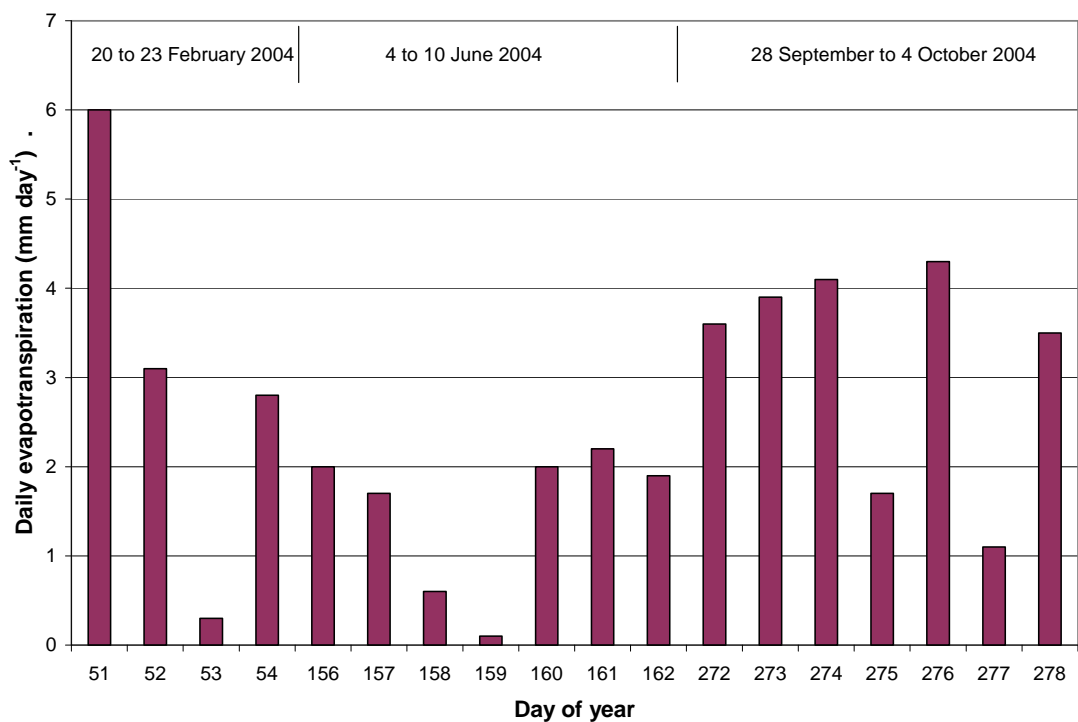
Figure 3.13   Total daily evapotranspiration recorded by the scintillometer technique over 18 days in three periods during 2004.

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A suitable model was required to extend the estimates of ET to predict the whole-year and multi-year patterns of ET.

3.3.1   FAO reference evaporation (constant surface conductance)

The water-use of indigenous forests has been estimated in the past by using A-pan coefficients (Midgley *et al.*, 1994). The modern trend is towards the use of a formula describing evaporation from a reference crop (short green grass), to indicate the "atmospheric demand" under given weather conditions. This formula (Allen *et al.*, 1998) assumes a constant surface resistance of 70 s m^{-1} (a combination of canopy stomatal conductance and aerodynamic conductance) which is a reasonable assumption for short evergreen crops, but not for tall, well-ventilated forest canopies. Additional assumptions are a crop height of 0.12 m, and an albedo of 0.23.

The reference formula is widely incorporated into modern dataloggers, and so is increasingly used as a reference index in evapotranspiration studies. It was therefore considered useful to investigate the correlation between measured daily ET and FAO reference ET.

The formula is as follows:

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

(eq. 1)

where

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature [°C],
u_2 wind speed [m s^{-1}],
e_s saturation vapour pressure [kPa],
e_a actual vapour pressure [kPa],
$e_s - e_a$ saturation vapour pressure deficit [kPa],
Δ slope vapour pressure curve [kPa °C^{-1}],
γ psychometric constant [kPa °C^{-1}].

The FAO reference ET was calculated for all 18 sample days using the standard formulae, and compared to measured scintillometer-based daily ET (Figure 3.14). This scatter plot reveals a tendency for the reference ET to underestimate measured ET under conditions of high evaporative demand, and to overestimate under conditions of low evaporative demand. The aerodynamic conductance of tall forest canopies is understood to be higher than that of short crop canopies, leading to greater stomatal control of ET by trees, and therefore a greater response to ambient VPD. It is not surprising, therefore, that the range of reference ET over the sample days is less than the range of measured ET. We conclude from this result that ET from indigenous evergreen forest is not simply a constant fraction of reference ET, but instead varies in a more complex manner to this evaporation index. Consequently, it is not recommended for use in predicting ET from indigenous evergreen forests.
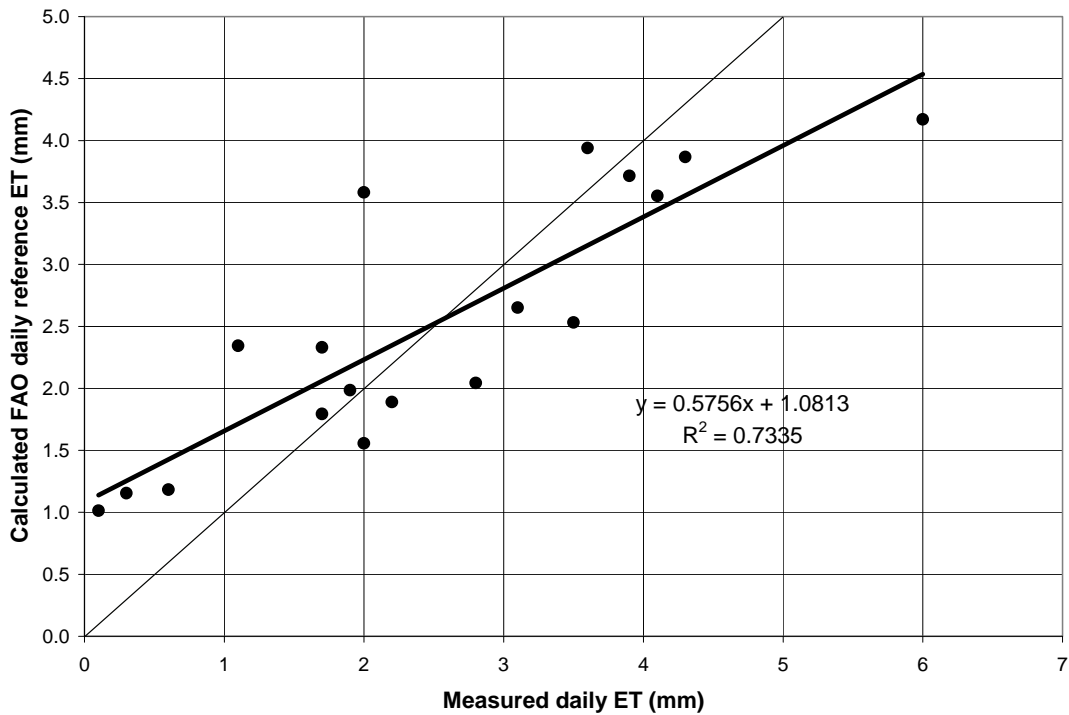
Figure 3.14 A comparison of measured daily ET and calculated daily reference ET. A linear regression line is compared to a 1:1 line.

3.3.2 Penman-Monteith equation (variable canopy conductance)

It was decided to test a more realistic version of the P-M equation, in which canopy conductance varies in response primarily to ambient vapour pressure deficit (VPD) and solar radiation. This approach includes a model of canopy conductance (g_c) reported by Jarvis (1976) and Stewart (1988). Such models are efficient in identifying the major environmental constraints on daily ET.

Canopy conductance (g_c) describes the control on transpiration rate that plants exert through stomatal control over the rate of water loss through their leaf stomata. This is in most cases the dominant control on transpiration rates from trees. Jarvis (1976) and Stewart (1988) proposed the following model:

$$g_c = g_{cmax} . f1(R,D) . f2(LAI) . f3(I_s) . f4(T_i) \qquad \text{(eq. 2)}$$

where

g_{cmax}	=	maximum g_c
R	=	global radiation (W m^{-2})
D	=	air vapour pressure deficit (kPa)
LAI	=	leaf area index
I_s	=	water stress index
T_i	=	air temperature index

Functions 1-4 all range from 0-1, and are multiplicative in their effects on reducing the maximum g_c. No interactions are assumed.

The data from this site suggest that solar radiation and air VPD are strong controls on daily ET, as is commonly found in forests elsewhere. There is a strong correlation between mean day-time solar radiation and daily ET (Figure 3.15). As is commonly the case, solar radiation is also correlated (non-linearly) to mean

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daylight vapour pressure deficit (VPD) of the air (Figure 3.16), which is also a major control on evaporation rates from plants.
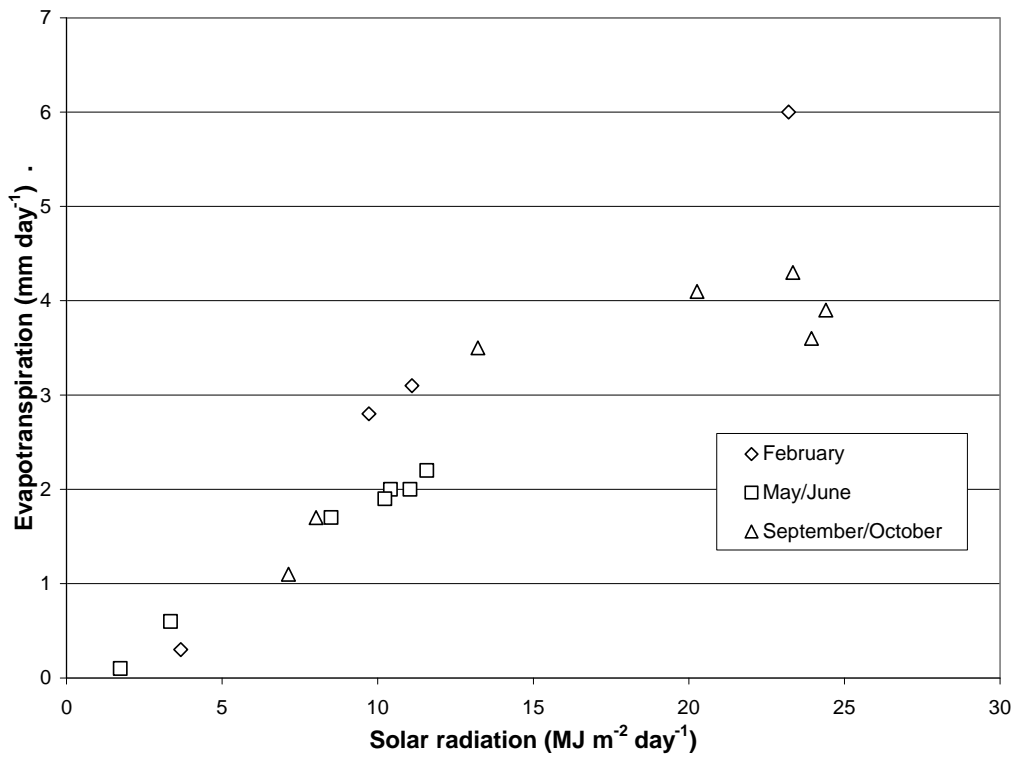
Figure 3.15   The relation between daily solar radiation and total daily evapotranspiration over 18 sample days in 2004.
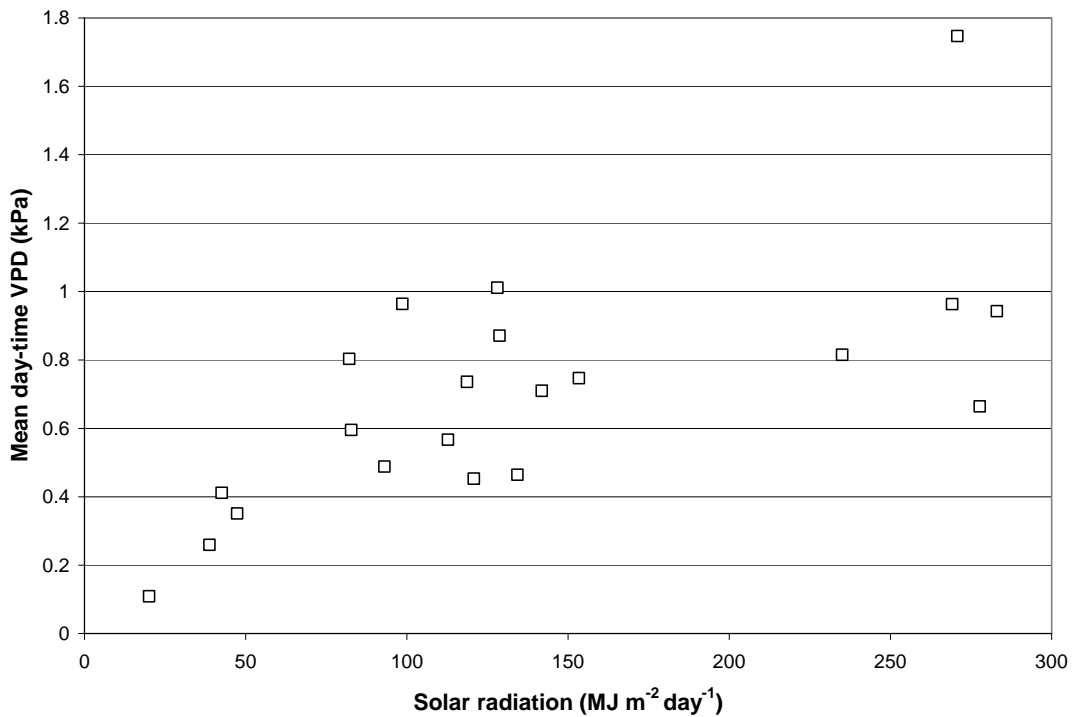
Figure 3.16   The relation between total daily solar radiation and mean daytime air vapour pressure deficit on 18 sample days.

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Since the available data from 18 days are too few to adequately describe all these functions, it was decided to evaluate generic forest functions developed by Granier (2000), and which have been found to fit 21 widely varying forests from tropical, temperate and boreal regions. It was hypothesized that g_c and daily ET on all sample days was not significantly reduced by soil water deficits, temperature extremes, or by marked changes in the leaf area index of the forest. The assumption was therefore that the forest possesses a high and relatively constant leaf area index, and that daily evapotranspiration may largely be explained by variation in total daily solar radiation and mean day-time air VPD. This assumption is supported by the findings of many other studies (e.g. Jarvis *et al.*, 1981; Leuning, 1995; Granier *et al.*, 2000).

Granier (2000) proposed the following Lohammar-type canopy conductance equation:

$$g_c = g_{cmax} * R/(R+R_0) * (1/(1+b*D)) \qquad \text{(eq. 3)}$$

where

g_{cmax}	=	a maximum canopy conductance (m s^{-1}) (4.047)
R	=	solar radiation (W m^{-2})
R_0	=	a parameter that alters the magnitude and shape of the curve (100)
B	=	a coefficient (2.0615)
D	=	air vapour pressure deficit (kPa)

The values for g_{cmax} were increased to 6 to get an improved fit. Values for the parameters R_0 and b remained unaltered. Daily g_c was then calculated and input to the P-M equation to estimate daily ET. Figure 4.17 illustrates the substantially better fit between model-predicted daily ET, and the measured ET over the 18 sample days. The good fit (judged by a high R^2, a slope close to 1 and an intercept close to 0) and consistency of sample days recorded during all three sample periods suggests that ET was not significantly limited by soil water deficits during any of the three sample periods.
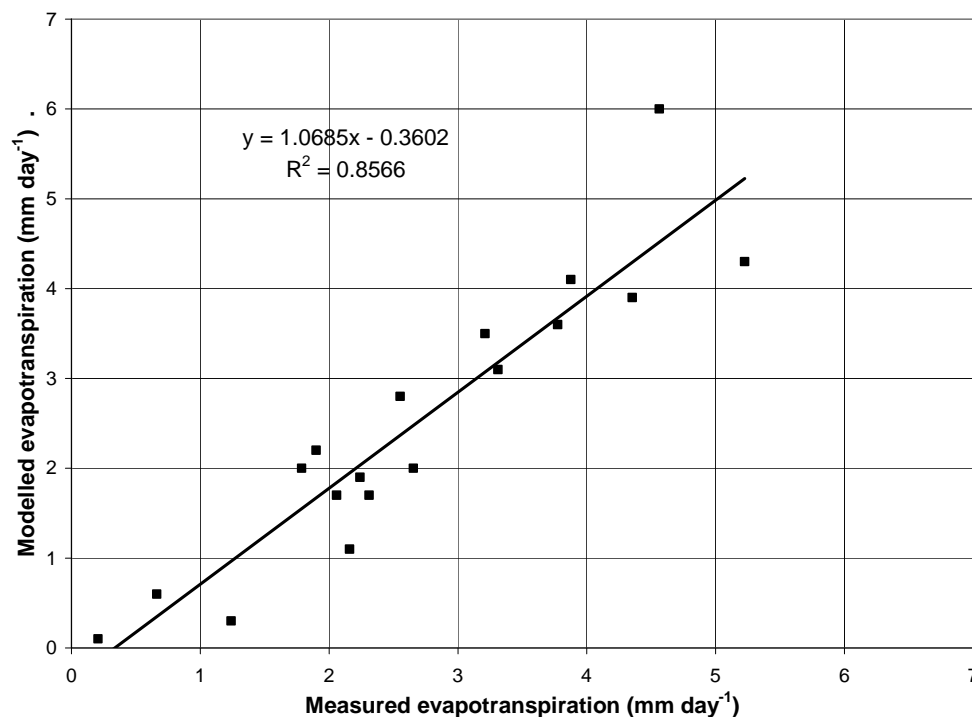
Figure 3.17   A comparison of modelled to observed daily ET over the 18 sample days.

The model was then used to predict daily ET over a five year period (arbitrarily chosen as 1980 to 1984) to illustrate the seasonal pattern of daily ET. Daily rainfall and daily maximum and minimum temperatures were obtained from databases described by Lynch (2003) and Schulze and Maharaj (2004) respectively. The temperature data were used to estimate daily solar radiation using the Bristow-Campbell equation. Mean

daylight VPD was also estimated from daily maximum and minimum temperatures using a commonly used equation by modellers (SVP$_{Tmax}$ – SVP$_{Tmin}$)/2, together with a further empirical polynomial correction to account for the increasingly poor fit as daily VPD increases (Dye, 2001). The 5-year simulation is shown in Figure 3.18.
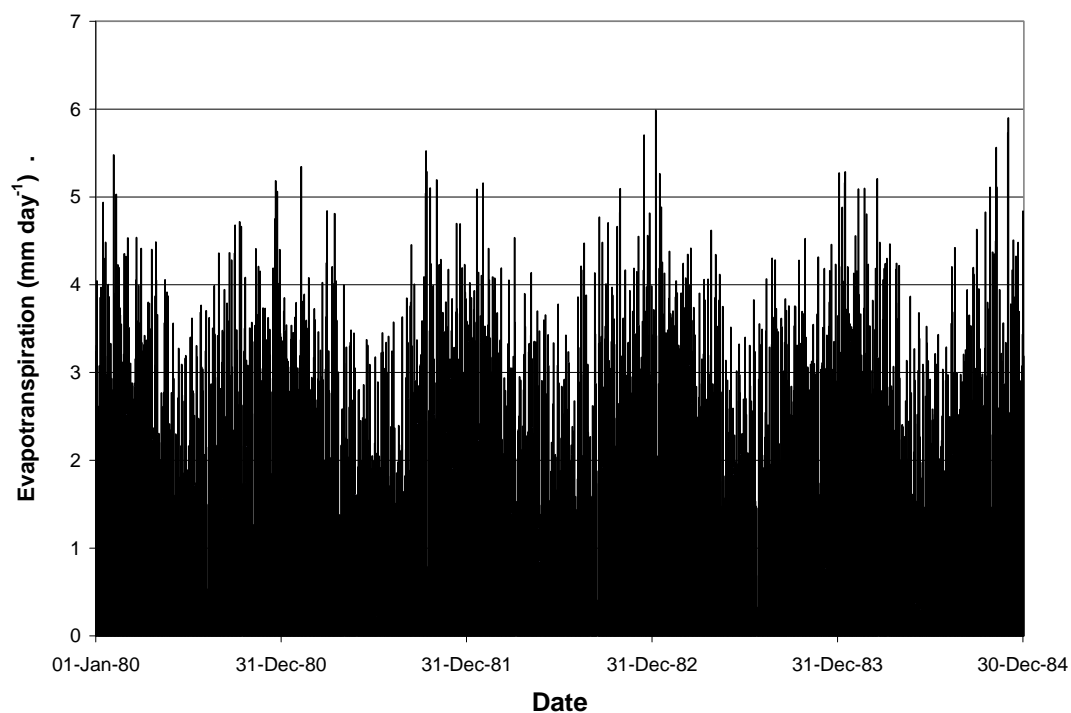
Figure 3.1   The pattern of daily ET simulated over a five-year period from 1980 to 1984.

Finally, the model was used to simulate 21 years of ET to examine the predicted total annual ET of the forest (Table 3.1).

Table 3.1   A comparison of simulated annual ET to annual rainfall recorded at the Saasveld campus, from 1970 to 1990.

Year	ET (mm)	Rainfall (mm)	Difference (mm)
1970	948.5	805.1	143.4
1971	872.9	1 027.0	-154.1
1972	969.9	685.6	284.3
1973	956.5	633.9	322.6
1974	927.0	631.0	296.0
1975	915.1	797.2	117.9
1976	916.7	842.9	73.8
1977	914.4	795.8	118.6
1978	943.1	595.7	347.4
1979	934.6	702.2	232.4
1980	955.5	678.3	277.2
1981	894.6	1 484.8	-590.3
1982	939.1	802.0	137.1
1983	942.9	811.2	131.7
1984	960.9	599.3	361.6
1985	947.8	779.7	168.1
1986	964.1	669.4	294.7
1987	950.6	678.2	272.4

Year	ET (mm)	Rainfall (mm)	Difference (mm)
1988	914.1	635.3	278.8
1989	916.4	721.4	195.0
1990	914.9	619.3	295.6
Average	933.3	761.7	171.6

It is evident that annual rainfall measured on the campus is less than the simulated annual ET over the Groenkop forest. This largely reflects the higher rainfall falling over the forest than over the campus weather station. The forest is at a slightly higher elevation than the rainfall station, and is also closer to the mountain. Lübbe and Versfeld (1991) estimated that the annual rainfall at the experimental site in the centre of the Groenkop forest is 850 mm, while another estimate reported in a DWAF-sponsored brochure on the forest is 860 mm. The calculated long-term difference between mean annual rainfall and mean annual ET is therefore only 73-83 mm.

Three possible additional factors should be borne in mind in comparing modelled ET to rainfall. Firstly, there is evidence of the importance of fog drip in augmenting the store of soil water in the forest. Phillips (1931) recorded moisture interception from mist in the indigenous forests of the southern Cape. Over a 1-year period, rainfall interception was monitored at a site at an altitude of 518 m. A 30 cm high wire mesh frame was mounted above a rain gauge, and supported four *Podocarpus latifolius* branches, each with approximately 30 leaves. A control gauge without overhanging branches measured a 1 321 mm catch, while the gauge with branches measured 2 401 mm (an increase of 81.7%).

Secondly, there is the possibility of the forest trees experiencing some degree of soil water deficit and reduced ET during dry spells. Although such limiting soil water deficits appear not to have occurred during the 2004 sample days, it is possible that some degree of ET reduction could have occurred at other periods of the year. It is very likely that such conditions do occur at times during years of low rainfall.

Thirdly, soil characteristics associated with the moist high forest of the research site are described by Geldenhuys and Theron (1994). According to these authors, medium-moist forest is characterised by 35-45 cm sandy loam topsoil which overlies clay subsoil. This clay is very dense and lateral movement of water occurs above this layer. A soil pit situated approximately 100 m south of the experimental site has been observed to be always full of water up to the upper level of the pronounced clay layer (Coert Geldenhuys, pers. comm.). This suggests the presence of a lateral flux of water across the site, since the trees would otherwise rapidly deplete the available soil water stored in the relatively shallow soil profiles of the area during spells of dry weather. Additional water could possibly originate on the higher mountain slopes, where lateral flow of water can be expected to be promoted by higher rainfall, cooler temperatures, higher air humidity, more frequent mist events, steeper slopes, and a covering of Fynbos vegetation which is periodically burnt. Moist evergreen indigenous forests mostly occur in riparian situations and other localities where a degree of soil water augmentation is likely.

3.3.3   The WAVES ecohydrological model

There are many detailed hydrological models that are potentially capable of revealing more insights into forest water balances, and better estimates of ET. The WAVES ecohydrological model (**Wa**ter, **V**egetation, **E**nergy, **S**olute) is one such model which was chosen to evaluate its usefulness in predicting the water balance of the Groenkop forest. Major strengths of this model include the following:

- WAVES comprehensively models the daily water balance of a site, taking into account rainfall, canopy rainfall interception, overland flow and infiltration into the soil, redistribution within the soil profile, deep drainage below the rooting zone, evaporation from the soil surface, uptake by plant roots (overstorey and understorey), and transpiration from the plant canopies (one or two). The treatment of soil water dynamics is particularly detailed. The hydrological properties of soil texture classes are modelled according to the Broadbridge-White model, and may be adjusted by running a subsidiary programme (BWSOIL.EXE). The influence of shallow water tables within the rooting zone

may be simulated, and is an important feature when modelling riparian vegetation. Slow declines in water table levels resulting from lateral drainage may be simulated.

- The effects of site, aspect and slope on the interception of solar radiation by plant canopies are modelled. This is an important feature for simulations in areas of heterogeneous topography, since the interception of solar radiation is closely correlated to gross primary production. Solar radiation also governs net radiation at a site, which is an important controlling factor in the rate of evapotranspiration.

- WAVES is relatively simple by process-based model standards. Required weather input data are minimal. Daily maximum and minimum temperatures and daily rainfall are the minimum input requirements.

- WAVES allows simulation of separate overstorey and understorey canopy layers.

WAVES was developed by the Land and Water CRC of the CSIRO in Canberra, Australia, and arose out of earlier work on the TOPOG model. It simulates energy, water, carbon and solute balances on a daily time step within a one-dimensional soil-plant-atmosphere system (Dawes and Short, 1993: Zhang *et al.*, 1996). It is well suited to investigations of hydrological and ecological responses to changes in land management and climatic variation. The model is available free of charge from http://www.clw.csiro.au/products/waves/. A detailed description is available from a comprehensive manual obtainable at the web site. It is also described by Slavich *et al.* (1998), Hatton *et al.* (1995), Zhang *et al.* (1999) and Zhang *et al.* (1996).

The WAVES model was set up to model daily ET from the Groenkop indigenous forest. Parameter values were mostly estimated from information reported in the scientific literature (Appendix 3). Separate overstorey and understorey canopy layers were simulated in view of the distinct floral and structural differences between them. The initial leaf area index at the start of each model run is an important feature of the forest, for which no field measurement could be obtained. Destructive sampling of tree leaf area was not feasible, and the LI-COR Canopy Analyser was of limited use, owing to the high proportion of stem and branch contributing to light interception. The overstorey LAI was judged to be approximately 2 – 2.5, while the understorey LAI was judged to be approximately 2. Initial live leaf mass was adjusted for each canopy layer to return an LAI of approximately 2, assuming a specific leaf area (based on mass of carbon and not total dry weight) of 18 (Midgley *et al.*, 1995). A constant fraction (0.75) of net primary production was allocated to above-ground biomass. An important parameter in WAVES which determines both growth rate and transpiration rate is the maximum assimilation rate. This parameter determines the rate of CO_2 uptake as well as the rate of transpiration from the leaves. This parameter was allocated a low value (0.01 kg carbon m^{-2} day^{-1}) in view of the following information:

- The mean annual volume increment of the forest is very low (4.2 m^3 ha^{-1} yr^{-1}).
- Leaf stomatal conductances recorded with a porometer on sample trees of *Podocarpus henkelii*, *Nuxia floribunda* and *Rapanea melanophloeos* on the grounds of the Saasveld campus were found to be low in comparison to exotic tree species such as *Eucalyptus grandis* and *Acacia melanoxylon* (Figure 3.19).
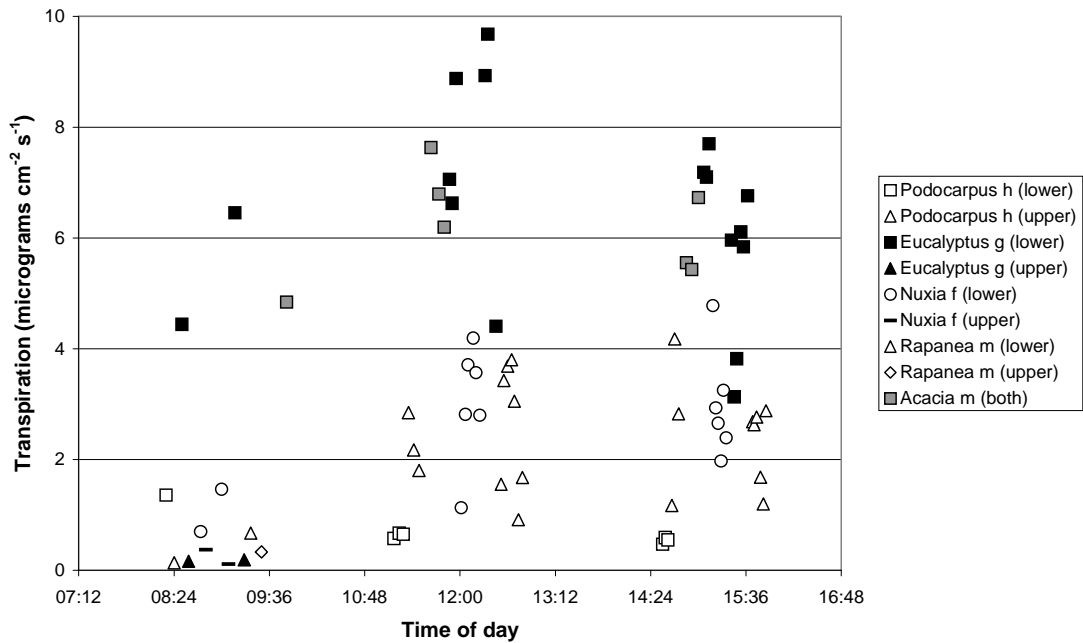
Figure 3.19 A comparison of leaf conductance rates recorded with a porometer for selected indigenous and exotic trees situated on the Saasveld campus grounds. Species measured were Podocarpus henkelii, Eucalyptus grandis, Nuxia floribunda, Rapanea melanophloeos *and* Acacia melanoxylon.

A rainfall interception parameter was adjusted to return an annual interception loss of 27 % (Lübbe and Versfeld, 1991). The bedrock below the subsoil was assumed to be impermeable. A slope of 20% and an aspect of 180° were judged to be typical of the Groenkop forest along the scintillometer beam path. Observations of root systems reported by Kotze and Geldenhuys (1992) confirm a concentration of roots in the upper 300 mm of soil (often set by the presence of a shallow water table), and a maximum rooting depth varying from 700 mm to 1 400 mm. The remaining vegetation parameters were assigned values according to the best available data, and constrained within limits recommended in the WAVES manual.

WAVES was run to simulate the period that included the 18 sample days. A comparison of modelled to measured daily ET is shown in Figure 3.20, while the overall pattern of modelled daily ET is illustrated in Figure 3.21.

Figure 3.20/...
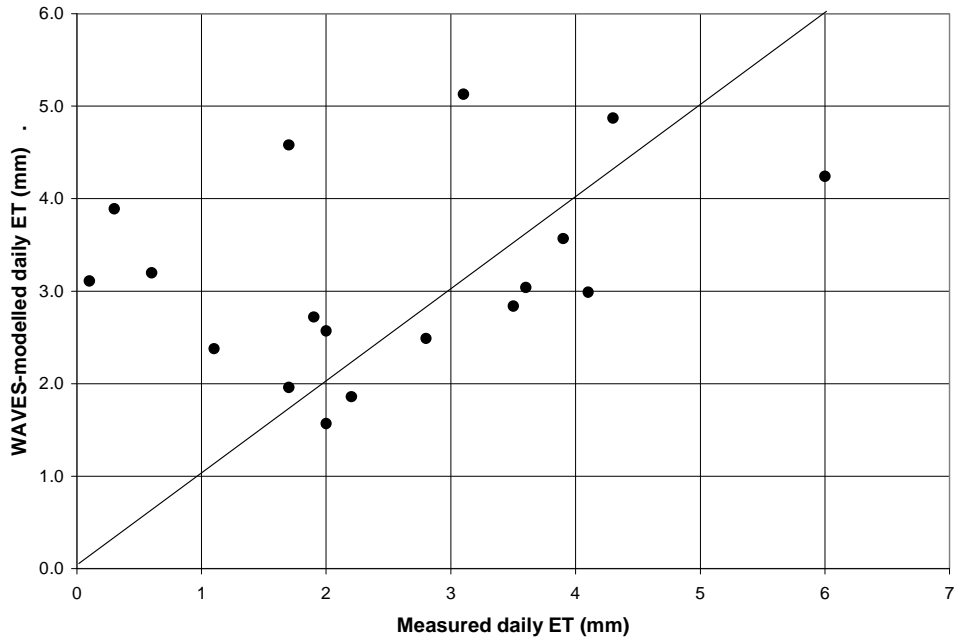
Figure 3.20   Measured daily ET in relation to modelled daily ET using the WAVES model.
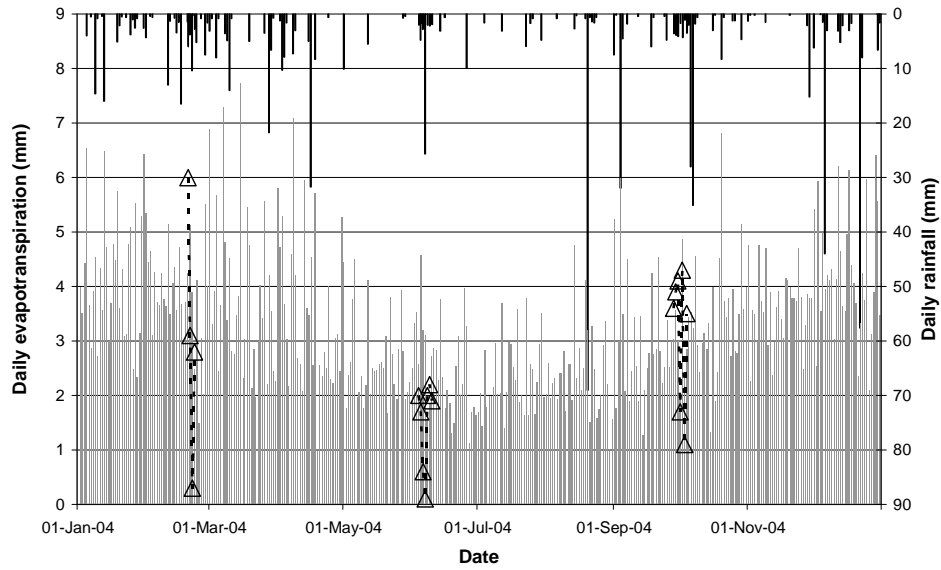
Figure 3.21   WAVES-simulated daily ET over 2004, shown in relation to measured daily ET (scintillometry) during the three measurement periods.

Modelled ET over the 18 sample days overestimated measured ET by 45 mm, representing a 27% overestimation. Overestimation is particularly obvious on days with low measured ET, and this is also clear from Figure 3.21. The fit to measured data is poorer than that of the simpler Penman-Monteith model. We concluded that until more information becomes available to parameterise the WAVES model more realistically, the Penman-Monteith model with Granier canopy conductance sub-model should be the preferred model for estimating ET from moist evergreen indigenous forests experiencing no soil water deficits. Where soil water deficits cause significant reductions in ET, the model would need to include a further term describing this limitation on ET. A suitable function is described by Granier *et al.* (2000). It would be a valuable research topic to obtain suitable remote sensing imagery of southern Cape indigenous forests for different seasons of the year and in different years, in order to investigate the spatial and temporal occurrence of water stress.

3.4   *Forest productivity estimation*

The following section is based on a report by Geldenhuys (2005).

3.4.1   Introduction

In the mixed evergreen forests, a tree grows in height until it reaches the canopy. Thereafter the height growth stabilizes. Diameter growth is initially very slow until the tree reaches the canopy. Thereafter the diameter growth increases. Geldenhuys (1998) categorized trees into four categories, depending on their position within the forest canopy: 1 = understorey, no direct light; 2 = lower canopy, some overhead light; 3 = canopy, full overhead light; and 4 = emergents. Growth increased from trees in category 1 to category 4. In the management of the forests in the Southern Cape, stand growing stock is rather calculated in basal area, i.e. the total of the cross-sectional area at breast height of all individual stems. Stand timber volume is seldom calculated, but volume is only calculated for individual harvested stems. However, the relationship between stem diameter and utilizable timber volume was calculated (Geldenhuys & Van Laar 1975). Tree height added very little to the variation in estimated stem volume.

In the study of water-use by indigenous trees, it was necessary to compare the stand growth of natural forest with that of plantation stands of *Pinus radiata*. The purpose of this report is to document how the mean annual increment of natural forest in the Groenkop Forest Study Site can be estimated from available data.

3.4.2   Methods

3.4.2.1   *Study site*

The Groenkop Forest Study Site is located at approximately 33°56,5′S, 22°33′E, and lies between 190 and 300 m above mean sea level (Geldenhuys 1998; Figure 3.22). The Groenkop forest lies at the western end of the belt of mixed evergreen forest on the coastal platform of the southern Cape, classified as Coastal Platform Forest (Geldenhuys 1993) within the Southern Cape Afrotemperate Forest (Von Maltitz, 2003). The area lies immediately below the Peninsula quartzitic sandstones of the mountain foothills. The northern portion of the study area occurs on quartzitic schists and the southern portion on mica schists. Mean annual rainfall at the Saasveld Meteorological Station 2.5 km away and of similar altitude is 860 mm, and the rain is distributed throughout the year.   Rainfall peaks during autumn (March) and early summer (October-November). Mean maximum temperature of the hottest month and minimum temperature of the coldest month for the eight years since 1977 were 20.8°C and 12.2°C.

Immediately below the foothill zone (area between lines b and c, Figure 3.22) the forest is dominated by multi-stemmed *Platylophus trifoliatus*, scattered *Ocotea bullata* and *Ilex mitis*, associated with the main species of the platform forest. A shrub layer is absent but a dense fern layer of *Rumohra adiantiformis* exists.
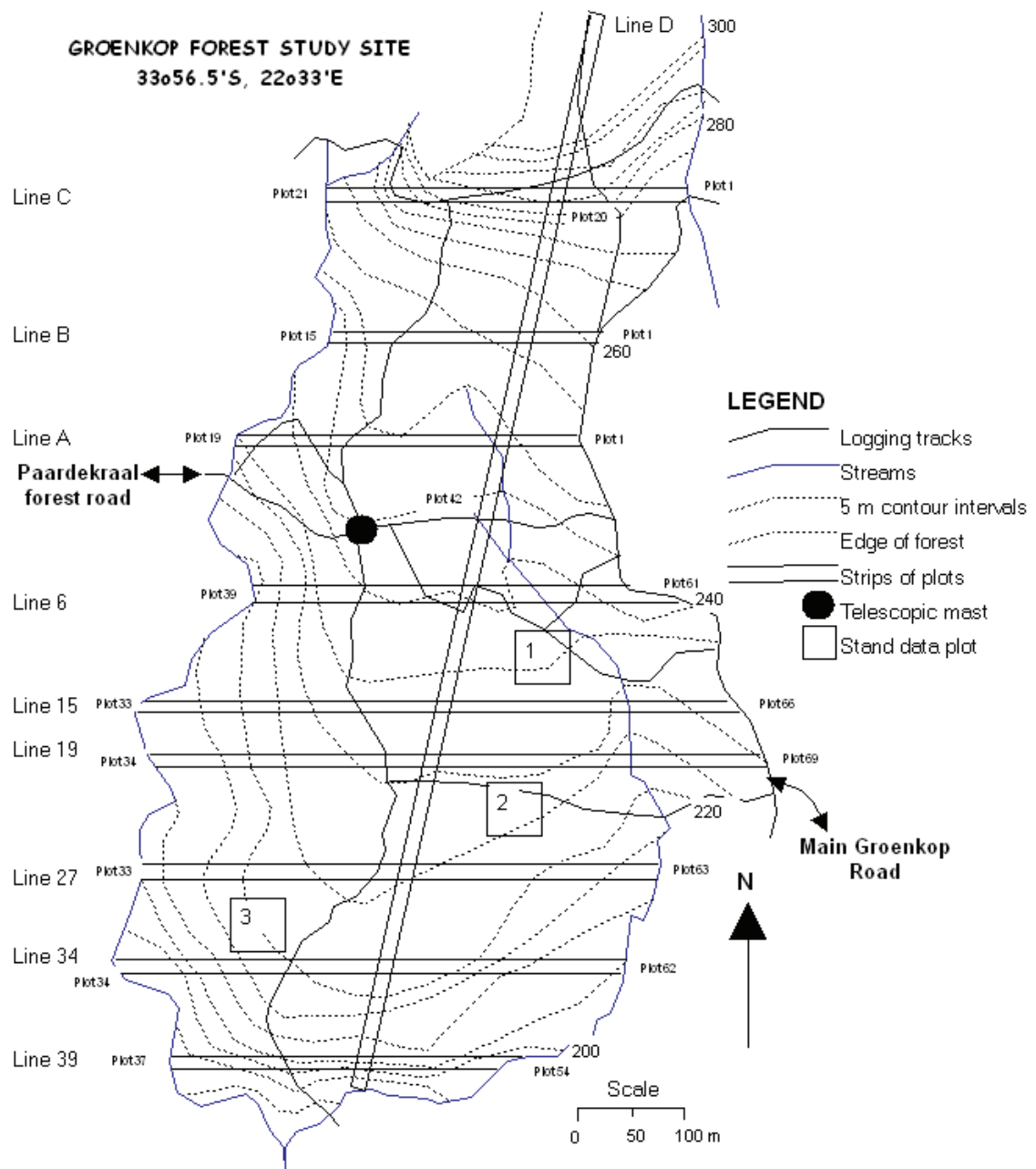
Figure 3.22   Groenkop Forest Study Site, showing location of the telescopic mast for collection various data related to water-use by natural forest, and the three sample plots for calculation of mean annual increment.

The fine textured topsoil is only 250 mm deep and overlies a leached horizon of 200 mm over a deep ferri-humic horizon (Lamotte soil form). To the south this forest grades into the typical coastal platform forest dominated by *Olea capensis* subsp. m*acrocarpa, Podocarpus latifolius* and *Pterocelastrus tricuspidatus* as the main canopy species amongst a range of other species. *Trichocladus crinitus* forms a dense shrub layer which varies in height from site to site. The topsoil (350 to 450 mm) overlies poorly-drained clayey subsoil with indications of a fluctuating water table on level terrain (Kroonstad and Westleigh soil forms) and better drained sub-soils on the slopes (Clovelly soil form).

3.4.2.2   *Stand and growth data*

A full inventory of all trees ≥10 cm diameter at breast height (DBH) was performed in 1972, on permanently marked contiguous plots of 14.3 m x 14.3 m (Van Laar & Lewark 1973), in the area south of the Paardekraal Road. Some lines of the plots were used in a forest growth study and the trees on these plots, down to 5 cm DBH, were marked with a number and measuring line at approximately breast height, for calculating growth, ingrowth and mortality (Geldenhuys 1998). These lines are indicated in Figure 3.22.

Three plots were random selected from the area south of the Paardekraal Road, to form the north-western plot of a stand plot of 5 x 5 plots. The requirement was that the stand plot should not cover any of the lines of plots used for the growth study. Each stand plot was 0.5 ha in size. The tree data for each group of 25 plots were extracted from the data of the full survey of 1972.

Tree data on species, DBH, stem length (to the start of the main branches) and diameter at mid stem length, that were collected for developing local volume equations in six tree groups (Van Laar & Geldenhuys 1975), were used to develop volume equations for each of the species. The volume equations were applied to each tree in each of the selected stand plots to calculate the stand timber volume during year 0 and year 10. The DBH of each tree at year 10 was based on the following tree growth equations developed by Geldenhuys (1998):

Species Growth Group 1: Less common, fast growing canopy species, often considered as early regrowth species: *Podocarpus falcatus, Ocotea bullata, Rapanea melanophloeos &, Olinia ventosaa capensis.* The equation is: Diameter growth cm per 10 years = 0.16985 + 0.10128 (DBH) – 0.0008 $(DBH)^2$. R^2 = 0.346 ** Standard Error of Y estimate = 0.4297.

Species Growth Group 2: Common to less common canopy species with a relatively greater shade tolerance and relatively fast growth: *Podocarpus latifolius, Olea capensis* subsp. *macrocarpa, Psydrax obovata & Ilex mitis.* The equation is: Diameter growth cm per 10 years = 0.1014 + 0.06962 (DBH) – 0.0006 $(DBH)^2$. R^2 = 0.610 ** Standard Error of Y estimate = 0.4297.

Species Growth Group 3: Mostly common canopy species with relatively slower growth: *Pterocelastrus tricuspidatus, Curtisia dentata, Apodytes dimidiata, Cassine papillosa, Maytenus peduncularis & Cassine eucleiformis.* The equation is: Diameter growth cm per 10 years = 0.40649 + 0.00069 (DBH) + 0.00036 $(DBH)^2$ R^2 = 0.569 ** Standard Error of Y estimate = 0.2998.

Species Growth Group 4: Two canopy species with coppicing behaviour with large stems: *Platylophus trifoliatus & Nuxia floribunda.* The equation is: Diameter growth cm per 10 years = 1.8468 – 0.0372 (DBH) + 0.00048 $(DBH)^2$. R^2 = 0.058 ns Standard Error of Y estimate = 0.7167.

Species Growth Group 5: all sub-canopy species. The equation is: Diameter growth cm per 10 years = 0.51049 + 0.02705 (DBH) – 0.0004 $(DBH)^2$. R^2 = 0.104 ns Standard Error of Y estimate = 0.2969.

3.4.3 Results

3.4.3.1 Stand plots

The following plots were selected to determine the standing stock of the Groenkop forest study site as basis for estimating mean annual increment (MAI).

- Stand plot 1: plots 55, 56, 57, 58 & 59 on lines 9, 10, 11, 12 & 13.
- Stand plot 2: plots 53, 54, 55, 56 & 57 on lines 21, 22, 23, 24 & 25.
- Stand plot 3: plots 39, 40, 41, 42 & 43 on lines 29, 30, 31, 32 & 33.

The Power Function ($Y = aX^b$) gave the best fit (based on R^2 value) of four functions (Linear; Exponential; Logarithmic & Power: $Y = aX^b$). The values of the constants a and b of the Power Function, for the individual species, are given in Table 3.2.

Table 3.2   Values for the constants a and b in the Power Function $Y = aX^b$, to calculate the timber volume of each of the species in the three Groenkop stand plots.

Species	Constant a	Constant b
Podocarpus falcatus	0.000144	2.37
Podocarpus latifolius	0.000123	2.39
Ocotea bullata	0.000182	2.30
Platylophus trifoliatus	0.000236	2.12
Ilex mitis	0.000214	2.18
Maytenus peduncularis	0.000202	2.23
Pterocelastrus tricuspidatus	0.000178	2.26
Cassine eucleiformis*	0.000174	2.25
Cassine papillosa	0.000233	2.10
Apodytes dimidiata	0.000176	2.28
Ochna arborea*	0.000188	2.22
Olinia ventosa	0.000366	2.05
Curtisia dentata	0.000150	2.31
Rapanea melanophloeos	0.000183	2.27
Diospyros whyteana*	0.000250	2.09
Chionanthus foveolatus*	0.000133	2.43
Olea capensis subsp. *macrocarpa*	0.000194	2.23
Olea capensis subsp. *capensis**	0.000307	1.88
Nuxia floribunda	0.000181	2.19
Gonioma kamassi*	0.000151	2.27
Halleria lucida*	0.000225	2.08
Burchellia bubalina*	0.000127	2.27
Rothmannia capensis*	0.000107	2.56
Canthium mundianum*	0.000179	2.28
Psydrax obovata	0.000244	2.14

* Sub-canopy tree species

3.4.3.2 Stand composition

The growth study recorded 35 indigenous tree species along the transects (Geldenhuys 1998). Twenty-five tree species were included in the three stand plots. The number of stems per plot is shown in Table 3.3, and the stem diameter distribution of all tree species in each of the three stand plots is shown in Table 3.4.

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Table 3.3   Number of stems per 0.5 ha stand plot in Groenkop Forest

Species	Stand plot		
	1	**2**	**3**
Podocarpus falcatus	2	3	2
Podocarpus latifolius	60	41	63
Ocotea bullata	-	2	-
Platylophus trifoliatus	1	-	-
Ilex mitis	-	2	5
Maytenus peduncularis	12	5	3
Pterocelastrus tricuspidatus	7	6	84
*Cassine eucleiformis**	1	-	2
Cassine papillosa	8	13	19
Apodytes dimidiata	69	57	56
*Ochna arborea**	1	4	9
Olinia ventosa	1	-	-
Curtisia dentata	59	18	37
Rapanea melanophloeos	-	-	3
Diospyros whyteana[1]	2	5	-
*Chionanthus foveolatus**	-	-	1
Olea capensis subsp. *macrocarpa*	74	74	88
Olea capensis subsp. *capensis**	2	-	-
Nuxia floribunda	7	13	7
*Gonioma kamassi**	20	18	18
*Halleria lucida**	3	-	-
*Burchellia bubalina**	1	-	-
*Rothmannia capensis**	-	7	-
*Canthium mundianum**	3	3	2
Psydrax obovata	7	4	6
Total	340	275	405
Stems/ha	680	550	810

Table 3.4   Number of stems per ha per diameter class in each of the stand plots.

Stand plot	Stem diameter class (cm)					
	10-19	**20-29**	**30-39**	**40-49**	**50-59**	**60+**
1	306	168	134	62	6	4
2	278	112	68	50	28	14
3	446	176	132	42	8	8

Stand growing stock in cubic meter in 1972 and the growth of the stand after 10 years, converted into mean annual increment is shown in Table 3.5. No adjustment was made for tree mortality or ingrowth, as was calculated for the Groenkop Forest Study Site (Geldenhuys, 1998). The mean growing stock for the stands in 1972 was 680 stems per ha and utilizable timber volume was 220.93 m^3 ha^{-1}. The MAI for Groenkop forest is 4.22 m^3 ha^{-1} or 1.9% of the initial growing stock, and the population standard deviation is 1.025 m^3 ha^{-1} (or 24.3% coefficient of variation), based on the three stand plots.

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[1] Sub-canopy tree species

Table 3.5   *Stand growing stock in m³ per plot for the different species in 1972 for the three stand plots, and mean annual growth in timber volume for all trees.*

Species	Stand plot		
	1	2	3
Podocarpus falcatus	1.648	16.875	9.188
Podocarpus latifolius	11.557	10.541	15.000
Ocotea bullata	0.000	0.402	0.000
Platylophus trifoliatus	0.720	0.000	0.000
Ilex mitis	0.000	0.297	1.291
Maytenus peduncularis	3.458	1.003	0.222
Pterocelastrus tricuspidatus	4.665	3.911	23.170
Cassine eucleiformis[2]	0.056	0.000	0.186
Cassine papillosa	0.941	1.982	2.031
Apodytes dimidiata	20.328	19.652	18.945
*Ochna arborea**	0.031	0.258	0.327
Olinia ventosa	3.068	0.000	0.000
Curtisia dentata	23.721	3.682	5.936
Rapanea melanophloeos	0.000	0.000	3.485
*Diospyros whyteana**	0.131	0.660	0.000
*Chionanthus foveolatus**	0.000	0.000	0.036
Olea capensis subsp. *macrocarpa*	26.091	49.163	23.777
Olea capensis subsp. *capensis**	0.080	0.000	0.000
Nuxia floribunda	1.132	2.396	1.536
*Gonioma kamassi**	2.273	1.283	1.315
*Halleria lucida**	0.198	0.000	0.000
*Burchellia bubalina**	0.036	0.000	0.000
*Rothmannia capensis**	0.000	0.029	0.000
*Canthium mundianum**	0.597	0.328	0.120
Psydrax obovata	4.132	2.377	5.137
Total timber volume in 1972, m³	104.86	114.84	111.70
Total timber volume in 1972, m³ ha⁻¹	209.72	229.68	223.40
Total timber volume after 10 years, m³ ha⁻¹	240.54	285.34	263.44
Mean Annual Increment, m³ ha⁻¹	3.082	5.566	4.004
Mean annual increment, % of 1972 growing stock	1.5	2.4	1.8

[2] Sub-canopy tree species

3.4.4 Discussion

The Groenkop Forest Study Site was, and still is, the focus of the study of forest growth, recruitment (or ingrowth) and mortality. In the area of the study of the Eddy Covariance System, i.e. the compartment known as Groenkop B6d, growth was studied over a period of 17 years (until 1997). The mean basal area for the sampled plots for stems >5 cm DBH was 44.6 m^2 ha^{-1} and the mean increase was 8.3% over the 17 years, or 0.49% per year. In the area north of where the telescopic tower was erected, the basal area increase was 3.5% over 12 years or 0.29% per year. Mortality varied between 4.0% and 6.1% of the original stems and 2.9% and 5.3% of the original basal area. This included 27 of the 35 species. Six species contributed about 70% of the loss, i.e. *Apodytes dimidiata, Pterocelastrus tricuspidatus, Olea capensis* subsp. *macrocarpa, Curtisia dentata, Podocarpus latifolius* and *Olea capensis* subsp. *capensis.* Mortality occurred in almost equal proportions in all diameter classes. It was also considerably more in the second measurement period, which suggests that suppression of trees in inferior positions has increased. Ingrowth varied between 3.1% and 11.5% of the original stems. It included 27 of the 35 species, and ten species contributed more than 85% of the stems, with particularly high levels of ingrowth of two important timber species, *Ocotea bullata* and *Podocarpus falcatus*. The mean growth of all trees was 0.89 cm per 10 years. A good number of trees grew more than 3.0 cm per 10 years. Various species had trees which grew 0.5 to 0.8 cm per year. Crown position of a tree had a major influence on its growth. In general, the total stand of Compartment B6d did not show a nett gain which exceeded the basal area of the timber that was initially harvested, although the growth of live trees exceeded the mortality during the study period. However, several species showed a nett gain over the timber removed in the harvest. These included species such as *Podocarpus falcatus, P. latifolius, Ocotea bullata* and *Pterocelastrus tricuspidatus*. The conclusion was that after about 27 years since the last timber harvest, mean tree growth was decreasing whereas tree mortality was increasing, and that a tree harvest, which focuses on mortality retrieval and improved growth of remaining trees, would improve the overall growth of the stand.

This study merely used the relationship between DBH and utilizable stem volume for each individual species, to calculate the standing volume of three selected stands within compartment B6d (in 1972). The stem diameter of each individual tree was increased over a 10-year period, using the quadratic functions for the relationship between stem diameter and diameter growth over 10 years, for five species groups developed by Geldenhuys (1998). This showed that the initial growing stock of utilizable timber volume was 220.93 m^3 ha^{-1}, with a mean annual increment of 4.22 m^3 ha^{-1} (with a 24.3% coefficient of variation).

In comparing this MAI for the closed evergreen forest in a stable state, with the growth of plantation stands of *Pinus radiata*, the following need to be considered:

- The forest is a mixture of different canopy, sub-canopy and shrub species, and of different sizes of trees within a species;
- Many trees are suppressed with a slow growth rate due to their position within the canopy.
- Some tree species show a faster growth rate than other species because they are adapted to more open stand conditions, such as during disturbance.

The estimated volume growth, or MAI, did not consider the individual species, and did not incorporate the recruitment and mortality rate within the stands.

3.5   *Water-use efficiency*

Table 3.6 summarises the mean annual growth increment and ET estimated for the Groenkop forest. These are used in Chapter 8 (Table 8.1) in an analysis of the economic WUE of this forest.

Table 3.6   *A summary of the WUE (utilisable stem wood produced in relation to water used as ET) estimated for the Groenkop forest.*

Annual volume increment (m³ ha⁻¹)	Annual ET (mm)	WUE (m³ wood m⁻³ ET from forest)	Estimated wood density (kg m⁻³)	WUE (g wood kg⁻¹ ET from forest)
4.2	933	0.00046	600	0.27

4. INDIGENOUS *PODOCARPUS FALCATUS* PLANTATION, MAGOEBASKLOOF, LIMPOPO PROVINCE

It is well known amongst foresters that the growth of trees is greatly influenced by competing vegetation. It is important, therefore, in this comparative study of indigenous and exotic tree species, to investigate the growth and water-use of an indigenous tree species under plantation conditions where competitive effects are managed through weed control and a regular planting espacement. A stand of riparian indigenous Yellowwood trees (*Podocarpus falcatus*) in the Woodbush/De Hoek/Tzaneen district was considered to be a suitable case study in view of the high value of the timber, warm temperatures, fertile soils and presumed year-round availability of soil water. Conditions for maximising the economic return from a plantation of indigenous species of tree were considered to be high under these conditions.

4.1 Description of site

A stand of *Podocarpus falcatus* on De Hoek Forest Plantation (23° 49′ 50.4″ S; 30° 02′ 31.2″ E, 857 m.a.m.s.l.) was selected for study in view of its relatively large size and suitability for measurement with micrometeorological ET systems. The stand (compartment C15e) comprises a provenance trial, and a detailed description is reported by Geldenhuys and von dem Bussche (1997). Tree spacing is 3 m by 3 m, and most planting took place between October 1982 and December 1983. Blanking took place over the first three years. No thinning has been performed. Diameter surveys took place in January 1987, February 1988, February 1989 and October 1993. Competing understorey vegetation has been slashed regularly. At the time of the field campaigns, however, the stand was covered by a dense growth of *Lantana camara*. The experimental site is within 50 m of a perennial stream. A soil pit revealed a uniform sandy alluvium to a depth of 80 cm. The trees were believed at the time to have access to some groundwater at greater depths, in view of the proximity to the stream. The site is classified by Komatiland as 10Hd4.w1 with the characteristics listed in Table 4.1.

Table 4.1   Site characteristics of the Podocarpus falcatus stand.

Site type no.	10Hd4.w1.A
Mean annual precipitation (MAP)	1 001 mm
Mean annual temperature (MAT)	19.0 – 19.1°C
Soil general description	Red neocutanic soils with underlying wetness
Dominant soils (70%)	
Lithology	Alluvium
Soil form and family	Tukulu 1 210
Depth limiting material	Short periods of wetness
Effective soil depth	80 – 110 cm
A horizon texture	SaClLm – SaCl
B horizon texture	SaCl – Cl

4.2 Evapotranspiration measurement

Three measurement systems (In Situ Flux Systems Eddy Covariance system, R.M. Young Eddy Covariance system, and Surface renewal system) were deployed during each of three field campaigns to measure the total ET from the site (Figure 4.1). A first field visit to this site took place in mid-September (18th September to 29th September 2005). The area was extremely dry, with significant drought damage and mortality seen in *Eucalyptus* stands in the vicinity of the nearby J.D.M. Keet Research Station. A soil pit dug within the

experimental site to a depth of 80 cm revealed a dry sandy alluvium. The site energy balance, as recorded from a net radiometer, soil heat flux plates, and RMY Eddy Covariance system) is illustrated in Figure 4.2.

Figure 4.1   A view of the instrument mast and sensors positioned above the Podocarpus falcatus *tree canopy at the Magoebaskloof site.*
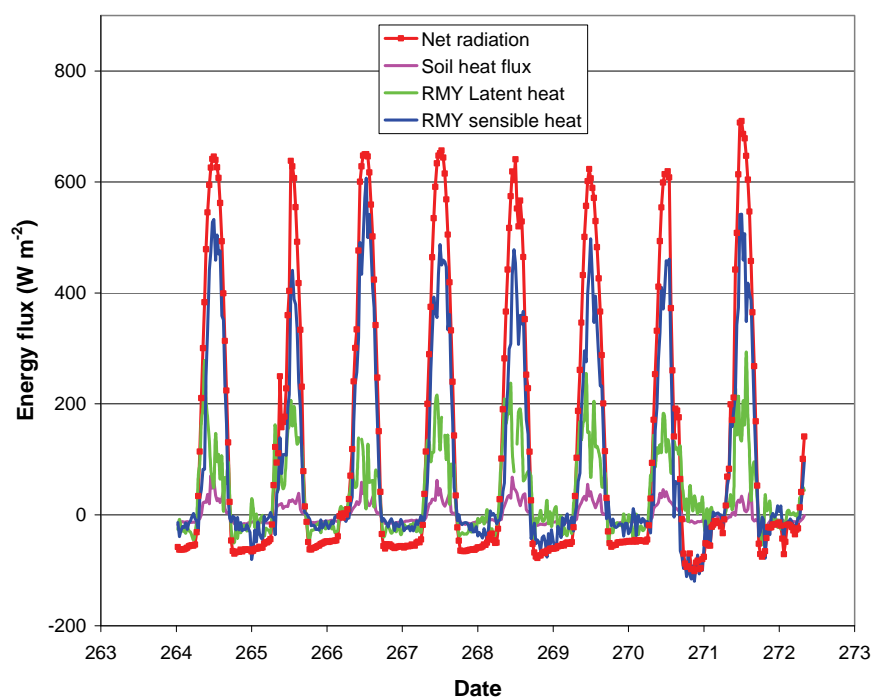
Figure 4.2   Energy balance components at the Magoebaskloof site as recorded during the September 2005 field campaign. Sensible and latent heat fluxes were estimated from the RMY Eddy Covariance system.

During a second field campaign, ET was measured from 9 to 15 February 2006 (7 full days). The weather was unusually wet over this period, but some spells of dry weather did occur on most of these days. All three ET measurement systems were again deployed.

A third field campaign took place in August 2006, with the same set of instruments being successfully deployed. Eight full days of data (23rd to 30th August) were recorded. The weather over this period was generally fine and dry. All the estimates of daily ET over each of the three field campaigns are illustrated in Figure 4.3.
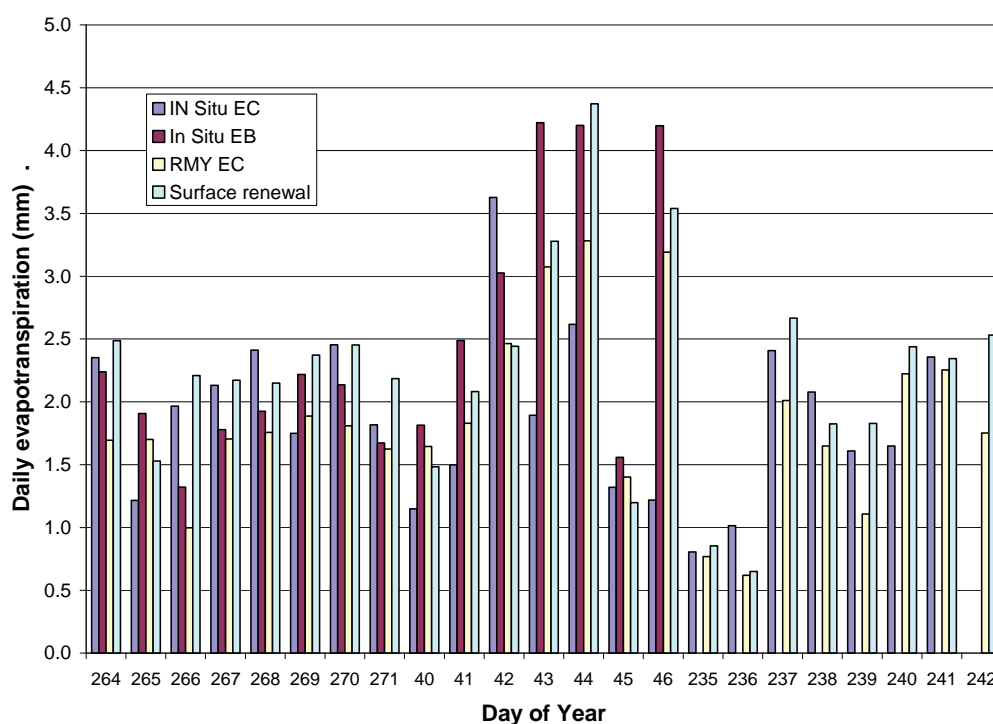
Figure 4.3   Daily evapotranspiration at the Magoebaskloof site as estimated from the Eddy Covariance In Situ system (ISEC; two calculations performed, one based on a direct calculation of vapour gradients, and the other based on sensible heat measurement with latent heat estimated from the site energy balance), the Eddy Covariance RM Young sonic system (RMY), and the Surface Renewal system (SR).

During the first two field campaigns, the In Situ sensors were deployed at a height of 18 m above ground. In light of results from this and other experimental sites, it was subsequently realised that this height was too high, and that the footprint from which the sensors were recording evaporative rates most likely extended beyond the *Podocarpus* stand into the surrounding plantations. During the third field campaign, a lower sensor height (12.2) was adopted. The heights to which the R.M. Young sonic anemometer (12.2 m) and Surface Renewal systems (11.2 m) were mounted remained unchanged over all three field campaigns.

4.3   *Sap flow measurements*

The *Podocarpus* stand was relatively open, supporting a vigorous understorey of *Lantana camara* and a wide variety of herbaceous plants. Previous porometer data collected from *Podocarpus henkelii* trees (Figure 3.19) indicated a low transpiration rate in this genus, and suggested that the understorey ET could comprise a significant fraction of the total ET at this site. It was important, therefore, to measure sap flow in the *Podocarpus* trees to estimate the fraction originating from the understorey canopy layer. Following a diameter survey of the *Podocarpus* trees in the vicinity of the micrometeorological systems at the start of the first field campaign, five sample trees were selected to each represent one of five size classes of tree (Figure 4.4). Table 4.2 shows the diameter of each sample tree and the number of heat pulse probe sets installed in each.

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Figure 4.4   A view of one of two heat pulse velocity systems used to monitor sap flow rates in a sample of Podocarpus falcatus *trees at the Magoebaskloof site.*

Table 4.2   The breast height diameter and number of heat pulse probe systems used in each sample tree.

Tree no.	Diameter (cm)	Probe set no. per tree
1	18.3	4
2	16.4	4
3	8.3	4
4	12.4	4
5	22.4	8

A bark thickness of 6 mm was measured on one tree and taken as constant across all trees. Heat pulse probe insertion depths were 10, 15, 22, 31 mm beneath the surface. First measurements of hourly sap flow occurred on 3 September 2004.

Figure 4.5 illustrates the typical HPV pattern recorded by the various probe sets in three sample trees over two days in December 2005. HPV peaked at around 20 cm hr^{-1} near midday, with higher morning rates than afternoon rates.
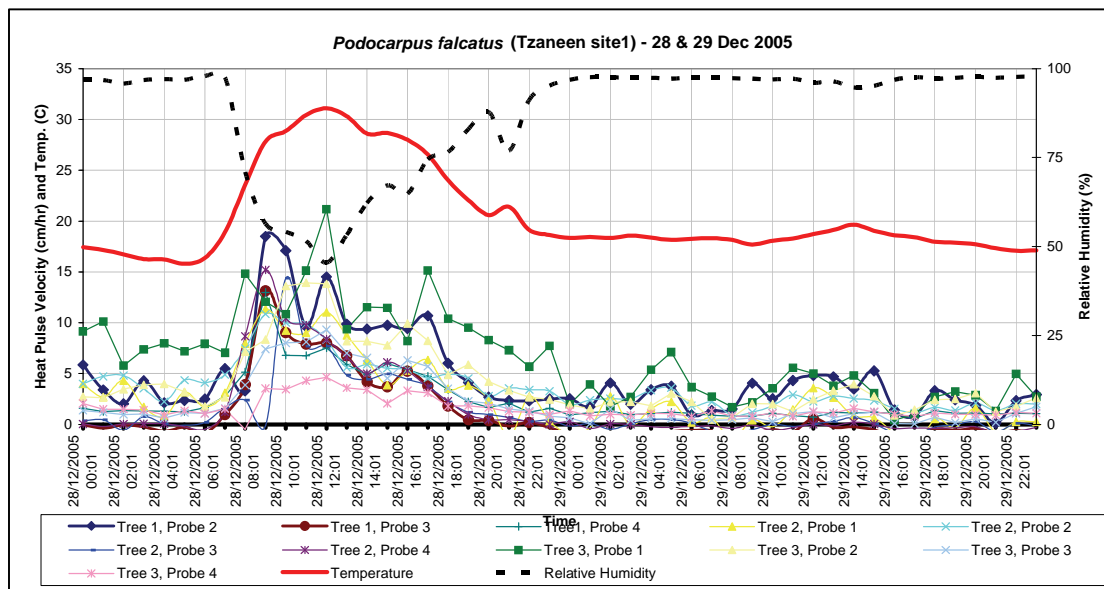
*Figure 4.5   Hourly heat pulse velocity data from a Yellowwood (*Podocarpus falcatus*) tree at the Magoebaskloof site, for a 48-hour period (28 and 29 December 2005).*

At the close of the third field campaign in August 2006, all the HPV systems were dismantled and brought back to the office, after having provided sap flow data over a full year. Important sapwood properties (sapwood area, moisture content, basic density, wound size) required for the conversion of heat pulse velocity to sap flux density and whole-tree sap flow were recorded in each sample tree. Data were quality checked, patched and processed to calculate whole-tree sap flow over the full monitoring period. Further details of the HPV technique and data analysis procedures are provided in Appendix 2.

The whole-year pattern of sap flow in the sample trees revealed relatively low sap flow rates compared to many other species (Hinckley *et al.*, 1978). Data from tree 1 are shown in Figure 4.6. There is a declining trend in daily sap flow over the dry September/October 2005 period. Subsequent sap flow rates increased in response to rainfall and the longer day lengths typical of summer. Sap flow declined abruptly at the end of February and remained low throughout the winter months. A broadly similar pattern was observed in tree 3 (Figure 4.7), but sap flow was much less due to the smaller size of this tree.

The estimated whole-stand daily tree water-use was calculated for the periods of the three field campaigns, and is shown in relation to the total stand ET recorded with the micrometeorological systems (Table 4.3, Figure 4.8). The results show that tree transpiration accounts for a seasonally variable fraction of ET from the whole stand. During September 2005, tree transpiration accounted for virtually the entire stand ET. The period was one of drought, and the understory plants were mostly brown and presumed to be transpiring at very low rates (Figure 4.10). The high but declining sap flow rate seen in Tree 1 (Figure 4.6) at this time suggests that the trees were still transpiring at a relatively high rate, in response to residual soil water. The situation during February 2006 is quite different with tree transpiration accounting for far less of the total ET. To some extent, this may be the result of enhanced evaporation from wet canopies, since intermittent rainfall occurred on most of these days. The understorey at this time was dense and displayed a high green leaf area (Figure 4.9). During the last field campaign in August 2006, tree transpiration was again a small fraction of stand ET. A likely explanation for this is that the trees had exhausted available soil water by this late stage in winter. This hypothesis is supported by the rise in sap flow recorded during May 2006, when unseasonal rainfall occurred (Figure 4.6 and 4.7). However, stand ET was relatively high throughout, implying that the understorey plants were still green and contributing most to the total stand ET measured above the canopy. It is intriguing why this should be so, and this question deserves more detailed investigation.

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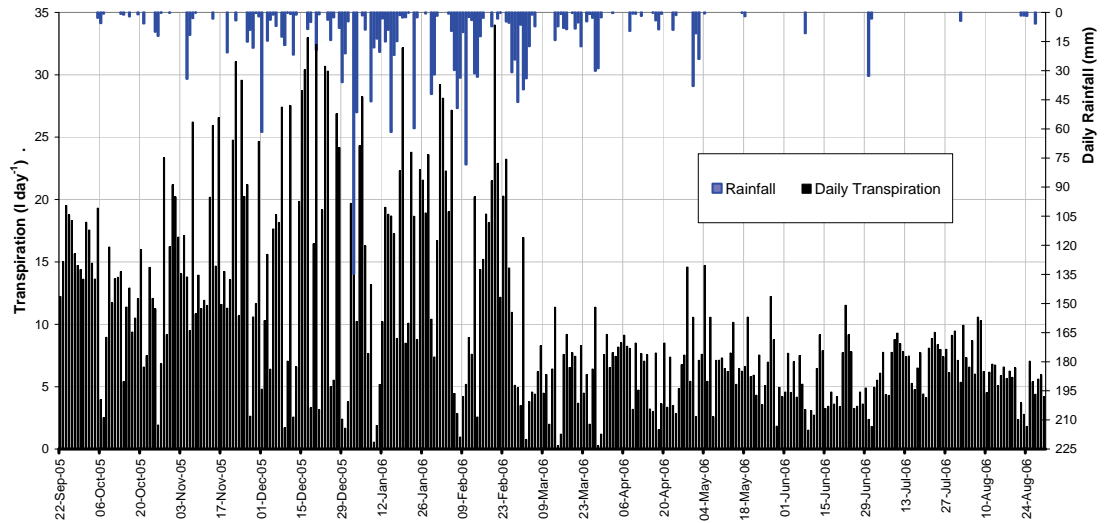
Figure 4.6   The whole-year pattern of sap flow (transpiration) recorded in tree 1 with an over-bark diameter of 18.3 cm.
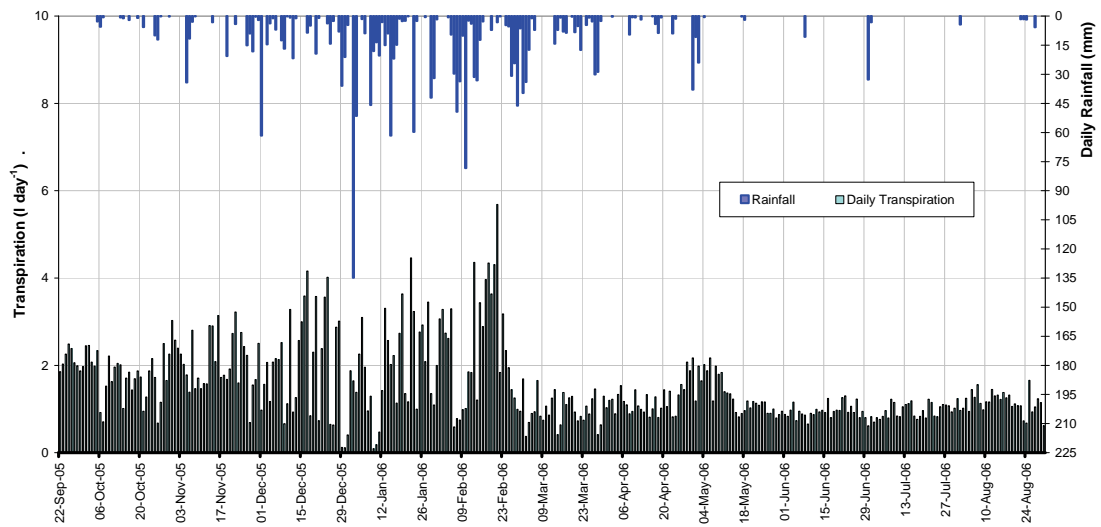
Figure 4.7   The whole-year pattern of sap flow (transpiration) recorded in tree 3 with an over-bark diameter of 8.3 cm.

Table 4.3   Estimated Podocarpus falcatus transpiration on the sample days, in relation to the total stand ET.

Sample day	Stand ET (mm)	Daily sap flow in sample trees (l) and number of trees per size class in the measured plot										Total (l)	Plot area (m²)	Mean tree sap flow (mm)	Fraction of stand ET
		Size class 1	Tree no.	Size class 2	Tree no.	Size class 3	Tree no	Size class 4	Tree no	Size class 5	Tree no.				
22 Sep	1.701	1.85	3	5.92	19	15.71	20	12.22	10	8.99	2	572.41	486	1.18	0.69
23 Sep	0.998	2.03	3	8.22	19	25.87	20	15.00	10	10.99	2	851.7	486	1.75	1.76
24 Sep	1.704	2.26	3	8.09	19	26.12	20	19.52	10	12.98	2	904.1	486	1.86	1.09
25 Sep	1.757	2.49	3	8.86	19	25.33	20	18.77	10	13.01	2	892.3	486	1.84	1.05
26 Sep	1.887	2.39	3	6.21	19	21.49	20	18.33	10	12.16	2	762.6	486	1.57	0.83
27 Sep	1.810	2.06	3	6.09	19	21.35	20	15.65	10	11.63	2	728.7	486	1.50	0.83
28 Sep	1.626	1.99	3	6.09	19	17.41	20	14.72	10	10.55	2	638.2	486	1.31	0.81
9 Feb	1.646	0.99	3	1.64	19	2.03	20	4.20	10	1.33	2	119.4	486	0.25	0.15
10 Feb	1.830	1.01	3	2.22	19	3.26	20	5.18	10	3.36	2	171.4	486	0.35	0.19
11 Feb	2.463	1.85	3	3.67	19	4.66	20	8.94	10	7.62	2	275.0	486	0.57	0.23
12 Feb	3.074	1.84	3	3.67	19	4.05	20	7.59	10	4.58	2	245.0	486	0.50	0.16
13 Feb	3.282	4.36	3	6.27	19	16.61	20	20.21	10	19.50	2	702.3	486	1.45	0.44
14 Feb	1.403	1.21	3	1.69	19	1.84	20	2.57	10	1.65	2	102.1	486	0.21	0.15
15 Feb	3.192	3.44	3	4.38	19	7.14	20	14.39	10	8.09	2	395.7	486	0.81	0.26
23 Aug	0.769	0.73	3	1.21	19	2.60	20	2.78	10	6.39	2	117.9	486	0.24	0.32
24 Aug	0.619	0.68	3	1.61	19	1.22	20	1.80	10	6.10	2	87.0	486	0.18	0.29
25 Aug	2.012	1.66	3	3.41	19	3.64	20	7.05	10	5.96	2	226.0	486	0.47	0.23
26 Aug	1.649	0.94	3	2.15	19	4.13	20	5.39	10	6.46	2	195.2	486	0.40	0.24
27 Aug	1.108	1.05	3	2.35	19	2.66	20	4.39	10	4.11	2	153.3	486	0.32	0.28
28 Aug	2.224	1.24	3	2.80	19	4.96	20	5.61	10	4.56	2	224.3	486	0.46	0.21
29 Aug	2.254	1.15	3	2.63	19	3.57	20	5.95	10	8.45	2	204.5	486	0.42	0.19
30 Aug	1.753	0.62	3	1.52	19	3.66	20	4.21	10	6.56	2	162.6	486	0.33	0.19
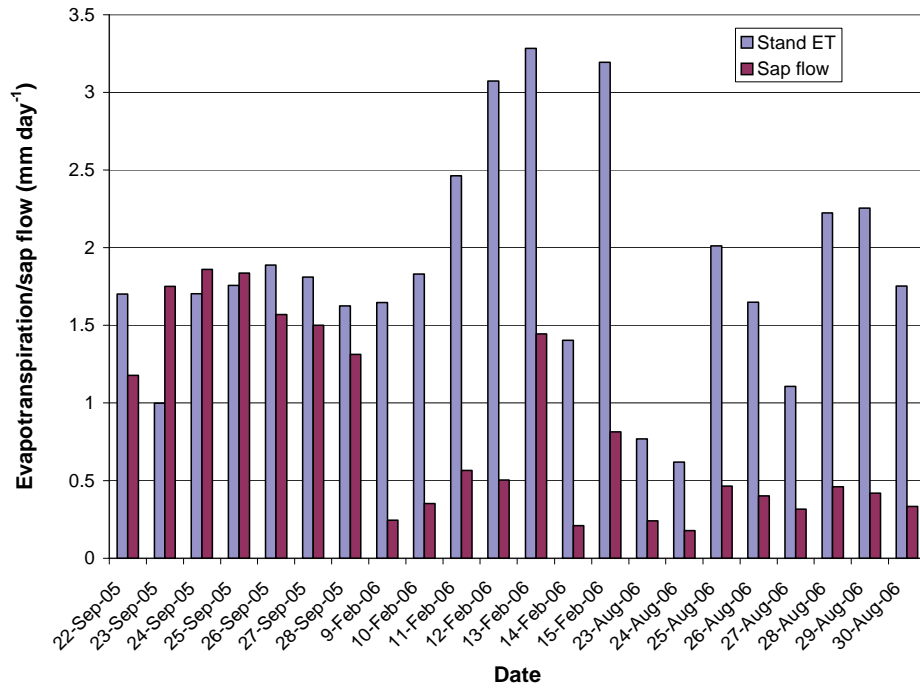
Figure 4.8   A comparison of stand ET (mm) to Podocarpus falcatus *mean stand sap flow (mm)
over the three sample periods.*

Figure 4.9   A green and well developed understorey layer recorded in February 2006.

Figure 4.10   A well developed but dry understorey layer recorded in September 2005.

4.4   *Evapotranspiration modelling*

In view of the sensor height change with the In Situ system, it was decided to use the R.M. Young system data for modelling ET. The Surface Renewal system needed to be calibrated against the R.M. Young data, and was therefore not an independent measure of ET at this site.

The measured daily ET recorded over all three field campaigns was first compared to mean daytime net radiation, and mean daytime vapour pressure deficit, variables that are expected to explain much of the day-to-day variation in ET. Day-time was defined as the period from 06:00 to 18:00 for each day. The sensors

were positioned on the telescopic tower above the canopy. Figure 4.11 shows the correlation between mean day-time net radiation and measured daily ET. A high degree of correlation is shown by the February 2006 and August 2006 data, although the trends are clearly different. Data recorded during the first September 2005 campaign do not conform to either trend, but show uniformly low daily ET rates under conditions of high net radiation.
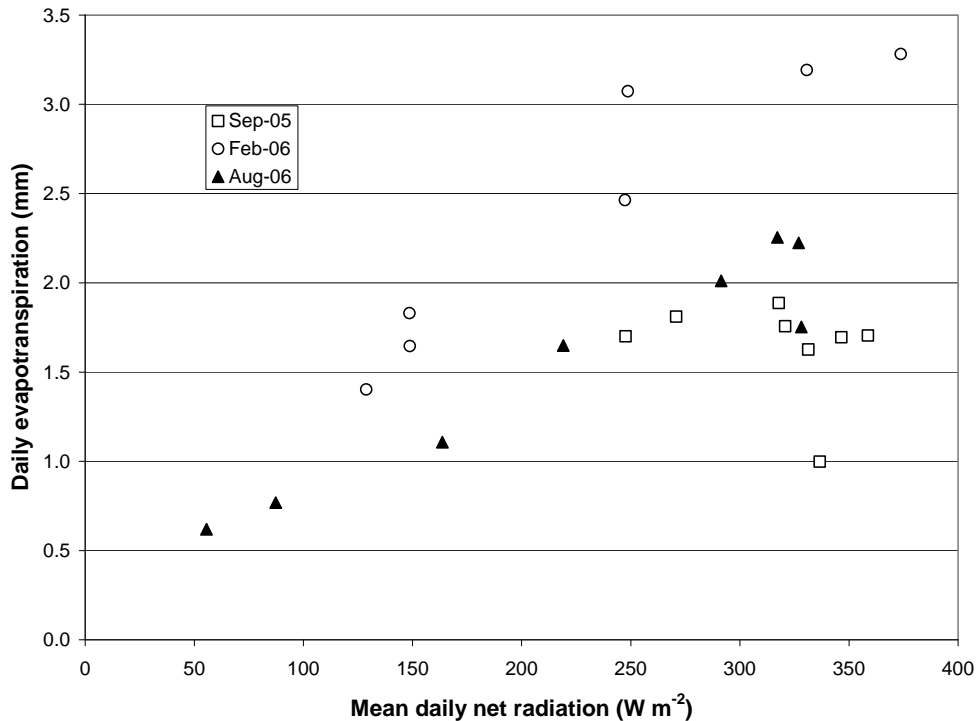
Figure 4.11 The relation between mean daytime net radiation and daily ET recorded on sample days during three field campaigns.

A greater scatter of data points was observed in the relation between mean daytime VPD and daily ET (Figure 4.12). Once again, different trends were evident for each period. For a given mean daily VPD, highest daily ET was recorded during February 2006, and lowest during September 2005. The site was observed to be extremely dry during the first (September 2005) field campaign. Despite the proximity of the trees to a water course and stream, a soil pit showed the soil to be dry down to the observed depth of 80 cm. It is perhaps significant that the Tree 1 HPV data shows a declining trend over this period (Figure 4.6).

The high daily ET recorded during the very wet February field campaign may reflect some enhanced evaporation from wet canopies, since rain was recorded on most days over this period. The weather during the third field campaign was again dry, although not as much as during the first field campaign.
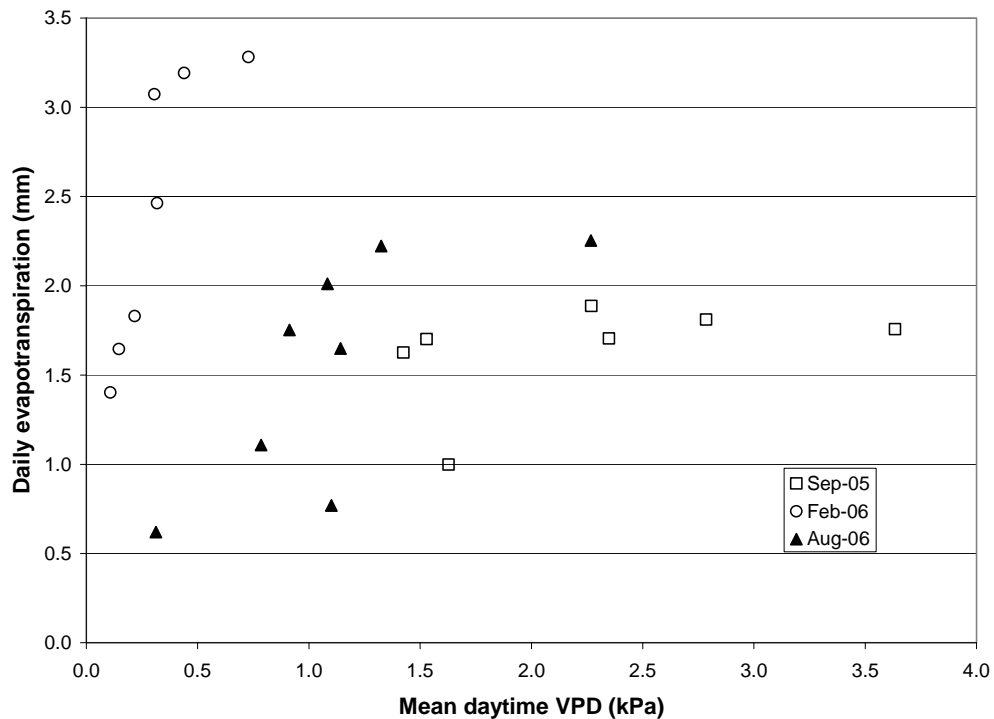
Figure 4.12   The relation between mean daytime VPD and daily ET recorded on sample days during three field campaigns.

The daily net radiation and VPD data were used as inputs to the Penman-Monteith model for each of the 22 sample days. A constant aerodynamic conductance value of 0.2 m s^{-1} was assumed throughout. The Granier *et al.* (2000) model of canopy conductance was again used, and parameter values were modified to return a reasonable fit of modelled to measured daily ET (Table 4.4, Figure 4.13) for the February data when soil water deficits were insignificant. Daily modelled canopy conductance varied from 0.017 to 0.023 m s^{-1}.

Table 4.4   Parameter values used in the estimation of canopy conductance for the purpose of Penman-Monteith model predictions of daily ET.

G_c model inputs	Values fitted to February data
gc_0	10
R_0	300
b	2
LAI	3
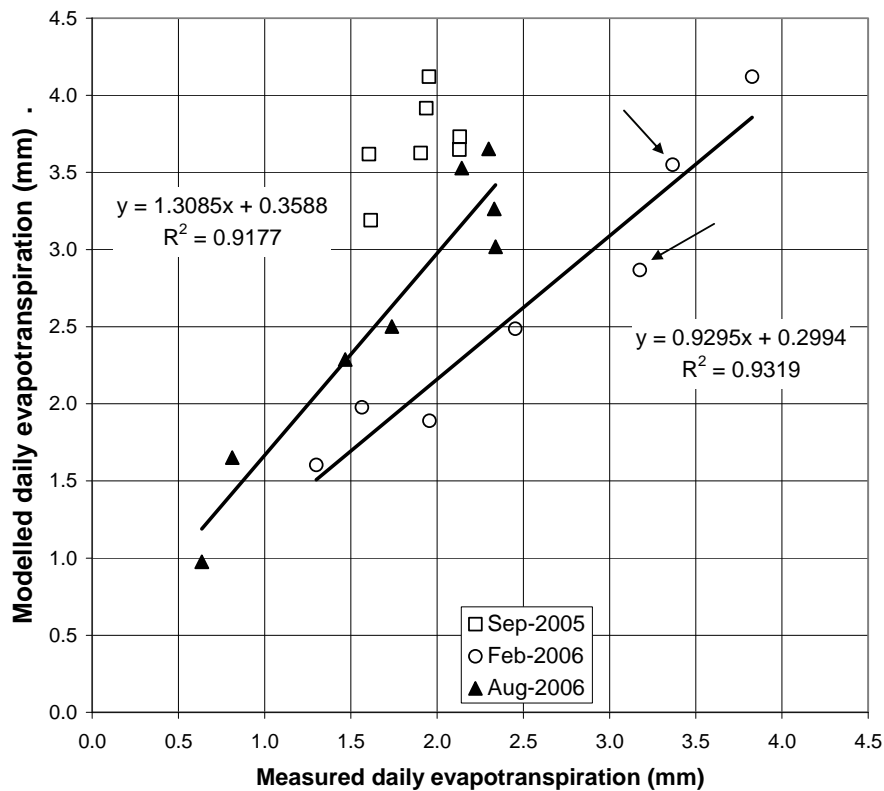
Figure 4.13   A comparison of measured to modelled daily ET, in which the fitted parameters shown in Table 4.5 were used to estimate daily canopy conductance. Arrows indicate days that were mostly dry.

Some concern remained over whether the measured February daily ET totals were enhanced due to faster evaporation from the wet canopies. Figure 4.14 shows the occurrence of 30-minute cumulative rainfall (recorded at the nearby J.D.M. Keet research station) in relation to the 10-minute RMY estimate of mm of water evapotranspired during this period. Day 43 and day 46 were relatively dry, and these daily data points are identified in Figure 4.13. Since these two data points conform to the overall trend over this period, it is assumed that the February daily ET data points are representative of general ET rates at this time of year.
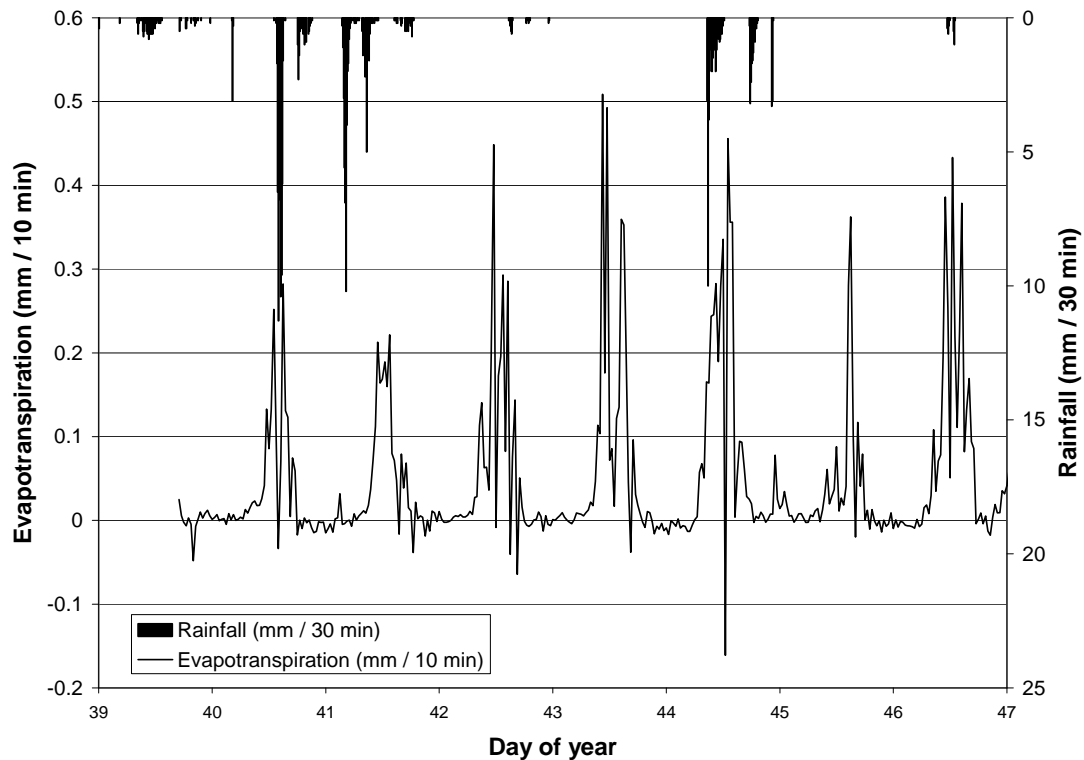
Figure 4.14   The pattern of 10-minute ET during the February sample period shown in relation to 30-minute rainfall data.

Potential daily ET during September 2005 and August 2006 are suggested by the model to be of the order of 3.5 – 4 mm which is believed to be realistic considering the high VPDs experienced over these periods. Similar daily ET at these times of year have been recorded from a stand of unstressed *Eucalyptus* trees (Dye *et al.*, 1997). Seasonal dry soil conditions at this site are therefore assumed to account for the relatively low measured ET during these periods.

Some important insights arose out of this modelling exercise:

- Results suggest that *Podocarpus falcatus* trees are sensitive to soil water availability, responding quickly to limit transpiration as soil water availability declines. This is perhaps as a result of shallow or spatially restricted root systems. The relatively low sap flow rates suggest that the species is a cautious user of water, managing to retain a high green leaf area throughout the year, but limiting water-use through low leaf stomatal conductance and quickly reducing this further as dry conditions develop.

- Effective simulation of such stands requires a model with a detailed soil water balance component so that the onset and severity of plant water stress can be followed. Close proximity to a water course is no guarantee that species such as *Podocarpus falcatus* are able to source sufficient soil water. Roots of this species have been observed to run near the surface for a distance exceeding 40 m in the Groenkop forest (C. Geldenhuys, pers. comm.), but this may be a feature of older trees in an environment where deep rooting is inhibited by shallow, poorly drained soils. Field data reflecting changes in soil water would be required to verify this assumption. However, additional tree-based data reflecting water stress would be valuable since the extent of the vertical and lateral spread of the root systems is often difficult to ascertain, and therefore to sample adequately. Examples of roots extending over a distance of 40 m in the Groenkop forest (C. Geldenhuys, pers. comm.) attest to the potential lateral spread of tree roots. Measurements of pre-dawn water potential are very instructive, but logistically difficult to conduct regularly at remote sites since measurements must be performed manually. Stem water potential may be directly measured by fixing a sensitive hygrometer to a

section of exposed xylem, but would require considerable effort and expense by researchers to maintain over periods of months. Sensitive dendrometers are relatively inexpensive and amenable to automation, and have been shown in recent years to be able to indicate the timing of water stress in trees (e.g. Giovannelli *et al.*, 2007). This technique has much potential as an adjunct to soil water data in determining tree responses to soil water deficits.

- A model is required that can separately simulate overstorey and understorey canopy layers. The understorey contribution to the whole stand ET was shown to be highly significant at this site, owing to the relatively high light penetration through the tree canopies (Figures 4.9 and 4.10). Furthermore, the relative contributions of overstorey and understorey canopies towards whole-stand ET were shown to be variable over time. Vigorous *Lantana camara* dominated the site. Although untouched during this work, such weed infestations are generally slashed regularly by forestry staff. This would cause an abrupt decline in understorey leaf area, with significant consequences to the simulation of the site water balance.

The 3-PG model (Landsberg and Waring, 1997) was developed to simulate the growth and water-use of plantation forests through a simplified treatment of the processes involved. The usefulness of this model for simulating the *Podocarpus* plantation is likely to be limited by its inability to model overstorey and understorey canopies separately.

The WAVES ecohydrological model is believed to adequately meet these specifications. However, it was not parameterized and evaluated for this site, due to too many uncertainties regarding the local climate, soil conditions, and the structure and physiology of both canopy layers.

In an attempt to see the broad picture of stand ET from this site, a simple modelling exercise was performed. Figure 4.15 illustrates the pattern of daily reference ET calculated using the FAO formulation of the P-M equation (Allen *et al.*, 1998). This FAO model is widely used on many crops, and is therefore reasonably appropriate to the *Podocarpus* stand in which the understorey vegetation contributed a major proportion of the stand ET during the summer growing season. The annual pattern of reference ET clearly shows the strong seasonal variation in daily ET due to factors such as daylength and temperatures, as well as day-to-day variation caused by changing daily weather conditions.
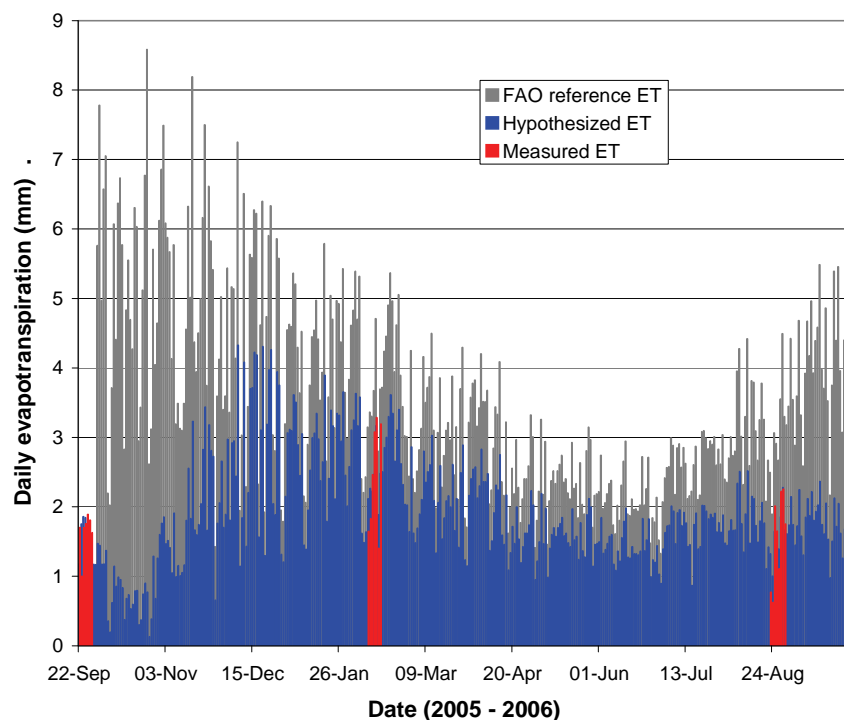
Figure 4.15   A comparison of FAO reference ET, modelled actual stand ET and measured ET recorded during three field campaigns during 2005/6 in a Podocarpus falcatus *plantation stand.*

Actual ET was estimated on the basis of measurements of ET obtained during the three field campaigns, rainfall records, the continuous record of sap flow in the *Podocarpus* stand, and some assumptions concerning the leaf area development and transpiration rate of the understorey plants. The simulation year (1 October 2005 to 30 September 2006) was divided into four periods where the following assumptions were made:

- From 1 to 25 October 2005, drought conditions prevailed, and the understorey plants were dormant. *Podocarpus* sap flow was the only contribution to stand ET.

- From 26 October to 15 December, rains commenced and continued without any significant dry spells. We assumed a linear increase in leaf area development and transpiration by the understorey plants. Modelled peak ET was assumed to reach 0.67 of the FAO potential ET at the end of this period, based on a match of measured to modelled ET performed during February in the next period.

- From 16 December to 15 July, the understorey plants were assumed to maintain a constant maximum leaf area index. Regular rainfall continued to keep the understorey plants in an active physiological state. Modelled ET was determined to be approximately 0.67 of the reference evaporation over this period.

- From 16 July to 30 September, the rains ceased, and it was assumed that there was a linear decline in soil water availability as the understorey plants progressed towards dormancy. The rate of decline in the ratio of actual to reference ET was adjusted so that modelled ET corresponded with measurements recorded at the end of August 2006 during the third field campaign.

This analysis is crude, but is nevertheless useful in showing that the annual stand ET (702 mm) is considerably less than the reference ET (1 299 mm) for this site, and in fact is comparable to what is typical of grasslands. This reflects the seasonality of understorey growth at this site, as well as the slow sap flow rates and low transpiration rates in *Podocarpus* trees.

4.5 Tree growth estimation

Tree growth rates over the 12-month measurement period were required for the calculation of WUE. Direct measurement of stem circumferences at fixed heights in a sample of 50 trees were recorded, but these failed to show stem growth adequately due to very low diameter increments, and problems with bark shedding and epiphytic growth on the stems. An additional concern was that tree size varied noticeably among the different provenance plots of the trial. The 50 sample trees were therefore not necessarily representative of the entire trial from which a mean ET was recorded. We obtained growth survey data for the entire trial from Komatiland, and extracted the data shown in Table 4.5.

Table 4.5   Mean stem growth data recorded at the P. falcatus trial in 1993 and 2001, and calculations of mean annual increment over this time interval.

	DBH (cm)	Stem volume OB* (m^3)	Stem volume ($m^3 ha^{-1}$)	Difference over 7.6 years ($m^3 ha^{-1}$)	MAI ($m^3 ha^{-1}$)
Oct 1993	10.4	0.0347	38.55	30.89	4.07
May 2001	13.15	0.0625	69.44		

*Over-bark

It was assumed that the stem growth rate remained relatively constant since the 1993/2001 period. Figure 4.16 shows a relationship between stem diameter at breast height to stem volume, derived from a sample of *Podocarpus falcatus* trees in the southern Cape with diameters less than 40 cm (data courtesy from C.J. Geldenhuys).

Podocarpus falcatus

R-square = 0.955   # pts = 121
y = 9.96e-005x^2.5
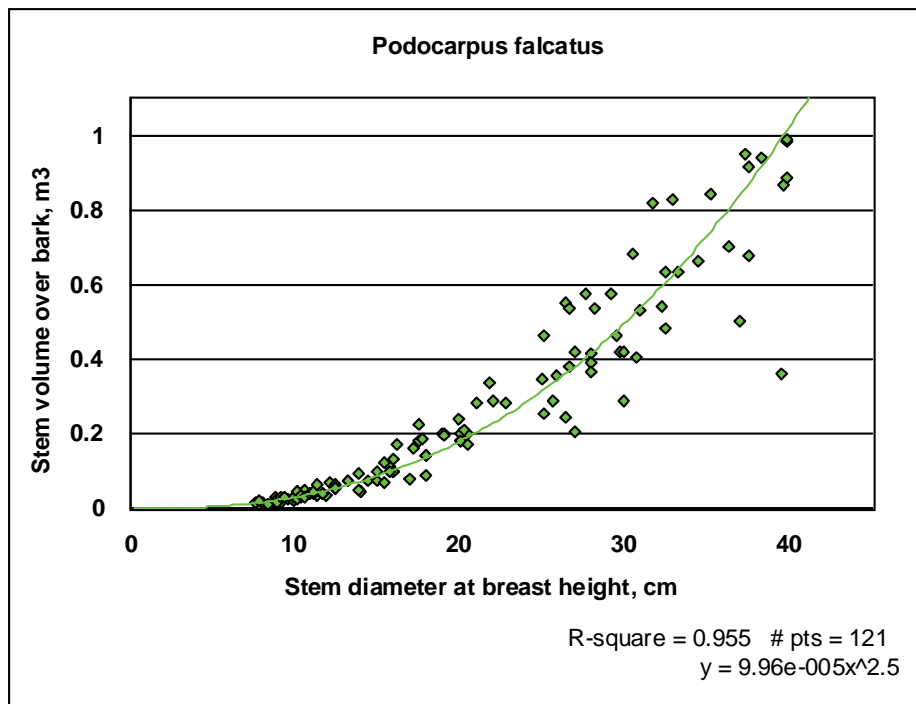
Figure 4.16   The relation between stem diameter at breast height and stem volume (over-bark) for Podocarpus falcatus *trees sampled in the southern Cape.*

Table 4.6 summarises the major water balance components and estimate of WUE for the site. These form the basis for an analysis of the economic WUE of this plantation in Chapter 8 (Table 8.2).

Table 4.6   A summary of the water balance and tree WUE estimated for the P. falcatus *plantation, Magoebaskloof.*

Stand ET (mm)	~702*
Mean annual volume growth increment (m^3 ha^{-1})	4.07
WUE (m^3 wood m^{-3} ET from stand)	0.00057
WUE (m^3 wood m^{-3} TR from trees)	0.00183
Wood density (kg m^{-3})	470
WUE (g wood kg^{-1} TR from trees)	0.860

5. SANDVELD SAVANNA, KRUGER NATIONAL PARK

The following section incorporates information contained in a report by Scholes and Archibald. Indigenous trees are an important component of the savanna biome, and provide valuable browse, fuelwood, and many other products (van Eck *et al.* 1997; Dovie *et al.* 2002; Gush and Dye, 2004). The Groenkop forest and the *Podocarpus falcatus* stand in Magoebaskloof both have canopies that are largely closed over, making it possible to treat the tree canopy as a single big leaf. Tree leaf area is relatively stable at these sites, and thus seasonal patterns of canopy growth and senescence can largely be ignored. The situation in savannas is, however, very different. The vegetation is phenologically much more dynamic as a result of the low and uncertain rainfall distribution within the growing season, with most trees displaying a deciduous canopy. Physiological responses to rainfall and soil water availability are marked and rapid. In addition, the spatially discontinuous tree canopies introduce significant additional complexity in describing the energy balance of tree canopies.

5.1   Description of site

A site situated close to an existing flux measurement site was selected to investigate the water-use of indigenous trees in a savanna environment. A detailed description of this locality is reported by Scholes *et al.* (2001). It is situated at 25º 01.184′ S, 31º 29.813 E, and is semi-arid (MAP = 570 mm), and hot (MAT = 22 ºC). The vegetation is described as sandveld savanna, and supports broadleaved tree species, with *Combretum apiculatum* the dominant species.

5.2   Evapotranspiration measurements

Scintillometry was judged to be the most appropriate technique for measuring the total ET from the area, due to the advantage of spatial averaging in this floristically heterogeneous area. As the nearby flux tower was not sufficiently rigid to support the scintillometer transmitter or receiver, we installed the receiver near the summit of a small hill adjacent to road S65 (Lat 25.0602; Long 31.5157), and deployed the transmitter near the summit of another hill (Figure 5.1, 5.2) near the junction of H1-1 and H3 (Lat. 25.0915; Long. 31.5431). The two hills are 4.25 km apart (Figure 5.3). Three visits to the site took place to record evaporation and energy balance information under varying climatic and vegetation conditions in spring, mid-summer and autumn. The spring visit took place from 23 August to 3 September 2004, while the summer visit took place from 31 January 2004 to 11 February 2005. A last autumn field campaign took place from 9 to 20 May 2005.

Figure 5.1   The LAS scintillometer transmitter deployed in the Kruger National Park.

Figure 5.2   A view through the scintillometer sighting scope along the beam path to the transmitter station.
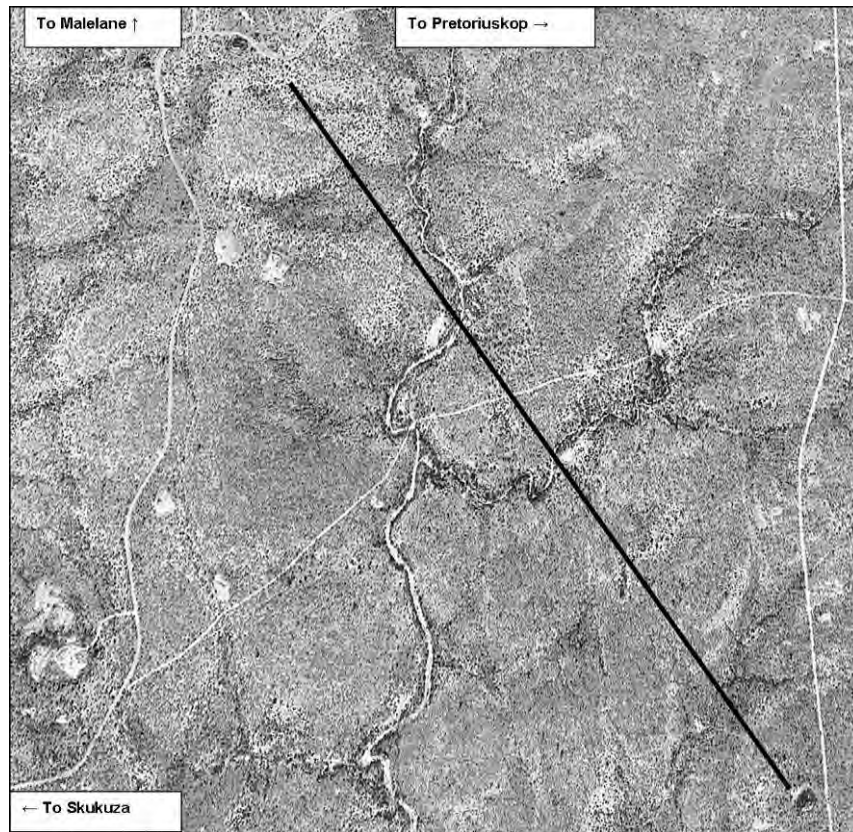
Figure 5.3   An aerial photograph of the experimental area showing the orientation of the
4.25 km scintillometer transect.

Scintillometer data analysis involved the following steps:

- Measurement of the topographic profile between the scintillometer transmitter and receiver. This was performed by walking along a transect between transmitter and receiver, and taking regular GPS altitude measurements.

- Calculation of the weighted mean height above the vegetation canopies. The weighting factor is based on a normal curve and recognises that the instrument is most sensitive to scintillations towards the centre of the beam path.

- Measurement of solar radiation (automatic weather station at the receiver site)

- Measurement of net radiation above a tree canopy, and over open grassland. These were recorded close to the receiver station (Figure 5.4).

- Weighting overall net radiation according to the proportions of tree and grass canopies along the measurement transect. An aerial photograph of the area was obtained from Scientific Services (KNP). The scintillometer transect was marked on the photograph. The proportion of tree, shrub and grass cover was noted at 25 m intervals along the transect. On the basis of this analysis, it was established that trees, shrubs and grass made up 21.8%, 48.2% and 30.0% of the transect, respectively. Assuming that shrubs are similar to trees in their reflectance and absorbance characteristics, it was concluded that the tree/grass ratio of the area was 70:30%.

- Measurements of soil heat flux beneath trees and in open grassland were also performed near the receiver site, to adequately estimate this variable along the entire beam path.

- Further details of the technique are given in Appendix 2.

Figure 5.5 illustrates the 10 minute fluxes in net radiation (R_n), sensible heat (H), latent heat (LE) and soil heat flux (G) over the August sample days, together with the daily total evaporation calculated from the latent heat fluxes.

Figure 5.4   View of the net radiation sensors located over grassland and over a Combretum tree canopy. Soil heat flux was also measured under grass and under trees.
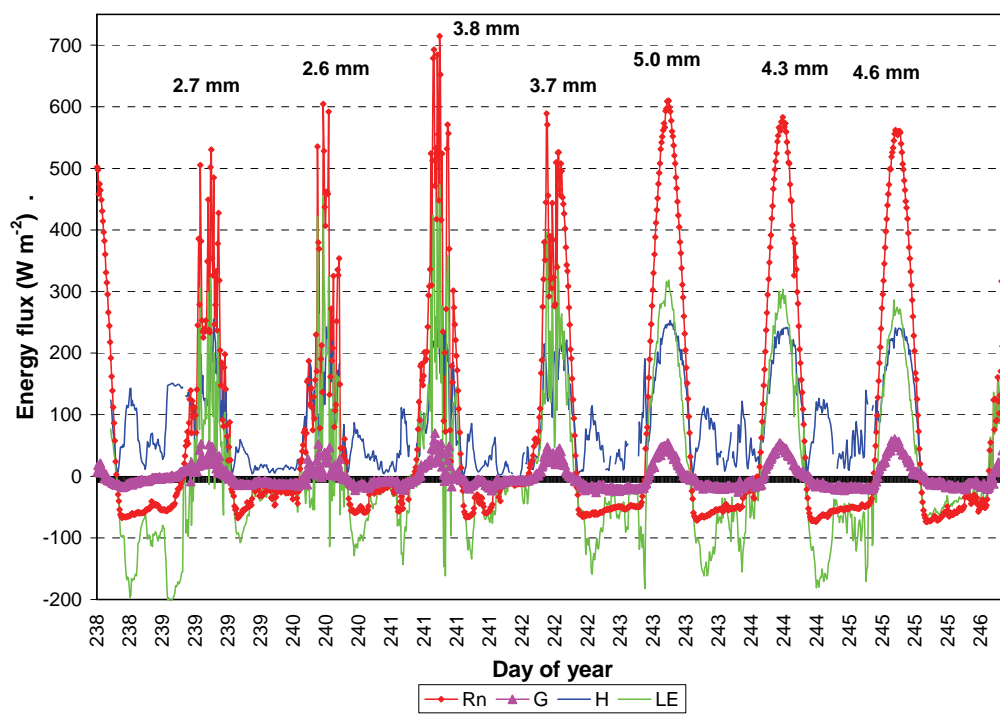
Figure 5.5   Patterns of net radiation (R_n), soil heat flux (G), sensible heat flux (H) and latent heat flux (LE) recorded across the scintillometer transect during the August 2004 field trip.

The data collected over the summer (February) and autumn (May) field trips are shown in Figure 5.6 and Figure 5.7, respectively.
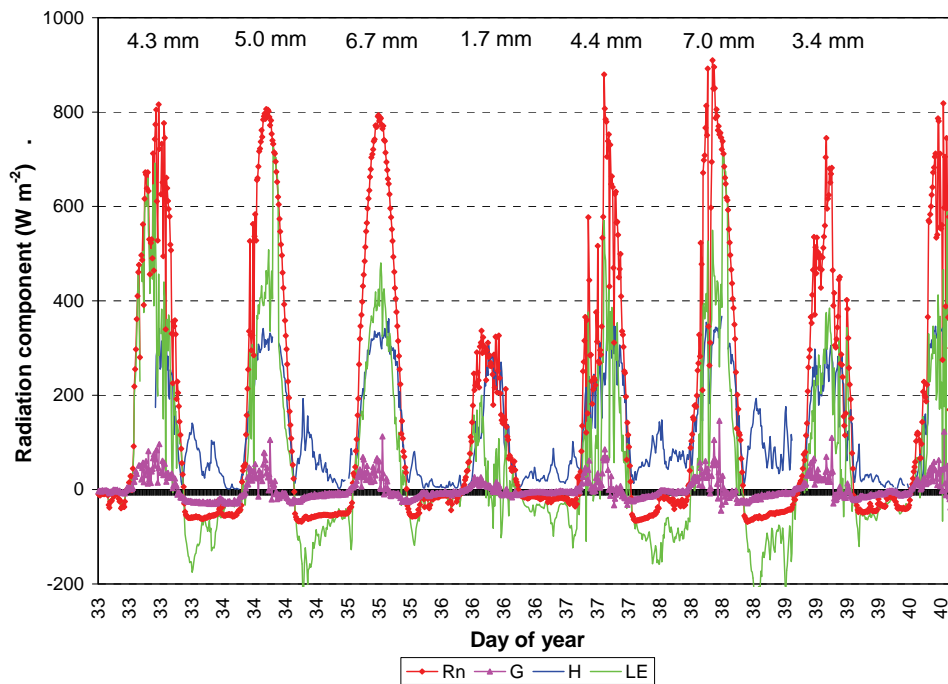
Figure 5.6   Patterns of net radiation (R_n), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE) recorded across the scintillometer transect during the February 2005 field trip.
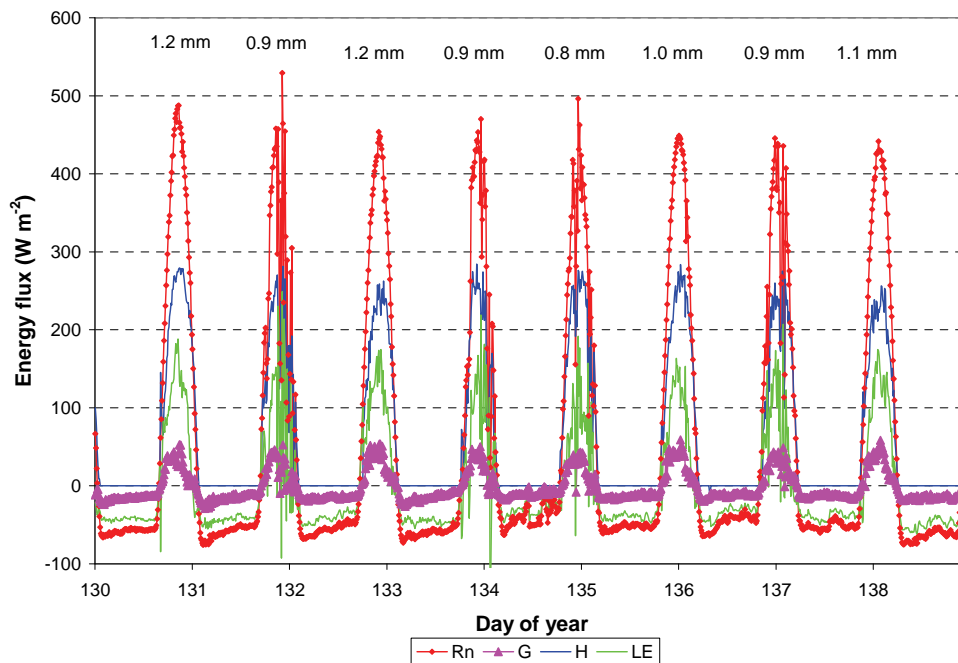
Figure 5.7   Patterns of net radiation (R_n), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE) recorded across the scintillometer transect during the May 2005 field trip.

Daily ET and energy balance data were thus recorded over a total of 22 days (Figure 5.8), and reflected a wide range of evaporative conditions and vegetation growth phases. During August 2004, daily ET showed an increasing trend, reflecting leaf area growth following the spring flush of vegetation. During early February, leaf areas had peaked, with maximum daily ET reaching 7 mm under conditions of high evaporative demand. Daily ET during this period was very variable due to changing temperature, humidity and solar radiation. During May, the vegetation was senescing, leading to substantially lower daily ET.
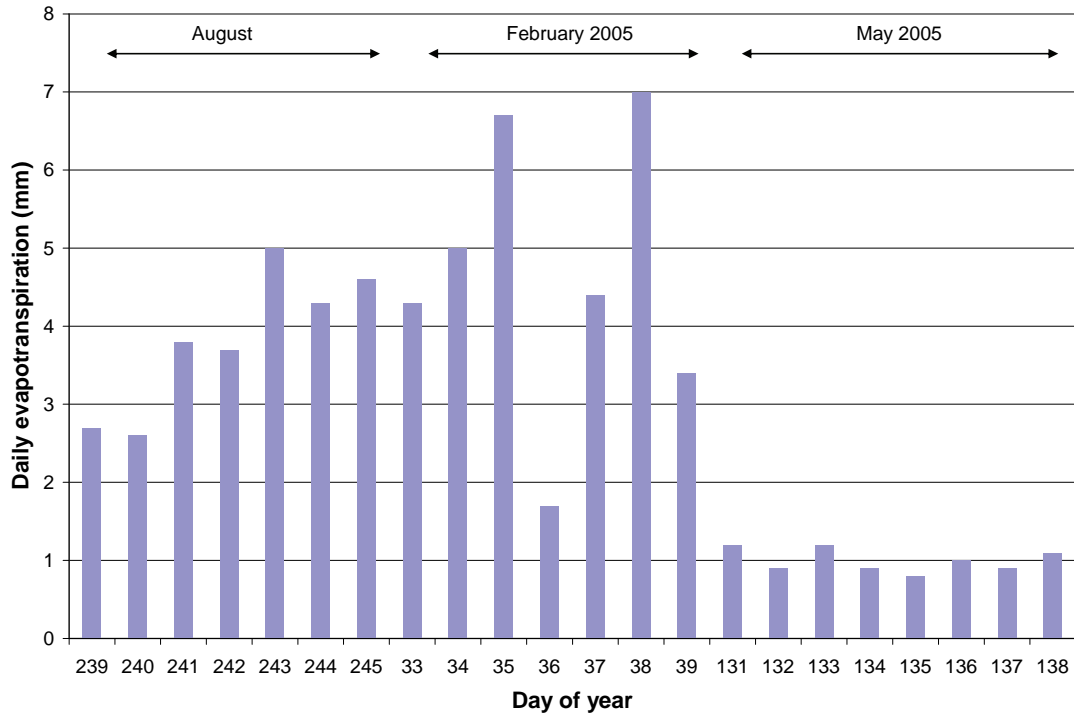
Figure 5.8   The range of daily evapotranspiration estimated with the scintillometer for 22 days in three sample periods within the 2004/5 summer growing season.

5.3   Sap flow studies

Little information is available to indicate the water-use characteristics of Sandveld tree species in this environment, and what fraction of total ET originates as transpiration from trees. Heat pulse systems were deployed at a site situated within 200 m of the flux tower. Sample trees were selected to represent the surrounding tree species composition, and included three *Combretum apiculatum* (Red Bushwillow), two *Sclerocarya birrea* (Marula) and two *Lannea schweinfurthii* (False Marula) trees. Table 5.1 shows the size of these trees and the number of HPV probe sets installed in each.

Table 5.1 *Details of sample trees selected for sap flow measurement using the Heat Pulse Velocity technique.*
Leaf area index (LAI) measurements recorded with a Li-Cor Canopy Analyser show seasonal changes.

Species	Breast height stem circ. (m)	Height (m)	Crown circumference (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

Heat pulse systems were installed during August 2004, and maintained over the 2004/5 and 2005/6 summer growing seasons. Details of the technique and the data analysis procedures are provided in Appendix 2. The probes and supporting electronic systems were protected from damage by animals by erecting a weld-mesh enclosure around each sample tree (Figure 5.9, 5.10). This was supported by a treated pole framework. Shade cloth was fixed over the upper portion to reduce the temperature of the data loggers and multiplexers, as well as minimizing temperature fluctuations in the exposed portions of the probes. Data were recorded in Campbell data loggers (Figure 5.11) and transmitted via a modem to the office in Pietermaritzburg via the cellular network.

Figure 5.9   A sample tree showing the weld mesh enclosure and shade cloth awning used to protect the heat pulse equipment. The vegetation depicts the green conditions that existed during the February 2004 visit.

Figure 5.10 A view of several of the heat pulse sample trees. The grass was dry and dormant during this period in September 2004.

Analysis of the heat pulse data is complex, involving procedures to adjust for asymmetrical probe alignment, removal of "spikes" caused by electrical noise or poor grounding, identification of malfunctioning thermocouple and heater probes, and patching of bad or missing data. The procedures followed are described in Appendix 2.

The HPV probes were removed from the Marula and False Marula sample trees at the end of the autumn field trip (May 2005), since sap flow rates had dropped to very low levels, and most of the leaves were either already shed or in a state of senescence. The probes in the *Combretum* sample trees were left in place, since functional leaves were still in evidence. Low sap flow rates in these trees were monitored throughout the winter months. Probes were reinstalled in newly drilled holes in the spring of 2005, and HPV was monitored over a second (2005/6) growing season. In May 2006, shallow wood cores were carefully removed to determine the wound widths, sapwood moisture content and density, and total sapwood areas of each sample tree.

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Figure 5.11   A view of a datalogger and multiplexer wired to only four of the potential 12 probe sets per multiplexer and 24 probe sets per datalogger.

Figures 5.12 and 5.13 show the complete pattern of sap flow estimated for the smaller *Lannea schweinfurthii*, sample tree. The data show clearly how this species rapidly builds up to a peak rate of sap flow, but also how this is closely controlled by rainfall and soil water availability. The correlation between sap flow and rainfall is especially marked when monthly totals are compared (Figure 5.13). Figures 5.14 and 5.15 show comparable data for one of the *Combretum apiculatum* sample trees at the same site, while Figures 5.16 and 5.17 illustrate comparable data for one of the *Sclerocarya birrea* trees. All species show growing season changes due to a spring build-up in leaf area, and an autumn decline as the leaves senesce (Figure 5.18). *C. apiculatum* retains leaves to some extent in winter, and this keeps sap flow from declining to zero. All three species are also very responsive to rainfall and the decline of available soil water during dry periods. The *Sclerocarya birrea* sapwood was found to be unusually deep (~10 cm), and the junction between sapwood and heartwood proved to be indistinct. Since the HPV probes could only reach approximately 4 cm into the sapwood, there was uncertainty about the radial HPV profile within the sapwood. This uncertainty was enhanced when the deepest HPV probes yielded high HPV rates. For the purpose of this analysis, we arbitrarily assumed the sapwood to be 6 cm deep, a distance that was adequately sampled by the HPV probes. This limited the daily sap flow estimates to what we judged to be realistic rates. Thus, the overall pattern of ET over the growing season, as well as the responses to rainfall, are accurately portrayed for this species, but there is a degree of uncertainty on the absolute amount of sap flow involved.
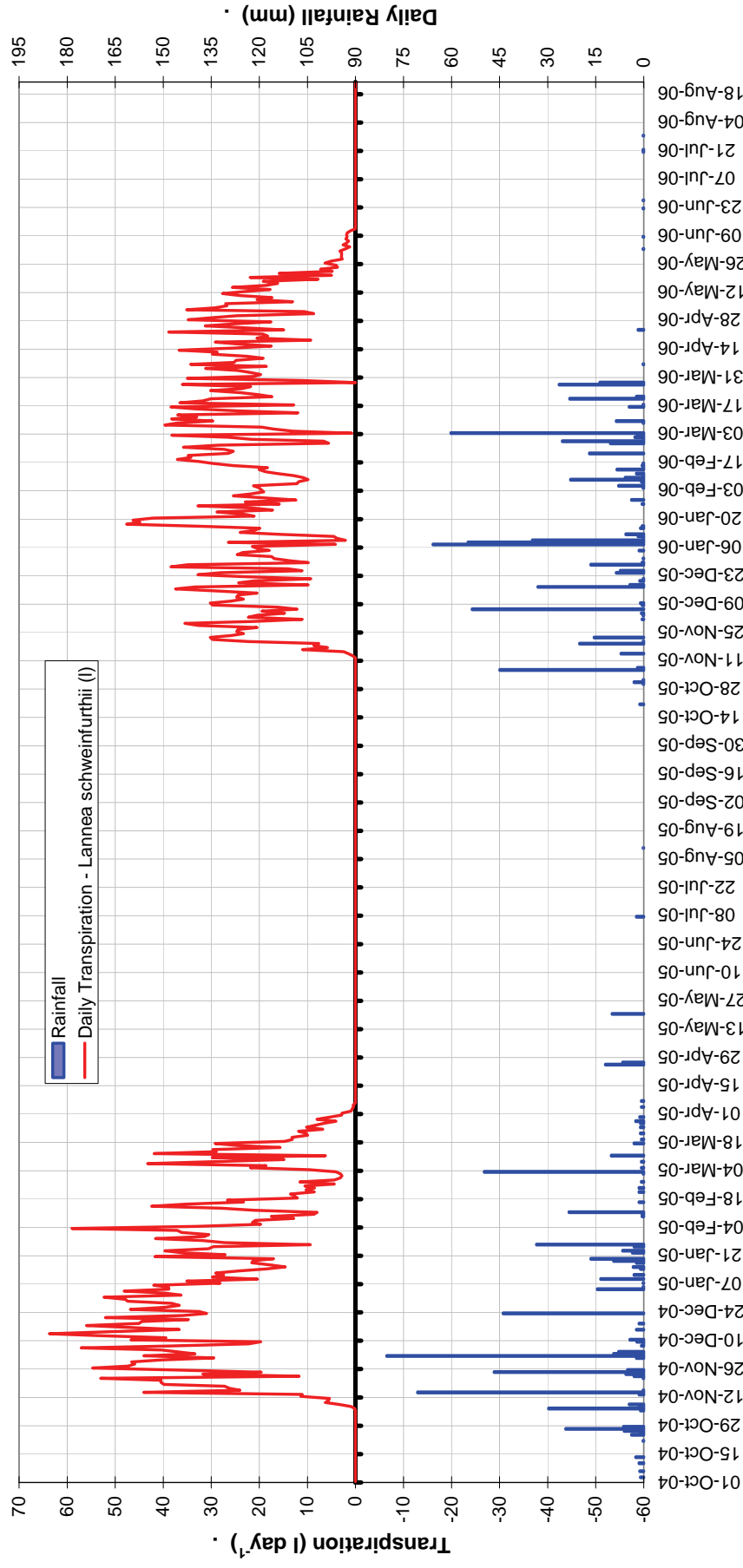
Figure 5.12   Daily transpiration and daily rainfall in a Lannea schweinfurthii *sample tree recorded at the* Combretum *savanna site in the Kruger National Park over a period of two growing seasons.*
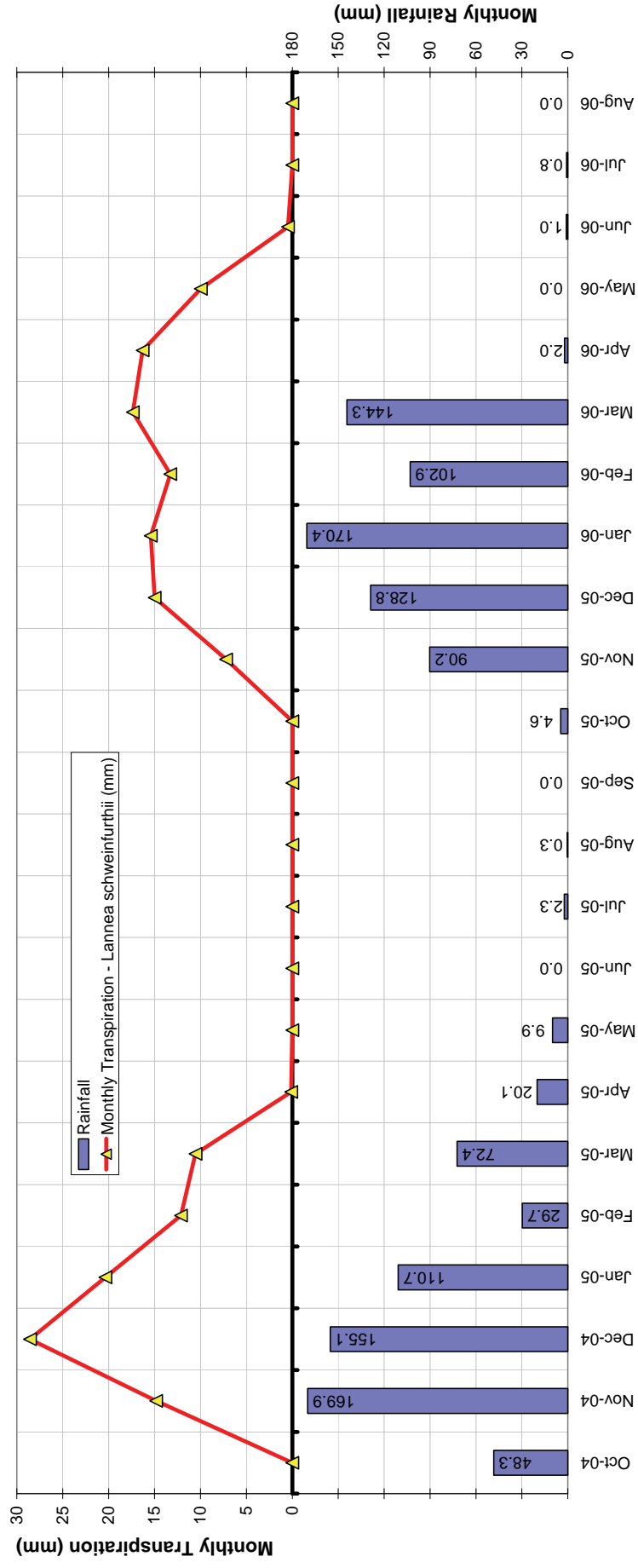
Figure 5.13 A comparison of monthly transpiration recorded in the *Lannea schweinfurthii* sample tree to monthly total rainfall recorded over two growing seasons at the Combretum site in the Kruger National Park.

60
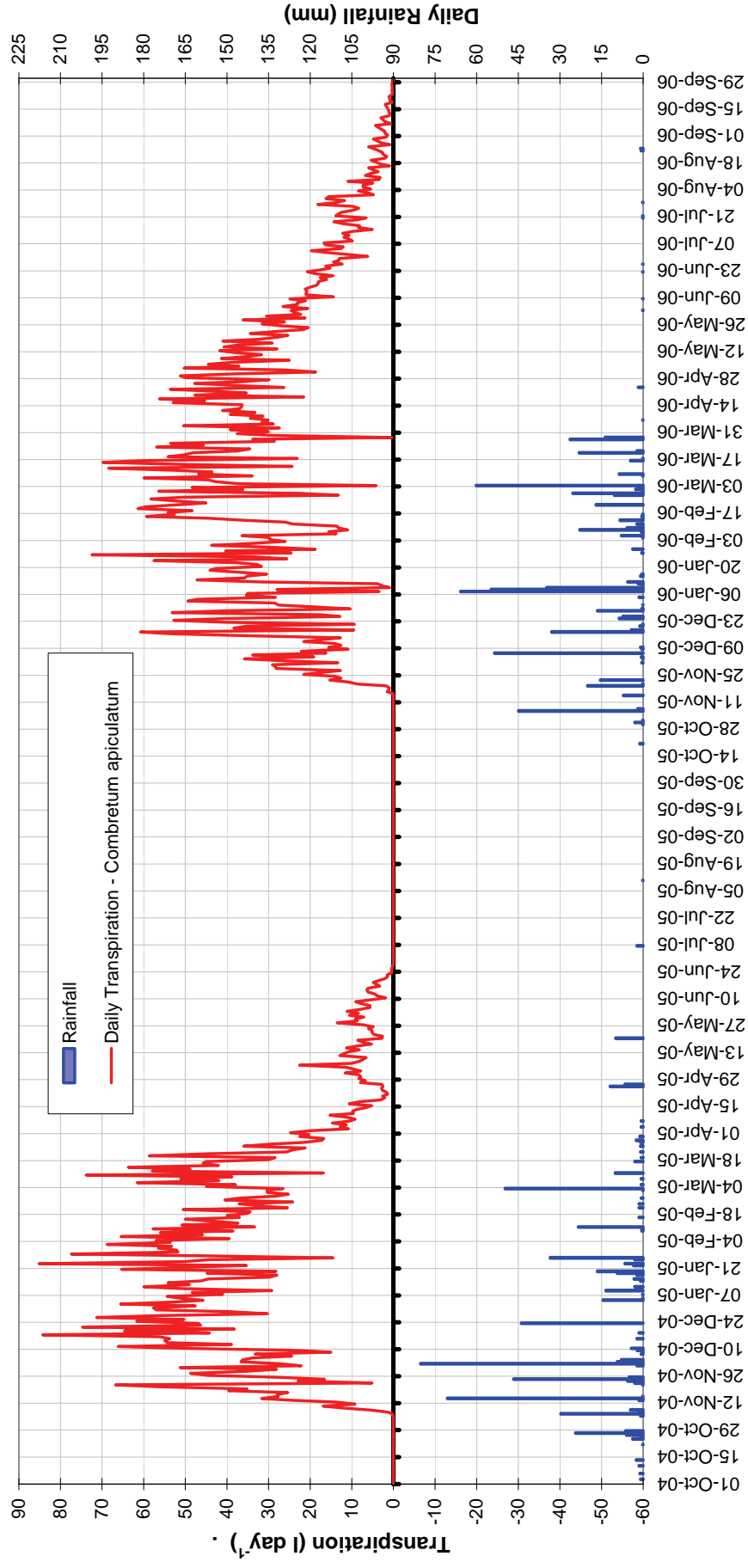
Figure 5.14 Daily transpiration and daily rainfall in a Combretum apiculatum sample tree recorded at the Combretum savanna site in the Kruger National Park over a period of two growing seasons.

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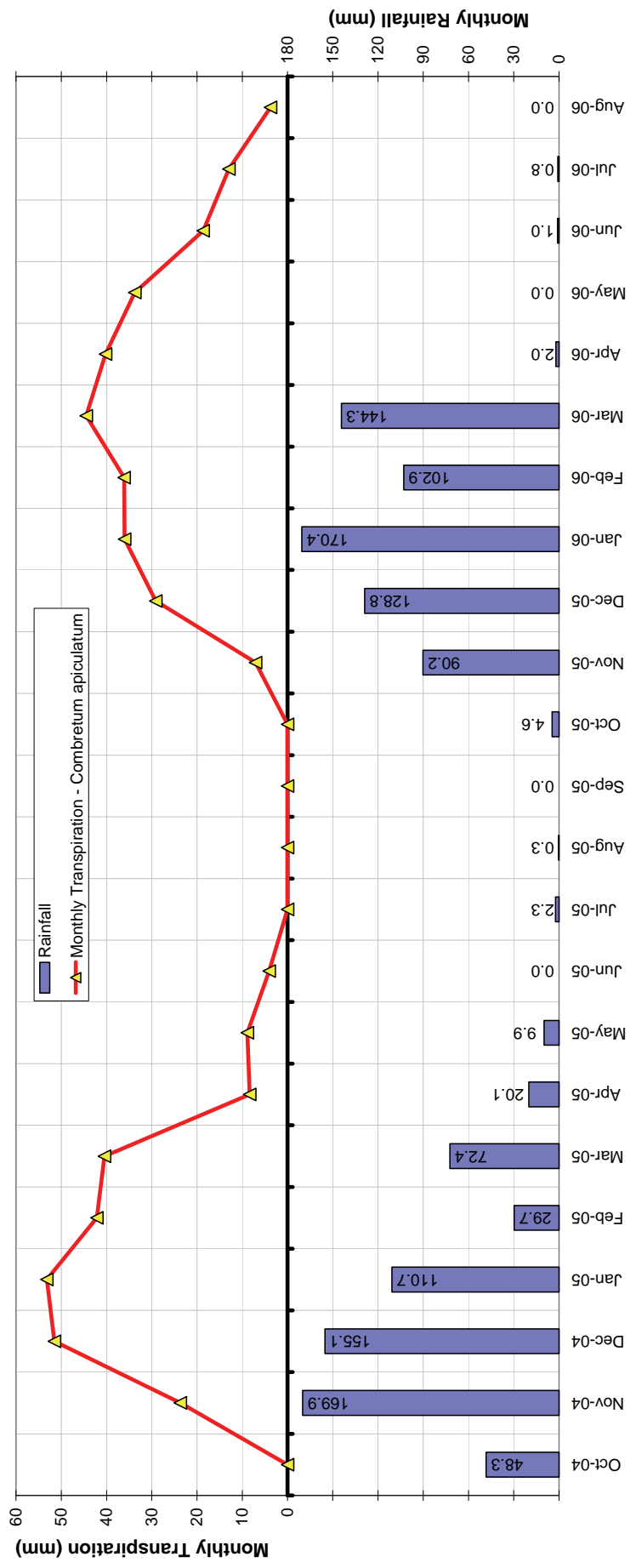
Figure 5.15   A comparison of monthly transpiration recorded in a Combretum apiculatum sample tree to monthly total rainfall recorded over two growing seasons at the Combretum site in the Kruger National Park.

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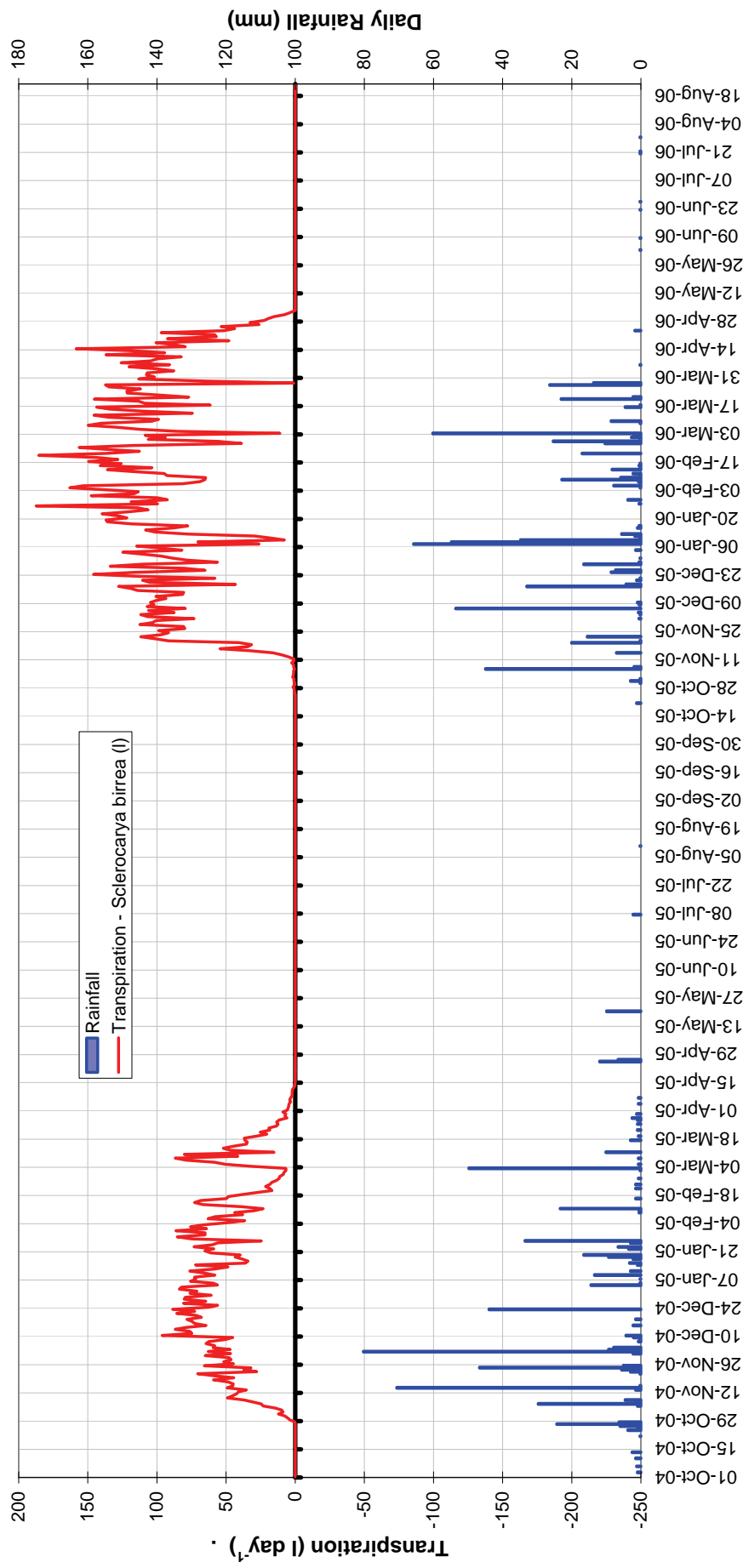
Figure 5.16   Daily transpiration and daily rainfall in a Sclerocarya birrea sample tree recorded at the Combretum savanna site in the Kruger National Park over a period of two growing seasons.

63
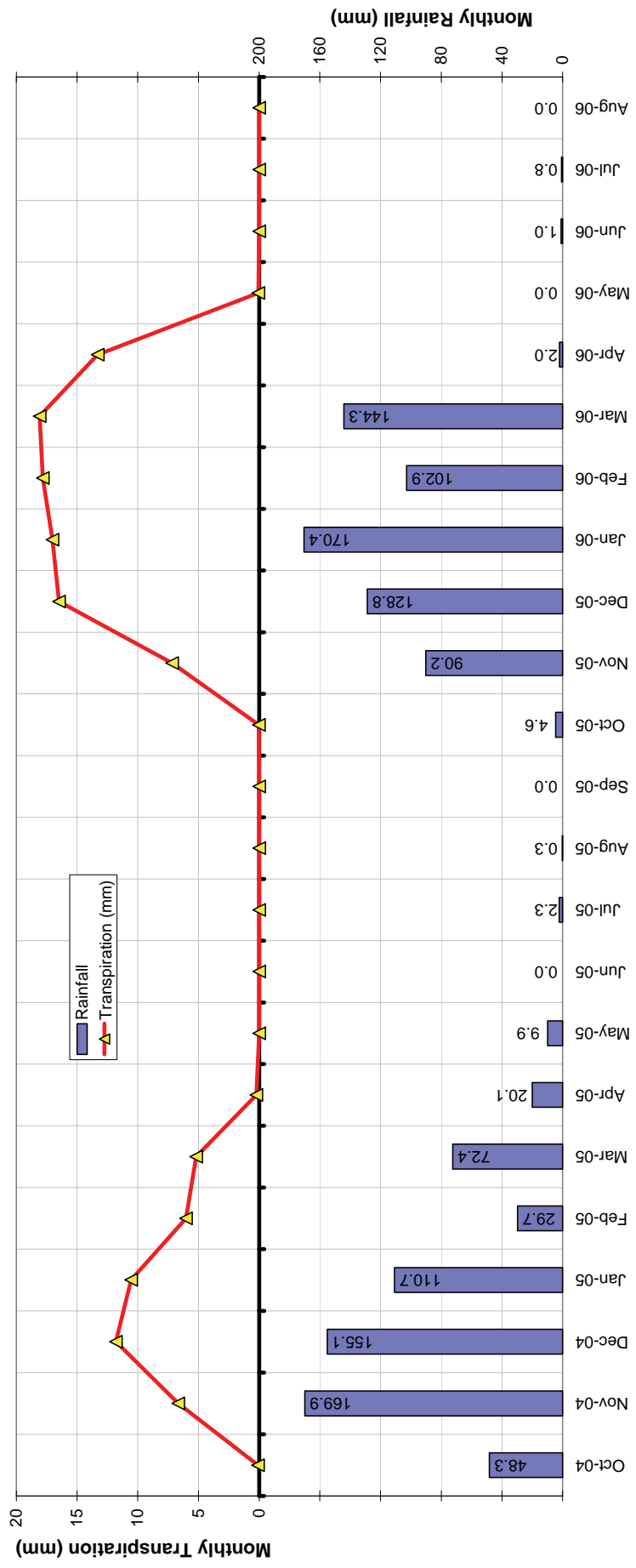
Figure 5.17   A comparison of monthly transpiration recorded in a Sclerocarya birrea sample tree to monthly total rainfall recorded over two growing seasons at the Combretum site in the Kruger National Park.

64
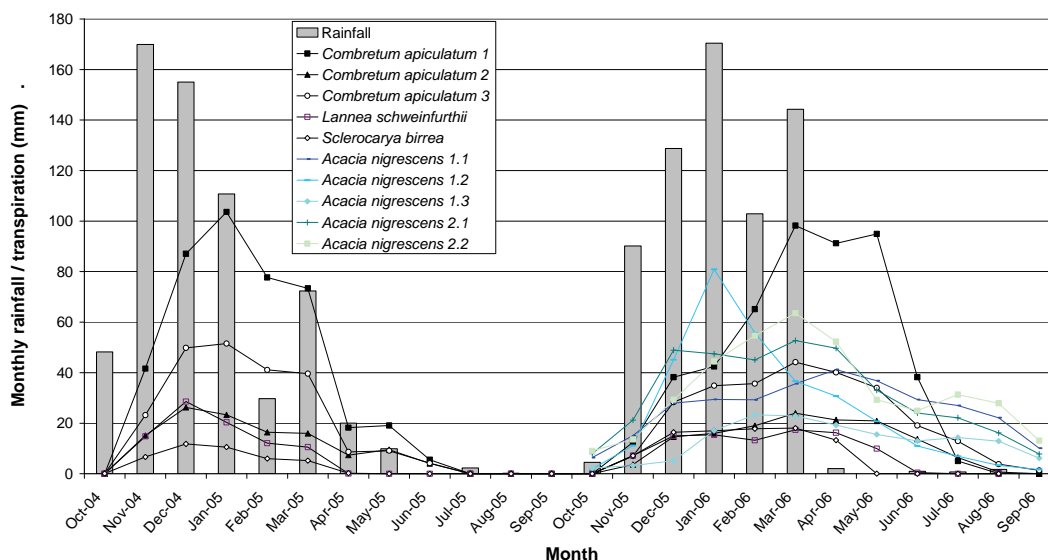
Figure 5.18 Mean monthly transpiration from six trees of four species recorded over two growing seasons in the Kruger National Park. Bars illustrate monthly rainfall.

Table 5.2 illustrates the manner in which mean monthly tree transpiration was estimated for the site. Monthly total sap flow is shown for six different trees. These monthly values were adjusted by 0.7 to account for the observed proportion of tree and shrub canopies in the vicinity. Estimated annual transpiration from trees/shrubs amounted to 149.7 mm and 150.0 mm in 2004/5 and 2005/6, respectively, comprising 24.2% of rainfall in 2004/5 and 23.3% in 2005/6.

Table 5.2   Monthly transpiration from six sample tree canopies extrapolated to landscape scale.

Month	Rainfall (mm)	Mean transpiration from 6 sample trees (mm) on a canopy area basis	Fraction of tree canopy in landscape	Estimated mean tree transpiration (mm)
Oct 2004	48.3	1.3	0.7	0.9
Nov	169.9	20.5	0.7	14.3
Dec	155.1	42.1	0.7	29.5
Jan 2005	110.7	42.8	0.7	30.0
Feb	29.7	33.1	0.7	23.2
Mar	72.4	32.9	0.7	23.0
Apr	20.1	14.1	0.7	9.8
May	9.9	11.8	0.7	8.3
Jun	0.0	6.3	0.7	4.4
Jul	2.3	3.7	0.7	2.6
Aug	0.3	2.8	0.7	1.9
Sep	0.0	2.5	0.7	1.8
	618.6	**213.9**		**149.7**
Oct	4.6	0.0	0.7	0.0
Nov	90.2	7.5	0.7	5.3
Dec	128.8	22.5	0.7	15.8
Jan 2006	170.4	25.2	0.7	17.6
Feb	102.9	30.2	0.7	21.1
Mar	144.3	40.4	0.7	28.3
Apr	2.0	36.5	0.7	25.5
May	0.0	32.0	0.7	22.4
Jun	1.0	14.3	0.7	10.0
Jul	0.8	4.9	0.7	3.4
Aug	0.0	0.9	0.7	0.6
	645.0	**214.4**		**150.0**

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5.4 Evapotranspiration modelling

A realistic model simulation of the Sandveld site was recognized from the outset to be an important requirement for the estimation of WUE in savanna trees. Direct measurement of tree growth increments is made difficult by the variation in species and tree age, as well as slow growth rates and variable stem and branch structure. Sap flow measurement has been shown to be possible in three of the dominant species in Sandveld, but the degree of replication among different trees is severely limited by the availability of HPV equipment, and data can only provide a rough estimate of the landscape-scale transpiration loss from trees.

Due to tree/shrub/grass composition of the savannah, and the associated variation in plant structure and leaf area, a big-leaf model was deemed inappropriate for this situation. The model CENTURY, on the other hand, is a generic ecosystem model which has been parameterised by Dr Bob Scholes and his co-workers for the Sandveld site in the vicinity of the flux tower. The model is described in a manual available on the internet site (http://www.nrel.colostate.edu/projects/century/manual4/man96.html) and a useful description is provided by Landsberg and Gower (1997). The following brief description of the model is drawn primarily from these two publications.

Century (Parton *et al.*, 1988) has been designed and parameterised to simulate the water, carbon and nutrient budgets (N, P and S) of grassland, crops, forest and savanna vegetation. Different plant production sub-models are used for each of these, but there is a common soil organic matter sub-model. Savanna simulations are performed using both grassland/crop and forest sub-systems and allows for these to interact through shading effects and nitrogen competition. The soil organic matter sub-model simulates the flow of C, N, P, and S through plant litter and the different inorganic and organic pools in the soil. The model runs using a monthly time step and the major input variables for the model include:

1) monthly average maximum and minimum air temperature
2) monthly precipitation
3) lignin content of plant material
4) plant N, P, and S content
5) soil texture and soil depth
6) atmospheric and soil N inputs
7) initial soil C, N, P, and S levels.

The water budget plays a very important role in plant production in savannas. It is simulated using a simplified monthly time step sub-model that calculates evaporation and transpiration, soil water content, and flow of water between soil layers. Soil water holding capacity for each soil layer is calculated as a function of bulk density, soil texture and soil organic matter content using the equation developed by Gupta and Larson (1979). Water loss by transpiration is derived empirically as a function of live leaf mass, rainfall and potential ET.

The potential evapotranspiration rate (PET) is calculated as a function of the average monthly maximum and minimum air temperature using the equations developed by Linacre (1977), and may be modified by a user specified multiplier. Bare soil water loss is a function of standing dead and litter biomass (lower for high biomass levels), rainfall and PET. Interception water loss is a function of aboveground biomass, rainfall and PET. Potential transpiration is a function of the live leaf biomass and PET. Interception and bare soil water losses are calculated as fractions of the monthly precipitation and are subtracted from the total monthly precipitation, with the remainder of the water added to the soil.

Water is distributed to the different soil layers by adding the water to the top layer and then cascading excess water (water above field capacity) to the next layer. Transpiration occurs after the water is added to the soil. Water loss occurs first as interception from plant surfaces; followed by bare soil evaporation and transpiration (the sum does not exceed the PET rate). The maximum monthly evapotranspiration water loss rate is equal to PET.

Monthly weather data for 2005 and 2006 (recorded at the flux tower) were appended to the CENTURY weather file, and the period from July 2005 to June 2006 modelled using version 4.5 of the model. Some important site variables of significance to the calculation of site water balance are shown in Table 5.3.

Table 5.3   Important site variables of significance to the calculation of site water balance.

Variable	Value	Description
SAND	0.69	Volume fraction
SILT	0.05	Volume fraction
CLAY	0.26	Volume fraction
ROCK	0.1	Volume fraction
BULKD	1.71	Bulk density
NLAYER	6	Number of soil layers
NLAYPG	4	Number of soil layers primarily governing plant growth rates
AWTL(1)	0.8	Fraction of available soil water that can be used by the roots in each soil
AWTL(2)	0.6	layer
AWTL(3)	0.4	
AWTL(4)	0.3	
AWTL(5)	0.2	
AWTL(6)	0.2	
AWTL(7)	0.2	

5.5   *Tree growth modelling*

A modelling approach to the estimation of tree/shrub productivity was adopted for the following reasons:

- In many of the trees and shrubs at this site, stems may be multiple and poorly defined. The overall above-ground growth increment is a more appropriate measure of tree productivity, especially if firewood is the most likely economic use where trees are permitted to be harvested.

- Growth rates are very slow, and may be negative over successive years of poor rainfall.

- There are formidable sampling problems in estimating tree productivity, due to great spatial variation in tree density and species composition, as well as damage by large herbivores.

Consequently, it was considered that a more reliable tree growth estimate could be based on the modelled carbon balance of the whole system, after validation against measured carbon fluxes. Carbon comprises a reasonably constant proportion of plant biomass. The general ecosystem model CENTURY has been parameterised by Dr Bob Scholes for the flux tower site, and validated against available field data. The proportion of total ET originating from trees and shrubs, as well as the above-ground net primary production of the trees and shrubs, was estimated using the standard monthly version of the model (CENTURY 4.0; Parton *et al.*, 1993) and based on a simulation over the period from 1960 to 2003. Weather data from the weather station at Skukuza was used for the period 1960 to 1999, and thereafter from the data collected at the flux tower. The result of a 43-year simulation showed mean wood production (stems and branches) to be 297 kg ha^{-1} yr^{-1} (Table 5.4).

Table 5.4   Estimates of various components of net primary production (NPP) and water-use for the Skukuza site, Combretum savanna on sandy soils, using the CENTURY model calibrated for the site, and partially validated against predicted soil and plant carbon stock data.

	Whole system NPP	Above-ground NPP	Wood production
	Kg ha^{-1} yr^{-1}		
Mean	6 372	3 413	297
Std deviation	1 228	652	149
Range	5 322	2 726	585
n	43	43	43
Std error	189	101	23

5.6   Water-use efficiency

Table 5.5 shows relevant outputs from the CENTURY simulation that was used in the estimation of WUE. A summary of WUE calculations is shown in Table 5.6. These data form the basis for an analysis of the economic WUE of trees at this site (Chapter 8, Table 8.3).

Table 5.5   The calculation of WUE based on outputs from the CENTURY simulation.

	System water-use (ET)	Transpiration	System WUE	Above ground WUE	Wood WUE
	mm yr^{-1}		kg ha^{-1} mm^{-1}		
Mean	621	354	10.27	5.50	0.84
Std deviation	106	71	1.28	0.70	0.42
Range	403	268	5.91	3.18	2.17
N	43	43	43	43	43
Std error	16	11	0.20	0.11	0.07

Table 5.6   A summary of WUE calculations averaged for all species for the Sandveld savanna site

Total mean annual ET (mm)*	621
Total transpiration (trees and grass) (mm)	354
Tree transpiration (mm)	150
Wood annual volume increment (m^3 ha^{-1})**	0.424
WUE (m^3 wood m^{-3} ET from stand)	0.000068
WUE (m^3 wood m^{-3} TR from trees)	0.000283
Wood density (kg m^{-3})	700
WUE (g wood kg^{-1} ET from stand)	0.0476
WUE (g wood kg^{-1} TR from trees)	0.1981

* ET assumed equal to MAP
**Wood volume increment applies to the sum of both stem and branches

6. COMPARATIVE WUE IN COMMERCIAL FOREST PLANTATIONS

An important requirement of this project was the comparison of growth and water-use rates recorded from the various indigenous forest and woodland systems, to those of commercial forestry species. This was based on two separate analyses:

- A 3-PG model simulation of the growth and water-use of a stand of *Pinus radiata* at a typical site in the southern Cape
- A review of available published information on the WUE of commercial forest stands (mainly *Eucalyptus* species).

6.1 *Pinus radiata in the Southern Cape*

Pinus radiata is the most appropriate forestry species to compare to indigenous forests in the Southern Cape, since it is the dominant commercial timber species in the region. The growth and physiology of this species is comparatively well known, and much information is available in the scientific literature. This literature was reviewed by the project team. Yield tables for this species in the southern Cape (Kassier and Kotze, 2000) were used to portray typical growth rates for this species. A typical saw-timber rotation was simulated, assuming a medium-quality site (2), a rotation length of 28 years, and a planting density of 1 111 stems per hectare.

Species parameter values finally adopted for the *Pinus radiata* simulations are shown in Appendix 7. These simulations were run for the period 1971 to 1994. Input weather data from the Saasveld weather station were obtained from a database made available by the School of Bioresources Engineering and Environmental Hydrology, UKZN. Tree growth was simulated from age four until harvest age. Two scenarios were simulated. In the first, it was assumed that the trees only had access to soil water originating from rainfall falling on the site. No additional source of water was simulated. In the second scenario, it was assumed that soil water was augmented by additional water originating from lateral drainage to the site from upslope areas, or from fog-drip. The reason for the two scenarios is that evidence of soil water augmentation in the Groenkop forest has been obtained (see Chapter 3). It is not known whether *P. radiata* plantations would thrive under the same site conditions, especially in light of the known preference of this species for well-drained soils (Schutz, 1993). Consequently, WUE is estimated for both scenarios.

6.1.1 Results

Figures 6.1, 6.2 and 6.3 illustrate modelled mean monthly leaf area index, diameter at breast height and stand volume, respectively. Typical values of mean DBH and stand cumulative volume obtained from the yield tables are superimposed on figures 6.2 and 6.3.

Figure 6.1   The trend in leaf area index (LAI) simulated for Pinus radiata *for a scenario in which soil water originates only from infiltrating rainfall.*
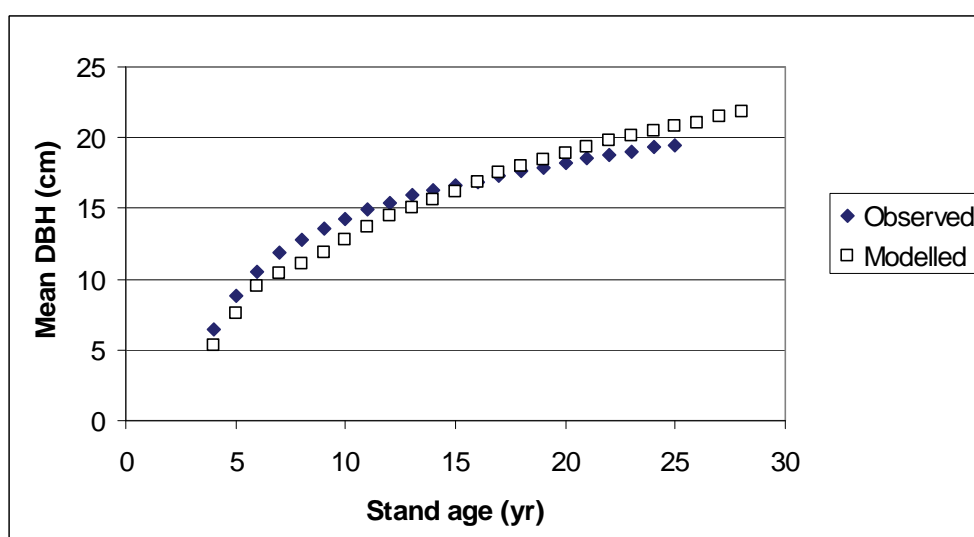
Figure 6.2   A comparison of "observed" and 3-PG modelled mean tree diameter at breast height (DBH) over the course of a 28-year rotation of P. radiata *under conditions where soil water originates solely from infiltrating rainfall.*

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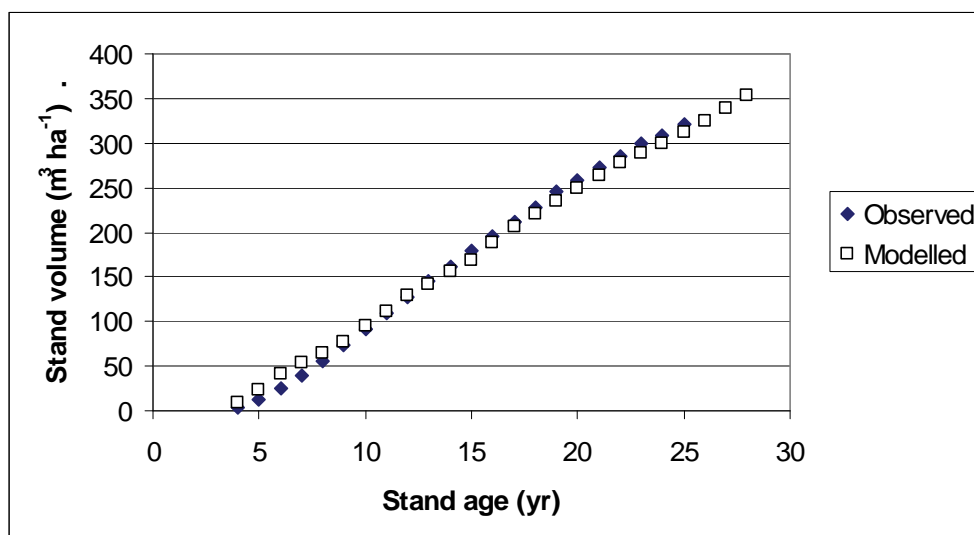
Figure 6.3   A comparison of "observed" and 3-PG modelled whole-stand stem volume over the course of a 28-year rotation of P. radiata, *under conditions where soil water originates solely from infiltrating rainfall.*

The total cumulative stand volume from age 4 to age 25 was 345 m^3 ha^{-1}. Over the same period, cumulative evapotranspiration totalled 17 222.8 mm. Given that 1 mm over a hectare is equivalent to 10 m^3, total ET amounts to 172 228 m^3. Thus, 1 m^3 of wood produced over the rotation is equivalent to 499.2 m^3 of water evapotranspired (equivalent to 0.8013 g utilizable stem per kg ET from stand, assuming a wood density of 400 kg m^{-3}). Total rainfall recorded over this period amounted to 18 400.4 mm. ET therefore comprised 93.6% of rainfall at the site, the remainder accounted for through deep drainage, lateral soil drainage, and overland flow. Cumulative transpiration from the trees totalled 16 538 m^3. Thus 1 m^3 of wood was produced per 479 m^3 of water transpired (equivalent to 0.835 g utilizable stem per kg TR from trees, assuming a wood density of 400 kg m^{-3}).

6.1.1.1   Additional soil water scenario

The available water capacity (AWC) of the *P. radiata* scenario was increased to an arbitrary 750 mm to ensure that transpiration was not limited by soil water deficits at any time through the simulation period. In this way, it was possible to evaluate the change of WUE resulting from site conditions that more closely resemble the Groenkop forest site. Figures 6.4, 6.5 and 6.6 illustrate modelled trends in LAI, mean DBH and stand volume.
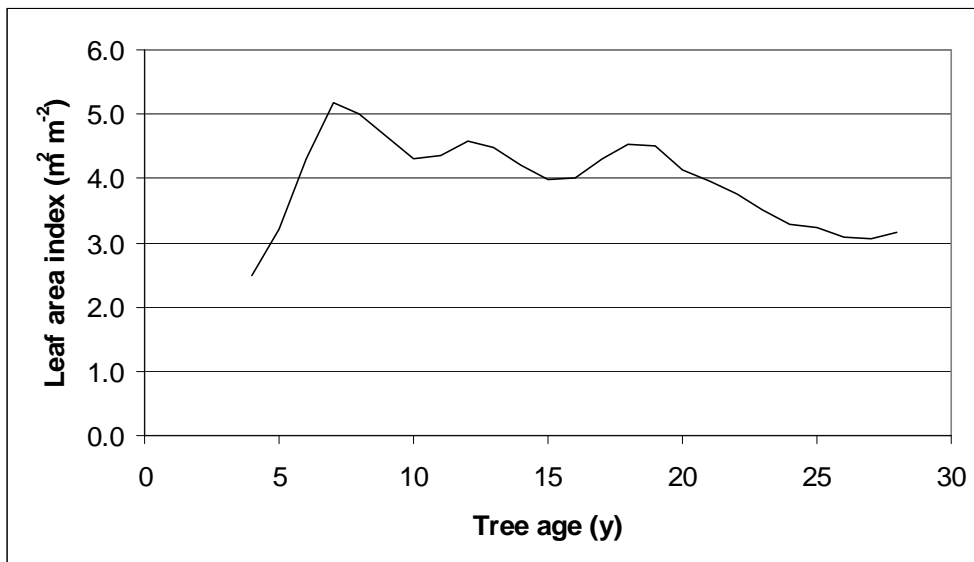
Figure 6.4   The trend in leaf area index (LAI) simulated for Pinus radiata for a scenario in which soil water originating from infiltrating rainfall is augmented by lateral in-flow.
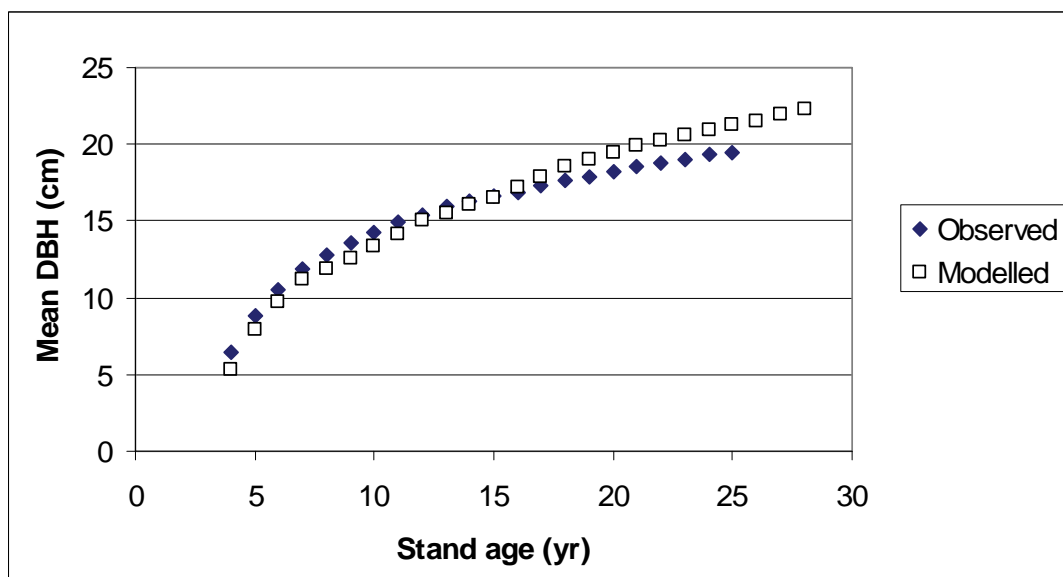
Figure 6.5   A comparison of "observed" and 3-PG modelled mean tree diameter at breast height (DBH) over the course of a 28-year rotation under conditions where soil water originating from infiltrating rainfall is augmented by lateral in-flow.
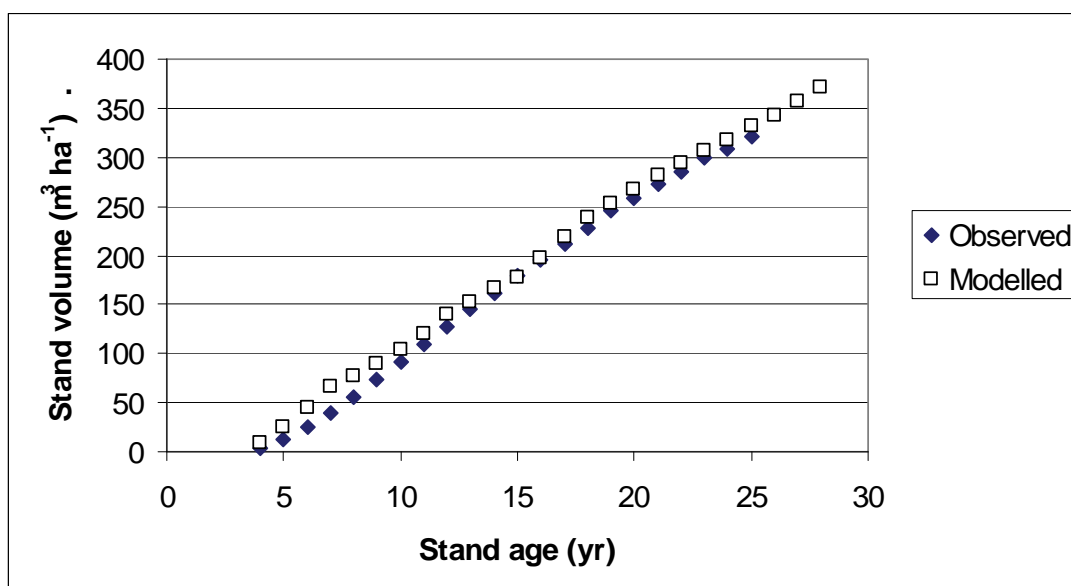
Figure 6.6   A comparison of "observed" and 3-PG modelled whole-stand stem volume over the course of a 28-year rotation, under conditions where soil water originating from infiltrating rainfall is augmented by lateral in-flow.

The total cumulative stand volume from age 4 to age 25 was 362.9 m^3 ha^{-1}. Over the same period, cumulative evapotranspiration totalled 17 914.8 mm. Given that 1 mm over a hectare is equivalent to 10 m^3, total ET amounts to 179 148 m^3. Thus, 1 m^3 of wood produced over the rotation is equivalent to 493.7 m^3 of water evapotranspired. Total rainfall recorded over this period amounted to 18 400.4 mm. ET therefore comprised 97.4% of rainfall at the site.

There is thus little difference in the growth yields, ET and WUE between the two scenarios, indicating that the distribution of rainfall and soil water storage capacity in this environment is sufficient for the trees to avoid significant drought stress and reduction in transpiration and growth rates. The WUE difference between the two scenarios is small, illustrating that a simulation of a typically well-drained *P. radiata* site can be usefully compared to the Groenkop forest.

6.2   Review of WUE of commercial forests

Due to the lack of reliable ET measurement systems until very recently, there are few data describing measured ET rates from South African forest plantations. What few estimates we have are indirectly inferred from long-term catchment water balance measurements, from modelling studies, or from soil water balance measurements over a period of time. Such indirect estimates are subject to numerous errors, and these are discussed later in Chapter 7. They are thought to be responsible for much of the poor correlation between annual rainfall and annual growth increments recorded in a variety of ICFR spacing trials reported by Smith *et al.* (2005) and illustrated in Figure 6.7. Figure 6.8 illustrates that this measure of WUE declines as site index drops.
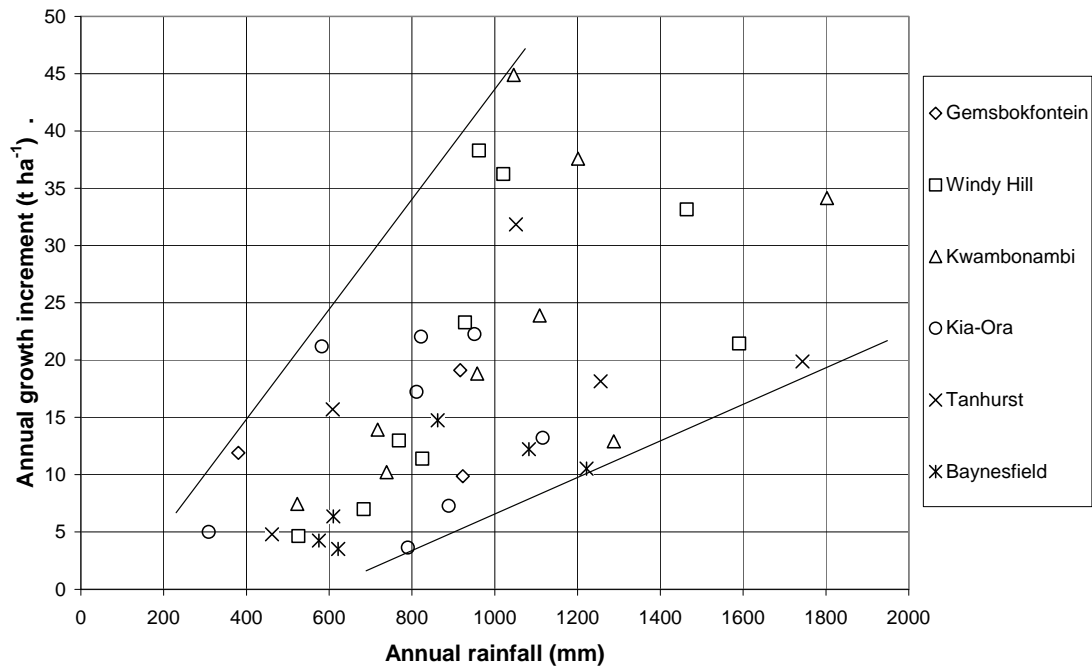
Figure 6.7   The relation between annual rainfall and annual growth increment recorded in six spacing trials in KwaZulu-Natal and Mpumalanga (Smith et al., 2005).
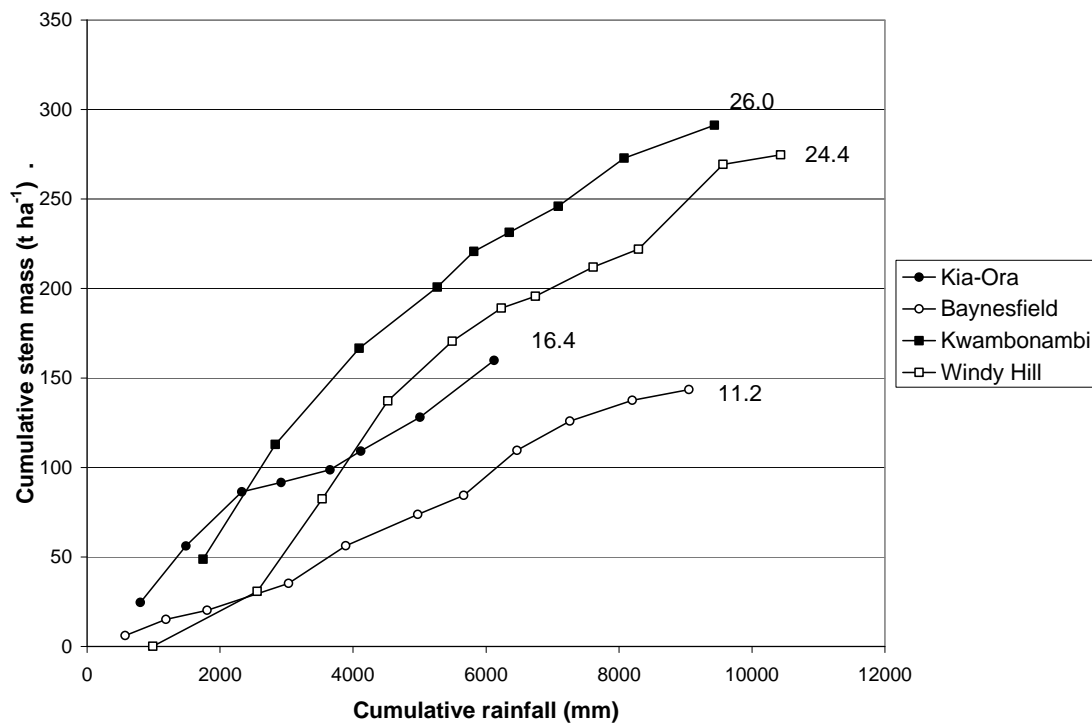
Figure 6.8   The relation between cumulative rainfall and cumulative stem growth recorded at four sites with varying site quality (indicated by site index numbers on the graph).

In contrast to ET measurement systems, sap flow measurement systems have been available to South African forest scientists for many years, and several *Eucalyptus* spp. and *Pinus patula* WUE studies have been performed over the past 15 years in diverse plantation forests and districts (KwaMbonambi, Kruisfontein, Witklip, Mkuzi, Frankfort, Legogote). In these investigations, tree diameters and heights of sample trees were measured 12 months apart or occasionally at longer intervals. Sap flow was measured directly in the sample trees using the heat pulse velocity technique. Total 12-month sap flow was then

compared to the annual growth increment. The disadvantage of such studies is that measurement periods are relatively short (mostly one year). As has been demonstrated above, annual growth increments are variable from year to year, and may be markedly reduced by drought conditions. An advantage, however, is that actual tree water-use (sap flow) is measured, which is expected to be closely correlated to tree structural and physiological properties, since losses due to canopy rainfall interception, overland flow, deep drainage, etc. are not included.

Figure 6.9 illustrates the range in WUE (t stem mass per t transpiration) recorded at the various sites. Further details of these sites are reported by Dye *et al.* (2001).
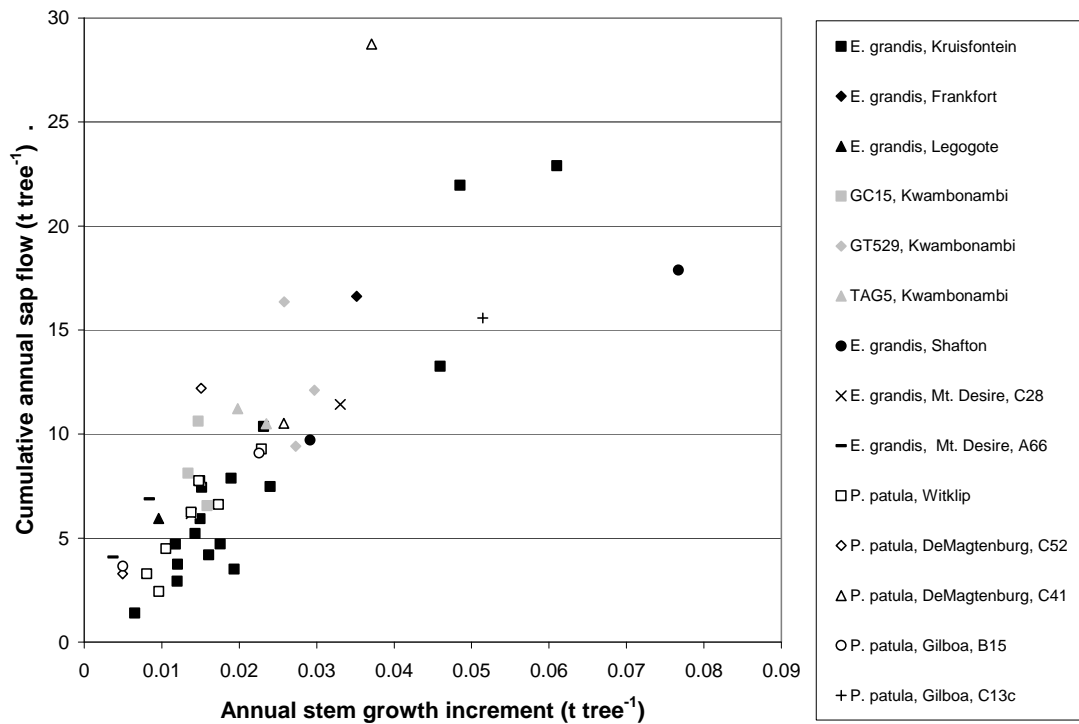
Figure 6.9   The relation between annual stem growth increment and cumulative annual sap flow recorded in plantation-grown Eucalyptus *and* Pinus *trees of various ages at 14 sites in KwaZulu-Natal and Mpumalanga.*

Variability in WUE increases with increasing annual stem growth increment, and this may reflect poorer sampling of the larger sapwood area by the heat pulse probes.

Figure 6.10 illustrates the numeric range of WUE (g stem mass kg^{-1} water transpired) recorded at all sites.
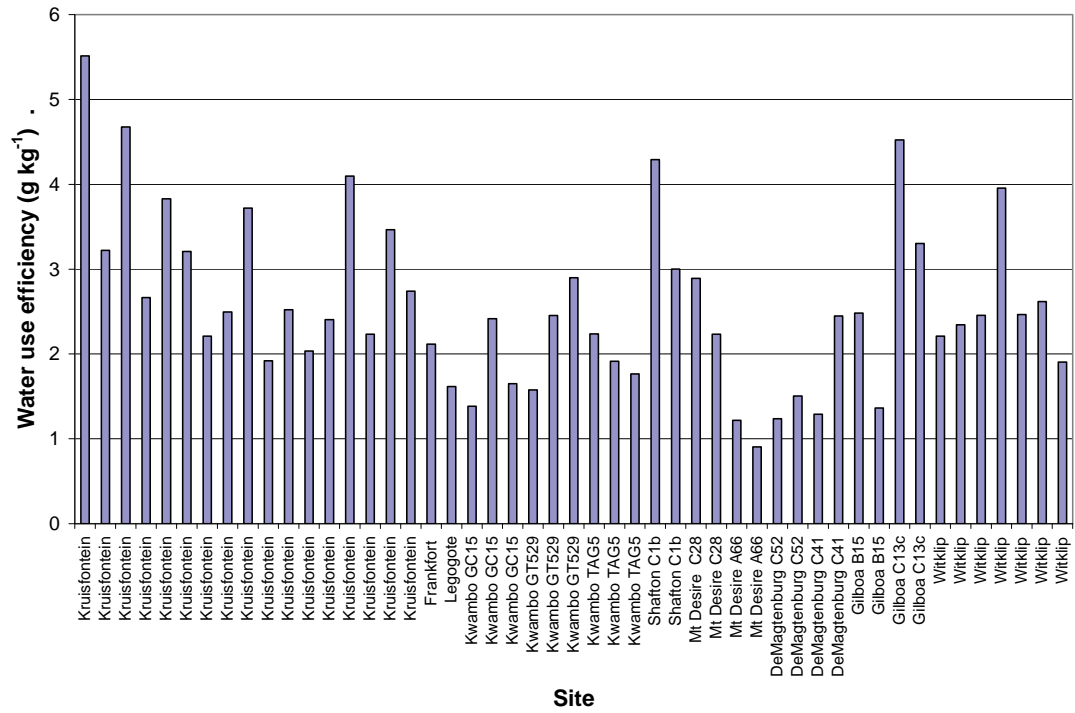
Figure 6.10   WUE (g of utilizable stem mass per kg of water transpired) recorded in a variety of E. grandis *and* P. patula *trees at locations in Mpumalanga and KwaZulu-Natal.*

7. SOME REFLECTIONS ON MODELLING THE WATER-USE OF INDIGENOUS FORESTS, FOREST PLANTATIONS, WOODLANDS AND SAVANNAS

This project has demonstrated that the greatest limitation to improving the understanding of water-use efficiency in forests is the dearth of information on water-use. This is because of the technical difficulty of measuring ET directly, and the difficulty and expense of maintaining measurements over periods that are long-enough to adequately cover seasonal and year-to-year variation in weather conditions and tree condition. Models necessarily play an important role in linking measured ET rates to soil, plant and atmospheric conditions, and then extending predictions over time. Adding to this complexity is the floristic and structural variations among different forests, and an almost infinite degree of site variation that exists in South Africa, and which play a significant role in governing ET rates. Consequently, an important output of this project is a modelling framework to assist in the selection of appropriate models for estimating water-use.

The selected study sites for this project were purposefully diverse, to permit assessment of different ET patterns, their environmental controls, and the various modelling challenges. From the earlier discussions, it is evident that the sites differed in fundamental ways, and that different modelling approaches are indeed needed to best simulate ET. This section attempts to highlight the important features of forests, woodlands, savannas and tree plantations that affect ET patterns, and which determine the choice of appropriate model. It is assumed that models are required to evaluate the water-use and hydrological impacts of stands or patches of trees/forests. Models describing individual trees are not considered. The emphasis is on ET prediction, and so little or no coverage of growth, economics, social impacts, streamflow impacts, etc. are provided.

An assumption made here is that the crop coefficient approach is not appropriate for tree-dominated systems, for reasons described earlier. In most recent models, ET estimation is based on one of the many forms of the Penman-Monteith (P-M) equation (Monteith, 1965). This equation has stood the test of time, and successfully combines the energy balance, aerodynamic and plant controls on the evaporation process. It is described in numerous publications (e.g. Landsberg and Gower, 1997; Allen *et al.*, 1998; Landsberg, 1999). The treatment of energy availability and aerodynamic resistance to evaporating water is relatively straightforward and calculated using tried and trusted formulae. The necessary input data are generally readily available or estimated. Cognisance must be taken of the effects of aspect and restricted sky views on receipt of solar and net radiation in rugged topography that is commonly associated with high rainfall forests in South Africa.

The plant control over evaporation rate is embodied in the canopy conductance term of the P-M equation, which incorporates the influence of leaf area and mean leaf stomatal conductance to water vapour. Leaf stomatal conductance is particularly sensitive to changes in atmospheric evaporative demand, and the supply of water from the soil to the leaves, and varies greatly on an hourly, daily and seasonal basis. Since it is governed by many atmospheric, plant and soil controls, it must be modelled to obtain a realistic ET prediction. This particularly applies to tall plants such as trees, where canopy ventilation is effective, and where stomatal conductance is therefore closely coupled to ambient humidity and temperature.

A widely used canopy conductance model developed by Jarvis and modified to fit a wide range of forest types by Granier *et al.* (2000), was described in equation 3. However, there are many complexities in estimating g_c correctly for forests, and these often determine the type of model required for a given forest. Some of the more important model requirements are discussed below.

7.1   Single species/even-aged versus multi-species/multi-aged forests

Single species/even-aged stands are typical of intensively-managed forest plantations. The structure and functioning of such forests are relatively simple to describe, and this permits more detailed simulation of growth and water-use processes. A good example of this kind of "process-based" model is 3-PG (Landsberg and Waring, 1997).

The multi-species situation is typical of natural forests, and is characterised by much greater structural and physiological variation. Where the species composition and forest structure is relatively uniform, it may be possible to treat the entire forest as a big leaf, as was the case in the Groenkop forest. This approach assumes a low degree of spatial variability, and is most likely to work in climax forests with maximum leaf areas and minimal environmental perturbation. A more complex type of model is based on separate analyses of all individual trees located in a specific sample area, where the structure and physiological characteristics of each tree is described. This type of model appears to be impractical for all but research applications.

7.2   Soil water availability

The availability of soil water to trees is critically important in estimating canopy conductance and ET, since leaf stomata close to reduce evaporation when the supply of water to the leaves drops below the rate of evaporation to the atmosphere. Water balance accounting is commonly built into models to predict periods of low soil water content causing water deficits in trees. Granier *et al*. (2000) presents a general function relating fraction of soil water in the soil profile to the ratio of actual to potential transpiration, and similar functions are described for many other models. It is important, however, to be aware of the possibility of errors when attempting to describe the site water balance.

7.2.1   Lateral fluxes of water through the site

A common model assumption in one-dimensional SVAT (Soil Vegetation Atmosphere Transfer) models is that there is no horizontal flux of water into and out of the site. However, it is often the case that soil water may enter the rooting zone laterally from upslope regions through the influence of gravity. This could be a particularly common situation in South African indigenous forests, which frequently occur in areas of convergent groundwater flow. There may also be a net loss of water from the soil in the downslope direction. In both such situations, simple water accounting at a site may give erroneous estimates of the water availability to trees, and a hill-slope or whole-catchment model may be necessary to simulate the movement of soil water over larger scales.

7.2.2   Subsoil water availability

There are many reported cases where sub-soils have been shown to store significant amounts of water draining below the soil profile, and where deep-rooted trees are shown to abstract such water (Kimber, 1972; Dye *et al*., 1997). The growth and water-use of trees may be essentially disconnected from the current balance between soil gains and losses of water, until the store of subsoil water is depleted. This can introduce a lag of several years before trees are fully responsive to the current rainfall conditions (Scott and Lesch, 1997). Groundwater originating largely off-site may often be shallow enough for trees to access and augment their water supply. In such situations, simple water balancing may underestimate the true rate of water-use. Again, a model that simulates the wider hydrological environment may be required.

7.2.3   The availability of soil water to tree roots

A frequent assumption in simpler models (e.g. 3-PG) is that tree roots can access the entire quantity of soil water stored within the soil to the maximum rooting depth. Soil water uptake has been shown in many studies to be less efficient with depth, due to shorter root lengths and incomplete soil exploration by the root system (Gardner, 1983). An important recent modelling advance has involved the development and successful application of models (sometimes referred to as surface energy balance models) linked to low-cost remote

sensing imagery that allows frequent monitoring of actual ET and comparison to the potential ET rate calculated from weather station data. This allows convenient spatial monitoring of water stress in different seasons of the year (limited primarily by the need for cloud-free images) and represents a powerful means of understanding spatial patterns of soil water availability.

7.3 Seasonal changes in canopy conductance

In many forests, woodlands, savannas and plantations, leaf area dynamics profoundly influence the seasonal pattern of g_c. This was particularly evident in the *Podocarpus* plantation, and the sandveld savanna. Deciduous trees lose their leaves for a portion of the year, but the timing and rate of leaf area decline varies from species to species. Even in evergreen forests such as Groenkop, a flush of new leaves is commonly seen in many tree species (September and October), while leaf fall peaks in December and January (Geldenhuys and Theron, 1994). Models used for simulating such systems may require the capability to mimic leaf loss, separately account for different cohorts of leaves, and initiate leaf growth at the start of the growing season. Models can successfully incorporate an empirical algorithm to describe the emergence of new leaves, based on a threshold temperature for initiation of translocation, an assumed daily rate of leaf mass increase, and a cessation point.

The relation between stomatal conductance (g_s) and ambient light, humidity and temperature conditions has been reported to vary seasonally (Dye and Olbrich, 1993). It is unclear which of many possible physiological mechanisms is responsible for this phenomenon, but it may be important in some forests to consider it.

Seasonal changes in g_c may also have pathogenic causes. Dye *et al*. (1996) reported a case of g_c declining abruptly in poplars after mid-season, which was attributed to proliferation of rust fungal hyphae which increasingly block leaf stomata towards the end of the growing season. It is important to look for such phenomena when testing models against field measurements.

7.4 Long-term (year-to-year) developmental changes (e.g. rotation changes)

In the case of plantation forests, it is important to model the trees over the entire rotation, including the early years when trees are still small and canopies are not fully developed. Rates of ET at these times are markedly lower than later in the rotation when the trees have developed to fully occupy the site, and need to be reflected in assessments of the whole-rotation, longer-term impacts of such forest plantations. Similar developmental trends are commonly observed in Fynbos vegetation when structure and species composition change in the intervals between fire episodes. Changes in leaf area, rooting depth, nutrient and soil water availability are likely to be significant in such systems. Tall, older trees need to overcome greater resistance to the flow of water from soil to leaf, and this is shown in some tall forest species to reduce g_c and transpiration rates (Kuczera, 1987). Modelling long-term developmental changes in forests, woodlands and savannas requires a growth routine in which net assimilated carbon is allocated to leaves, branches, stem and roots, and this introduces a significant new level of model complexity.

7.5 Understorey and overstorey canopies

The results of the Magoebaskloof study show clearly that patterns of ET from understorey and overstorey canopies do not necessarily track each other, but may show very different seasonal patterns. It is necessary therefore to model both canopies separately, and this introduces a marked increase in complexity, especially in partitioning light, water and nutrients to each group of plants. WAVES is one such model that permits two-canopy simulations. A separate vegetation parameter set is required for each canopy layer.

7.6   Management changes to structure

Managers of forest plantations recognize that a dense understorey of weeds, especially in the early stages of stand development, severely reduce tree growth. Maximum forest productivity is therefore dependent on periodic weed control operations when the understorey is reduced through slashing or herbicide application. Where significant ET originates from a vigorous understorey canopy, the whole-stand ET will show a reduction until the plants regain their maximum leaf area.

Forest plantations managed for sawlogs are periodically thinned and pruned to enhance the growth of the larger trees and improve the quality of logs. Both operations may reduce whole-stand ET, although compensatory reactions by the trees and understorey may shorten the duration of the effect.

7.7   Spatial changes in species composition and structure

Many models assume a uniform canopy structure, so that canopy processes may be estimated using simple algorithms. An example is the estimation of light interception by leaves using Beer's law. Discontinuous canopies and species changes introduce many sources of error in energy balance components. Such conditions are particularly characteristic of many woodlands and savannas, and require a very different approach to modelling that is broader in spatial scale and more efficient in detecting and monitoring spatial differences in vegetation structure and the energy and water balance.

7.8   Time step (minute, hour, day, week, month)

The time steps over which models operate are variable and based on the level of simulation detail required. Balance must be sought between describing the system in a realistic way, and minimising the time and effort associated with the greater complexities characteristic of short time step modelling.

There are very many models described in the literature that have been used to investigate ET from forests, woodlands and savannas. Each has various pros and cons, making it very difficult to determine which is likely to be most effective for a given purpose. New models are continually described, and advantages over older models are often hard to discern. Table 7.1 provides a simple framework on which the selection of an appropriate class of model can be based. It lists some of the more important model attributes of forests, woodlands, savannas and tree plantations, highlighted by the results of this project, and may be used as a checklist to ensure that a potential model possesses the necessary capability to describe the system.

Data requirements are linked to the level of detail simulated by models. Input weather data are generally readily available for various sources in South Africa, especially at the hourly and daily time scale. Broad site information is also available from forest databases and maps. The most limiting data requirement is often the field data required to verify model output. The greater the detail simulated, the greater the need for this kind of data to set up the model and parameterise model variables realistically. If there are too many unverified functions within the model, and too little verification of model outputs, then the simulation becomes of questionable value. This problem relates directly to model complexity, and again highlights the need for a good choice of model that describes the important features of the forest/woodland/savanna without including unnecessary detail.

Table 7.1   *Model requirements likely to be important in simulations of ET from forests, woodlands, savannas and tree plantations. Illustrative importance ratings for the Groenkop forest, Podocarpus plantation and KNP savanna are shown.*

Required model attributes	Groenkop forest	*Podocarpus* plantation	KNP savanna
	Importance rating		
Single species/even aged trees	N	Y	N
Soil water availability			
Site water accounting	N	Y	Y
Lateral gains/losses	N	?	N
Subsoil water dynamics	N	?	N
Root distribution effects	N	?	N
Nutrient dynamics	N	N	Y
Intra-annual tree canopy changes	N	N	Y
Inter-annual developmental changes			
Leaf area	N	Y	N
Rooting depth	N	Y?	N
Stomatal response to evaporative demand	Y	Y	N
Age-effects	N	Y	N
Growth simulation	N	Y	N
Periodic structural changes (managed or natural)	N	Y	Y
More than one canopy layer	N	Y	Y
Discontinuous tree canopy layer	N	Y	Y
Catchment scale	N	N	N
Hourly time step	N	N	N

8. COMPARISON OF THE ECONOMIC AND BIOPHYSICAL WATER-USE EFFICIENCIES OF INDIGENOUS AND COMMERCIAL FORESTS IN SOUTH AFRICA

(chapter based on a report compiled by Dr R. Wise)

8.1 Introduction

Indigenous forest species are often criticised for their slow growth rates and rates of return but praised for the efficiency with which they use water[3] and for the ecosystem services they provide. Conversely, exotic tree plantations are criticised for their high use of water, especially when compared to the natural vegetation they often replace, but praised for the economic returns generated from the large quantity of timber and fibre that is rapidly produced. These comparisons and criticisms, however, are often made without the necessary and relevant supporting data. In this study, the efficiency with which indigenous and exotic forests and plantations use water for biomass production is compared based on estimates of the economic returns per unit of water used to generate wood. The economic criteria for this purpose are the volumetric net present value (NPV per cubic metre of water) and the levelised volumetric NPV.

Water that is allocated to both exotic and indigenous forests generates a number of economic benefits to society. These benefits can be direct in nature, such as the provision of pulpwood or saw-timber products from commercial forestry and the provision of timber, fuelwood, poles, and fruits from indigenous systems. Or they can be indirect in nature, such as the ecosystem services they provide in the form of ameliorating degraded soils, encouraging forest regeneration, providing habitat for endangered species, preventing watershed erosion and flash floods, mitigating climate change through carbon sequestration, and maintaining ecosystem integrity and health in the long term (Hobbs and Norton, 1996; Harrington and Ewel, 1997; Montagnini, 2001). It is important to acknowledge the many secondary value-added benefits derived from the products of forests (such as paper, furniture, medicines, and beverages, which are produced by secondary industries using the forest products as inputs), but these were not included in this analysis.

A review of the literature on water-use efficiency, both physical and economic, reveals most research in this area has focused on agriculture (excluding forestry) and more particularly irrigation agriculture. In general these studies have investigated various measures for water-use efficiency for the primary purpose of improving the productivity and profitability of water-use. Barrett Purcell & Associates (1999) for example, completed a comprehensive report for the Australian Land and Water Resources Research and Development Corporation in which they determined a framework, terms and definitions for 'water-use efficiency' in irrigation. Cai *et al.* (2001) investigated the relationships between physical efficiency and economic efficiency noting that the values of these measures may indicate different directions for water policy and investments in irrigation. The scale of the analysis of water-use efficiency has also been highlighted as pivotal in analyses of water-use efficiency. Cai *et al* (2001), Seckler (1996) and Keller (1992), for example, show that being water-use efficient at the farm scale may not necessarily enhance economic efficiency at the basin scale. Other studies have undertaken detailed economic analyses of water-use efficiency and estimated the economic returns to different agricultural activities per unit of water used (Wigginton and Raine, 2000; Moolman *et al.*, 2006) to provide support for decision makers in the allocation of water between these activities across landscapes.

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[3] Water-use efficiency (WUE) is an eco-physiological measure quantifying the ratio of net CO_2 uptake from the atmosphere during photosynthesis versus net H_2O loss (Gulamhussein, 2005). In the context of this study, WUE is estimated by dividing the volume or mass of utilisable wood produced by the total evapotranspiration from the forest/woodland/savanna.

From the experiences and lessons presented above it is clear that comparing and contrasting the economic returns to water for various agriculture and/or forestry systems is an appropriate way for assessing existing land and water management strategies and should provide additional support to decision and policy makers in the allocation and use of these scarce resources. This study compares and contrasts the economic water-use efficiencies of commercial and indigenous forests along a rainfall gradient of between 774 and 1461 mm in South Africa and Swaziland, based on the discounted net economic returns generated from the sale of the outputs produced. The FAO definition of a forest has been adopted and includes any land with greater than 10% cover by woody, perennial plants (FAO, 2003). It is thus an all-embracing term which includes indigenous forests, savannas and plantations. The forest systems investigated include: afro-temperate forest, pine plantations (*Pinus radiata* and *P. patula*), *Eucalyptus* species plantations, a Yellowwood plantation (*Podocarpus falcatus*), and the sandveld savanna[4]. Implications for management and policy are discussed based on the findings of these analyses.

This chapter is structured as follows: firstly, the biophysical and climatic characteristics of the selected sites along the rainfall gradient are briefly described. The forests grown at different sites along the gradient are also discussed and the main biophysical parameter values for each are presented (Section 8.2). In Section 8.3 the methodological approach, including the theoretical basis for the analysis and the economic model, is described. The economic data used to calibrate the economic model are also presented in Section 8.3. The results of the analysis are presented and discussed in Section 8.4. The main findings of the report are then summarised in Section 8.5 and final conclusions made on the appropriateness of the approach adopted, the relevance of the results and the implications for management, policy and future research.

8.2   *Study Sites*

The study sites chosen to compare and contrast the economic and biophysical water-use efficiencies of exotic and indigenous forestry types were selected to represent a range of climatic conditions under which such systems grow within South Africa and Swaziland. The sites selected are: 1) the Knysna/George district in the southern Cape region of South Africa (Chapter 3; 2) Magoebaskloof in the Limpopo province of South Africa (Chapter 4); 3) the Bushbuckridge area outside of the southern Kruger National Park (i.e., the sandveld vegetation) Chapter 5; 4) 12 *Eucalyptus* sites along a rainfall gradient in KwaZulu-Natal and Mpumalanga, and 5) a pine plantation in Swaziland.

8.2.1   The Southern Cape forests

The southern Cape indigenous and exotic forests occur on the coastal strip between Mossel Bay in the west and Kareedouw in the east. The area is predominantly an all-year rainfall region (Geldenhuys, 1991). Mean annual precipitation is reported to be 860 mm and mean maximum (minimum) temperatures range from 23.8ºC (19.7ºC) in February to 18.2 ºC (8.9ºC) in August.

The **base-case** land-use type is an example of a warm temperate forest that appears to be approaching ecological equilibrium (see section 3.4). The forest (Groenkop) has a high standing biomass, a low mean annual increment and a stable composition of tree species (Gush and Dye, 2004; Dye *et al.*, 2007). *Olea capensis* subsp. *macrocarpus* is the most common of these species, *Podocarpus latifolius and P. falcatus* are particularly representative of this forest type and *Ocotea bullata* is the most valuable (Geldenhuys, 1980). The southern Cape forest complex is the most extensive in South Africa, covering an area of about 60 500 ha, and the Knysna forest in particular is the largest single forest of this type in southern Africa (25 706 ha). These forests were extensively harvested in the 19th and early 20th century, but have been intensively managed under the strict control of scientists since 1964. A brief description of the management strategy developed over this time, known as the *Senility Criteria Harvesting* (SCH) yield regulation system (Seydack *et al.*, 1990; Seydack, 1995), is given below and a thorough review is available in Gush and Dye (2004).

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[4] In this context the word forest/s conforms to the international definition used by the FAO, to mean any land with greater than 10% cover by woody, perennial plants. It is thus an all-embracing term to include indigenous forests, savannas and plantations.

The SCH yield regulation system combines forest rehabilitation with high-grade timber production by allowing trees to be harvested on a single-tree selection basis from 26% of the area. Only marketable timbers are harvested and auctioned based on: 1) species-specific growth and mortality rates and 2) dead and dying trees of commercially valuable species (Geldenhuys, 1999). Also, the detrimental effects of tree harvesting on the forest are minimised by adopting an intensive management regime involving: the topping of large trees (i.e., branch by branch removal of crown) before felling to reduce canopy damage and gap disturbance; using special extraction equipment to reduce soil compaction and drainage disturbances.

The main exotic plantations in the area are *Pinus radiata* plantations, grown for timber. The management strategy (i.e., that which maximises net-financial returns from the sale of a range of timber products) for a *Pinus radiata* plantation under the environmental conditions prevailing at the study site involves: rotation lengths of between 28 and 30 years; a planting density of 1 111 stems per hectare (3m x 3m spacing); fertilising using inorganic fertilisers; controlling pests; and intensive weeding in the first three years (or until canopy closure) and pruning until about 5 m tall (FES, 2007). The parameter values for the biophysical variables that characterise the forestry system are summarised in Table 8.1 and include: the annual rate of evapotranspiration (m^3 ha^{-1}); the annual timber volume accumulation rate (m^3 ha^{-1}); and the annual volume of timber harvested (m^3 ha^{-1}) (see Appendix 6a).

Table 8.1 *Summary table of the biophysical parameter values for an Indigenous forest and a* Pinus radiata *plantation in the southern Cape region South Africa. The source of data relating to harvesting is shown in Appendix 6.*

Output	Unit	Indigenous forest	Timber plantation	Source
Evapotranspiration	m^3 ha^{-1} yr^{-1}	9 330	5 641	(Dye *et al.*, 2007)
Volume increment	m^3 ha^{-1} yr^{-1}	4.3	11.5 – 12.5	(Dye *et al.*, 2007; FES, 2007)
Annual harvested volume	m^3 ha^{-1} yr^{-1}	2.12 – 3.51	7.6 – 10.6	(Durrheim, 2007; FES, 2007)
Total area	ha	60 500	100 000	(FES, 2007)
Area selectively harvested (average)	ha yr^{-1}	560	3 000	(Durrheim, 2007; FES, 2007)

The evapotranspiration rates of the two forest types were simulated using the models described in this report. The difference in the evapotranspiration rates between the indigenous Groenkop forest and pine plantation is contrary to the generally-held view that indigenous trees and forests are conservative water-users compared to commercial forest plantations of exotic trees. This result is thought to arise from the following differences between sites and forest systems:

- The indigenous forest displays a constant high leaf area index, including leaf area fractions from both overstorey and understorey plants. By comparison, over the first few years, the LAI is low and still increasing towards the maximum, which is only attained later in the rotation. ET during the early years is therefore below the maximum achieved in later years when the forest canopy is fully developed.

- In commercial forest plantations, it is very important to suppress understorey plants to avoid loss of tree growth increment due to competitive effects. The model assumed that understorey plants were controlled and therefore an insignificant component of stand ET.

- In Chapter 3, evidence for soil water augmentation from sources other than rainfall in the Groenkop forest is discussed. This may enhance the ET from this forest.

8.2.2 Magoebaskloof (De Hoek plantation), Limpopo Province

The Magoebaskloof area of the northern Limpopo Province falls within a summer-rainfall area with mean annual rainfall of 1 000 mm. The area forms a part of the Drakensberg escarpment, and the lower end of the valley in which the study site was located, experiences a sub-tropical climate.

A stand of riparian Yellowwood trees (*Podocarpus falcatus*) in the De Hoek State Forest (23°50'S, 30 ° 03'E, 860 m.a.m.s.l) near Tzaneen in the Limpopo Province forms the base-case forest system for this site (Geldenhuys and Von dem Bussche, 1997). Most of the stand was planted between October 1982 and December 1983. The tree spacing is 3 m by 3 m (1 111 stems ha^{-1}) and blanking took place over the first three years. No thinning, weeding or fertilising has been performed but competing under-storey vegetation has been slashed regularly, although at times the under-storey of the stand has been covered by a dense growth of *Lantana camara* (Dye *et al.*, 2007). The experiment was planted in a valley bottom on a level alluvial site next to a stream. Yellowwood trees were planted in this area because of the high value of the timber, warm temperatures, reasonably good rainfall, fertile soils and presumed year-round availability of soil water [5](Dye *et al.*, 2007). In other words, conditions for maximising the economic return from a plantation of indigenous species of tree were considered to be high under these conditions. The expected rotation length for this stand is approximately 40 years. The parameter values for the annual rate of evapotranspiration (m^3 ha^{-1}); the annual volume increment (m^3 ha^{-1}); and the annual harvested volume (m^3 ha^{-1}) and the clear-fell harvested volume (m^3 ha^{-1}) are summarised in Table 8.2.

Table 8.2   Summary table of the biophysical parameter values for a Yellowwood plantation in Magoebaskloof, Limpopo Province, South Africa.

Output	Unit	Indigenous plantation	Source
Evapotranspiration	m^3 ha^{-1} yr^{-1}	7 160	(Dye *et al.*, 2007)
Volume increment	m^3 ha^{-1} yr^{-1}	4.07	
Annual harvested volume	m^3 ha^{-1} yr^{-1}	-	
Clear-fell harvested volume	m^3 ha^{-1}	92 – 138	

8.2.3 Sandveld vegetation, Mpumalanga

The study area chosen for an analysis of Sandveld vegetation in the lowveld region was the Bushbuckridge local municipality in the Mpumalanga Province, South Africa. Although water-use measurements and tree growth estimates took place at a Sandveld site within the Kruger National Park, the economic analysis was based on conditions and data applicable to the Bushbuckridge area. This is because the underlying aim of the overall WRC project is to investigate alternative tree-production systems based on indigenous tree species. It was considered most appropriate therefore to analyse a system of utilization where the trees are directly harvested and used/sold as fuelwood, rather than a system where tree utilization is limited to browsing by animals.

The Bushbuckridge (BBR) district (31°0' E - 31°35' E and 24°30' S - 25°0' S), is located in the South African lowveld, on the border between the Mpumalanga and northern Limpopo provinces. Bushbuckridge covers an area of 240 km^2, is roughly bounded by the Orpen Road to the north, conservation areas (primarily the Kruger National Park) in the east, the Drakensberg mountains in the west and the Sabie River in the South. The Sand and the Sabie are the major rivers flowing through Bushbuckridge. The natural and socio-economic systems of the region have been extensively studied (Shackleton and Shackleton, 2000; Scholes *et al.*, 2001; Kahn *et al.*, 2007; Madubansia and Shackleton, 2007a; Ndengejeho, 2007).

The mean minimum and maximum temperatures for July and January in this region are 5.6° and 25.6°C and 20.6° and 32.6°C, respectively. Annual precipitation has a normal distribution with a mean of 547 mm and a

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[5] The trees were believed at the time to have access to some groundwater at greater depths, in view of the proximity to the stream.

range of 345 to 832 mm. The vegetation is representative of sub-tropical savanna[6] and is divided into three types based on vegetation/soil associations (Coetzee and Werger, 1978; Scholes, 1997): 1) Broad-leafed savanna on sandy soils (occupying about 60% of the area); 2) Fine-leafed savanna on clay soils (30% of the area); and 3) Riverine vegetation on silty-loam soils (10% of the area). The large tree *Sclerocarya birrea* is prominent in both the crest and midslope communities, and dominates the biomass in the area.

Savanna ecosystems provide goods such as herbs, fruits, insects, bushmeat, fuelwood, medicinal plants, construction poles, thatch grass for roofs and wooden cooking utensils. They also provide ecosystem services (e.g., carbon sequestration, air purification, and water supply), recreational services and cultural/spiritual services (Twine *et al.*, 2003; Shackleton and Shackleton, 2004; Dovie *et al.*, 2005; Shackleton and Shackleton, 2006). Many of these goods and services are used or experienced daily for domestic purposes and studies indicate that over 80% of rural South African households use these resources (Twine *et al.*, 2003; Dovie *et al.*, 2005)[7]. The **base-case** for this analysis therefore involves the existing traditional practice of directly harvesting products from the savanna system. In this analysis, however, only the fuelwood is included in the economic analysis. Fuelwood is the principle energy source for 90% of rural households (Madubansia and Shackleton, 2007a, b) and demand frequently exceeds supply with many studies showing this activity to be unsustainable (Banks *et al.*, 1996). In this analysis, the maximum quantity harvested is limited to being less than the annual regeneration rate, to ensure sustainability. The parameter values for the annual rate of evapotranspiration (m^3 ha^{-1}); the annual biomass increment (m^3 ha^{-1}); and the annual fuelwood harvested (m^3 ha^{-1}) are summarised in Table 8.3.

The **alternative** to the existing traditional harvesting practices involves developing a managed, sustainable-use system involving: selecting appropriate fuelwood-producing species based on their abilities to re-grow after harvesting and the quality of the wood (Kaschula *et al.*, 2005); denser planting patterns; appropriate harvesting of coppice growth; and the optimal use of fertiliser and water additions. In this study it is assumed that the productivity of the system is 35% higher than the subsistence case, as no data for this are available.

Table 8.3   Summary table of the biophysical parameter values for a savanna system in the Limpopo Province under subsistence and sustainable-use management regimes.

Output	Unit	Traditional harvesting	Sustainable use	Source
Evapotranspiration	m^3 ha^{-1} yr^{-1}	6 210	6 210	Dye (2007, pers. comm.)
Standing volume	m^3 ha^{-1} yr^{-1}	9.05	12.21	Wise *et al.* (under review)
Volume increment	m^3 ha^{-1} yr^{-1}	0.29	0.39	Dye (2007, pers. comm.)
Harvested volume	m^3 ha^{-1} yr^{-1}	0.26	0.38	-

8.2.4   Eucalyptus plantations in KwaZulu-Natal

Data from twelve ICFR *Eucalyptus* trial plantations situated within the provinces of KwaZulu-Natal and Mpumalanga in South Africa were used to assess the water-use efficiency (WUE) of commercial plantations of this genus. The trials covered a wide range of growing conditions and potential productivity. Mean annual precipitation (MAP) ranged from 735 to 1 154 mm, while mean annual temperature (MAT) varied from 17.2 to 21.2°C (Smith *et al.*, 2005). The trials were managed for pulpwood, and consequently were not thinned or pruned, and were harvested after a relatively short rotation length of 7-15 years. All plots received full weed control, fertilization, and pest control where necessary. Growth data were taken from plots planted at a density of 1 667 stems per hectare. The parameter values for the biophysical variables that characterise these plantations are listed in Table 8.4.

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[6] Savannas are one of the most widespread ecosystem types in the world and cover about a sixth of the land surface, and a much larger fraction of the land in developing countries than developed countries. For instance, two thirds of Africa is under savannas of various forms.

[7] The proportion of goods harvested by local communities were estimated by Shackleton and Shackleton (2000) as the following: wild herbs (33%), fuelwood (15%), wild fruits (21%), poles for fencing/kraals (3%) poles for housing (4%), thatch grass (2%), reed/grass for weaving (5%) and medicinal plants (17%).

Table 8.4   Summary table of the biophysical parameter values for 12 Eucalyptus plantations along a rainfall gradient in KwaZulu-Natal Province, South Africa (derived from Smith et al., 2005).

Plantation	Rotation length (yr)	Mean Annual Increment (m^3 ha^{-1} yr^{-1})	Total rainfall (mm)	Mean annual precipitation (mm)	Evapo-transpiration* (mm)
M1 Gemsbokfontein	9	21.04	7 911	879	7 911
M2 Windy Hill	12	34.81	11 376	948	11 376
M3 Kwambonambi	11	41.15	11 473	1 043	11 473
M4 Kia-Ora	11	24.01	8 514	774	8 514
M5 Tanhurst	11	27.87	9 801	891	9 801
M6 Baynesfield	14	15.12	11 550	825	11 550
M15 Palm Ridge	11	22.81	9 284	844	9 284
M20 KT	10	50.32	14 610	1 461	14 610
M25 Futululu	8	50.82	7 896	987	7 896
M29 Amangwe	7	35.30	7 287	1 041	7 287
M22 Bushlands	10	24.45	8 260	826	8 260
M17 Bushlands	7	32.30	5 782	826	5 782

* ET data were not available for these sites. For the purpose of economic analyses, it was assumed equal to total rainfall.

8.3   Method

In this section the general economic model to assess the water-use efficiency of tree-based land-use systems is presented. A general model is developed to allow each forestry system to be evaluated and compared in a consistent, replicable manner. This is important because the different systems involve diverse management regimes and experience benefits and costs at different times over a planning horizon. The model is based on a cost-benefit-analysis framework and uses the volumetric net-present-value (NPV per unit of water) criterion and the levelised volumetric NPV criterion to compare and contrast the different forestry systems. The former criterion (i.e., the present value of the net returns to a forestry system per unit of water used) over a planning period of *T* years is calculated as:

$$volumetric\_NPV_T = \frac{\sum_{t=0}^{T}\left[h_t \cdot p_h - vc_t\right]\cdot \delta^{-t} - E}{\sum_{t=0}^{T} ET_t}$$ (eq. 4)

where volumetric NPV_T is the net present value of profits obtained by the landholder per unit of water used (R m^{-3}) over a planning horizon of *T* years; ET_v is the quantity of water used by the forest annually, measured as the rate of evapotranspiration; p_v is the price of timber net of harvesting costs ($ m^{-3}); h_t is the amount of forest products harvested during year *t*; p_h is the farm-gate price of harvested products (i.e., gross of harvest and transport costs). The units of h_t depend on the type of forestry system and the outputs harvested. For the purpose of this analysis, timber was the only product from the afro-temperate forests and Yellowwood plantation considered for this analysis. The exotic commercial plantations are grown for either saw-timber (m^3 ha^{-1}) or pulpwood (t ha^{-1}). Only the fuelwood harvested from the savanna system (kg ha^{-1}) is accounted for in this economic analysis. In both the exotic and indigenous systems, the areas under trees are large, and small sub-sections (compartments) or individual trees (natural forests) are harvested annually. Economic returns are therefore experienced annually. A single, species-weighted average for the annually harvested volume is calculated for this purpose. The quantities of the harvested products (h_t) depend on the types of trees, their growth rates, and the ways in which the forest systems are managed. The rotation lengths for the forests and plantations vary between 7 and 40 years, depending on the prevailing silvicultural practices, product and climate. vc_t are annual input costs (fertiliser, labour, herbicides, etc.); *E* is the upfront cost of establishing a plantation or developing harvesting capabilities (R ha^{-1}) and δ is the discount.

The model can be easily modified to account for payments for ecosystem services provided by forestry systems and the natural variability in many of the economic and biophysical parameter values. This requires that the vectors h_t, p_h, vc_t, and E are expanded to include the additional outputs, prices, variable costs and establishment costs and that the probability distributions for the parameter values are known and included in the model, respectively. The NPV values estimated using equation (1) were then levelised:

$$levelised\_vol\_NPV_T = \frac{\left[\sum_{t=0}^{T}[h_t \cdot p_h - vc_t] \cdot \delta^{-t} - E\right] \cdot \left[\dfrac{r}{(1-(1+dr)^{-T})}\right]}{\sum_{t=0}^{T} ET_t} \qquad \text{(eq. 5)}$$

The levelised volumetric NPV criterion is the same as the "Equivalent Annual Income" (EAI) criterion, which converts NPV to an annual value paid at the end of each year over the lifespan of a project with interest calculated at the appropriate discount rate (Uys and Daugherty, 2000). The NPV value for each forest/plantation is levelised to account for the effects on NPV of differences in life-span and differences the trajectory of cost and benefits over time.

8.3.1 Economic parameter values and assumptions

Both primary and secondary economic data are used in this analysis and were collated from the literature and personal communication with stakeholders. Where necessary, all prices are adjusted for inflation to 2007 values using the average annual producer price inflation rate over the period concerned. The parameter values for the economic variables used in the base runs of the model are presented in Table 8.5.

Table 8.5 Parameter values and assumptions for the economic variables of all the tree-based systems investigated. All values are expressed in ZAR (2007).

Output	Unit	Pine plantation	Eucalyptus plantation	Indigenous forests		Sandveld savanna	
				Afro-temperate	Yellow-wood plantation	Traditional	Sustainable use
Price of timber / fuelwood	R m^{-3}	251.0	248.6	1 586.0	1 038.0	519.7	519.7
Price of pulp	R t	168.0	-	-	-	-	-
Input cost	R ha^{-1}yr^{-1}	920.0	920	897.0	842.0	10.0	41.0
Annualised establishment cost	R ha^{-1}yr^{-1}	116.0	233 – 465	-	-	0	90.5
Establishment cost	R ha^{-1}	-	-	-	3 258.0	-	-
Harvest & transport cost	R ha^{-1}yr^{-1}	125.0	125	839	297	343.0	223.0
Time horizon	years	28	7 to 15	40	40	28	28
Discount rate	%	5	5	5	5	5	5

Note: Prices and costs are time averages and site-weighted averages. The explanation for how each of these values was estimated and the sources are summarised in Appendix 6.

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8.4 Results and discussion

8.4.1 Within-site comparisons of the water-use efficiencies of indigenous and exotic timber plantations

Due to limited availability of data, within-site comparisons of the efficiencies with which different tree-based land-management systems use water could only be done for two sites: the southern Cape region (where exotic plantations are compared with afro-temperate forests) and the Bushbuckridge district near the Kruger National Park (where traditional and sustainable-use management regimes are compared).

8.4.1.1 Southern Cape region

On a per hectare basis, the indigenous afro-temperate forest is about seven times more profitable than the pine timber plantations (Table 8.6), with the former generating average annual returns of R466 ha^{-1} compared with R64 ha^{-1} for the latter. When measured in terms of the water used to generate the profits, however, this difference decreases from seven to five times. This decrease in the relative profitability of the two systems is because the pine plantations are more efficient at using water to generate the volume of harvestable timber than indigenous trees (bottom row of Table 8.6). In other words, the larger profitability shown by the indigenous forest is due to the high price received for the indigenous timber and not because the indigenous forests are necessarily more productive or cost-effective.

Table 8.6   *The economic and biophysical water-use-efficiency values and the per-hectare Net Present Values (NPV) for indigenous and exotic forests in the Southern Cape region of South Africa; at base-case parameter values.*

Variable	Units	Afro-temperate forest	*Pinus radiata*
NPV	R ha^{-1}	R 18 632.7	R 1 785.12
Time averaged NPV	R ha^{-1} yr^{-1}	R 465.8	R 63.8
Levelised profit	R ha^{-1} yr^{-1}	R 1 085.9	R 119.8
Volumetric NPV	R m^{-3}	R 0.050	R 0.009
Levelised volumetric NPV	R m^{-3}	R 0.116	R 0.018
Harvested timber per unit water	m^3 m^{-3}	0.00028	0.00133

The relative per-hectare profitability of these systems must be put into context, however, by considering the total returns to the total afforested area for each forest type. For example, the average area of the indigenous forest that is harvested annually is 0.9% of the entire area of forest (560 ha of 60 500 ha), which equates to a per-hectare annual return of R4.3 for the entire area. The average area of pine trees harvested annually is 3% of the approximately 100 000 ha of afforested land, which gives an annual net economic return to the entire area of R1.9 per hectare.

From these results, exotic plantations are clearly more efficient users of water relative to indigenous systems in terms of the timber that is harvested per unit of water used (e.g., the exotic plantations produces almost 5 times the timber that indigenous plantations produce, per cubic metre of water used). However, in terms of the annual net returns per cubic metre of water used, indigenous forests are between 5 and 7 times more profitable than pine plantations. The sensitivity of these results to changes in key economic and biophysical parameter values requires investigation.

8.4.1.2 Sandveld – Bushbuckridge

More than 90% of households in rural South Africa make use of fuelwood as a source of energy (Shackleton and Shackleton, 2000; Twine *et al.*, 2003; Dovie *et al.*, 2004). Ndengejeho (2007) estimated that about 70% of the households in the Agincourt rural district within the Bushbuckridge region actively harvest fuelwood

from the surrounding vegetation. The availability of fuelwood, however, is becoming increasingly scarce. Evidence supporting this scarcity of fuelwood is the 12% increase in the time spent on collection trips between 1991 and 2002 (Madubansia and Shackleton, 2007a), which is attributed to having to travel long distances to collect fuelwood. The possibility of intensifying the production of fuelwood through a more commercial, sustainable-use system is under investigation (Kaschula *et al.*, 2005) and requires further research and development.

In this study, the economic and biophysical efficiencies with which the sandveld vegetation uses water to produce fuelwood were estimated for two scenarios: 1) traditional harvesting (column 3, Table 8.7); and 2) managed for sustainable harvesting (column 4, Table 8.7). Under the prevailing situation of traditional harvesting with little or no management, the water-use efficiency with which the sandveld vegetation produces fuelwood is 0.041 kg of fuelwood per cubic metre of water. The economic water-use efficiency under base-case assumptions is between R0.003 and R0.006 per cubic metre of water. Under the assumptions defining the alternative sustainable-use practice, these efficiencies increase to 0.061 kg per cubic metre of water and to between R0.0064 and R0.012 per cubic metre of water, respectively (Table 8.7).

Table 8.7   The economic and biophysical water-use-efficiency values and the per-hectare Net Present Values (NPV) for the sandveld vegetation in the Bushbuckridge district, South Africa; at base-case parameter values.

Variable		Traditional management	Sustainable use management
NPV	R ha^{-1}	R 547.4	R 1 117.6
Time averaged NPV	R ha^{-1} yr^{-1}	R 19.6	R 39.9
Levelised profit	R ha^{-1} yr^{-1}	R 36.7	R 75.0
Volumetric NPV	R m^{-3}	R 0.0031	R 0.0064
Levelised volumetric profit	R m^{-3}	R 0.0059	R 0.012
Volume harvested per unit water	m^3 m^{-3}	0.00004	0.000061

Little can be deduced from these estimated values because no estimates for these criteria from other studies are reported in the literature. The relative efficiencies of these systems are, however, compared with the water-use efficiencies of other indigenous and exotic tree-based systems along a rainfall gradient in South Africa in Section 8.4.2. The annual net economic return per hectare estimated for the traditional system in this study (R19.6 ha^{-1} yr^{-1}), however, compares well with the annual gross revenue per household (R311 hh^{-1})[8] estimated by Dovie *et al.* (2004) for the Thorndale village in Bushbuckridge.

It should be emphasised that no data are available for the costs of harvesting fuelwood. Since women and children are largely responsible for harvesting fuelwood, the time spent doing so does have an opportunity cost in the form of other productive activities forgone to do so. However, no information exists on the relative value of time spent on different activities that could be readily converted to the monetary cost of harvesting fuelwood. It was therefore assumed that the cost of harvesting fuelwood was 66% and 40% of the value of the fuelwood for the traditional and sustainable-use systems, respectively. This assumption is based on the fact that households in this area have the choice of buying fuelwood for between 38c (Twine *et al.*, 2003) and 50c (Dovie, 2002) per kg, or collecting it themselves. According to Ndengejoh (2007), 70% choose to collect it themselves, implying that the value of their time is less than the cost of purchasing the firewood. Their time costs were therefore assumed to be 66% of the value of the unit price of fuelwood collected in a traditional harvesting system (40% within a sustainable-use system due to its greater value).

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[8] This value equates to R26.7 ha^{-1} yr^{-1} using Ndengejoh's (2007) estimate of 10 384 households in the Agincourt district, and a total area of 121 000 ha that is required in order for Dovie *et al's* (2004) harvest rate of 4 343 kg hh^{-1} to be sustainable. hh = household.

8.4.2 Comparison of water-use efficiencies for different sites along a rainfall gradient

It is generally the case that the biophysical water-use efficiency of trees increases with increasing mean annual precipitation (MAP) (Law *et al.*, 2002; Binkley *et al.*, 2004; Stape *et al.*, 2004). This positive relationship clearly also exists for the biophysical water-use efficiencies of a range of tree-based systems across a rainfall gradient in South Africa (Figure 8.1). The tree-based systems plotted in Figure 9.1 are made up of 12 *Eucalyptus* plantations, two pine plantations and four indigenous tree plantations/forests. These systems were described in detail in Section 8.2. The values plotted in Figures 8.1, 8.2 and 8.3 are summarised in Appendix 5. Unfortunately, the statistical significance of this positive relationship could not be tested because of insufficient observations or data points.
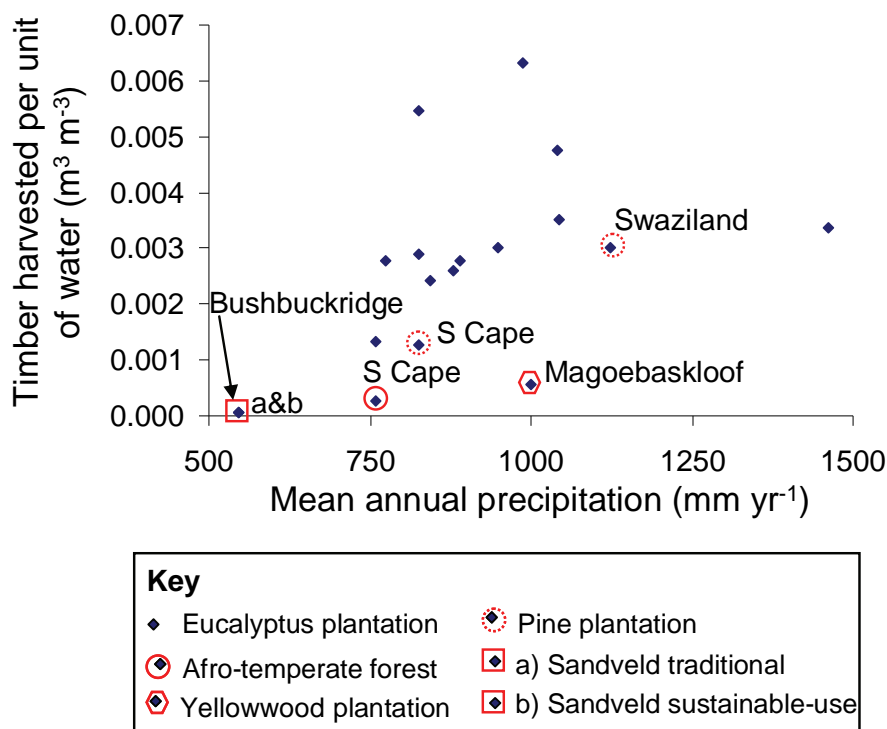
Figure 8.1   The relationship between biophysical water-use efficiency (harvested wood volumes per cubic metre of water) and mean annual precipitation along a rainfall gradient in South Africa

An additional trend clearly discernable from the outputs plotted in Figure 8.1 is that the *Eucalyptus* plantations are the most efficient at using water to produce harvestable wood volumes, at all levels of MAP. The second most efficient are the pine plantations and the indigenous tree-based systems have the lowest biophysical water-use efficiency. The factors that drive these rankings are numerous and diverse including species physiology, plantation management, and site quality.

Plotting the *economic* water-use efficiency of these tree-based systems, in this case the levelised volumetric NPV values are used (Tables 8.6, 8.7 & 8.8), against MAP (Figure 8.2) reveals a similar positive relationship to that of the biophysical measure for water-use efficiency. However, a completely different picture exists in terms of the relative water-use efficiencies of the various tree systems investigated (i.e., the ranking of the WUE of the forests is different to that of the biophysical measure of water-use efficiency).
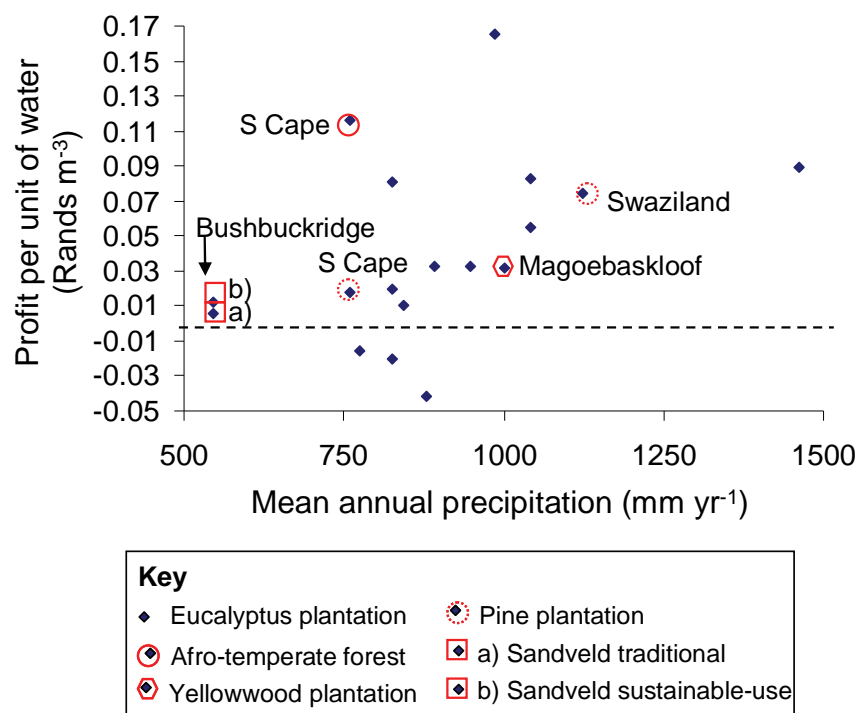
Figure 8.2   The relationship between economic water-use efficiency (levelised Net Present Value per cubic metre of water) and mean annual precipitation along a rainfall gradient in South Africa

When the levelised volumetric profit is used as the measure for WUE, the indigenous afro-temperate forest ranks higher than all the other systems investigated except for the extremely productive *Eucalyptus* plantation at Futululu[9]. This is likely due to the fact that this system incurs no establishment costs and because of the high value of the fully-mature timber that is harvested. The other indigenous tree system grown for timber is the Yellowwood stand in Magoebaskloof. This system does not perform nearly as well as the afro-temperate forest because it incurs large upfront establishment costs, periodic weed control expenses, and a single return at the end of 40 years.

The ranking of the remaining systems is not easily determined from the few observations available. Initial indications from these limited data are that the pine plantations have higher economic water-use efficiencies than *Eucalyptus* plantations at low MAP, but that this difference becomes negligible as MAP increases. The economic WUE of the sandveld seems to be competitive with the pine and *Eucalyptus* plantations at low MAP, particularly with a couple of the *Eucalyptus* plantations showing negative profits[10]. Due to the low number of observations and the lack of economic data, these results should be interpreted with caution and should not be extrapolated to other similar systems or sites. An analysis of the sensitivity of these findings to changes in the underlying parameter values is highly recommended.

The above analysis of the economic WUE was based on the levelised volumetric NPV criterion. It is necessary to levelise the present values of economic variables in cases of time horizons and the trajectories of benefits and costs differ between forestry systems (i.e., to account for the effects that discounting has on costs and benefits experienced at different times over a planning horizon). The effect that levelising economic WUE has on the relative performance of the different systems can be clearly seen when using a non-levelised economic criterion such as the volumetric NPV (Figure 8.3). In this situation, long-rotation systems perform poorly relative to systems with shorter rotations because their economic WUE values decrease by between 45% and 133% for rotations of between 15 and 40 years, respectively (i.e., the large benefits experienced in

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[9] This plantation is highly productive because of the high temperature and high humidity along coastal Zululand and because the trees have unlimited water due to the presence of a shallow coastal aquifer.

[10] Using the base-case economic parameter values, the *Eucalyptus* plantations are only able to show positive net returns when the mean annual increment in timber volume exceeds 28 m^3 ha^{-1} yr^{-1}.

the future are heavily discounted). This is particularly noticeable in the case of the indigenous timber forest and timber plantation.
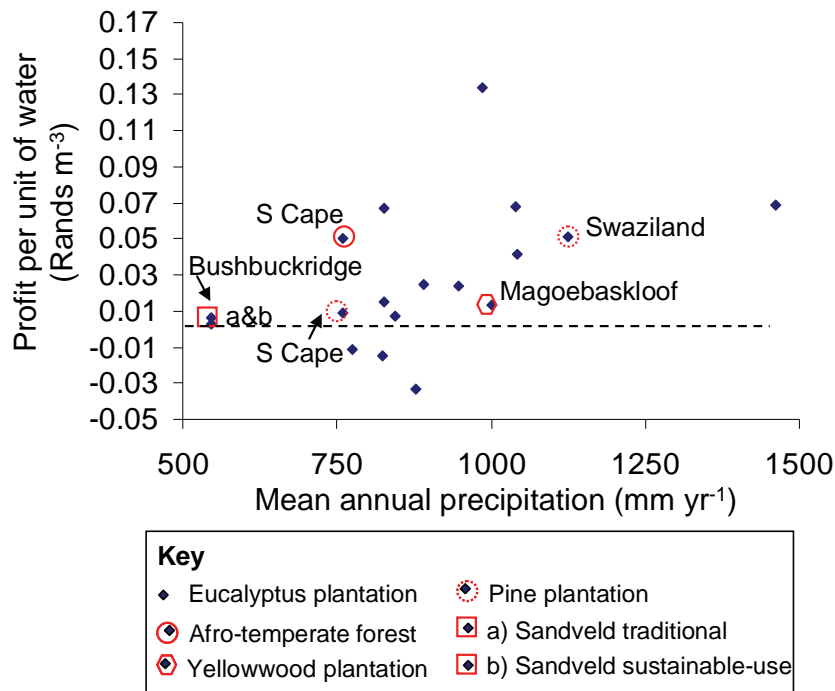
Figure 8.3   The relationship between economic water-use efficiency (Net Present Value per cubic metre of water) and mean annual precipitation along a rainfall gradient in South Africa

8.5   *Conclusions*

This chapter explored the use of biophysical and economic criteria for measuring the water-use efficiencies of indigenous and exotic trees in South Africa. The biophysical measure for WUE was estimated as the volume of harvested wood (sawlogs, pulpwood, fuelwood) per cubic metre of water. Two economic measures for WUE were estimated: 1) the present value of net returns (NPV) from the sale of harvested wood per cubic metre of water (volumetric NPV); and 2) the levelised NPV from the sale of harvested wood per cubic metre of water (levelised volumetric NPV). Numerous indigenous and exotic forests and plantations under a range of management regimes and along a rainfall gradient were investigated. Some of the main findings of the research are summarised below, along with their implications for management, policy and future research.

Firstly, the ranking of each forest/plantation in terms of its WUE varies depending on the criterion used to measure WUE. For example, based on the biophysical measure of WUE, the exotic plantations outperform the indigenous species for all the levels of mean annual precipitation tested. However, when an economic measure for WUE is used the afro-temperate forest and the Yellowwood plantation compare favourably with the exotic plantations. In fact, when using the levelised volumetric NPV criterion, the afro-temperate forest ranks higher than all the systems investigated except one of the *Eucalyptus* plantations. The improved performance of these systems based on economic criteria is because these systems have relatively low costs (are not intensively managed) and have substantially larger product prices. The afro-temperate forest outperforms the Yellowwood plantation because it is a mature system in equilibrium and super-mature trees are harvested annually, whereas the plantation only generates positive economic returns after 40 years. These findings reinforce the argument for conserving existing mature indigenous forests under sustainable-use management regimes.

Secondly, the levelised volumetric NPV gives a more accurate reflection of the relative economic WUE of the different systems than the un-levelised volumetric NPV. This is because the former method takes account of the effects of discounting on the present values of costs and benefits experienced at different times over a

planning horizon. Levelising benefits and costs in this way ensures that systems with large upfront costs and long rotations – typical of stands of indigenous trees – can be compared with shorter-rotation plantations and not unfairly selected against. For example, it was found in this study that the estimated economic WUE increases by 45% and 133% when 15-year and 40-year NPVs are levelised. Evaluating tree-production systems in this way may promote their adoption more widely.

Thirdly, the lack of economic data and the many assumptions that had to be made requires that a sensitivity analysis of some of the key variables is undertaken. This, however, has not yet been done as it was out of the scope (terms of reference) of this study. It is therefore recommended that additional efforts are spent in quantifying the uncertainties surrounding the economic assessment and getting an understanding of the sensitivity of the optimal solutions to changes in the values of key variables.

Lastly, a major impediment to the completion of this study was the fact that so little data are available on the economics (primarily the costs) of growing indigenous and exotic trees. This made it necessary to make simplifying assumptions (all of which have been clearly and accurately documented) before any analysis could be undertaken. The implications of this are that caution should be adopted when interpreting the results and when extrapolating or making generalisations based on these outputs. One of the main reasons for the lack of economic data is because the purpose of the indigenous systems is not to make profits but tends to be for conservation or research purposes; making the monitoring of costs a low priority. It is strongly recommended that those involved with the conservation and research of indigenous tree species begin to record the costs (establishment, management and harvest) incurred and that a central database is created where these data can be stored and verified and made accessible to interested parties.

9. Additional single tree studies

9.1 Introduction

There is much evidence from many sources to suggest that indigenous trees generally grow far slower than commercial forestry species which are selected and bred for fast above-ground growth. To some extent, this may reflect the fact that many indigenous trees are found in established forests, where slow growth rates are at least partly caused by a high degree of competition from other trees and understorey plants, sub-optimal site conditions, and the fact that dominant trees tend to be old and therefore slow-growing. In the context of this project, it was important to examine the potential of various indigenous species for the production of useful timber, and to examine how their rates of growth and water-use compared to those of commercial plantation species. Data from the mature *Podocarpus falcatus* plantation at Magoebaskloof were described in Chapter 4. In this phase of work, WUE was recorded in trees representing a wider selection of species, and growing on different sites.

Species were selected that:
- produce potentially valuable timber
- represent early and late successional phases of forest development
- include both fast and slow-growing species
- include evergreen and deciduous species
- occur in relatively wet and dry sites
- were relatively young
- possessed well-formed canopies
- were well exposed to sunlight.

The last three conditions were set to mimic conditions associated with the early phase of rapid growth in plantation conditions before competition and mean annual increments (MAI) peak, and before growth rates begin to slow down. It was also considered important to avoid variable shading effects caused by surrounding trees. Major research questions posed in this phase of work were:
- What is the variation in WUE amongst indigenous tree species?
- How does the WUE of indigenous species compare to exotic plantation species?
- Is variation in the WUE of indigenous species correlated to environmental, structural or physiological features?
- Are there easily measurable correlates to indicate the likely WUE of a particular species?

9.2 Materials and Methods

Single-tree scale assessments of WUE were particularly suited to this phase of the project and the methodology required was developed, refined and repeated during the course of the work, as detailed below.

9.2.1 Species selections and site descriptions

Three monitoring sites were selected along a rainfall gradient within KwaZulu-Natal. These sites consisted of:
1. A *Trema orientalis* tree in a residential garden situated in the suburb of Winterskloof on the outskirts of Pietermaritzburg.
2. A group of three indigenous species, consisting of a *Celtis africana*, a *Podocarpus falcatus* and a *Ptaeroxylon obliquum* tree in the Karkloof West nature reserve near Howick.

3. A group of three indigenous species, consisting of an *Olea europaea* subsp. *africana*, an *Acacia karoo* and a *Berchemia zeyheri* tree in the Weenen Game Reserve near Estcourt.

9.2.1.1 Winterskloof

The Winterskloof site was located approximately 10 km west of Pietermaritzburg (grid reference 29º 35.0′ S; 30º 17.926′ E″ and altitude 1 051 m.a.m.s.l). A 10-year rainfall record at the site showed the Mean Annual Precipitation (MAP) to be 1 207 mm. Measurements were conducted on a large branch of a *Trema orientalis* (Pigeonwood) tree. The site consisted of a residential garden, and the sample tree was an isolated specimen, well exposed to sunlight, surrounded by kikuyu lawn, and growing in un-irrigated soil. The sample branch extended from near the base of the tree to approximately 5.6 m above the ground (Figure 9.1). Continuous measurements of sap flow (transpiration), certain meteorological variables (rainfall, solar radiation, air temperature and relative humidity) and soil water content in the top 10 cm of the soil profile, were taken hourly for a 15-month period from 1 November 2006 until 13 February 2008).

Figure 9.1   Winterskloof site (Trema orientalis).

9.2.1.2 Karkloof

The Karkloof site was located in the Karkloof West nature reserve near Howick (grid reference 29° 18.230′ S and 30° 13.699′ E and altitude 1 253 m.a.m.s.l). The Karkloof forest was originally described by Rycroft (1944), and more recently has been classified as southern mistbelt forest (Mucina and Rutherford, 2006). A characteristic of the rainfall regime is a strong orographic effect, caused by the lifting (and convective cooling) of the summer south-east winds over the Karkloof mountain range (Figure 9.2). The forest, by virtue of its south-easterly aspect, is sheltered from the hot, dry "bergwinds" of late winter and, as it lies within the mist belt, is subject to heavy soaking mists during summer (Taylor, 1961). Lynch and Schulze (2006) give the MAP for this site as 1 273 mm.

Figure 9.2   Mist-belt forest of the Karkloof nature reserve.

Measurements at this site were conducted on three trees, namely a *Celtis africana* (White Stinkwood), a *Podocarpus falcatus* (Outeniqua Yellowwood) and a *Ptaeroxylon obliquum* (Sneezewood), all in the same vicinity (Figure 9.3). The trees were approximately 20 m apart from each other, in line, on a gently sloping valley-bottom site. The site was non-riparian although there was a stream approximately 70 m away. The site appeared to have been cleared of alien invasive plants within the last few years as there was evidence of *Eucalyptus* stumps and logs still evident at the time that monitoring commenced. The site was open and all three trees were isolated specimens, with well-developed canopies, fully exposed to sunlight, and with single main stems. They were in an open area approximately 50 m from the closed-canopy forest, although the site appeared to be in the process of being re-colonised by indigenous species as a result of the removal of the eucalypts. Continuous measurements of sap flow (transpiration), certain meteorological variables (rainfall, solar radiation, air temperature and relative humidity) and soil water content in the top 10 cm of the soil profile, were taken hourly for a 15-month period from 19 October 2006 until 13 February 2008.
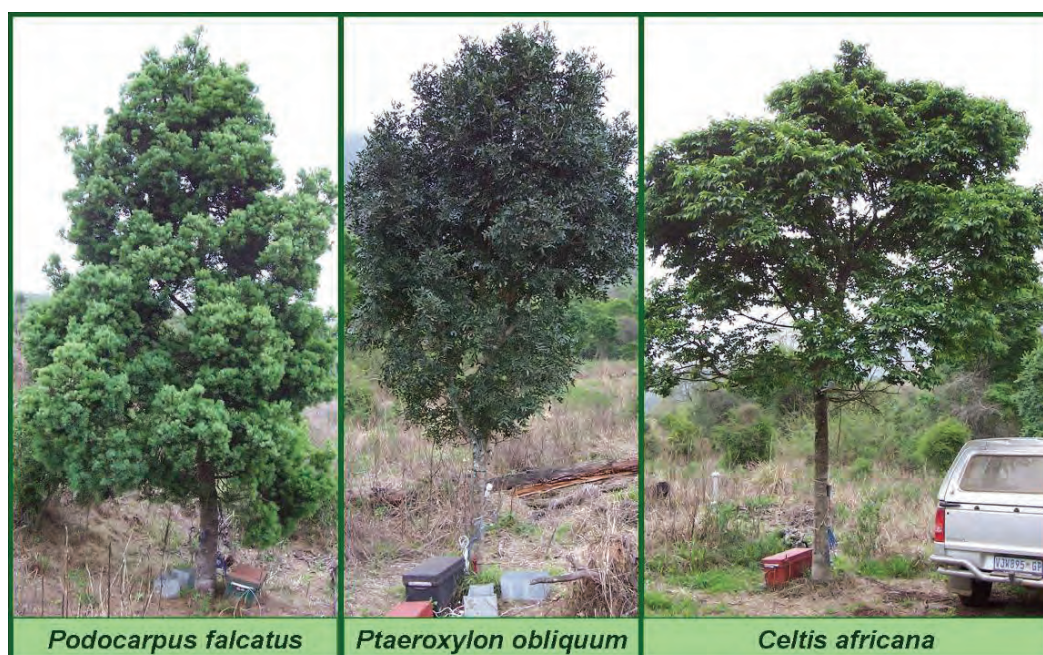
Figure 9.3   Tree species monitored at the Karkloof site.

9.2.1.3 Weenen

Two sites at Weenen were located within the Weenen Game Reserve near Estcourt. Lynch and Schulze (2006) give the MAP for this area as 730 mm. Sample trees were situated in a lower-lying valley bottom site (grid reference 28° 50.842′ S and 30° 01.549′ E and altitude 1 010 m.a.m.s.l) (Figure 9.4) and a higher-altitude plateau site (grid reference 28° 52.613′ S and 30° 01.857′ E and altitude 1241 m.a.m.s.l). The lower site is situated on a steep, warm, north-facing slope, approximately 50 m upslope from an ephemeral stream, and consists of woodland thicket dominated by *Euphorbia*, *Acacia*, *Cussonia* and *Olea* species. Soils are shallow and extremely rocky. Measurements at this site were conducted primarily on an *Olea europaea* subsp. *africana* (Wild Olive) tree (Figure 9.5). Additional measurements were attempted on an *Acacia karoo*. However due to the extremely poor quality of sap flow data obtained from this tree (most likely due to complications arising from wounding and resin exudation in the stem), these results were excluded. A fully automatic weather station was installed at this site. Continuous measurements of rainfall, solar radiation, air temperature, relative humidity and wind speed, together with measurements of sap flow (transpiration), and soil water content in the top 10 cm of the soil profile, were taken hourly for a 15-month period from 12 October 2006 until 12 February 2008.

Figure 9.4   Valley thicket at the lower-lying Weenen site.

Figure 9.5   *Olea europaea subsp. africana (Wild Olive), monitored at Weenen.*

The higher-altitude site was situated on the edge of a plateau, characterized by open grassland savanna dominated by *Acacia sieberiana* trees. This site was noticeably more windy and cooler than the lower site. Due to its higher altitude and proximity to the steep cliffs dropping to the Weenen valley below it is likely that it benefited from additional precipitation in the form of orographic rainfall and occasional mists. Although this site was flat, soils were shallow and stony. Sap flow measurements at this site were conducted on a *Berchemia zeyheri* (Red Ivory) tree (Figure 9.6). Continuous measurements of air temperature and relative humidity, together with measurements of sap flow (transpiration), and soil water content in the top 10 cm of the soil profile, were taken hourly for a 15-month period from 12 October 2006 until 12 February 2008.

Figure 9.6   Berchemia zeyheri (Red Ivory), monitored at Weenen.

9.2.2   Water-use (sap flow / transpiration) measurements

The aim of this phase of work was to record the WUE of the sample trees over a full year, in order to cover all seasonal changes in growth and transpiration. Hourly sap flow in each sample tree was continuously monitored using the heat pulse velocity technique. This technique is recognised internationally as an accepted method for the measurement of sap flow in woody plants (Bleby *et al*, 2004) and has been extensively applied in South Africa (Dye and Olbrich, 1993; Dye, 1996; Dye *et al.*, 1996). The heat ratio method (HRM) of the HPV technique (Burgess *et al.*, 2001) was selected for this study because of its ability to measure low rates of sap flow, often characteristic of plants growing under dry conditions typically experienced in South Africa. Details of this technique are described in Appendix 1. Table 9.1 provides additional details of tree size, leaf area index (LAI) and heat pulse probe insertion depths.

Table 9.1   *Tree height, diameter at breast height, crown circumference, leaf area index, and HPV thermocouple probe depths for each sample tree.*

Tree Species	Tree Height (m)	Breast height stem circ. (cm)	Crown perimeter (m)	Mid-summer LAI	TC Probe sets	TC probe over-bark insertion depths (mm)
Trema orientalis	5.65	34.4	17.28	1.26	4	8, 20, 30 and 40
Celtis africana	6.45	52.8	14.0	1.73	4	6, 16, 27 and 40
Podocarpus falcatus	6.10	60.2	10.0	2.73	4	15, 28, 48 and 70
Ptaeroxylon obliquum	5.16	37.8	8.5	1.68	4	8, 20, 30 and 40
Olea europaea subsp. *africana*	5.00	40.5	12.0	1.20	4	7.5, 20, 32.5 and 45
Berchemia zeyheri	5.43	62.8	19.8	3.98	4	10, 16, 22 and 23

Once sap flow monitoring had been completed, additional sapwood information required to complete the HPV data analysis was collected. Measurements of sapwood area, sapwood moisture content, wood density and the width of wounded (non-functional) xylem around the thermocouples ("wound widths") were recorded on all the trees. The trees could not be destructively sampled by virtue of their location in private gardens and nature reserves, so small wood samples and tree cores were taken to determine these variables. A tree corer (fitted to an electric drill powered by a battery and inverter) was used to extract cores from the tree stems, and these were scrutinised to determine sapwood depth. Additional blocks of wood incorporating the thermocouple and heater probe insertion holes were chiselled out of the tree to determine the wounding widths, sapwood moisture content and wood density (Figure 9.7). Table 9.2 summarises the data obtained from these samples. Raw heat pulse velocity data were converted to whole-tree sap flow rates following the procedure described in Appendix 1.

Table 9.2   *Summary of additional data from wood samples extracted from the monitored trees.*

Tree Species	Bark Thickness (mm)	Sapwood Depth (mm)	Sapwood Moisture Content (%)	Wound Width(s) (mm)	Wood Density (g cm^{-3})
Trema orientalis	6	65	55.92	3.5 (all)	0.422
Celtis africana	4	79	46.71	3 (all)	0.605
Podocarpus falcatus	7	95	52.1	3.5 (all)	0.468
Ptaeroxylon obliquum	3	35	33.96	4 (all)	0.716
Olea europaea subsp. *africana*	3	40	34.33	4.5 (all)	0.916
Berchemia zeyheri	5	30	28.18	5.5 (1), 5 (2), 4.5 (3), 4 (4)	0.807

*Figure 9.7   Collection of wood samples to determine sapwood properties required
for final HPV calculations.*

9.2.3   Above-ground biomass measurements

Above-ground (branch and stem) biomass measurements were conducted on all the sample trees in conjunction with the sap flow and tree physiological measurements. Initial biomass surveys were carried out shortly after the individual trees had been instrumented with the HPV systems, and the final surveys were performed as closely as possible to one year thereafter. During the course of these surveys, stem circumferences / diameters at increasing heights up the tree, as well as branch circumferences / diameters (at base) and lengths were measured. Measuring points on stem and branches were marked for future reference by scoring the tree at that point. Canopy architecture was mapped during the initial survey using a numerical system to aid the identification of individual stem and branch locations during the final survey (Figure 9.8).
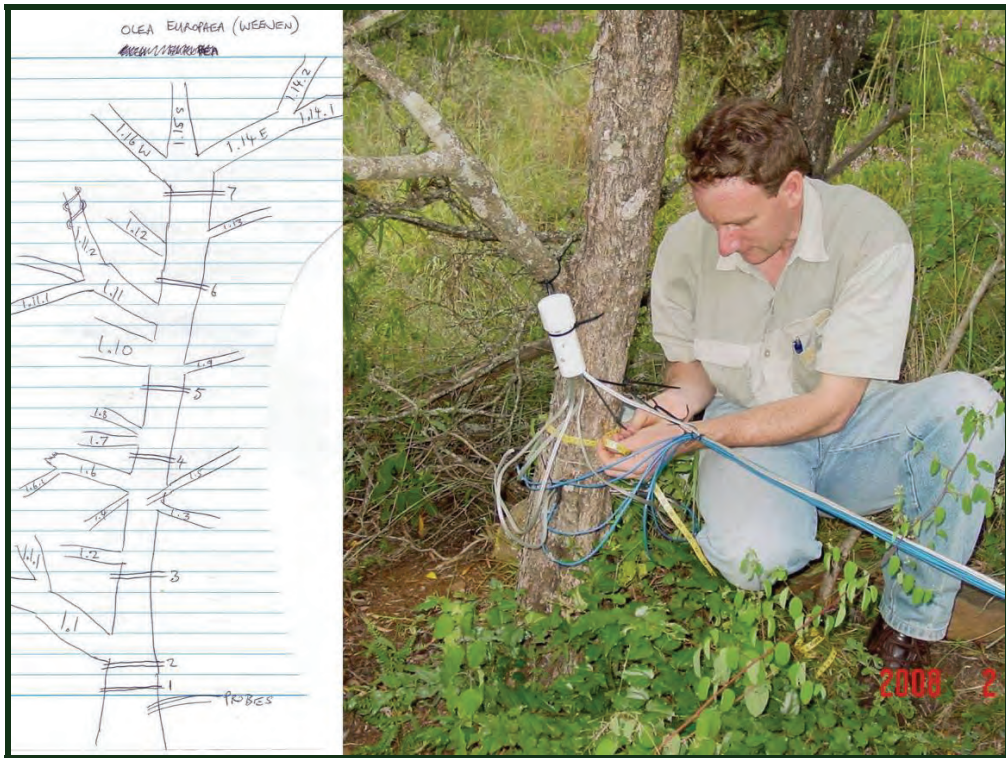
Figure 9.8   Measuring 1-year branch and stem growth increments for the Olea europaea subsp. africana *tree at the Weenen site. The measurement points and numbering convention are illustrated on the left.*

Good correlations between branch length and diameter were found for most of the species, and the relationship appeared consistent across those species (Figure 9.9). These relationships could be used to aid future biomass assessments, and also to evaluate how the stem / branch biomass ratios may vary amongst indigenous tree species, especially under different growing conditions (e.g. plantation vs. single tree environments).
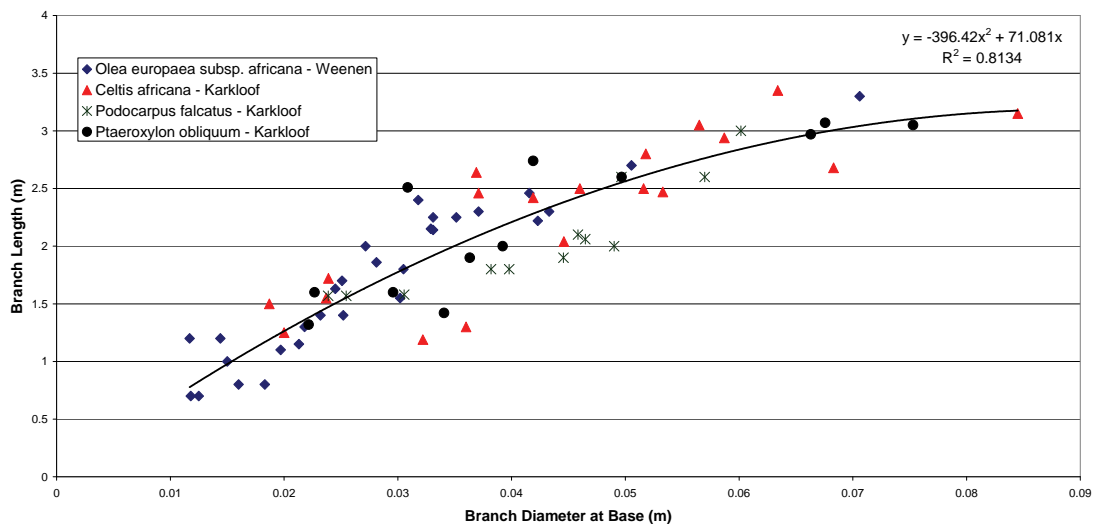
Figure 9.9   The relationship between branch length and branch diameter at base, for a selection of indigenous tree species.

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The stem and branch measurements were used to calculate initial and final biomass volumes. This was done by assuming that the stem consisted of a series of truncated cones with a complete cone at the top, while the branches consisted of individual elongated cones. The volumes of the cones were calculated according to Cavalieri's Principle (i.e. the volume of a cone is equal to that of a pyramid with the same base and height), and hence the following equation was used:

$$V = (\pi r^2 h) / 3 \qquad \qquad (eq. 6)$$

Where: V = Volume of the cone (m³)
          r = Radius of the base of the cone (m), and
          h = Height of the cone (m)

The volumes of the truncated cones were calculated according to the same principle, and the following equation was used:

$$V = (\pi h (r_1^2 + r_1 r_2 + r_2^2)) / 3 \qquad \qquad (eq. 7)$$

Where: V = Volume of the truncated cone (m³)
          r_1 = Radius of the base of the truncated cone (m)
          r_2 = Radius of the top of the truncated cone (m), and
          h = Height of the truncated cone (m)

The individual stem section volumes and branch volumes were totalled for each tree. This allowed for the calculation of stem, branch and total above-ground volume growth increase in the year. In conjunction with the sap flow / water-use results this allowed the calculation of water-use efficiency in terms of stem volume (m³ stem wood per m³ water) and in terms of total above-ground wood volume (m³ total wood per m³ water). Volume increments were converted to mass according to the mean wood densities of individual species as shown in Table 9.2.

9.2.4 Additional measurements

During the course of this phase of the project additional physiological and physical measurements on the sample trees were carried out. These consisted of measurements of photosynthesis, single-leaf transpiration, stomatal conductance, pre-dawn xylem pressure potential, leaf-litter fall, leaf area index, canopy dimensions, canopy extinction coefficients relating to solar radiation variation within the canopies, changes in the C:N ratios of the leaves, and carbon isotope ratios in sample leaves.

Two individual field campaigns of intensive field measurements were carried out between 2-6 July 2007 (winter) and 3-6 December 2007 (summer). A Li-COR LI-6400 portable photosynthesis meter (Infra-Red Gas Analyser or IRGA) was used to measure photosynthetic rates of the sample trees. Instantaneous measurements of photosynthesis (using the "SunSky" chamber), as well as light response curves (using the "RedBlue" chamber), were conducted. Measurements of pre-dawn xylem pressure potential (using a PMS pressure chamber) and stomatal conductance / leaf transpiration (using a Li-COR LI-1600 Steady State Porometer) were also performed (Figure 9.10). Measurements were conducted on healthy leaves of average size, occurring in both sun-lit and shaded parts of the canopy. Pressure chamber measurements were only performed during the winter campaign, as the trees were un-stressed during the summer campaign due to good prior rains.

Figure 9.10   Measurements of pre-dawn xylem pressure potential (left) and photosynthesis using a "SunSky" chamber (right, top) and a RedBlue chamber (right, bottom).

Leaf litter-fall rates were initially sampled using metal trays with a catch area of 800 cm², but were later expanded to larger shade-cloth traps. These traps were only placed beneath the evergreen tree species as the leaf drop pattern of the deciduous species was more intuitive (summer maximum leaf area, winter leafless). The traps were emptied approximately monthly and the samples were oven-dried and weighed, after which the results were scaled up to whole-tree equivalents using the ratio of trap size to canopy cross-sectional area.

Estimates of changes in leaf area per species over time were obtained using the Li-COR LI-2000 Plant Canopy Analyser, with the sensor head positioned at the base of the live crown and close to the main stem. Radiation extinction coefficients for the canopies of the various tree species were estimated using solarimeters / pyranometers (for solar radiation measurements) and quantum sensors (for photosynthetically active radiation (PAR) measurements). Within-canopy sensors were placed in the north-facing, middle and south-facing parts of the tree canopies, and an additional control sensor (un-obstructed) was placed in the open (for total incoming solar radiation). Data from these sensors were logged every minute and within-canopy measurements were compared against each other and against the external control.

9.3   Results

9.3.1   Weather and sap flow (transpiration)

Monthly variations in mean maximum and minimum temperature, total rainfall and total solar radiation measured at the respective study sites are illustrated below. Raw heat pulse velocity data collected from the indigenous trees were wound-corrected and converted to hourly sap flow values using the techniques, formulae and additional information described in Appendix 1. These hourly data were aggregated to daily, monthly and annual totals for the trees at each site. Daily fluctuations in sap flow / transpiration (kg day^{-1}) for the trees at the various sites are also shown below.

9.3.1.1 *Winterskloof*

The lowest recorded temperature at the Winterskloof site was 2.9°C on 24 May 2007, while the highest recorded temperature was 40.1°C on 7 December 2006. Mean annual temperature was 18.2°C, and average daily solar radiation was 13.13 MJ m^{-2} day^{-1}. Rainfall for the same calendar year over which transpiration and biomass increment totals were recorded (14 Feb 2007 to 13 February 2008) amounted to 1 652 mm. Although the rainfall exhibited a typical seasonal pattern (Figure 9.11), the total was significantly above the long-term mean of 1 207 mm.
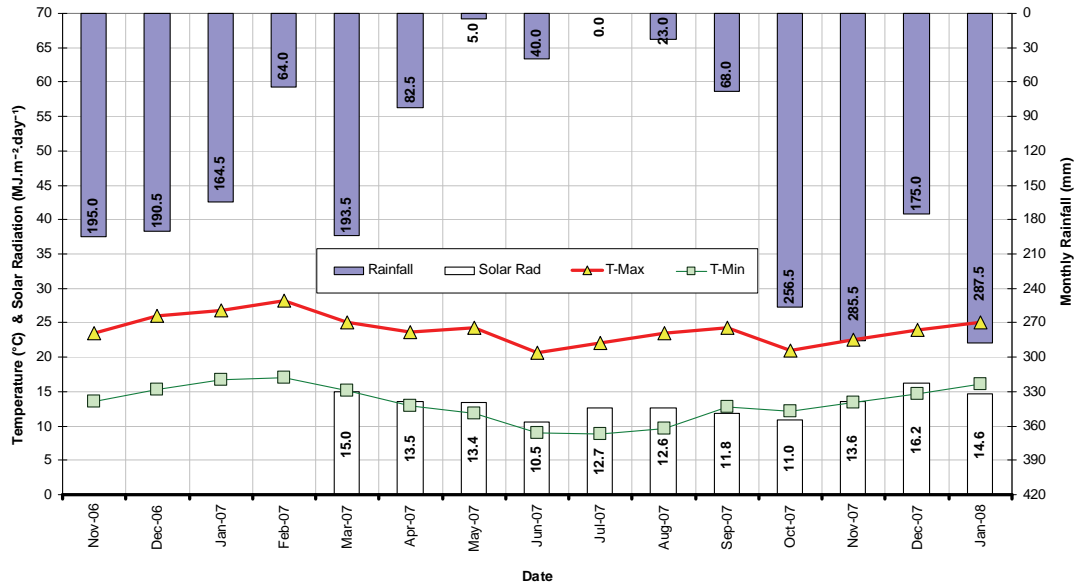
Figure 9.11   Monthly values of meteorological variables recorded between November 2006 and January 2008 at the Winterskloof site.

Sap flow in the *Trema orientalis* tree at this site declined during the colder winter months, although the highest sap flow rates were recorded late in the summer (April 2007) (Figure 9.12). The tree did not ever lose all of its leaves (likely due to the mild winter conditions experienced at the site) and lower sap flow rates were maintained throughout winter. Significant daily variation in sap flow is evident and is attributed to the weather conditions of the day. Typically on overcast rainy days (high humidity, low temperatures and low solar radiation energy inputs) sap flow rates were at their lowest (e.g. 27 June 2007). The transpiration total for the same calendar year used to calculate biomass increments (14 Feb 2007 to 13 February 2008) amounted to 8 089 litres.

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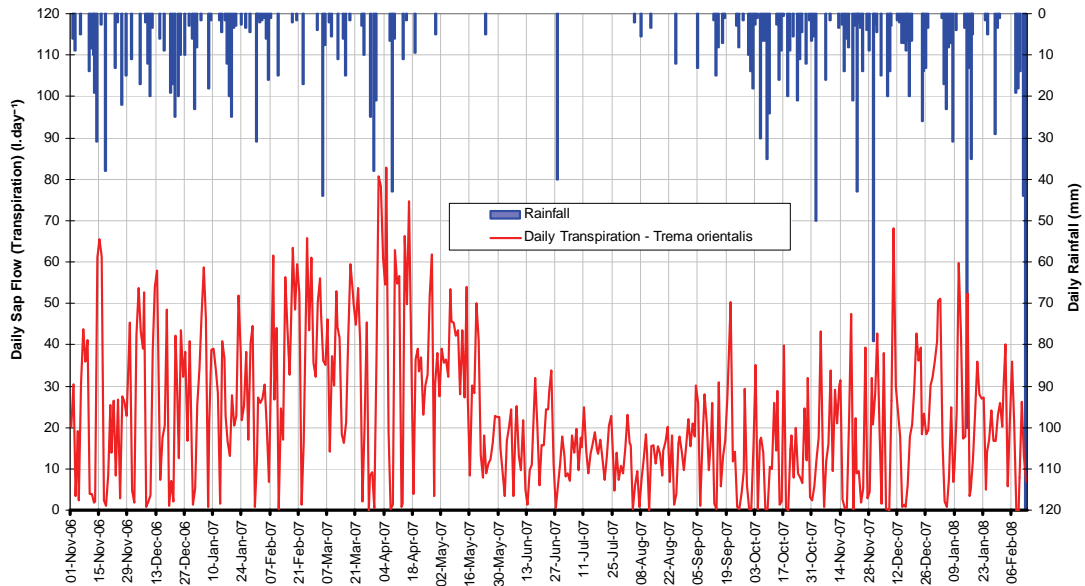
Figure 9.12   Daily sap flow totals (l day^{-1}) for a Trema orientalis *(Pigeonwood) tree, with rainfall at the Winterskloof site, between November 2006 and February 2008.*

9.3.1.2   *Karkloof*

Weather data for the Karkloof site exhibited a similar trend to the Winterskloof site, but with a number of notable exceptions. Temperatures were lower, with a mean annual temperature of 17.3°C, and average daily solar radiation of 12.6 MJ m^{-2} day^{-1}. Frost was a common occurrence in winter and the lowest recorded temperature at the site was -1.4°C on 2 July 2007. The highest recorded temperature was 35.3°C on 14 December 2006. Rainfall for the same calendar year used to calculate transpiration / biomass increments (14 Feb 2007 to 13 February 2008) amounted to 1 165 mm, which is approximately 100 mm below the long-term mean. October 2007 was a noticeably wet month, with a corresponding drop in temperatures (Figure 9.13).
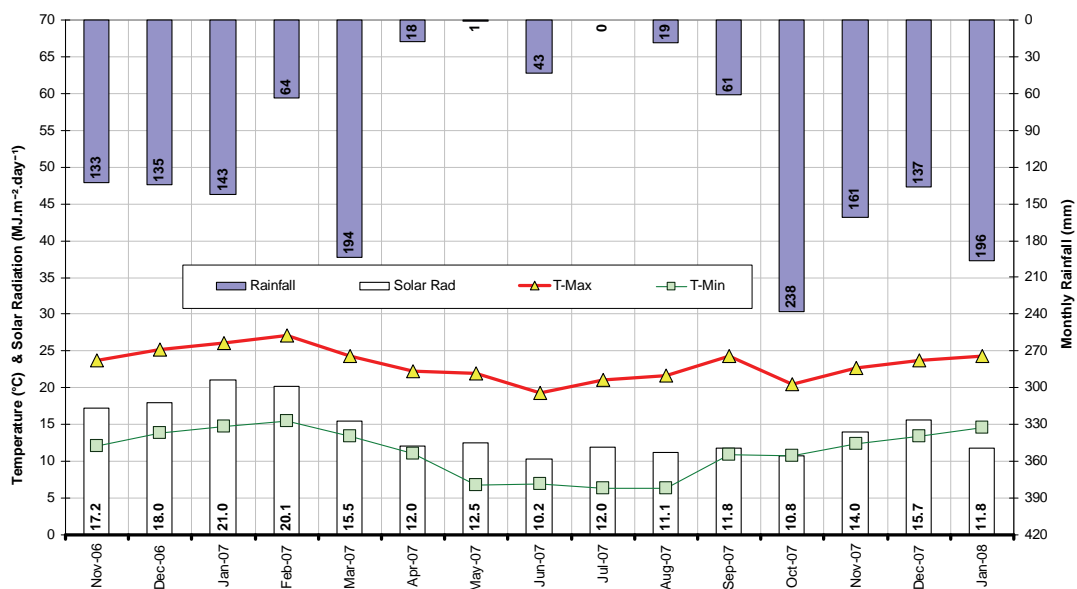
Figure 9.13   Monthly values of meteorological variables recorded between November 2006 and January 2008 at the Karkloof site.

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Sap flow recorded from the three sample trees at Karkloof showed distinctly different patterns. Sap flow in the deciduous *Celtis africana* declined sharply from mid-April and showed no discernable movement after 20 April (Figure 9.14). It was observed that there were still some green leaves on the tree at that stage, and they were only completely shed by the end of May. Sap flow totals were 60% higher for the 2007/08 summer season compared to the 2006/07 summer, while rainfall was 22% higher. Bud-burst in the *Celtis africana* tree occurred on 8 August 2007 and sap flow was immediately discernable in the tree and increased sharply thereafter. Interestingly, although this was a deciduous tree, it had the highest 1-year sap flow total of all the sample trees, which amounted to 8 396 litres. The *Podocarpus falcatus* and *Ptaeroxylon obliquum* (often deciduous when mature, but in this case evergreen) trees, on the other hand, showed far more conservative sap flow rates, with totals of 6 570 and a surprisingly low 4 407 litres respectively. Their sap flow patterns were typical of evergreen species and proved more consistent throughout the year (Figure 9.15 and Figure 9.16).
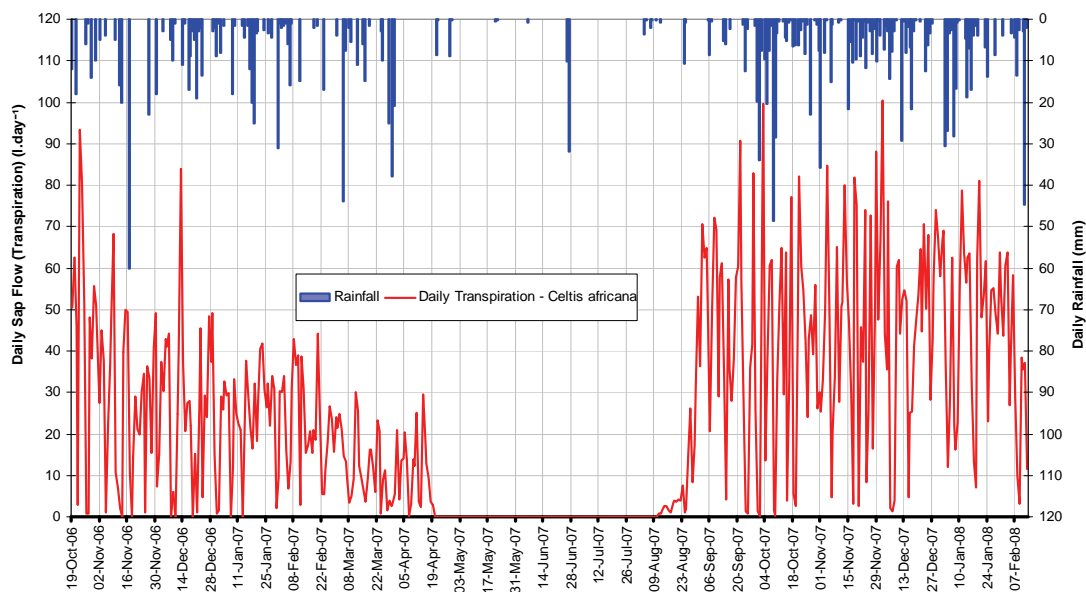
Figure 9.14   Daily sap flow totals (l day^{-1}) for a Celtis africana (White Stinkwood) tree, with rainfall at the Karkloof site, between October 2006 and February 2008.
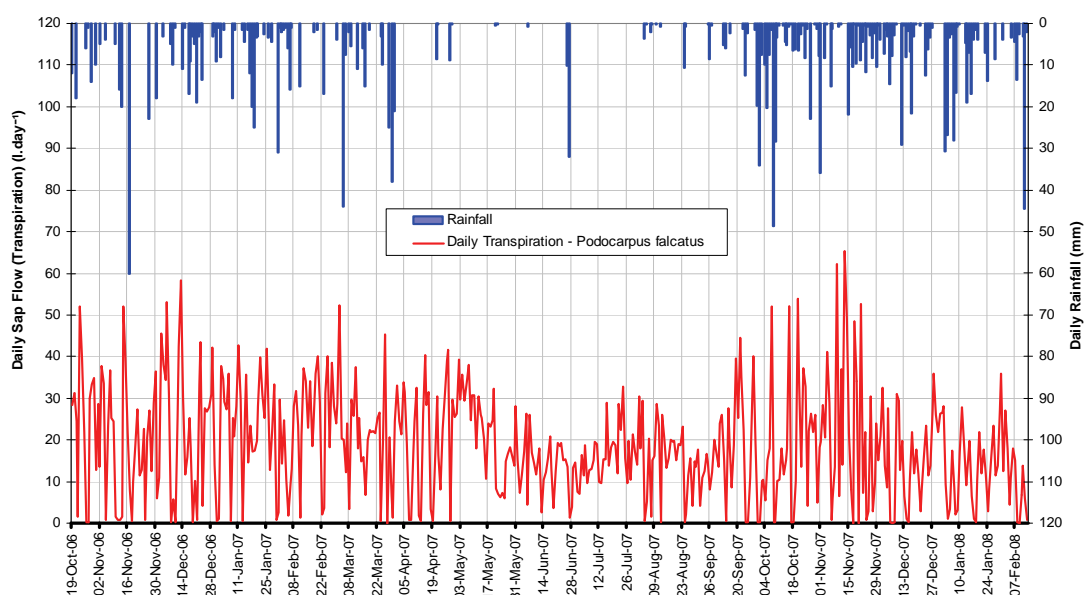
Figure 9.15   Daily sap flow totals (l day^{-1}) for a Podocarpus falcatus (Yellowwood) tree, with rainfall at the Karkloof site, between October 2006 and February 2008.

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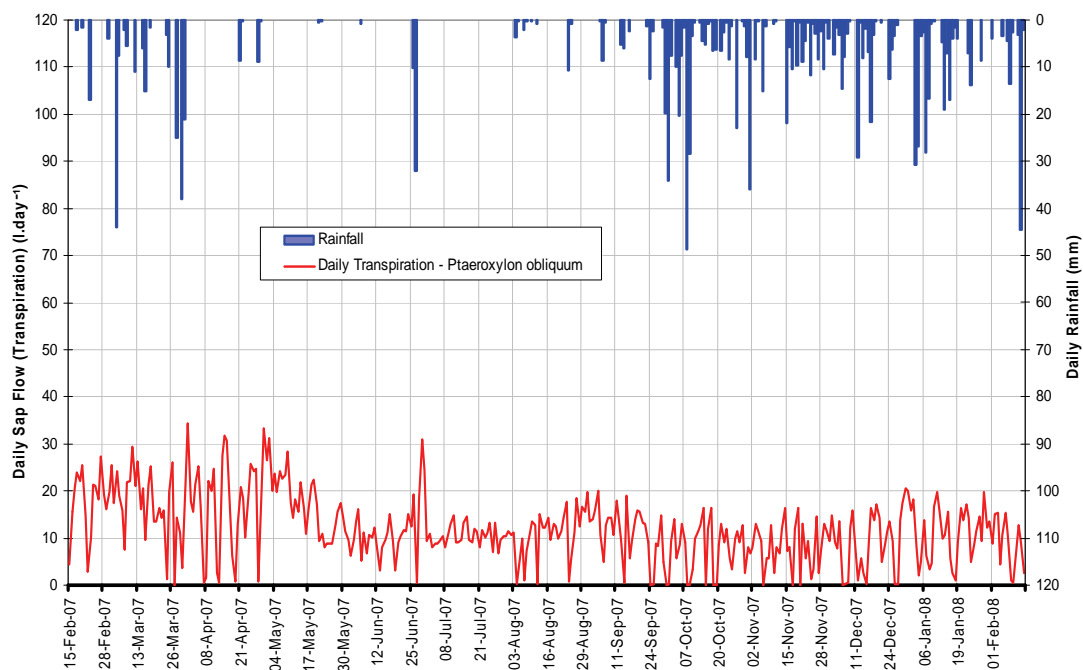
Figure 9.16   Daily sap flow totals (l day^{-1}) for a Ptaeroxylon obliquum (Sneezewood) tree, with rainfall at the Karkloof site, between February 2007 and February 2008.

9.3.1.3   Weenen

Climatic conditions at the Weenen sites were significantly more marginal than at the other two sites. Rainfall at the lower *Olea europaea* subsp. *africana* site during the sample year amounted to just 607 mm (Figure 9.17), which was significantly below the MAP of 730 mm. Temperatures were also more extreme and the site had the highest mean annual temperature (19.4°C), and average daily solar radiation (17.2 MJ m^{-2} day^{-1}) of all three locations. Frost was uncommon and the site only experienced below-zero temperatures once (-0.26°C on 24 May 2007). The highest recorded temperature was 39°C on 21 February 2007. Conditions were more favourable at the higher *Berchemia zeyheri* site. The mean annual temperature was a degree cooler (18.3°C) and the maximum temperature recorded was 35.3°C on 14 November 2007. The lowest temperature recorded at this site was 2.3°C on 22 May 2007. Rainfall at the site was determined by adjusting the rainfall record from the Wild Olive site according to the rainfall/altitude relationship in the KwaZulu-Natal Drakensberg region as determined by Schulze (1979). This equated to an increase of approximately 30 mm per 100 m rise in altitude, leading to an annual rainfall estimate of 670 mm.

Figure 9.17/...

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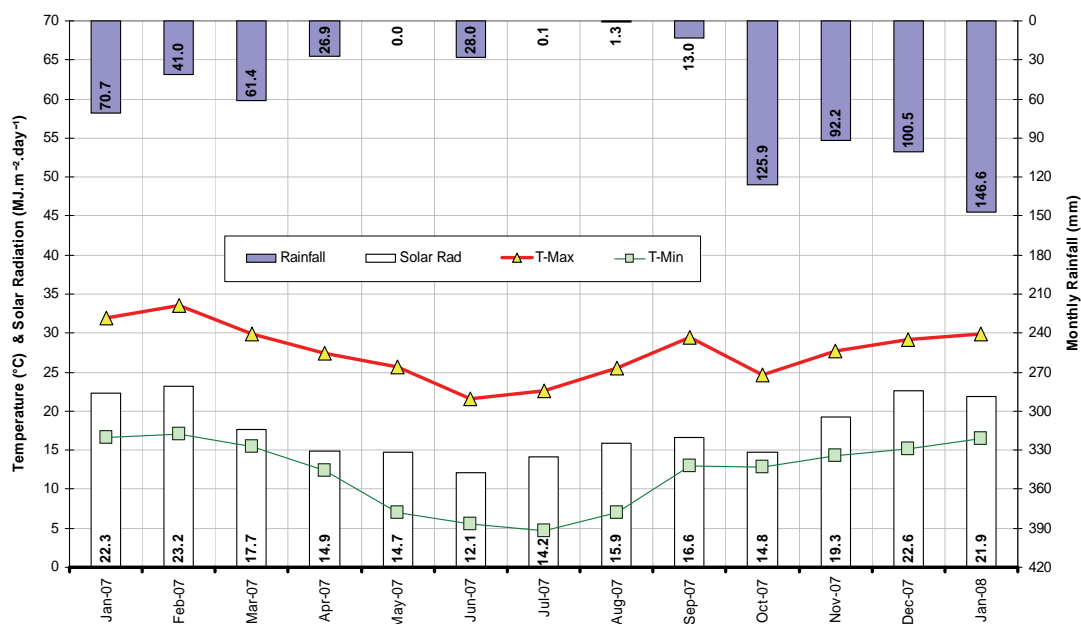
Figure 9.17   Monthly values of meteorological variables recorded between January 2007 and January 2008 at the lower Weenen site.

Sap flow recorded from the *Olea europaea* subsp. *africana* tree declined significantly during winter. Virtually no flow was recorded after the end of April and before the first rains in early October, apart from a period in July, being a response to an unseasonal mid-winter rainfall event of 23 mm on 27 June 2007 (Figure 9.18). Although the species is evergreen by nature, this decline in sap flow was indicative of the water stress that the tree experienced during winter. The overall 1-year sap flow total was a conservative 5 223 litres.

Sap flow in the *Berchemia zeyheri*, being a deciduous tree, declined sharply from as early as the end of February. No discernable sap flow was recorded between mid-May and the first rains in early October, apart from an unusual response shortly after the mid-winter rainfall event referred to above (Figure 9.19). The tree was completely leafless at this stage; however the sap flow movement may possibly be attributed to the re-hydration of the tree (by osmotic potential gradients) after a period of dry weather and low soil moisture values (Dr. E. February, pers. comm., 2007). Total sap flow for this tree during the sample period was 6 103 litres, which is comparatively high, but may be attributable to the greater overall size and leaf area of this tree.

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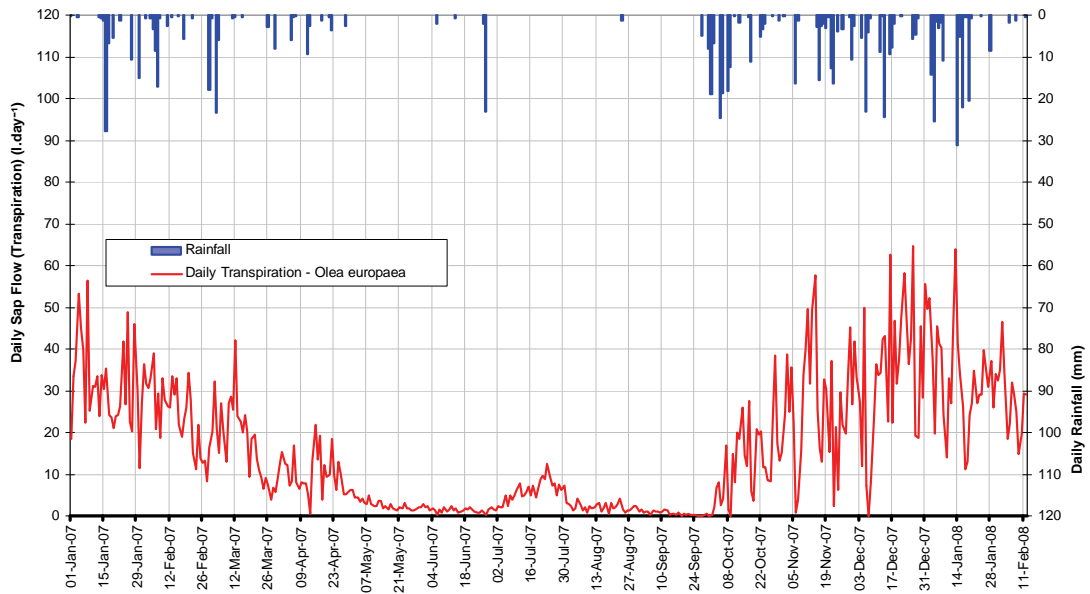
Figure 9.18 Daily sap flow totals (l day⁻¹) for an Olea europaea subsp. africana *(Wild Olive) tree, with rainfall at the Weenen site, between January 2007 and February 2008.*
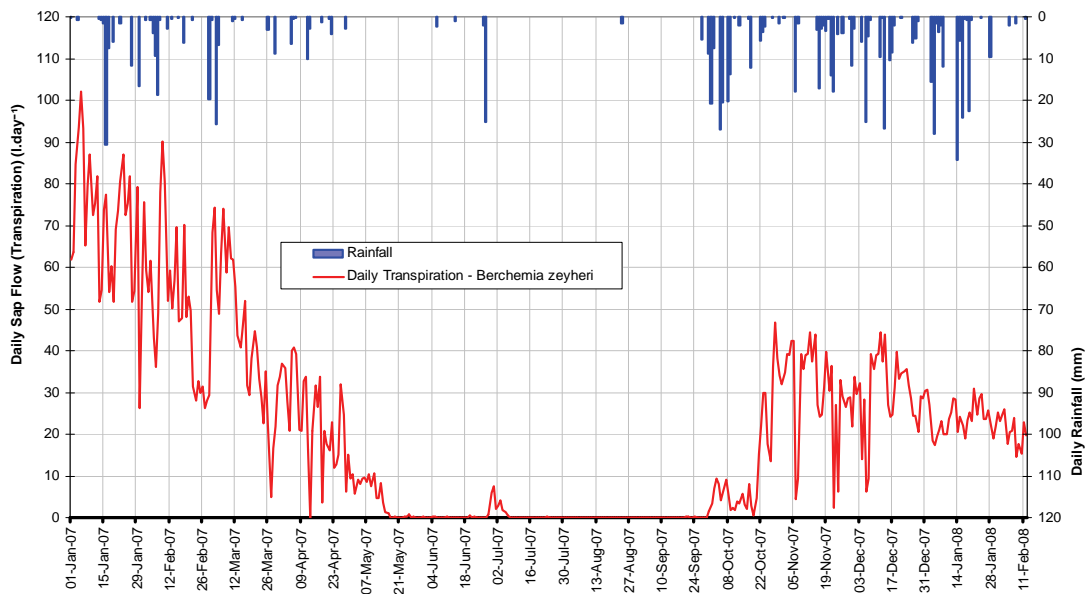
Figure 9.19 Daily sap flow totals (l day⁻¹) for a Berchemia zeyheri *(Red Ivory) tree, with rainfall at the Weenen site, between January 2007 and February 2008.*

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9.3.2 Growth increments and water-use efficiency

Table 9.3 summarises the WUE data measured on the indigenous species in this study. Figure 10.20 compares these data against those for exotic plantation species measured in previous studies.

Table 9.3   Summary of WUE (m³ stem wood or stem plus branch wood per m³ of water transpired) data for selected indigenous tree species, as calculated from a volume-based ratio of biomass increment over water-use.

Species	1-yr Rainfall (mm)	1-yr Water-use (m³)	Stem Volume Increment (m³)	Total Volume Increment (m³)	Water-use Efficiency (m³ stem wood / m³ water)	Water-use Efficiency (m³ total wood / m³ water)
Trema orientalis	1 437	8.089	0.0184	0.0252	0.0023	0.0031
Celtis africana	1 165	8.396	0.0219	0.0379	0.0026	0.0045
Podocarpus falcatus	1 165	6.571	0.0147	0.0181	0.0022	0.0028
Ptaeroxylon oblilquum	1 165	4.407	0.0081	0.0120	0.0018	0.0027
Berchemia zeyheri	667	6.103	0.0127	0.0152	0.0021	0.0025
Olea europaea subsp. *africana*	607	5.223	0.0018	0.0059	0.0003	0.0011
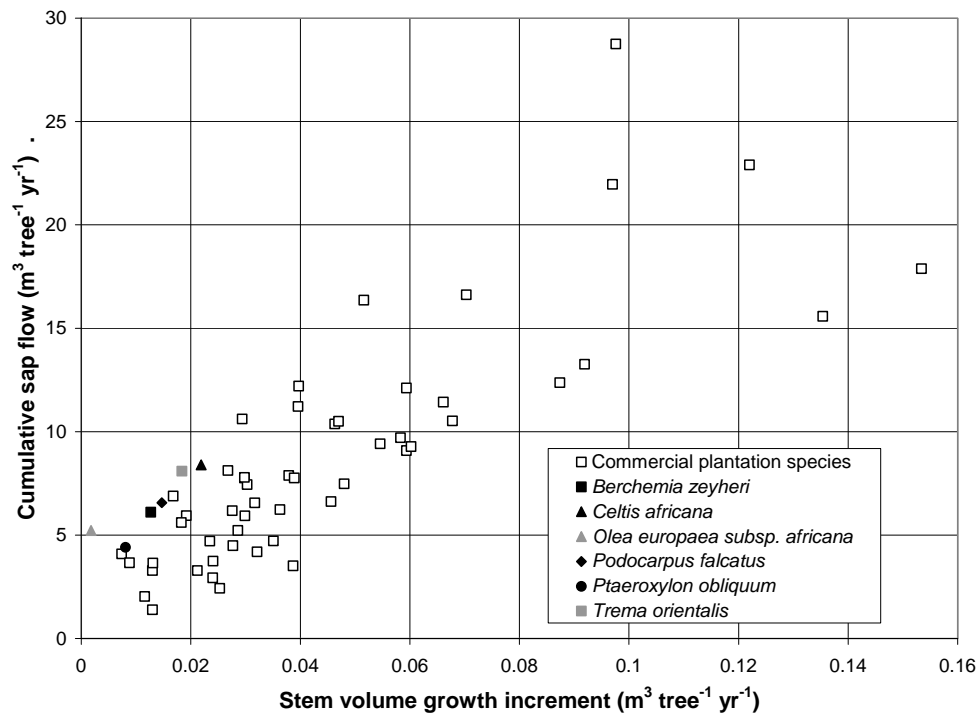
*Figure 9.20 A comparison between 1-yr **stem volume** growth increment and 1-yr total sap flow, for indigenous and exotic tree species.*

When WUE is expressed in terms of mass, i.e. as a ratio of utilizable biomass (kg tree[-1] yr^{-1}) over sap flow (kg tree[-1] yr^{-1}) the results indicate more competitive efficiencies amongst some of the indigenous species (specifically *Celtis africana, Berchemia zeyheri* and *Ptaeroxylon obliquum*) when compared against the exotic species. Data are presented in Table 9.4 and Figure 9.21.

Table 9.4   Summary of WUE data for selected indigenous tree species, as calculated from a mass-based ratio of biomass increment over water-use.

Species	1-yr Water-use (t)	Ave. Wood Density (g cm⁻³)	Stem Mass Increment (t)	Total Mass Increment (t)	Water-use Efficiency (t stem wood / t water transpired)	Water-use Efficiency (t total wood / t water transpired)
Trema orientalis	8.089	0.422	0.008	0.011	0.0010	0.0013
Celtis africana	8.396	0.605	0.013	0.023	0.0016	0.0027
Podocarpus falcatus	6.571	0.468	0.007	0.008	0.0010	0.0013
Ptaeroxylon oblilquum	4.407	0.716	0.006	0.009	0.0013	0.0020
Berchemia zeyheri	6.103	0.807	0.010	0.012	0.0017	0.0020
Olea europaea subsp. *africana*	5.223	0.916	0.002	0.005	0.0003	0.0010
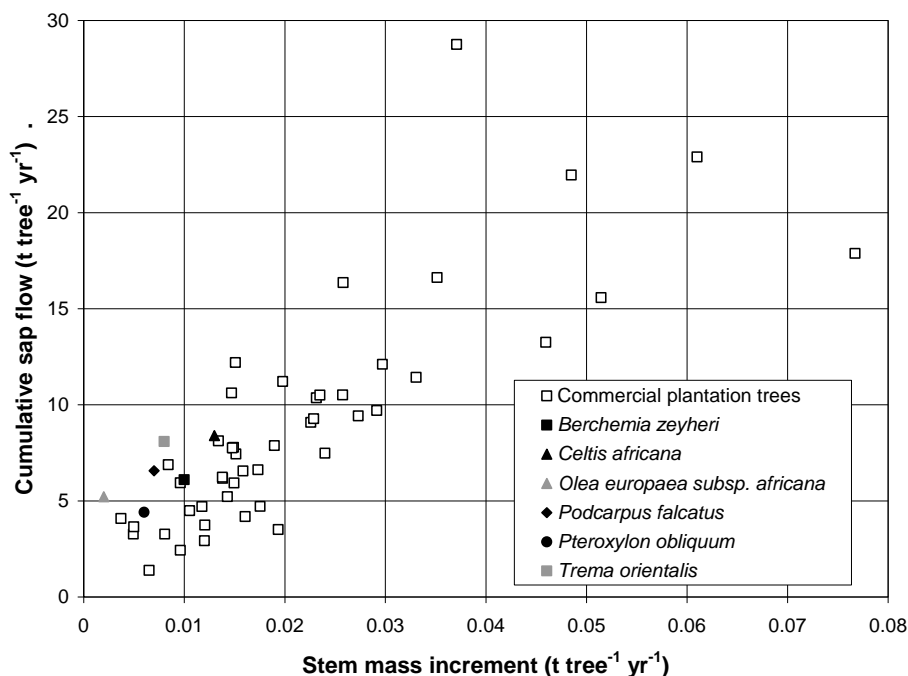
*Figure 9.21   A comparison between 1-yr **stem mass** increment and 1-yr total sap flow, for indigenous and exotic tree species.*

Figure 9.22 compares the WUE (g kg⁻¹) of the six indigenous trees (the last six bars) against the available data from commercial forest species.
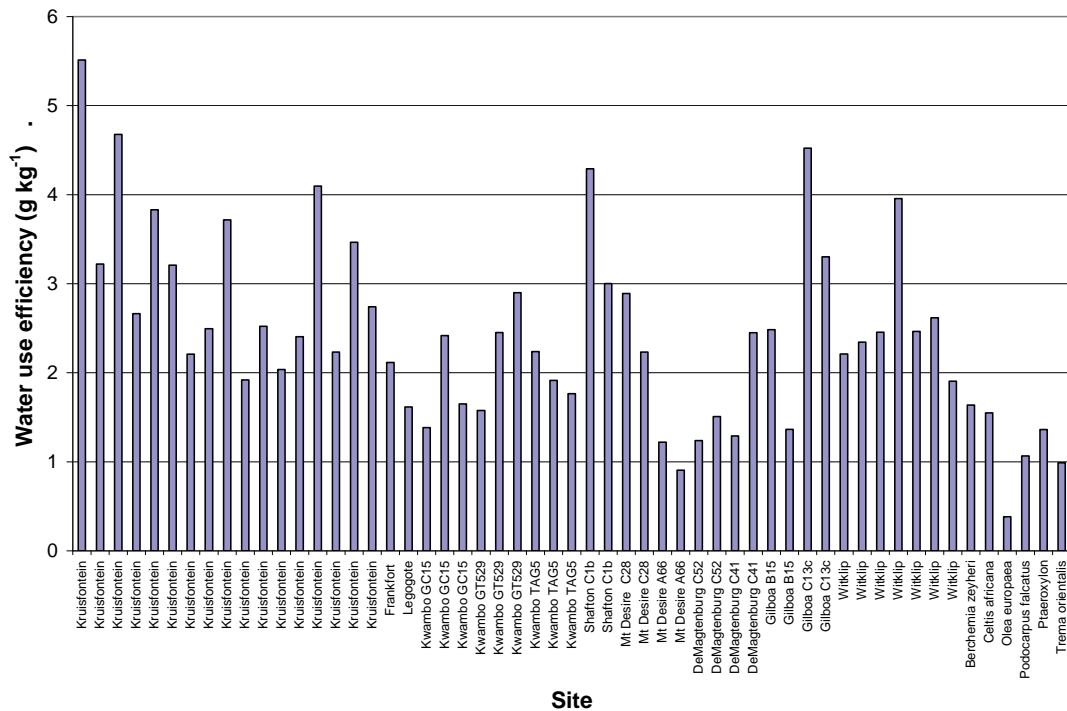
Figure 9.22   A comparison of water-use efficiency (stem mass increment per mass of water transpired) of commercial and indigenous trees.

9.3.3   Exploring the link between leaf gas exchange and whole-tree WUE in indigenous trees

The results of this phase of work have confirmed that indigenous species of trees exhibit a slower stem growth rate (expressed both by volume and mass) than commercial forest species. This is despite the fact that the indigenous sample trees were young, healthy, well exposed to sunlight and, particularly in the case of Karkloof and Winterskloof, growing on good quality sites. These trees all experienced minimal competition from surrounding plants, in contrast to the commercial forest trees which were all growing within stands of even-aged trees. This result is perhaps not surprising since forest species/clones have been selected for their high overall productivity and high stem growth rates. Furthermore, growth within high-density plantations can be expected to minimize branch development and enhance stem growth.

Figure 9.21 shows that for a given stem mass increment, cumulative sap flow in all the indigenous species is relatively high compared to the commercial species. The purpose of recording the additional physiological and structural measurements performed on each tree was to generate hypotheses as to why differences in WUE exist among indigenous species, and also to draw comparisons to commercial forest species (mainly *Eucalyptus* spp.) in an attempt to understand why indigenous trees appear to be associated with relatively slow growth rates and low WUE. With this understanding, it may be feasible to screen a much larger number of species to identify those that possess an optimum mix of higher growth rate, lower water-use and higher WUE. Comparisons are made under the following headings:

▪   **Air humidity levels**

It is very well established that tree WUE is markedly influenced by atmospheric humidity (Baldocchi *et al.*, 1987; Lindroth *et al.*, 1994) since high humidity levels reduce the rate of diffusion of H_2O without altering the CO_2 diffusion gradient. The higher rainfall Winterskloof/Karkloof sites are both prone to the occurrence of mist, and humidity levels are thought to be higher than those of the lower-rainfall Weenen sites. Figure 9.23, however, displays no evidence that WUE variation across these sites plays a dominant role in causing WUE differences. Similarly, figure 9.22 illustrates WUE recorded in individual *Eucalyptus* trees from various sites in Mpumalanga and KwaZulu-Natal. There is much variation in WUE among trees growing at the same site and

therefore experiencing the same weather conditions. We conclude that rainfall, soil conditions and clonal/species differences play more dominant roles in determining WUE differences than air humidity differences.
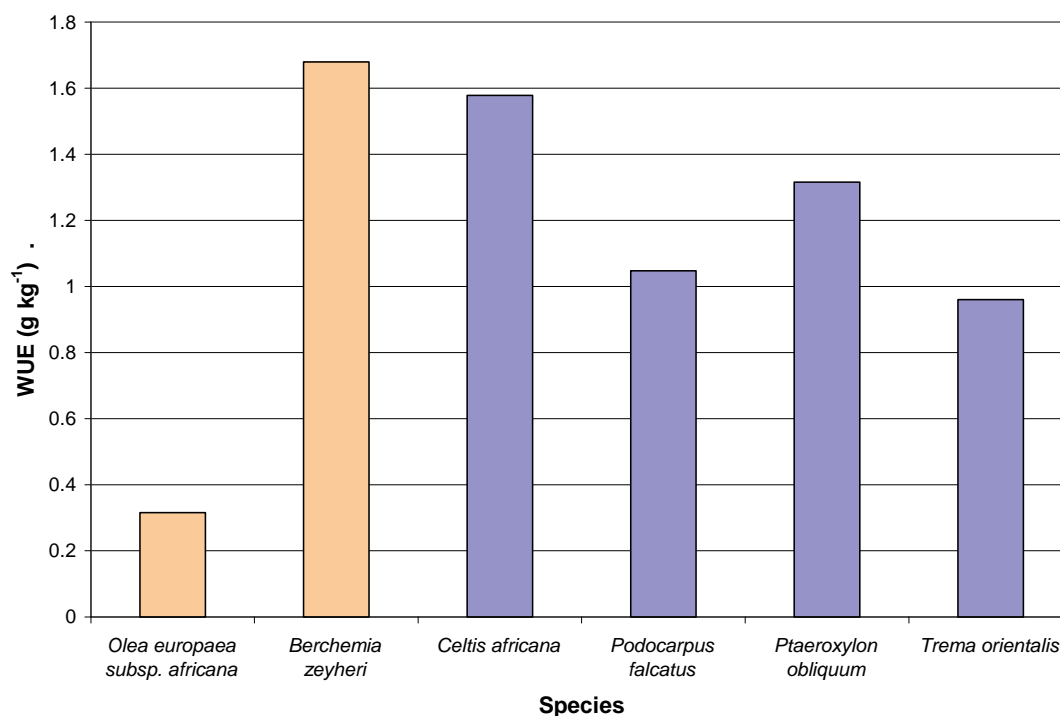
*Figure 9.23   A comparison of WUE (stem mass per unit of water transpired) recorded in species growing in the drier Weenen Game Reserve (*Olea europaea *subsp.* africana *and* Berchemia zeyheri*) and the wetter Karkloof and Winterskloof sites (*Celtis africana, Podocarpus falcatus, Ptaeroxylon obliquum *and* Trema orientalis*).*

▪   **Leaf maximum stomatal conductance**

Whitehead and Beadle (2004) summarize measurements of maximum stomatal conductance (g_{smax}) reported in the literature for a variety of *Eucalyptus* species. These values (Table 9.5) are compared to values recorded with a Li-Cor porometer on the indigenous sample trees. Stomatal resistance recorded in units of s m^{-1} were converted to molar units using a conversion factor of 0.0465 (Table A9, Pearcy *et al.*, 1989, assuming T = 25°C, and mean atmospheric pressure = 89 kPa associated with a mean altitude of 1 100 m.a.m.s.l., for conversion of mm s^{-1} to mol m^{-2} s^{-1}).

*Table 9.5   Maximum leaf conductance values reported for various species of *Eucalyptus*, and summarized by Whitehead and Beadle (2004).*

Species	g_{smax} (mmol m^{-2} s^{-1})
E. globulus	191-499
E. nitens	387
E. camaldulensis	278-725
E. leucoxylon	264
E. platypus	231
E. grandis	280-600
E. tereticornis	500-980
E. miniata	880
E. tetrodonta	440

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Figure 9.24 illustrates the range of summer-time stomatal conductance values recorded from the abaxial surfaces of sun-lit leaves on the six indigenous species. Due to good rains prior to these December measurements, we assumed that conductances were not reduced as a result of soil water deficits. It is evident that g_{smax} recorded for each species is much lower than the range of g_{smax} recorded for *Eucalyptus* species in Table 9.5.
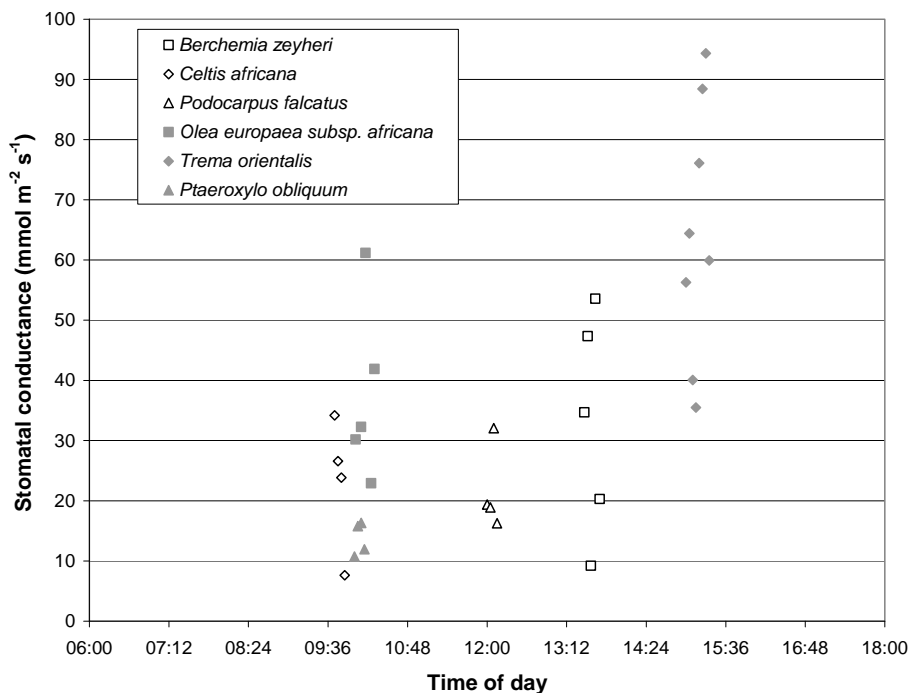
Figure 9.24   The range of summer-time stomatal conductance values recorded from the abaxial surfaces of sun-lit leaves on the six indigenous species.

Only the abaxial leaf surface conductance is shown in Figure 9.24, since the adaxial surfaces were generally characterized by much lower conductance values (Figure 9.25).
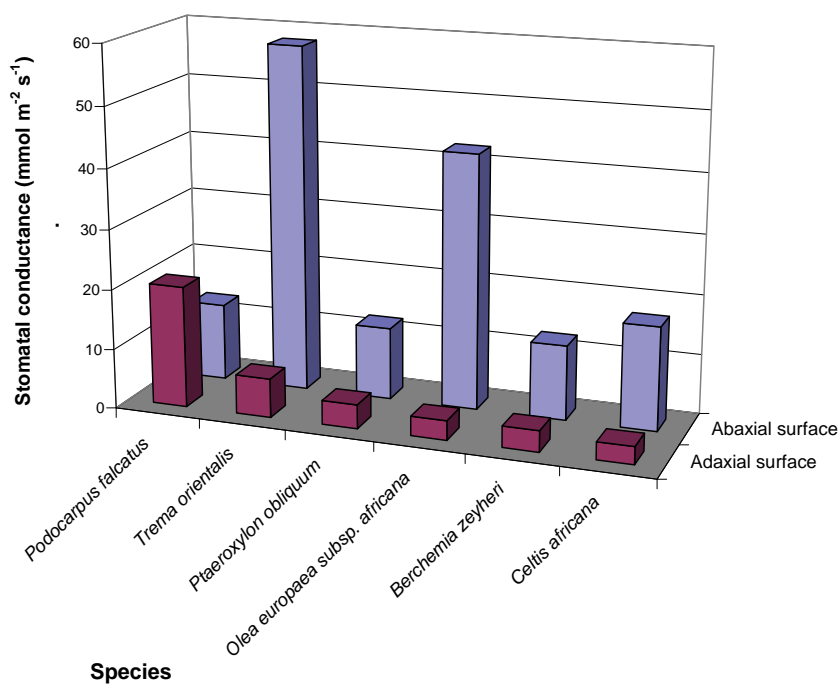
Figure 9.25 A comparison of summer-time mean stomatal conductance readings recorded on the abaxial and adaxial surfaces of sample leaves from each of the indigenous species.

- **Leaf net photosynthesis**

Light response curves were similarly measured during summer when significant antecedent rainfall ensured that all sample trees experienced adequate soil water availability. A_{max} varied substantially among the species (Figure 9.26). Comparable data recorded in various *Eucalyptus* species were summarized by Whitehead and Beadle (2004) and these are reproduced in Table 9.6. Once again, the *Eucalyptus* values greatly exceed those recorded in the indigenous species. Further data for a range of different tree species are provided by Landsberg (1986) and Holbrook and Lund (1995), showing typical values to range from 10-15 μmol m^{-2} s^{-1}. This is further evidence that the indigenous species sampled in this study exhibit relatively low net photosynthetic rates.
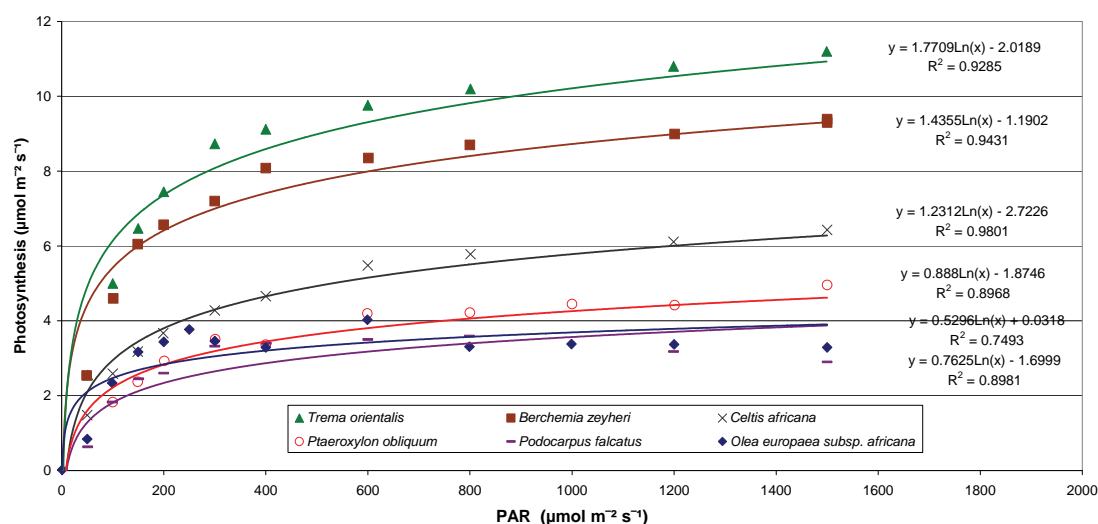
Figure 9.26   Light response curves recorded during summer showing net photosynthesis rates relative to increasing intensities of photosynthetically active radiation (PAR), for the six indigenous tree species.

Table 9.6   Values of maximum assimilation rate (A_{max}) reported for various species of Eucalyptus, *and summarized by Whitehead and Beadle (2004).*

Species	A_{max} (μmol m^{-2} s^{-1})
E. globulus	15.0-15.5
E. nitens	19.8 – 20.6
E. camaldulensis	~ 25
E. grandis	13.4 – 32.9
E. pellita	25
E. tetrodonta	15.9

9.4   Discussion

The above leaf-scale gas exchange results show that sun-lit leaves of all six indigenous species are characterized by relatively low stomatal conductance and low A_{max} when compared to high-productivity hardwood species such as *Eucalyptus* spp. These leaf attributes are likely to explain much of the difference in growth rates between the two groups, and perhaps also the lower whole-tree WUE.

The future role of indigenous tree species as a profitable land use will depend on their productivity (generally the utilizable stem volume) and the value of the wood produced, but also on their water-use and overall WUE. Regarding productivity, results confirm that stem growth is low in comparison to commercial forest species.

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However, we have seen in Chapter 8 that a higher value of wood may counteract this, leading to a greater profitability from indigenous species.

Regarding water-use, an important potential advantage of systems based on indigenous trees lies in their lower water-use and consequent reduced hydrological impact. Such systems could fill an important niche in areas where the current commercial hardwood species are disallowed as a result of their high water-use. The whole-tree WUE data suggest (bearing in mind the difference of plantation versus open-grown conditions) that the indigenous species are characterized by a lower water-use efficiency (greater water-use per unit of stem mass produced) than most of the sampled *Eucalyptus* trees. However, it is important to assess this against the full range of sap flow shown in Figure 9.21. The indigenous tree annual cumulative sap flows lie below 8 t tree^{-1} yr^{-1}, whereas sap flows in the more productive commercial trees may exceed 20 t tree^{-1} yr^{-1}. Assuming that these per-tree attributes are retained in plantations of these species, the overall water-use by the indigenous species will remain substantially below that of productive commercial forest plantations, leading to a lower streamflow reduction potential.

How useful are instantaneous leaf gas exchange measurements in identifying indigenous tree species with desirable growth and water-use attributes? Various relevant data shown in Table 9.7 indicate that no strong correlations exist linking leaf-scale gas exchange attributes to whole-tree growth, sap flow and WUE.

Table 9.7   *Ranked stem mass increment in relation to total stem + branch mass, WUE, leaf gas exchange properties and canopy properties recorded for the six indigenous trees.*

Species	Stem mass increment (t)	Stem + branch mass increment (t)	Total sap flow (m^3)	WUE (t stem / t water)	G_{smax} (sun-lit leaves) (mmol m^{-2} s^{-1})	A_{max} (sun-lit leaves) (µmol m^{-2} s^{-1})	Light penetration into canopy
Celtis africana	0.013	0.023	8.396	0.0016	34.19	6.5	High
Berchemia zeyheri	0.010	0.012	6.103	0.0017	53.57	9.5	
Trema orientalis	0.008	0.011	8.089	0.0010	94.32	11	High
Podocarpus falcatus	0.007	0.008	6.571	0.0010	32.07	3	Low
Ptaeroxylon obliquum	0.006	0.009	4.407	0.0013	16.32	5	Low
Olea europaea subsp. *africana*	0.002	0.005	5.223	0.0003	61.18	3.5	

This lack of strong correlation has been observed and commented on elsewhere (Mooney *et al.*, 1978; Pereira, 1994), and indicates that other factors are at play which influence the relation between above-ground growth and water-use. These include the following:

- Light penetration into the canopy, and the total quantity of PAR absorbed by the tree. Many investigations have shown a strong, linear species-specific relationship between intercepted PAR and above-ground dry matter production over periods of a growing season (Linder, 1985; Cannell *et al.*, 1987; Grace *et al.*, 1987. Differences in canopy structure are likely to play an important role in this regard. This property of trees has been shown to explain much of the variation in productivity, and is largely related to the canopy structure. A noticeable feature of the selection of indigenous sample trees has been the wide variation in canopy density.
- Stomatal sensitivities to light and ambient VPD are known to vary among tree species and within canopies of individual trees (Jones, 1983).

- Respiration losses. These losses commonly amount to almost half of gross primary production (GPP), but have been shown recently to be variable across species and tree age (Landsberg and Gower, 1997; DeLucia *et al.*, 2007).

- Carbon allocation patterns. These have likewise been shown to vary with species, and also with growing conditions. Greater physiological stress experienced by trees results in a higher proportion of assimilated carbon being allocated below-ground (Landsberg and Gower, 1997), thus altering WUE when defined here as utilizable stem growth per unit of water transpired.

- Changes in leaf physiology and soil water availability in different seasons. Differences between deciduous and evergreen canopies, and in the length of time over which leaves remain in their peak physiological state, are likely to influence the annual WUE of trees. Seasonal variation in stress factors, especially soil water deficits, is common in South Africa and also likely to alter whole-tree WUE. Figure 9.27 illustrates the marked differences in winter-time pre-dawn xylem pressure potential that existed among the evergreen species, illustrating that such differences existed among the sample trees used in this study. Comparative data for a young *Acacia melanoxylon* tree growing at the same site are also shown in this figure. Jarvis *et al.* (1989) used a modelling approach to illustrate the effects of different stress factors on growth, water-use and WUE in forest trees.
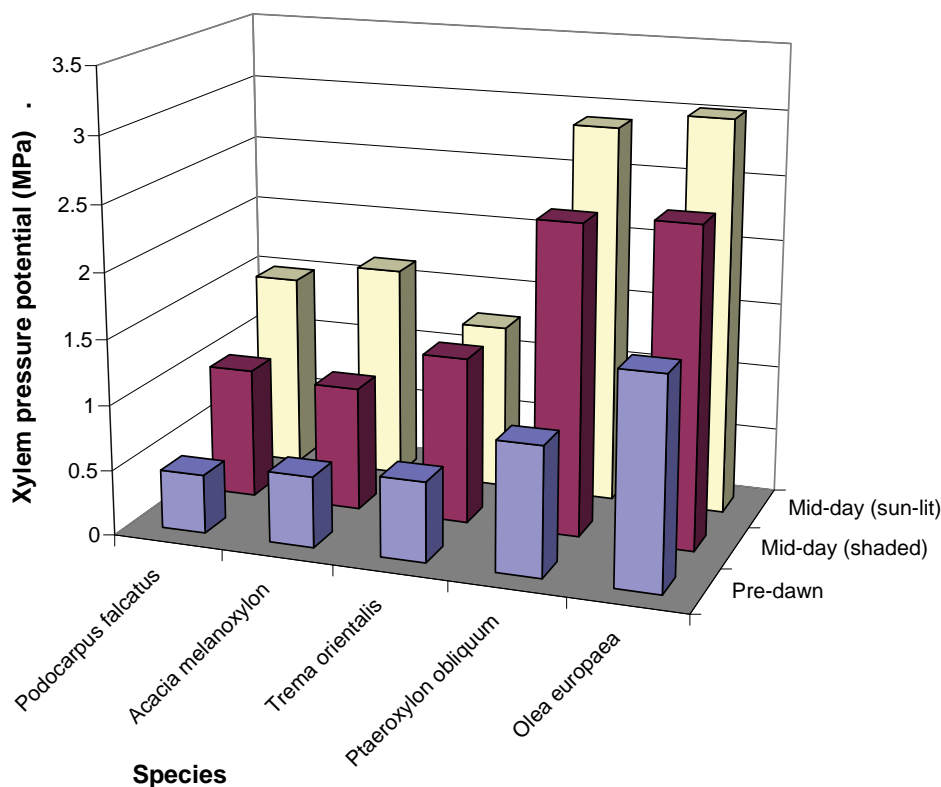
Figure 9.27   A comparison of xylem pressure potential recorded during winter on five evergreen tree species. Pre-dawn readings are compared to mid-day readings performed on shaded and sun-lit leaves.

10. GENERAL DISCUSSION AND CONCLUSIONS

10.1 Measurement of ET

This project has created significant opportunities for the testing of advanced micrometeorological systems under South African conditions and much of the experience gained has also been captured in a WRC report (Jarmain *et al.*, 2009). Specialist skills required to operate these systems have been developed across a wider group of researchers and students. These developments have opened up possibilities for direct measurement of WUE over a variety of forests, woodlands, savannas and plantations and will undoubtedly lead to improvements in water resource management.

Although the WUE of indigenous species of trees does not appear to be any higher than for commercial forest species (in fact it appears to be generally lower), transpiration remains relatively low in comparison to the more productive commercial species, particularly *Eucalyptus grandis*. Indigenous species are therefore confirmed to possess an advantage over commercial species in productive sites in their lower water-use and lower streamflow reduction impact.

10.2 Modelling of ET

Several models were used to gain insights into growth and evaporation processes, and for extrapolating daily ET from limited periods of measurement to whole years or longer. Different models were found to be required for different sites and species. Modelling experience during the course of the project has led to improved recognition of the important features of different forests, and the advantages and disadvantages of various models.

Evergreen indigenous forest in the southern Cape represented the simplest modelling situation with a dense evergreen canopy, a reasonably constant LAI, and no significant water stress. The forest could be treated as one big leaf, without the need to distinguish overstorey from understorey plants. The relatively simple P-M model is sufficient to describe such forests, provided that canopy conductance is modelled realistically.

The *Podocarpus falcatus* plantation system proved to be complex, with varying fractions of total ET originating from the tree and understorey canopies. To a large extent, this was attributed to pronounced seasonal changes in green leaf area of the understorey vegetation. Soil water availability from this riparian site, with soils associated with periodically high levels of soil water, was surprisingly shown to be a significant factor limiting transpiration from the trees. A model applicable to such sites needs to simulate ET separately for the overstorey and understorey layers, and be able to follow changes in soil water availability and green leaf dynamics, especially of the understorey plants. Plantation weeds are routinely slashed at intervals in managed plantations, so the effects of such management interventions also need to be simulated.

The savanna vegetation was probably the most difficult to simulate realistically, in view of the strong influence of leaf area dynamics, fast changes in soil water availability over the growing season and a high degree of spatial variation in tree density and species composition. The CENTURY model was difficult to parameterise successfully for savanna and this was attributed to the large number of parameters and insufficient locally-relevant information with which to describe processes and validate output. The monthly time step of the model version we used appeared to be too coarse to adequately describe the rapid changes in water balance and growth dynamics.

Choice of model is complex because of the large number of models available to the researcher and lack of clarity on their strengths and weaknesses. As an aid in selecting the most appropriate model for a particular forest, woodland, savanna or plantation, a list of model attributes which, from a review of literature and from experience in this project, may be necessary for achieving realistic simulations, are included in this report. This list should prove useful in matching simulation needs to an appropriate model.

10.3 Economic potential of indigenous trees

Economic analyses have clearly shown that volume yield is not the major criterion affecting the economic viability of forests. Timber value may be far higher for certain indigenous hardwood species than for commercial forest species. Low management costs can also play a role in increasing the economic viability of new forms of forestry based on indigenous species. When the many additional benefits from indigenous forests / plantations / savanna are taken into account (e.g. traditional medicine, fruits, recreation and tourism), their economic viability is likely to be further enhanced.

10.4 Recommendations for future research

In view of our optimistic assessment for developing economically feasible new forms of forestry based on indigenous species, we suggest that further research is warranted to establish a firmer knowledge basis from which to assess the potential for such systems in different regions of the country, and in different social and economic contexts.

Four major research tasks are proposed:

- Evaluate the commercial value of wood and marketability of a comprehensive range of tree species with potential suitability for woodlot/plantation establishment in different regions of South Africa. The focus need not necessarily be limited to wood production, but could include other valuable products such as bark for traditional medicine and fruits. The outcome would be a short-list of species to consider for further evaluation.

- Broaden our knowledge of growth rates and water-use efficiency (WUE) over a larger number of potentially useful species (identified on the short-list), and over a much wider range of site conditions. This work is likely to remain largely based on studies of single trees (due to the scarcity of even-aged plantations of indigenous species), but where possible, trees growing in such stands should be compared to open-grown trees of the same species and age to estimate the effects of a high degree of competition from neighbouring trees. As before, measurements of stem annual growth increments and annual sap flow will be required to estimate whole-tree WUE. Sample trees will need to be systematically selected from a number of sites that cover major rainfall, temperature and soil fertility gradients over the potential forestry range. Site quality plays a large role in determining the productivity of commercial forests, and the same is expected for indigenous trees.

- Investigate the possible economic profitability of indigenous plantations, especially in a rural social and economic context. This will permit setting target levels of growth rate and ET required for economic viability and acceptable hydrological impact. The value, management costs (e.g. establishment, maintenance, harvesting, transport), productivity and marketing costs of wood and other potentially valuable products would need to be investigated.

- Continue the search for rapid screening criteria that may be used to conveniently identify site conditions required by each species to permit economically sustainable productivity. There are numerous possible rapid measures that could prove useful in indicating potential growth and water-use. Some of the more obvious include the following:

    Growth ring analyses to establish mean growth rates over time.
    An index correlating short-term sap flow rates at different times of the year to annual cumulative sap flow
    Measurements of leaf/branch/stem carbon isotope ratios to indicate whole-tree WUE
    The use of leaf % nitrogen to indicate leaf photosynthetic capacity

Measurements of growth efficiency (ratio of wood production to leaf area index) as an index of vigour
The use of xylem anatomical structure to infer hydraulic architecture and water-use.

These would need to be measured on some or all of the trees used for WUE measurement to ensure wide applicability over a full range of growing conditions.

Our hope is that the research described in this report will further stimulate investigation of new forms of forestry based on indigenous tree species that are both economically viable, and compatible with the need to minimize ET to conserve catchment water yields.

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Appendix 2:
Evapotranspiration/sap flow techniques

Scintillometry

This is a fairly new technique developed over the last few years, primarily in the Netherlands. The Large Aperture Scintillometer offers the significant advantage of providing spatially-averaged evaporation estimates over distances up to 5 km, and also being reliable and robust because of the absence of moving parts and relative simplicity of design. Additional advantages are that the instruments are highly portable, and that post-processing of data is relatively uncomplicated.

The scintillation technique is based on measurement of the path-averaged structure parameter of the refractive index of air (C_n^2), and is based on the propagation statistics of electromagnetic radiation through the turbulent atmosphere. When an electromagnetic beam of radiation propagates through the atmosphere, it is distorted by a number of processes that remove energy from the beam, leading to signal attenuation. The most dominant of these are small fluctuations in the refractive index of air (n) caused by small temperature and humidity fluctuations. These refractive index fluctuations lead to signal intensity fluctuations that are known as scintillations. The system consists of a transmitter that beams a light source towards an accurately aligned receiver device (Figure 1). Light attenuation is particularly affected by temperature fluctuations. Together with supporting data on wind speed, air temperature and air pressure, measurements allow the calculation of mean surface sensible heat flux (H) along the light path. The latent heat fraction that equates to evaporation rate is derived from a simple energy balance calculation.
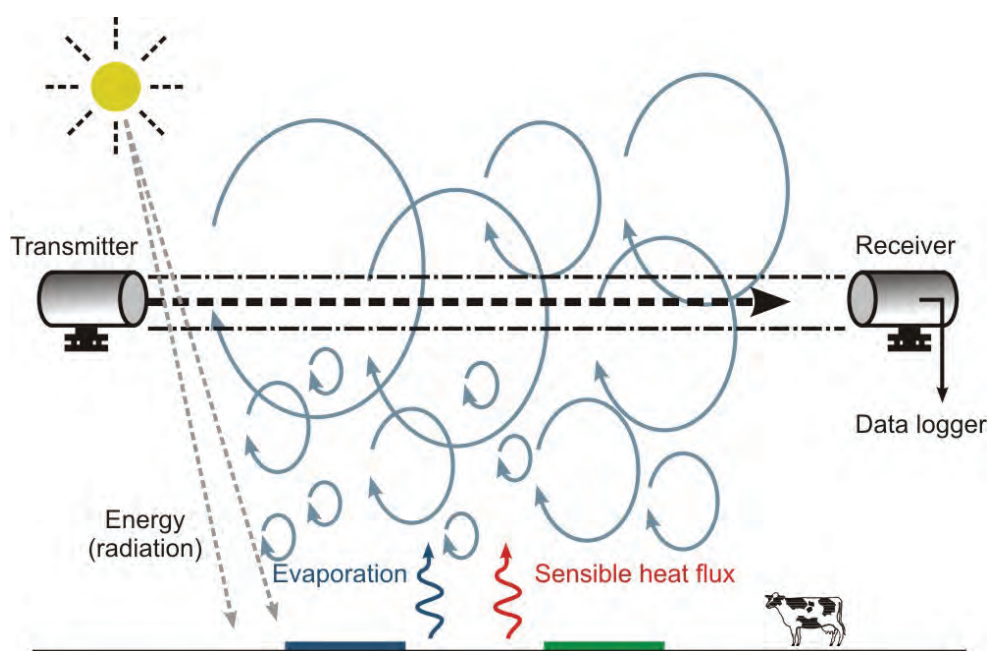
Figure A1   A diagramatic illustration of the principles surrounding the scintillometer technique

There are several significant advantages to the LAS system.

- It produces a good spatial average of sensible heat, from which an evapotranspiration rate can be derived.
- The relatively simple and robust design leads to reliable data acquisition. Time spent on patching and modelling periods of bad or no data is reduced or eliminated. Data gaps are predominantly caused by poor visibility along the beam path caused by fog or cloud. Such gaps may be of low significance, since evapotranspiration under such humid conditions is often close to zero. The instrument is completely enclosed in a weather-proof enclosure, and may be left in the field for extended periods.
- Data analysis is simple and rapidly accomplished.
- The near infrared beam is invisible and eye-safe.

Scintillometer measurements in the Groenkop forest were described in an earlier section of this report. At the start of each field campaign, the LAS transmitter was erected close to the upper edge of the forest on the lower slopes of the Outeniqua mountains (Figure 3.7) S 33° 56′ 16.1″; E 22° 33′ 21.6″. A rifle telescope mounted on top of the instrument allowed the beam to be accurately pointed towards a particular north-facing, first floor room (S 33° 57′ 17.9″; E 22° 31′ 45.9″) in the North Campus building of Saasveld College. With the help of a two-way radio system, team members at the transmitter and receiver stations communicated to align the instruments to achieve maximum signal strength at the receiver station. From GPS co-ordinates and topographical maps, the path length was estimated to be 3.1 km. A current adjust setting and path length potentiometer were adjusted to match optimum settings set out in the LAS manual. Scintillations (averages over 10 minute intervals) were continuously monitored for the entire duration of each field campaign. The intensity of scintillations is inferred from the structure parameter of the refractive index of air (C_n^2). Values are computed directly from the output signal using a standard equation, and then 10 minute means are stored on a Campbell datalogger. Net radiation was measured over the forest canopy (30 m), while soil heat flux was measured in a representative patch of forest soil, both at a site close to the beam path. The net radiometer and anemometer were attached to a cross-arm supporting instruments that was secured to the top of the telescopic mast. An automatic weather station was erected adjacent to the LAS transmitter to provide further information on solar radiation and wind speed.

The C_n^2 and radiation data were analysed further after the conclusion of each visit. The calculation of sensible heat by the LAS software requires a careful analysis of the height of the transmitted beam in relation to the tree canopy height along the entire path length. We accomplished this by using orthophoto maps with superimposed 10 m contours to estimate the ground elevation along the path at 50 m intervals. Figure 2 illustrates the variation in ground height in relation to the beam path. An average canopy height of 26 m above the ground was assumed to apply over the entire beam path. Superimposed on Figure 2 is a bell-shaped function that illustrates the relative sensitivity of the beam to scintillations along the beam path. This variation in sensitivity follows a normal distribution and is well proven in many studies. This variable sensitivity along the path length is explained (with difficulty!) by an analysis of the geometry of light beams and the greater tendency by turbulent wind eddies near the centre of the beam path to diffract light in a way that causes rays to interfere destructively with each other, thereby causing scintillations.
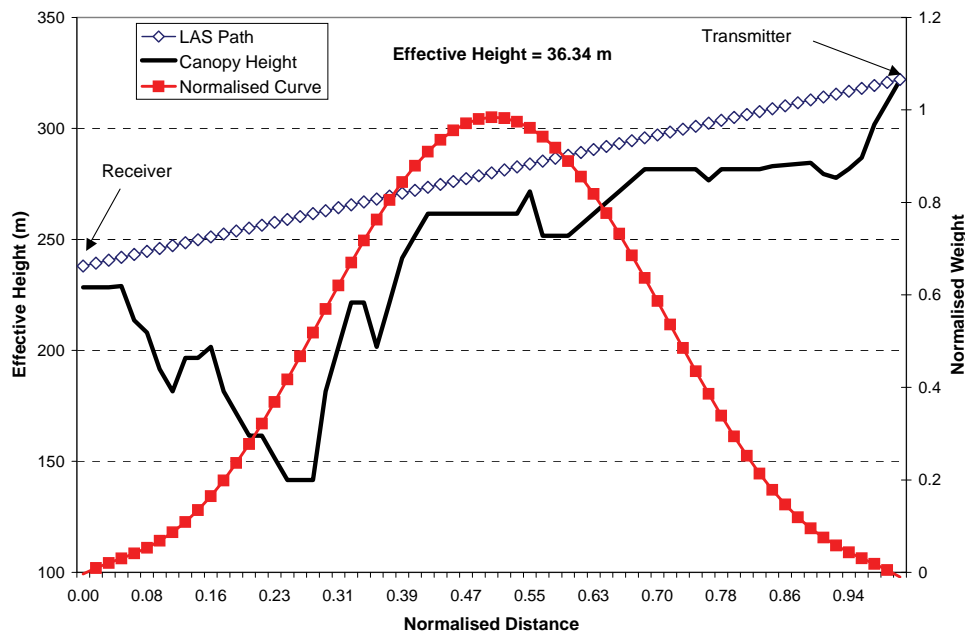
Figure A2   A diagram illustrating the height of the LAS beam in relation to the altitudinal profile of the ground as well as the sensitivity of the LAS to scintillations over the beam path.

Figure 2 illustrates that scintillations over the Groenkop forest are most easily detected in the middle section of the beam path. This was considered to be ideal, since the middle portion was close to the relatively flat research block in the Groenkop forest. Much of the deep Kaaimans River gorge was situated out of the zone of high sensitivity, closer to the LAS receiver. Except for approximately 100 m at either end of the beam path, the vegetation was entirely closed-canopy indigenous evergreen forest. The mean height of the beam above the tree canopies, weighted for the greater sensitivity in the central section of the path, was calculated to be 36.34 m.

The full analysis of scintillometer data requires additional information on wind speed and direction, air pressure, temperature and relative humidity of the air, as well as net radiation (R_n) and soil heat flux (G). An automatic weather station was erected close to the LAS transmitter at a site well exposed to wind. A net radiometer was attached to the top of the telescopic mast situated at the Eddy Correlation site that is described in more detail below. Soil temperature averaging probes, soil heat flux plates and a Campbell CS615 soil moisture probe) were used to derive the soil heat flux under the forest canopy at this site.

Further complex calculations were performed using the software WINLAS, leading to estimates of sensible heat flux. These are well described in the Kipp and Zonen LAS manual.

Eddy Covariance

The Eddy Covariance system is based on very high frequency measurements of water vapour and CO_2 above vegetation canopies (10 Hz). Such frequent measurements describe gas concentrations in eddies of air that are particularly important drivers of gas exchange above aerodynamically rough vegetation. The technique is especially valuable in studies where information on both the water and carbon fluxes are significant indicators of water-use efficiency, and which may be compared to similar data obtained over vegetation in other countries.

In fully turbulent flow the mean vertical flux F of an entity s per unit mass of the fluid is given by

$$F \ = \ \overline{\rho_a \, w \, s} \qquad\qquad (1)$$

where ρ_a is the density of air, w the vertical wind velocity, and the over bar denotes the average value during a time period of suitable length.

In the surface boundary layer all atmospheric entities exhibit short-period fluctuations about their mean value. Therefore, the instantaneous values of w, s, and ρ_a can be expressed by:

$$w = \overline{w} + w', \qquad s = \overline{s} + s', \qquad \rho_a = \overline{\rho_a} + \rho_a' \qquad\qquad (2)$$

where the prime symbol denotes an instantaneous departure from the mean. These expressions can be substituted into Equation (2) and if we neglect fluctuations in density, the mean vertical flux F reduces to:

$$F \ = \ \overline{\rho_a \, w \, s} \ + \ \overline{\rho_a \, w' \, s'} \qquad\qquad (3)$$

or by writing ρ_a for $_a$

$$F \ = \ \rho_a \, \overline{w \, s} \ + \ \rho_a \, \overline{w' \, s'} \qquad\qquad (4)$$

The first term on the right-hand side of Equation (4) represents the flux due to the mean vertical flow or mass transfer. The second term represents flux due to eddying motion or eddy flux. The mass transfer term may arise from a convergence or divergence of air due to sloping surface. For a sufficiently long period of time over horizontally uniform terrain the total quantity of ascending air is approximately equal to the quantity descending and the mean value of the vertical velocity will be negligible. Therefore, Equation (4) reduces to

$$F \ \approx \ \rho_a \, \overline{w \, s'} \qquad\qquad (5)$$

Based on the above equation, the sensible heat flux (H) and water vapour flux (E) can be expressed as:

$$H = \rho_a C_p \, \overline{w' T'} \qquad\qquad (6)$$

and

$$E = \frac{\varepsilon}{P} \rho_a \, \overline{w' e'_a} \qquad\qquad (7)$$

where u', T', and $e_{a'}$ are the instantaneous departures from the mean horizontal velocity, air temperature and vapour pressure; and ε is the ratio of molecular weights of water vapour and air and P is the atmospheric pressure.

The Eddy Covariance technique is often regarded as the standard, most direct method by which evaporation rates can be measured. The system was erected in a forest clearing within the research block of Groenkop forest. The sensors that comprise our Applied Technologies system were mounted on a cross-arm affixed to the top of the telescopic mast, and when fully extended, projected approximately 6 m above the forest canopy. The mast was transported from Pietermaritzburg on a custom-designed roof rack fitted to a Toyota Condor. During the first field campaign, great difficulty was experienced in unloading the heavy mast from the roof rack to the ground, and loading it back on at the end of the measurement period. In view of this, a portable gantry was designed and constructed. When assembled, the vehicle can be driven underneath, and the mast lifted off the roof rack with the aid of a pulley. After removing the vehicle, the mast is lowered to the ground for final positioning beneath a gap in the canopy. The first field campaign also saw difficulties with the stay wires snagging surrounding tree branches. The local forester assisted in sending tree climbers who were able to remove the problem branches.

The Eddy Covariance system includes a sonic 3-D anemometer, platinum resistance thermometer, open path gas analyzer, data packer, and logger/laptop. The system records changes in air movement, temperature, water vapour and CO_2 concentration every tenth of a second. Where vertical air movement and concentration of water vapour or CO_2 are correlated, there will be a net flux, and these are typically integrated over a period of 30 minutes. The equipment draws substantial power, and the batteries need to be regularly charged by a generator. A diesel generator was fitted with a sensor to detect when battery voltages dropped below a critically low threshold, and then automatically restart the generator.

Bowen ratio

The Bowen Ratio energy balance (BREB) technique has been comprehensively described by Savage *et al* (1997) and has been extensively deployed in a number of previous studies in South Africa (e.g. Everson *et al.*, 1998; Burger, 1999). The BREB technique estimates the components of the energy balance, and the latent heat flux is used to determine total evaporation above the vegetation canopy.

The main components of the canopy surface energy balance are as follows:

$$R_n - G - \lambda E - H = 0 \qquad (8)$$

where R_n is the net radiation, G is the soil heat flux density, λE is the latent heat flux density and H is the sensible heat flux density. The sign convention is that R_n is positive when directed towards the surface, and G, λE and H are positive when directed away from the surface.

Finite water vapour pressure and air profile temperature differences are measured over a vertical gradient in the atmosphere above the plant canopy, and an effective eddy diffusivity is assumed, to calculate the latent (λE) and sensible (H) heat flux densities.

$$\lambda E = (\lambda \rho_a \varepsilon K_v / P) \, ((\bar{e}_1 - \bar{e}_2) / (z_1 - z_2)) \qquad (9)$$

$$H = \lambda \rho_a K_h (T_1 - T_2)/(z_1 - z_2)) \qquad (10)$$

where the diffusivity coefficient for latent (K_v) and sensible (K_h) heat transfer, the density of the air (ρ_a), the ratio of the molecular mass of water (M_w) to that of dry air (M_d) ($\varepsilon = M_w/M_d$), atmospheric pressure (P), the specific heat capacity of dry air at constant pressure (c_p) and the vapour pressure ($\bar{e}_1 - \bar{e}_2$) / ($z_1 - z_2$) and air temperature ($\overline{T}_1 - \overline{T}_2$)/($z_1$ - z_2) gradient are defined.

Assuming the diffusivity coefficients (K_v and K_h) are equal, the Bowen ratio (β) is given by

$$\beta = H/\lambda E \qquad (11)$$

$$\beta = \gamma \, ((T1 - T2)/(e1 - e2)) \qquad (12)$$

where γ is the psychrometric constant.

Using the simplified surface energy balance (equation 8) and the computed Bowen ratio (equation 12), Bowen (1926) showed the sensible and latent heat flux densities (equation 9 and 10) to be

$$H = \beta \, (Rn - G)/(\beta+1) \qquad\qquad (13)$$

and

$$\lambda E = (R_n - G)/(\beta +1) \qquad\qquad (14)$$

where $\beta \neq$-1.

The Bowen ratio total evaporation is solved as

$$\lambda ET = (R_n - G) / (\beta + 1) \qquad\qquad (15)$$

where λ is the latent heat of vaporisation.

The net radiation is measured with a net radiometer, installed above the vegetation under study. The soil heat flux density is calculated from the average soil temperature, soil water content and heat flux measured 80 mm below the soil surface. The Bowen ratio system arms are installed at two known heights above the canopy. The spacing of these arms may be different above different kinds of vegetation. The air temperature profile difference is calculated from the air temperatures measured with fine wire, type-E thermocouples with a high resolution (0.006°C). The water vapour pressure difference is calculated from the water vapour pressure measured with a Dew-10 hygrometer with a resolution of 0.01 kPa.

Surface renewal
(by Professor M. Savage)

The surface renewal (SR) method for the estimation of sensible heat is relatively new and quite simple (Paw *et al*. 1995, Snyder *et al*. 1996, Spano *et al*. 2000). The SR method allows sensible heat to be estimated from measurements of air temperature at a single level using a fine-wire thermocouple. Frequency of measurement for the SR method is typically 8 Hz and post-measurement calculations are used to estimate F_h. Measurement of net irradiance and soil heat allows evaporation to be estimated using the shortened energy balance equation. The SR method is attractive because of its simplicity but also since it is relatively inexpensive. The method requires knowledge of the measurement height, the rate of change in air temperature, and a weighting factor. The weighting factor needs to be determined, for the vegetation type used, by comparison of the estimated sensible heat with other sensible heat measurements from other methods such as the EC and SLS methods. The weighting factor is 0.5 for coniferous forests, orchards and maize when the sensor is at canopy level and 1 for short grass for a sensor height of about 1 m (Paw U *et al*. 1995).

So, the SR analysis involves high frequency air temperature measurements and considering air temperature ramps (positive or negative) consisting of quiescent periods (for which there is no change in air temperature with time) and then ramping periods for which there is an air temperature ramp for unstable conditions (that is, an air temperature increase) or for stable conditions for which there is an air temperature decrease.

The amplitude of the air temperature ramp and the ramp period is estimated using an air temperature structure parameter approach based on measuring air temperature at a typical frequency of about 8 Hz or greater, using the Van Atta (1997) approach involving estimating the air temperature amplitude. The SR method has been used in South Africa by Savage *et al*. (2004) and Mengistu and Savage (2006) and the method has since been used above forests and *Chromolaena odorata*. Other temperature-based methods for estimating sensible heat have also proved satisfactory (Savage and Mengistu, 2006).

Heat pulse velocity

The Heat Pulse Velocity technique for measuring the flow of sap in trees has received much attention by researchers in recent years, and a wide variety of systems has been developed (Smith and Allan, 1996). The HPV measurements described in this report were all based on the heat ratio method which is described by Burgess *et al*. (2001). This method requires that a central line heater be implanted into the sapwood portion of the stem. The 60 mm long line-heaters were made from 1.8 mm outside-diameter stainless steel tubing, enclosing a constantan filament. Two additional holes are drilled 5 mm above and 5 mm below the heater probe. Thermocouple probes (consisting of type T copper-constantan thermocouples embedded in 2 mm outside-diameter PTFE tubing), are inserted into the upper and lower holes to a specific depth below the cambium. All drilling is performed with the drill bit projecting through a drill guide strapped to the tree, to ensure that the holes are as close to parallel as possible. The thermistor probes are wired to a multiplexer (AM16/32) or datalogger (mostly CR1000), while the heater probes are connected to a relay control module and 12 V battery. A solar panel is used to continuously charge the batteries that power the system. Generally, 4-12 sets of probes (each set comprises 3 probes) are implanted in a tree stem, depending on the size of the tree. The thermocouple probes are inserted to different depths below the cambium to sample different regions of the sapwood. Sap flow is generally fastest in the younger xylem closer to the cambium, but slows in the older, deeper xylem. To account for long-term changes in position as a result of stem diameter growth, the thermocouple probes are completely removed and repositioned to their correct depths once or twice a year. Data loggers are programmed to initiate measurements at pre-determined intervals (generally hourly). The temperatures in the upper and lower thermocouples are first measured and the ratio (upper over lower) is logged. Directly thereafter, the 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 heat pulse velocity, sap flux density and whole tree sap flow. Formulae are described in Burgess *et al.* (2001).

Cellular phone modems connected to the loggers allow remote downloading of HPV raw data as well as uploading of revised programmes to the data 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.

All available HPV data for an individual tree are initially screened to identify periods of missing data. The first step in the patching process is to determine if there are good quality data available from any of the other probes for the period in question. The probes with the highest correlation to the probes being patched are identified through a correlation analysis. A simple linear regression equation is then used to patch the missing data according to the functional probe set. High correlations among different probe sets within the same tree are observed in most cases, giving confidence in the patching technique. Where there are simultaneously missing data for all probe sets in a tree, data from adjacent measured trees may be used in a similar manner to correlate and patch. Where there are missing or suspect single hourly values, these may be in-filled using an average of the preceding and following values. Unrealistically high spikes or low negative values in the data are each checked for realism. If they are not evident in other probes, and/or do not follow any logical pattern in relation to preceding and following values, or environmental changes, they are assumed to be faulty and patched.

Once the above patching and analysis procedure is completed, it is necessary to confirm the "zero flux" value (i.e. those times of the day when HPV values / transpiration would be expected to be zero). This is necessary because the lowest values in the diurnal HPV trends (e.g. those values between 22h00 and 04h00) do not always stabilise around zero. This is a result of slight misalignment in the position of the thermocouple probes in the tree and is corrected by applying an offset to the data to align the lowest values with zero. In cases where destructive felling of sample trees is permitted, this correction may be estimated by simply cutting the stem of the tree, while continuing to monitor HPV data. Under these conditions the data will typically stabilise around a particular "zero flux" value, which, if not exactly at 0, will indicate the offset value necessary to be applied to the data to correct the measured zero flux values to actual zero values. However, from published literature it is known that some species of tree may show reverse sap flow at night (negative night-time HPV values) or actual night-time sap flow (positive night-time HPV values) (Benyon, 1999; Burgess *et al.*, 2001). In order to resolve this, it is consequently necessary to determine the ambient conditions under which zero sap flow (zero HPV values) are most likely to occur, and assume that at these times there is zero sap flow. The HPV values at these times may subsequently be adjusted to zero, and the average of these adjustments provides the offset value to be applied to the whole data set (providing the probes were not re-inserted at any point). This procedure therefore does not exclude periods of reverse flow, or night-time sap flow. The methodology used to determine this zero flux value is based on recommendations made by Dr. Stephen Burgess following the sap flow workshop attended by Mark Gush in Perth, Australia in November 2006. Essentially, the analysis is carried out using an "IF" statement in excel, written in the form of =IF(K3<94,"low RH",IF(O3<6000,"wet leaf",IF(C3>0.25,"not dawn",IF(C3<0.104167,"not dawn","zero flux")))), i.e. if all the conditions required for zero sap flow are not being met, relevant messages will indicate the failures (e.g. low RH, not dawn, etc.). Alternatively if all conditions are being met, the confirmatory message "zero flux" will be shown. These particular occurrences may be filtered and an average "zero flux" value calculated, so as to determine the offset value to be applied.

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 heat pulse velocity to sap flux density (Marshall, 1958) and whole-tree sap flow. These sapwood measurements are usually taken at the conclusion of the experiment due to the destructive sampling required. The conversion of sap flux density to sap flow is calculated as the product of sap flux density and cross-sectional area of conducting sapwood. Total sapwood area is calculated from the below-cambium radius and the radius of the heartwood. Heartwood is recognized by staining a wood core with Methyl Orange. Sap flux density is estimated at several radial depths. The total sapwood area is divided into concentric annuli delimited by midpoints between the thermocouple 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).

Automatic weather station sensors are used to monitor hourly air temperature, air humidity, solar radiation and rainfall. These measurements are very useful in interpreting sap flow patterns and assisting in the patching process.

Once the offset has been applied to the HPV data, the final analysis involves the conversion of the hourly HPV values to total daily sap flow (in litres and millimetres). Firstly the patched and corrected hourly HPV values are corrected for the effects of wound width using wound correction coefficients described by Swanson and Whitfield (1981). These are then converted to sap flux densities by accounting for wood density and sapwood moisture content (Marshall, 1958). Finally, the sap flux densities are converted to actual sap flow (litres per hour) by calculating the sum of the products of sap flux density and cross-sectional area for individual tree stem annuli (determined by probe insertion depth and sapwood depth). Hourly sap flow values are totalled into daily values.

Appendix 3:
A description of the WAVES model

WAVES is a model of the soil-vegetation-atmosphere continuum which accounts for the major processes affecting vegetation growth and water-use. It may be briefly described by outlining the four principle modules. The **energy balance module** calculates net radiation from incoming solar radiation, air temperature and humidity, and then partitions it into canopy and soil available energy using Beer's law. The **water balance module** handles surface runoff, soil infiltration, evapotranspiration (Penman-Monteith equation; Monteith, 1981), soil water redistribution (Richards equation; Richards, 1931), drainage and water table interactions. The model uses an efficient numerical solution to solve Richards' equation for unsaturated flow of soil water. The daily transpiration predicted by the Penman-Monteith equation is extracted from the profile using weighting factors determined by the modelled root density and a normalised weighted sum of the matric and osmotic soil water potential of each layer. The aerodynamic resistance of the plant canopy is assumed to be a constant value, while canopy resistance is calculated as a function of net assimilation rate, atmospheric water vapour pressure deficit (VPD) and CO_2 concentration. This is based on the empirical model of Ball *et al*. (1987) as modified by Leuning (1995). WAVES couples canopy and atmosphere using the omega approach described by Jarvis and McNaughton (1986). A particularly useful feature of WAVES is that it explicitly handles separate overstorey and understorey canopies that are a feature of forests, woodlands and savannas.

The **carbon balance and plant growth module** is based on calculating actual daily carbon assimilation from a maximum possible value, and the relative availability of light, water and nutrients. The effects of temperature and salt in the soil solution are also simulated. The integrated rate methodology (IRM) of Wu *et al*. (1994) is used to combine the effects of the limiting factors into a single scalar. The actual carbon assimilated for a day is then dynamically allocated to leaves, stems and roots (Slavich *et al.*, 1998). The IRM scalar is also the basis for calculating canopy resistance, which is crucial to the estimation of daily transpiration obtained by solving the Penman-Monteith equation. Growth respiration rate is linearly related to the gross assimilation rate, and maintenance respiration is linearly related to the mass of carbon, and doubles for a 10-degree increase in average daily temperature. The rate of leaf, stem and root mortality is linearly related to the carbon mass of these components.

WAVES also includes a **solute transport module** that predicts solute transport within the soil column using convective dispersion equations, and models the osmotic effect of salinity on water uptake by plants.

Daily inputs include day of year, maximum and minimum temperatures, mean VPD over daylight hours, total rainfall, rainfall duration, and solar radiation. Additional and optional inputs are flood height, groundwater depth and grazing intensity. Examples of the set of parameters describing the plant attributes are provided in appendix 1. A large array of output values is provided, allowing a detailed picture of changes in daily site water balance and vegetation growth increment to be assessed.

Appendix 4:
WAVES vegetation parameter values

Vegetation type		Savanna		Valley Thicket		Forest	
District		Nylsvley		Noodsberg		Groenkop	
Dominant genus		*Burkea*		*Acacia*		*Podocarpus*	
Canopy layer		OS	US	OS	US	OS	US
Parameters	Units						
1-albedo of the canopy		0.87	0.87	0.87	0.87	0.85	0.95
1-albedo of the soil		0.87	0.87	0.87	0.87	0.85	0.85
Rainfall interception coefficient	m LAI^{-1} d^{-1}	0.0015	0.0015	0.0003	0.001	0.0005	0.0005
Light extinction coefficient		-0.5	-0.6	-0.5	-0.6	-0.5	-0.5
Maximum carbon assimilation rate	kg C m^{-2} d^{-1}	0.01	0.01	0.02	0.02	0.01	0.01
Slope parameter for conductance model		1.2	1.2	1	1	1	1
Maximum plant available soil water potential	m	-200	-200	-300	-300	-150	-150
IRM weighting of water		2.1	2.1	2.1	2.1	1.5	2.2
IRM weighting of nutrients		0.5	0.5	0.5	0.5	0.5	0.5
Ratio of stomatal to mesophyll conductance		0.2	0.8	0.2	0.8	0.2	0.2
Temperature when growth is ½ of optimum	°C	15	15	15	15	10	10
Temperature when growth is optimum	°C	30	30	30	30	25	25
Year day of germination	d	-	-	-	-	-	-
Degree-daylight hours for growth	°C hr	-	-	-	-	-	-
Saturation light intensity of sunlit leaves	µmol m^{-2} s^{-1}	1 200	1 800	1 200	1 200	1 800	1 000
Maximum rooting depth	m	1.2	1.2	3.1	3.0	0.6	0.9
Specific leaf area	m^2 (kg C)$^{-1}$	16	24	16	24	8	18
Leaf respiration coefficient	kg C kg C^{-1} d^{-1}	0.0001	0.00001	0.0001	0.00001	0.0001	0.001
Stem respiration coefficient	kg C kg C^{-1} d^{-1}	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
Root respiration coefficient	kg C kg C^{-1} d^{-1}	0.0001	0.00001	0.0001	0.000001	0.0001	0.0002
Leaf mortality rate	kg kg^{-1} d^{-1}	0.001	0.01	0.01	0.01	0.003	0.0015
Above-ground partitioning factor		-	-	-	-	0.75	0.7
Salt sensitivity factor		1	1	1	1	1	1
Aerodynamic resistance	s m^{-1}	10	50	5	30	5	150
Soil nutrient index		0.5	0.5	0.5	0.5	0.8	0.8
Weekly carbon allocation		√	√	√	√	X	X
Spring carbon allocation		√	√	√	√	X	X
Frost effect		√	√	√	√	X	X

The economic and biophysical water-use-efficiency values and the per-hectare Net Present Values (NPV) for the 12 *Eucalyptus* plantations in KwaZulu-Natal, the pine plantation in Swaziland, and the Yellowwood plantation in Magoebaskloof; at base-case parameter values

Tree species	Plantation	NPV (R ha⁻¹)	Annual NPV (R ha⁻¹yr⁻¹)	Levelised NPV (R ha⁻¹yr⁻¹)	Economic WUE (R m⁻³)	Levelised economic WUE (R m⁻³)	Biophysical WUE (m³ m⁻³)
	M1 Gemsbokfontein	-R 2 351.0	-R 261.2	-R 330.8	-R 0.0330	-R 0.042	0.0026
	M2 Windy Hill	R 3 323.0	R 276.9	R 374.9	R 0.0243	R 0.033	0.0030
	M3 Kwambonambi	R 5 234.3	R 475.8	R 630.2	R 0.0415	R 0.055	0.0035
	M4 Kia-Ora	-R 1 079.4	-R 98.1	-R 129.9	-R 0.0115	-R 0.015	0.0028
	M5 Tanhurst	R 2 629.8	R 239.1	R 316.6	R 0.0244	R 0.032	0.0028
Eucalyptus	M6 Baynesfield	-R 2 342.7	-R 167.3	-R 236.7	-R 0.0145	-R 0.021	0.0013
	M15 Palm Ridge	R 765.9	R 69.6	R 92.2	R 0.0075	R 0.010	0.0024
	M20 KT	R 10 081.8	R 1 008.2	R 1 305.6	R 0.0690	R 0.089	0.0034
	M25 Futululu	R 8 447.4	R 1 055.9	R 1 307.0	R 0.1337	R 0.166	0.0063
	M29 Amangwe	R 3 479.4	R 497.1	R 601.3	R 0.0682	R 0.083	0.0047
	M22 Bushlands	R 1 223.1	R 122.3	R 158.4	R 0.0148	R 0.019	0.0029
	M17 Bushlands	R 2 709.6	R 387.1	R 468.3	R 0.0669	R 0.081	0.0055
Yellowwood	Magoebaskloof	R 3879.5	R 97.0	R 226.1	R 0.0135	R 0.0316	0.0006
Pine	Usutu, Swaziland	R 7 094.5	R 473.0	R 683.5	R 0.0516	R 0.075	0.0030

Appendix 6:
Economic parameter values, assumptions and information sources
(Russell Wise)

A. INDIGENOUS TIMBER – SOUTHERN CAPE REGION

1. Price of Indigenous timber – R1 586.3 m^{-3}

The values in column 1 were estimated as the 9-year time-averaged mean, min and max of the timber prices received when sold between 1998 and 2006 (2007 data are not included as no area is known) (Durrheim, 2007 pers. comm.).

The values in column 2 were estimated as the average mean, min and max of the price of timber received from the sale of timber harvested from 12 compartments in Diepvalle (du Toit, 2007)[11].

Table 1 Indigenous species timber prices (R m^{-3})

	Durrheim (2007)	Du Toit (2007)
Avg	1 586.30	2 067.66
Min	1 037.78	1 804.60
Max	2 401.39	2 375.08

2. Annually Harvested Indigenous timber – 2.58 m^3 ha^{-1} yr^{-1}

This value is estimated as the 9-year time-averaged mean of the timber volumes sold between 1998 and 2006 (2007 data are not included as no area is known) (Durrheim, 2007 pers. comm.).

Table 2 Harvested indigenous timber sold from the Knysna Forest between 1998 & 2006 (Durrheim, 2007 pers. comm.)

	Total Volume harvested (m^3 yr^{-1})	Area ha yr^{-1})	Volume harvested per (m^3 ha^{-1} yr^{-1})
Avg	1 374.38	564.33	2.58
Min	770.26	397.00	2.12
Max	2 129.30	695.00	3.51

Carol Whitcher (2007) of SANParks gave me estimates of harvested timber for numerous compartments in the Tsitsikamma forest for the year 2005/06. These have been averaged and are summarised in Table 3.

Table 3 Timber harvested from the Tsitsikamma forest in 2005/06 (Whitcher, 2007)

	Tot Indig Vol (m^3 yr^{-1})	Area (ha yr^{-1})	Vol harvested (m^3 ha^{-1} yr^{-1})
Avg	95.86	21.87	3.75
Min	53.64	11.70	2.54
Max	166.73	33.20	5.94

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[11] Raw data are available at request from Russell Wise (rwise@csir.co.za)

3. **Annual input costs (excl. harvest & transport; incl. overheads)**
   – R896.6 ha^{-1}
   This is estimated as the sum of the direct cost of approx R300 ha^{-1} involved in selecting trees for harvesting (Durrheim, 2007) and the overhead costs of MTO consolidated estimated by FES (2007). The Overhead costs include: replacing hand tools, road & building maintenance, administration, head office charges, registration, R&D, electricity & water, security, insurance, contractors, communications and general office expenses. The average overheads per hectare for the entire MTO operations in the Cape was R596 per hectare.

4. **Establishment costs – R0 ha^{-1}**
   Since the harvesting of this forest is based on the single-tree selection process, there are no establishment costs involved.

5. **Timber harvest costs – R839.35 m^{-3}**
   The mean, min and max are average values for the many compartments harvested in the Tsitsikamma and Diepvalle forests.

   Minimum, maximum and average values of harvest costs per cubic meter, for numerous compartments in the Tsitsikamma forest (2005/06) and the Diepvalle forest (2004 to 2006) are summarised in of Table 4 (du Toit, 2007; Whitcher, 2007).

Table 4 Costs (R m^{-3}) incurred to harvest indigenous timber from the Tsitsikamma and Diepvalle forests between 1998 & 2006

	Whitcher (2007)	Du Toit (2007)	Avg
Avg	651.19	1 027.50	839.35
Min	302.38	291.30	296.86
Max	1 000.00	2 030.75	1 515.37

B. EXOTIC TIMBER (PINUS RADIATA) – SOUTHERN CAPE REGION

6. **Price of exotic timber – R251.0 m^{-3}**
   This is the weighted average price (Rands / tonne) received for the various classes of timber delivered to the mill. The percentages of each product relate to 2006/7 data for the George area. The George prices (middle column) and the MTO prices (last column) are for 2006/7. The value of R251 is calculated using the R241.2 in the middle column of the table below, divided by 0.96 to convert from tonnes to m^3 (FES, 2007).

	Percent	George Prices	MTO Prices
Sawlogs	16%	68	69.92
Sawlogs:Class A	9%	142.49	200.48
Sawlogs:Class B	35%	251.33	239.89
Sawlogs:Class C	25%	353.68	308.09
Sawlogs:Class D	10%	436.44	392.68
	95%	**241.2176**	**227.5224**

7. **Annually harvested exotic timber – 9.1 m^3 ha^{-1} yr^{-1}**
   All values in the table below are from the MTO consolidated data for the period 2004 to 2007 (FES, 2007).

	Min	Avg	Max
Vol increment	11.5	12.0	12.5
Vol harvested	7.6	9.1	10.6

8. **Annual input costs (excl. harvest & transport; incl. overheads) – R920 ha^{-1}**

The average overhead[12] for the MTO operations in the Cape was R596 ha^{-1}. The additional R323.19 is the sum of the averages of the min (2006) and max (2006) values for tending (R136.5) and forest protection (R176.4) for the MTO consolidated data.

	Min	Max	Avg
Tending	135.29	156.22	**145.755**
Forest protection	158.90	195.96	**177.43**
		Sum	**323.19**

9. **Establishment costs – R3258.5 ha^{-1} (R116 per year for 28 years)**

This is the average (R3 258.5 ha^{-1}) of the minimum (R3 009.5 ha^{-1}) and maximum (R3 507.8 ha^{-1}) establishment costs incurred in 2004 (inflated to 2007 value) and 2007 for MTO. The annualised average is R116 ha^{-1} yr^{-1}.

10. **Timber harvest costs – R124.9 m^{-3}**

The timber harvest costs are the sum of harvest costs (R67.9/m3) and transport costs (R56.9/m3). These two values are the average values of the min and max values reported between 2004 and 2007 for the MTO consolidated data. The original values are summarised below.

	Min	Max	Avg
Transport	48.30	65.59	**56.945**
Harvest	58.91	76.93	**67.92**

C. EUCALYPTUS & PINE PLANTATIONS (PAPER & PULP) – ALONG A RAINFALL GRADIENT

11. **Price of pulpwood – R168 m^{-3}**

The values below are for tonnes of pulpwood delivered to the mill. The minimum is for the MTO consolidated data for 2004 (inflated to 2007 values), the max is for 2007. The value of R168 is calculated using the max value below, divided by 0.96 to convert from tonnes to m^3 (FES, 2007).

	Min	Max	Avg
Pulpwood	135.76	161.32	136.64

12. **Annually harvested exotic timber – 98% of the MAI**

MAI values were collected by Peter Dye for numerous *Eucalyptus* plantations (mainly ICFR trials) along a rainfall gradient in the Eastern seaboard of SA. It was assumed that 98% of the MAI was available for use in the production of paper and pulp. The MAI for each plantation are listed below in the biophysical data section.

13. **Annual input costs (excl. harvest & transport; incl. overheads) – R842 ha^{-1}**

The overhead costs of MTO consolidated estimated by FES (2007) include: replacing hand tools, road & building maintenance, administration, HO charges, registration, R&D, electricity & water, security, insurance, contractors, communications and general office expenses. The average overheads per hectare for the entire MTO operations in the Cape was R596 per hectare. The additional R245 comes from the sum of the averages for protection (R190) and conservation (R55) from Kotze and Luckhoff (2007). In this paper, however, the *Eucalyptus* trees were grown for timber, and where intensively managed. The plantations

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[12] The overhead costs of MTO consolidated estimated by FES (2007) include: replacing hand tools, road & building maintenance, admin, HO charges, registration, R&D, electricity & water, security, insurance, contractors, communications and general office expenses.

included in our analysis are all for paper and pulp and do not involve any thinning or pruning, and therefore these costs have not been included.

14. Establishment costs – R3258.5 ha^{-1} (R116 per year for 28 years)

This is the average of the min and max establishment costs incurred between 2004 (inflated to 2007 value) and 2007 for MTO consolidated and summarised below (FES, 2007).

	Min	Max	Avg
Establishment	3 009.5	3 507.08	**3 258.5**

15. Timber harvest costs – R124.9 m^{-3}

The timber harvest costs are the sum of harvest costs (R67.9 m^{-3}) and transport costs (R56.9 m^{-3}). These two values are the average values of the min and max values reported between 2004 and 2007 for the MTO consolidated data (FES, 2007). The original values are summarised below.

	Min	Max	Avg
Transport	48.30	65.59	**56.945**
Harvest	58.91	76.93	**67.92**

D. YELLOWWOOD PLANTATION (TIMBER) – MAGOEBASKLOOF

16. Price of Indigenous timber – R1 037.8 m^{-3}

The price used was the minimum price given in communications with Graham Durrheim (2007) – see Table 1.

17. Annually harvested timber – 0 m^3

This plantation is too small to be considered the same as the large-scale estates where areas are clearfelled annually. This plantation is clearfelled once, in year 28.

18. Annual input costs (excl. harvest & transport; incl. overheads) – R842 ha^{-1}

Same as that for the southern Cape indigenous forests (see above)

19. Establishment costs – R3 258.5 ha^{-1}

Same as that for the southern Cape indigenous forests (see above), but in this case the single upfront value is used and not the annualised value.

20. Timber harvest costs – R124.9 m^{-3}

Same as that for the southern Cape indigenous forests (see above)

E. SANDVELD VEGETATION (FUELWOOD) – BUSHBUCKRIDGE

21. Price of fuelwood – R0.54 m^{-3}

Three prices are reported in the literature: R0.26 (Shackleton and Shackleton, 2000); R0.38 (Ndengejeho, 2007) and R0.50 Dovie *et al.* (2002)**. The average of the minimum and maximum values was used in the analysis, after these were converted into 2007 values using the 9-year average rate of inflation of 6.2%, from the CPI (StatsSA, 2007 - http://www.statssa.gov.za/keyindicators). The 2007 values for each of these prices are: R0.41, R0.69, and R0.39, respectively. The average of the min and max is: R0.54

22. Annual harvested fuelwood – 0.265 m^3 (subsistence) & 0.393 (commercial)

The annually harvested fuelwood value was estimated from quantities reported in the literature, but was modified to ensure the system was not exploited to destruction.

Three harvest quantities are reported in the literature: 3 836 kg per household (Shackleton and Shackleton, 2000); 4 987 kg per household (Ndengejeho, 2007) and 4 343 kg per household (Dovie *et al.*, 2002)**.

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These values were converted from 'per household' values into 'per ha' values by using Ndengejoh's (2007) and Kahn *et al*. (2007) household data from the 40 300 ha Agincourt rural district in Bushbuckridge, with 10 384 households. Ndengejoh (2007) collected data from 58 households (13 poor, 26 medium and 19 wealthy) and recorded that 70% of households harvested fuelwood from the surrounding vegetation. Therefore, the quantities of harvested fuelwood per household were multiplied by 7 269 hh (70% of 10 384) and divided by the area. The per ha values (692 kg, 899.5 kg and 783.3 kg, respectively), however, way exceeded the MAI of the vegetation (297 kg), indicating that the hh collect wood from an area substantially larger than their immediate surroundings. Therefore a sustainable value for the harvested fuelwood was used: 265 kg (which would require an area of 121 000 ha for 7 269 hh).

The value used for the commercial system is 35% greater than that of the subsistence system. It was also assumed the MAI of the commercial system is 35% greater than the natural MAI.

23. **Annual input costs (excl. harvest & transport; incl. overheads) – R10 ha^{-1} (subsistence) & R41 (commercial)**

    A cost of R10 per ha was assumed. No data was found to give us any indication for this cost. The commercial value was assumed to be the sum of the annual input cost and the overhead costs. The annual input cost was assumed to be 35% greater than the subsistence value, and the overhead cost was assumed to be double the annual input cost.

24. **Establishment costs – R0 (subsistence) R2 554 ha^{-1} or R91 ha^{-1} yr^{-1} (commercial)**

    The establishment cost used in this study is the same as that reported by McKean (2005) where he reports on a Eucalyptus woodlot developed in KZN to meet fuelwood demands and to take pressure of the natural vegetation which is being over harvested.

25. **Timber harvest costs – R0.3 m^{-3} (subsistence) & R0.2 m^{-3} (commercial)**

    No values for this exist in the literature. It was hoped to get an estimate from the harvesting efforts and distances walked to collect the wood. The values here, just ensure that the net returns are positive.

Appendix 7:
3-PG model parameter values used in the simulation of *Pinus radiata* forest stands in the southern Cape.

Meaning/comments	Name	Units	*P. radiata*
Biomass partitioning and turnover			
Allometric relationships & partitioning			
Foliage:stem partitioning ratio @ D=2 cm	pFS2	-	1
Foliage:stem partitioning ratio @ D=20 cm	pFS20	-	0.3
Constant in the stem mass v. diam. relationship	StemConst	-	0.04
Power in the stem mass v. diam. relationship	StemPower	-	2.65
Maximum fraction of NPP to roots	pRx	-	0.8
Minimum fraction of NPP to roots	pRn	-	0.5
Litterfall & root turnover			
Maximum litterfall rate	gammaFx	1/month	0.03
Litterfall rate at t = 0	gammaF0	1/month	0.001
Age at which litterfall rate has median value	tgammaF	months	24
Average monthly root turnover rate	Rttover	1/month	0.02
NPP & conductance modifiers			
Temperature modifier (fT)			
Minimum temperature for growth	Tmin	deg. C	3
Optimum temperature for growth	Topt	deg. C	23
Maximum temperature for growth	Tmax	deg. C	35
Frost modifier (fFRost)			
Days production lost per frost day	kF	days	1
Soil water modifier (fSW)			
Moisture ratio deficit for f = 0.5	SWconst	-	0.7
Power of moisture ratio deficit	SWpower	-	9
Fertility effects			
Value of 'm' when FR = 0	m0	-	0
Value of 'fNutr' when FR = 0	fN0	-	1
Power of (1-FR) in 'fNutr'	fNn	-	0
Age modifier (fAge)			
Maximum stand age used in age modifier	MaxAge	years	50
Power of relative age in function for fAge	nAge	-	2
Relative age to give fAge = 0.5	rAge	-	0.95
Stem mortality & self-thinning			
Mortality rate for large t	gammaNx	%/year	0.2

Meaning/comments	Name	Units	*P. radiata*
Seedling mortality rate (t = 0)	gammaN0	%/year	0.2
Age at which mortality rate has median value	tgammaN	years	4
Shape of mortality response	ngammaN	-	1
Max. stem mass per tree @ 1000 trees/hectare	wSx1000	kg/tree	340
Power in self-thinning rule	thinPower	-	1.5
Fraction mean single-tree foliage biomass lost per dead tree	mF	-	0
Fraction mean single-tree root biomass lost per dead tree	mR	-	0.2
Fraction mean single-tree stem biomass lost per dead tree	mS	-	0.2

Canopy structure and processes
Specific leaf area

Specific leaf area at age 0	SLA0	m^2/kg	5
Specific leaf area for mature leaves	SLA1	m^2/kg	5
Age at which specific leaf area = (SLA0+SLA1)/2	tSLA	years	2.5

Light interception

Extinction coefficient for absorption of PAR by canopy	k	-	0.51
Age at canopy cover	fullCanAge	years	0
Maximum proportion of rainfall evaporated from canopy	MaxIntcptn	-	0.15
LAI for maximum rainfall interception	LAImaxIntcptn	-	8

Production and respiration

Canopy quantum efficiency	alpha	molC/molPAR	0.05
Ratio NPP/GPP	Y	-	0.47

Conductance

Maximum canopy conductance	MaxCond	m/s	0.02
LAI for maximum canopy conductance	LAIgcx	-	3.33
Defines stomatal response to VPD	CoeffCond	1/mBar	0.05
Canopy boundary layer conductance	BLcond	m/s	0.2

Wood and stand properties
Branch and bark fraction (fracBB)

Branch and bark fraction at age 0	fracBB0	-	0.75
Branch and bark fraction for mature stands	fracBB1	-	0.19
Age at which fracBB = (fracBB0+fracBB1)/2	tBB	years	2

Basic Density

Minimum basic density - for young trees	rhoMin	t/m3	0.380
Maximum basic density - for older trees	rhoMax	t/m3	0.380
Age at which rho = (rhoMin+rhoMax)/2	tRho	years	5

Stem height

Constant in the stem height relationship	aH	-	0
Power of DBH in the stem height relationship	nHB	-	0
Power of stocking in the stem height relationship	nHN	-	0

Stem volume

Constant in the stem volume relationship	aV	-	0
Power of DBH in the stem volume relationship	nVB	-	0
Power of stocking in the stem volume relationship	nVN	-	0

Meaning/comments	Name	Units	*P. radiata*
Conversion factors			
Intercept of net v. solar radiation relationship	Qa	W/m2	-90
Slope of net v. solar radiation relationship	Qb	-	0.8
Molecular weight of dry matter	gDM_mol	gDM/mol	24
Conversion of solar radiation to PAR	molPAR_MJ	mol/MJ	2.3

Appendix 8.
Data archiving

The project has generated a large amount of valuable data, which is likely to be of value to future research projects in the field of land-use hydrology and forestry. All raw data and reports are stored on DVD data storage disks, which are lodged with the CSIR (UKZN Agriculture campus, Pietermaritzburg), as well as with the Water Research Commission, Pretoria.