MODELLING VEGETATION WATER USE FOR GENERAL APPLICATION IN DIFFERENT CATEGORIES OF VEGETATION

REPORT TO THE

WATER RESEARCH COMMISSION

by

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The title was subsequently changed, on recommendation by the Reference Group, to:

"Modelling vegetation water use for general application in different categories of vegetation".

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DWAF are also acknowledged for funding several past projects that have yielded useful evapotranspiration data that we have drawn upon in this report.

Executive Summary

INTRODUCTION

Water is a scarce resource in South Africa and requires increasingly sophisticated management to ensure that water availability keeps pace with growing demand. There is already a high degree of utilization of surface and groundwater resources in many catchments. Large areas of South Africa are semi-arid, where median annual runoff is less than 60 mm (Schulze 1997). These areas are characterised by a high degree of reliance on groundwater and riparian water resources. In the wetter areas of the country, median annual runoff is higher, but only exceeds 100 mm in restricted areas of highest rainfall, often associated with seaward-facing mountain or escarpment slopes, or high-rainfall coastal regions. Year-to-year variation in rainfall and river flows is also high throughout South Africa, and the frequency of critical periods of lowest flows, which may have a profound limiting effect on economic activity, are difficult to predict accurately.

Water yield from catchments may be significantly modified by vegetation management. Since the early 1900s, South Africa has witnessed one of the most hydrologically extreme changes in land use to be found anywhere in the world, which has demonstrated how influential land cover is in altering the proportions of "green water" (water evapotranspired from vegetation) and "blue water" (water in streams). Since the establishment of the first forest plantations in 1876, there has been a steady conversion of natural grassland and shrublands to forest plantations in the higher rainfall areas of South Africa. These plantations now occupy a total of nearly 1.5 million hectares. The original vegetation replaced during this afforestation programme was mostly seasonally dormant grasslands and Fynbos shrublands, with an annual ET of approximately 700-800 mm (Bosch and von Gadow, 1990). By contrast, evergreen and deep-rooting forestry species are characterised by a much higher cumulative annual ET, commonly in the region of 1100 mm or more, depending on available rainfall and soil water. Catchment water yields may therefore decline by several hundred millimetres following afforestation. Research results have demonstrated unequivocally that certain land cover change may have a very large influence on catchment water yields.

In more recent times, many developments have ensured a continued interest in the water use of vegetation, and how changes in land use are likely to affect catchment water yields. Some of these are listed below:

- Increasing water demand due to population growth, rising standards of living, and increasing industrial and agricultural development.
- The spread of alien invasive plants (AIP) and consequent reductions in catchment water yields.
- A need for information on the water use of a wider range of "baseline" vegetation for hydrological scenario studies.
- Controversial developments leading to greater water use by vegetation in areas of limited water availability. The issue of golf courses in the southern Cape is a good example.
- There is increasing interest in the use of artificially established vegetation to reduce rainfall infiltration into gold tailings storage facilities (slimes dams), coal dumps and fly ash dumps, thus reducing the seepage of contaminated water from these structures. The water

use of such vegetation is crucial in determining their effectiveness for this purpose.

- Certain shallow aquifers support valuable groundwater-dependent ecosystems. The water requirement of this kind of vegetation must be known before minimal abstraction levels can be set to ensure its continued survival.
- Similarly, estimating the water requirement of riparian vegetation has been an important aspect of setting limits to water abstraction in heavily utilized river systems. A good example of such studies has taken place in the Sabie River in the Mpumalanga lowveld.
- Water resource managers are required to make decisions on whether new crops are characterised by a high rate of water use, thus possibly qualifying as streamflow reduction activities. A recent example arose from a proposed plan to establish bamboo on a large scale in Limpopo province.
- Potential reductions in ET brought about by bush clearing programmes represent an important possible benefit to such programmes, and require verification.
- Forestry companies increasingly need to demonstrate to forest certification authorities that their plantations are sustainably managed and have minimal negative environmental (especially hydrological) impacts.
- Continued efforts to conserve vegetation of high conservation value such as wetlands, montane grasslands and indigenous forests are necessary to stave off numerous threats to their existence and integrity. Their impact on hydrological systems is often believed to be more favourable than alternative land use systems, but credible evidence is required.
- The government is in the process of setting up Catchment Management Agencies in 19 principle catchments covering South Africa. Decisions on land usage will need to be made, and these are likely to be controversial where different and competing options for land use are proposed. Realistic comparative water use figures will be required to evaluate the efficiency with which competing land covers use water.
- There is a growing need for environmental impact assessments and strategic environmental assessments to guide numerous development initiatives around the country. Potential changes in evapotranspiration are a vital aspect that requires attention, but again, good information is seldom available.

In summary, there are many examples of the need for realistic information on vegetation water use, but in most cases, accurate data are unavailable. Where information is available, such as for the forest plantation-grassland-Fynbos land use changes, the validity of extrapolating results to other localities is often questionable. To date, relevant information has been gathered from too few experimental sites to allow confident extrapolation over the full range of sites and growing conditions covered by the vegetation in question. Such factors as rainfall, temperature, aspect and slope, soil depth, texture, degree of stoniness, fertility and depth to a water table vary widely over South Africa, and all may be significant in influencing ET patterns.

PROJECT AIMS

The stated aims of the project are:

"To develop a framework of understanding about major controls of evapotranspiration in different types of vegetation and crops in South Africa. This work will lead to:

1. a better understanding of when a change of land cover may have a significant impact on surface water yields from an area of land,

2. recommendations for simple models to use in assessing these impacts, easing the task of simulating water use in a wide variety of vegetation, both indigenous and alien, existing in South Africa".

The development of a user-friendly water use prediction tool for general use by non-specialists was regarded from the outset as an important output of this project.

MODELLING APPROACH

The concept of identifying limits and controls on the process of ET was key to this project, and central to the development of a broad framework of understanding. A theoretical approach based on this concept has been expounded by Calder (1996, 1998, 1999). After lengthy evaluation, the project team decided that the best framework of understanding would be provided by a suitable biophysical processes model that could capture the main constraints on growth and water use experienced by the wide range of "plant functional types" that exist in South Africa. Modelling indigenous vegetation in South Africa is particularly challenging, since the diversity of plant life is enormous, encompassing great variation in structure and physiology. We therefore required a model with sufficient flexibility to be applicable to a wide variety of crops, forest, woodland, savanna, shrublands, and grasslands, growing in diverse biomes and responding to a wide variety of site factors. The model needed to take account of many physiological factors influencing plant growth and water use, such as seasonal patterns of leaf area development, canopy conductances, photosynthesis rates, carbon allocation and translocation patterns, temperature responses, respiration rates, rooting depths, etc. A review of international literature was conducted to examine the suitability of various process-based models as a possible general framework for understanding and predicting ET from a wide range of South African vegetation types. Important criteria were model availability, proven scientific credibility and application in hydrological studies, good documentation, a balance between simplicity and realism, and applicability to a wide range of vegetation types. The model needed to take account of the important limits and controls constraining water use by South African vegetation. Suitability for linkage to a user-friendly interface to permit model use by non-specialist users was a further consideration.

Against these criteria, the WAVES model was judged to be the most suitable model. It was developed by the Land and Water CRC of the CSIRO in Canberra, Australia, and simulates energy, water, carbon and solute (salt) 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/. Detailed descriptions are available from a comprehensive manual obtainable at the web site, and in the literature.

MODEL MODIFICATIONS

A review of WAVES identified areas of weakness that needed attention if the model were to be developed for use as a general model of vegetation/crop water use by non-specialist users. Required modifications and additions included:

- Development of a user-friendly interface.
- Establishment of links to a climate database for South Africa.
- Implementing modifications to carbon balance simulation. This involved introducing the process of spring translocation of carbon from roots or stem to leaves, and also introducing

greater flexibility in modelling how carbon is allocated to different plant parts at different stages during growth cycles.

- Introducing a graphical summary of simulated growth patterns to check for realistic output.
- Developing pre-defined parameter sets for each vegetation type.
- Improvements in the display of output files.
- Simulating the effect of frost in killing-off green leaf, and also permitting periodic removal of shoot biomass through burning, mowing or harvesting.
- Fixing the number and depth of soil horizons (identified by soil node depths in WAVES) to avoid problems with attaining numerical solutions to the unsaturated soil water flux calculations.

CHOICE OF VEGETATION TYPES

The aim of this project was to provide a general framework for predicting the water use of a wide range of natural vegetation, crops and forest plantations. It was therefore important to select a broad range of plant functional types to demonstrate that the prediction tool has wide applicability. Availability of field ET data was necessary for parameterisation of WAVES, and also to demonstrate the realism of simulations. A clear need for water use information for a particular vegetation type was a further requirement. Finally, emphasis was given to land cover types that are characteristic of the higher rainfall parts of South Africa. It is in these areas that changes of land cover have the greatest effects on catchment water yields.

The following categories and examples of land covers were included in this study.

- Plantation forests (*Eucalyptus grandis, Pinus patula, Populus deltoides, Acacia mearnsii*)
- Baseline vegetation in hydrological studies:
- Grasslands (C_4 and C_3 species)
- Fynbos
- Indigenous evergreen forest
- Savanna
- Valley thicket
- Wetlands (*Phragmites* reeds, riparian grassland, riparian Fynbos))
- Alien invasive trees (H*akea drupacea, Acacia longifolia, Acacia mearnsii*)
- Dryland crops (sugarcane, wheat).

SIMULATION STRATEGY

The modelling strategy involved obtaining field data describing the pattern of ET over as much of a full year as possible. Using rainfall and temperature data selected from an appropriate weather station, WAVES parameter values were then adjusted according to the best sources of information for that particular vegetation, and finally "tuned" to best resemble the measured seasonal pattern of ET. This process was governed as far as possible from knowledge of the vegetation in question, and parameter values were constrained within realistic limits set out in the WAVES manual. It is inevitable, however, that this process was somewhat subjective given the lack of required parameter data for many of the vegetation types. The vegetation parameter sets are nevertheless considered to provide credible estimates of the broad annual pattern of ET and growth in any year that WAVES is run. It is not envisaged that the general user need make any changes to these parameter sets. The reasonableness of the WAVES outputs is evaluated from the general shape of the trend of ET in different seasons of the year, the maximum ET in different seasons of the year, and the cumulative annual ET simulated for the site.

Available biomass data is also used in some simulations to further validate the output.

ET MEASUREMENT TECHNIQUES

Some hydrological field data are reported for most of the target categories of vegetation. A variety of different methods of measuring ET (scintillometry, Eddy Covariance, Bowen Ratio, Heat Pulse Velocity) have been used in these studies, and these are briefly reviewed.

RESULTS

WAVES was able to duplicate the annual trends in ET and growth displayed by a wide range of vegetation. Several examples are described below to illustrate some of the significant differences among these vegetation types, and what WAVES parameters and functions were particularly influential in reproducing the observed patterns of ET and growth.

Figure i illustrates the match between measured and modelled cumulative ET for montane grassland at Cathedral Peak, KwaZulu-Natal. This grassland is characteristic of higher altitudes in the summer-rainfall region. The grasses are seasonally dormant in winter, but growth is initiated at the start of the growing season by spring translocation of carbon to new leaves. There is a steady build up of green leaf area towards late-summer, after which there is a steep autumn decline in green leaf and ET due to rapid leaf senescence. The translocation function was activated to initiate green leaf development in spring. Carbon allocation was set up to allocate relatively more to leaves and stems in the first half of summer, but this declined in favour of roots later in the season. The frost function was activated to convert green leaves to litter with the advent of the first frost. A relatively low shoot growth rate resulted from a low peak LAI and a low maximum rooting depth. Annual ET amounted to 651 mm.

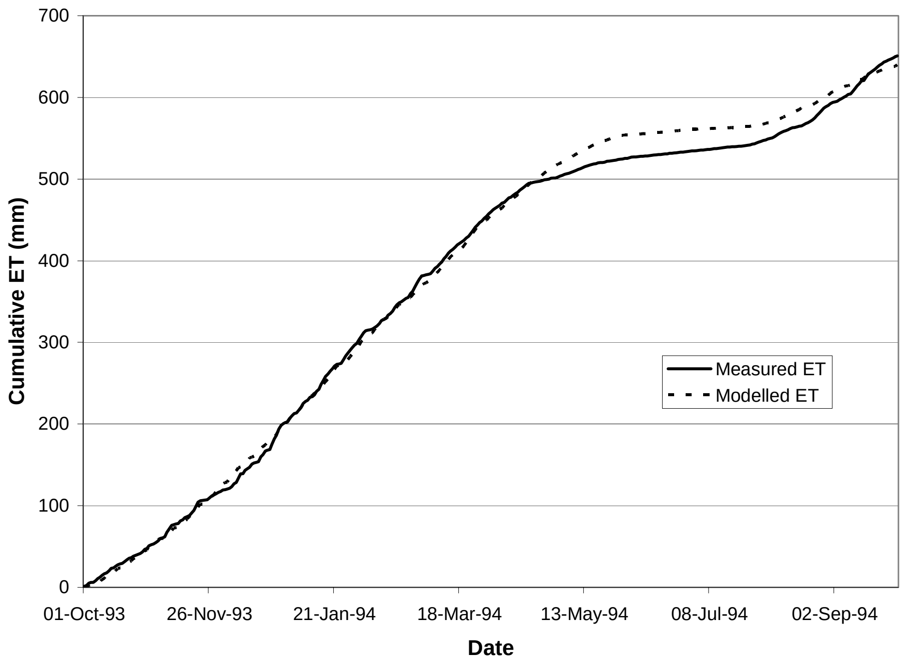

Figure i. A comparison of modelled versus measured cumulative ET from Cathedral Peak montane grassland over the period from 1 October 1993 to 30 September 1994.

By contrast, Figure ii shows the correspondence between measured and modelled transpiration for a four-year old *Eucalyptus grandis* forest plantation near Sabie in Mpumalanga. WAVES simulated realistic rates of transpiration and growth by maintaining a dense (LAI ~ 4) evergreen canopy throughout the year, a high maximum assimilation rate (0.04), a constant high carbon allocation ratio to stem (0.8) and a deep root system (4 m) drawing on stored groundwater. Annual ET amounted to 1347 mm.

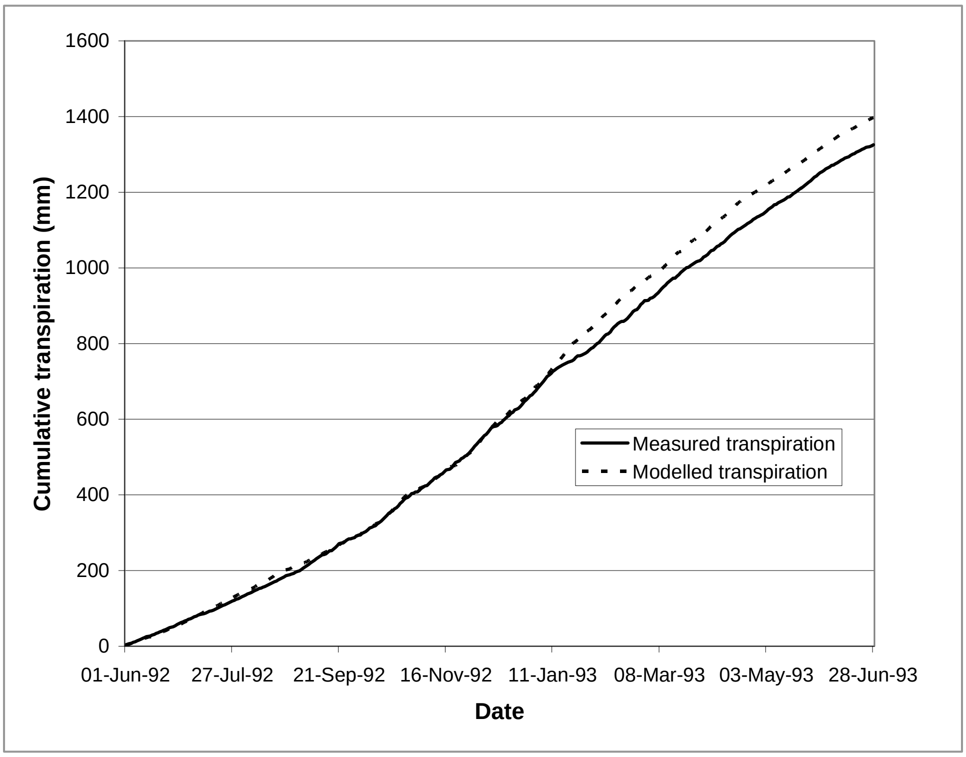

Figure ii. Simulated daily transpiration at the *Eucalyptus grandis* site (Sabie) over the period 1 June 1992 to 30 June 1993.

The influence of climate on the pattern of annual ET is evident in Figure iii which illustrates measured and modelled ET from Fynbos vegetation experiencing a winter rainfall climate in the Stellenbosch district of the Western Cape. Daily ET during the generally dry summer months is restricted by the availability of soil water, and rises in response to occasional rainfall events. ET during the wetter winter season is relatively low as a result of shorter days, lower temperatures and higher air humidity.

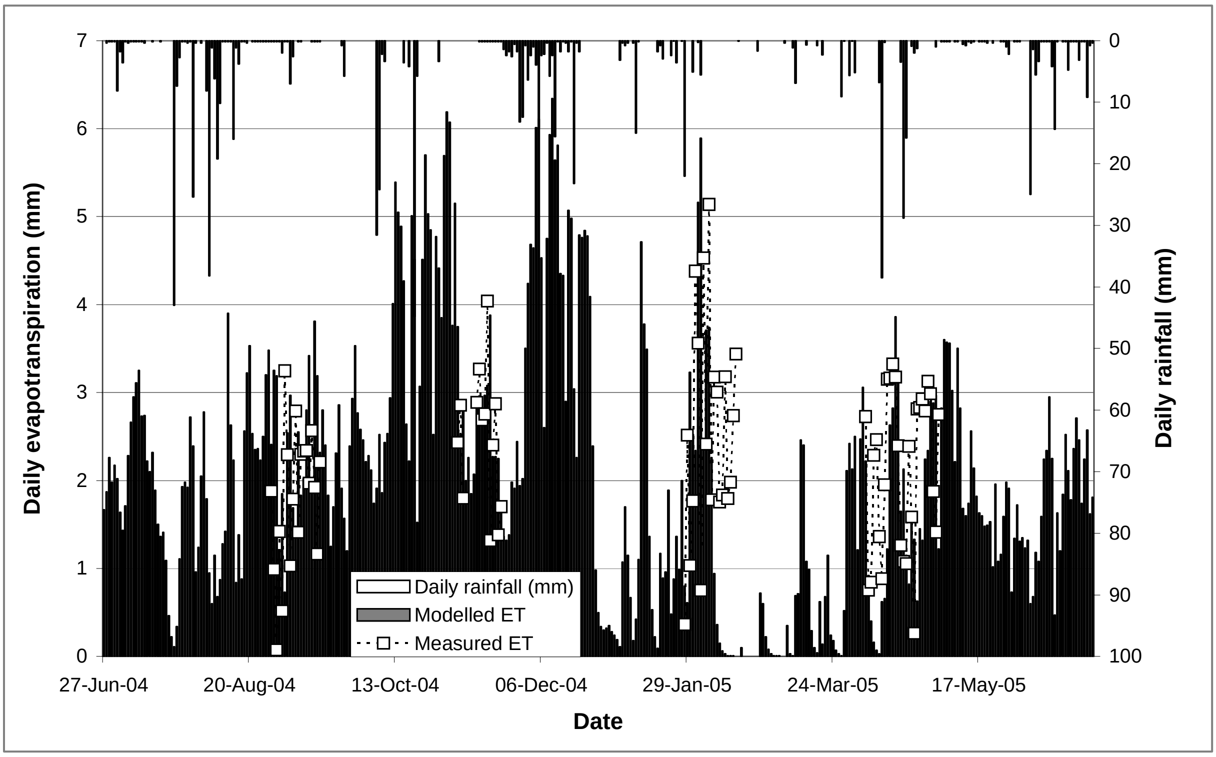

Figure iii. The pattern of daily ET recorded with a scintillometer system, and modelled with WAVES, over four different seasons at the Fynbos site in the Helderberg Nature Reserve, Western Cape. Daily rainfall is also shown along the X2 axis.

Figure iv depicts the pattern of ET for dryland winter wheat in the Riebeeck Wes district of the Western Cape. Growth is initiated from a small starting biomass at a specified planting date, and continues in response to a constant shoot carbon allocation fraction of 0.7. Growth ceases when cumulative degree-days exceed 25000. Maximum rooting depth was set at 1.5 m. Measurements of ET are unavailable from this site to test the realism of modelled ET. However, local end-of-season biomass data, and seasonal ET patterns reported in the literature, lead us to believe that the simulation is realistic.

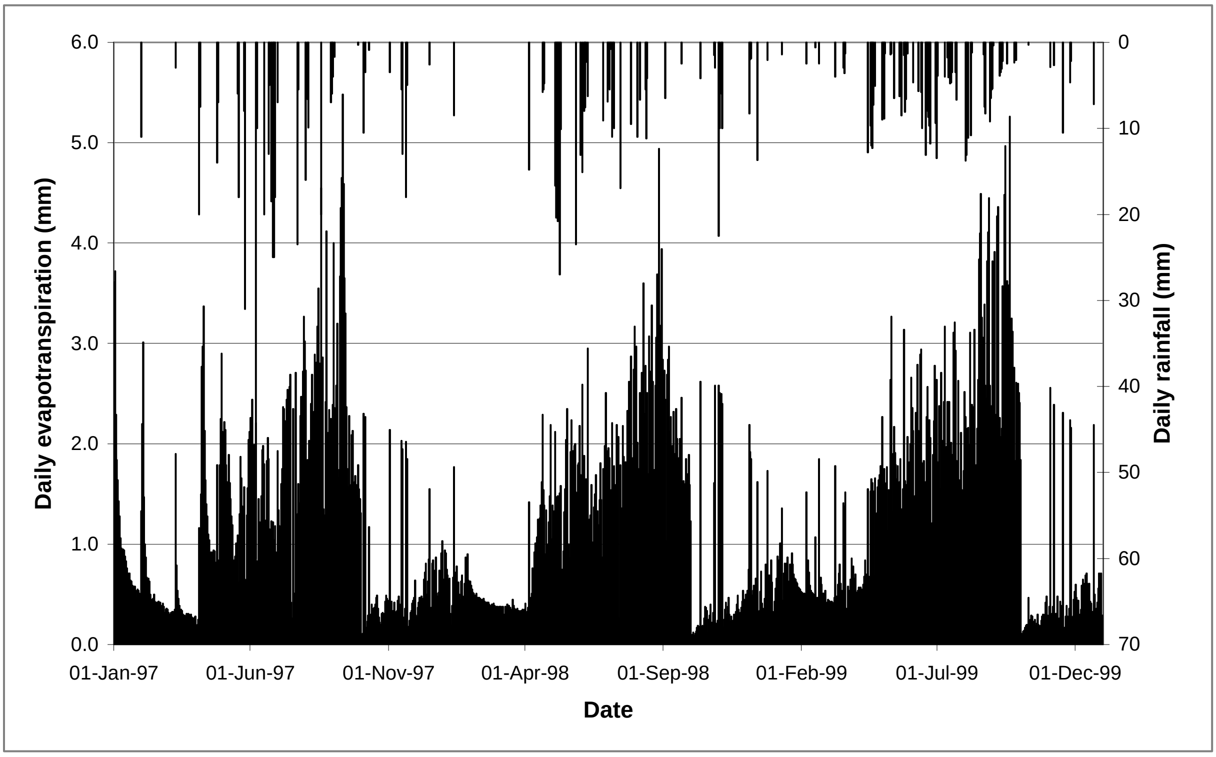

Figure iv. The three-year pattern of daily evapotranspiration simulated for a wheat crop growing in Riebeeck Wes (Western Cape).

Figure v illustrates the pattern of ET simulated for a *Burkea* dominated savanna at Nylsvley Nature Reserve, Limpopo Province. An overstorey tree canopy and understorey grass canopy were simulated for a four year period in this water-limited environment. Spring-time carbon translocation supported early growth in both the trees and the grass. Model output was compared (Table i) to water balance information summarised by Scholes and Walker (1993) for this vegetation.

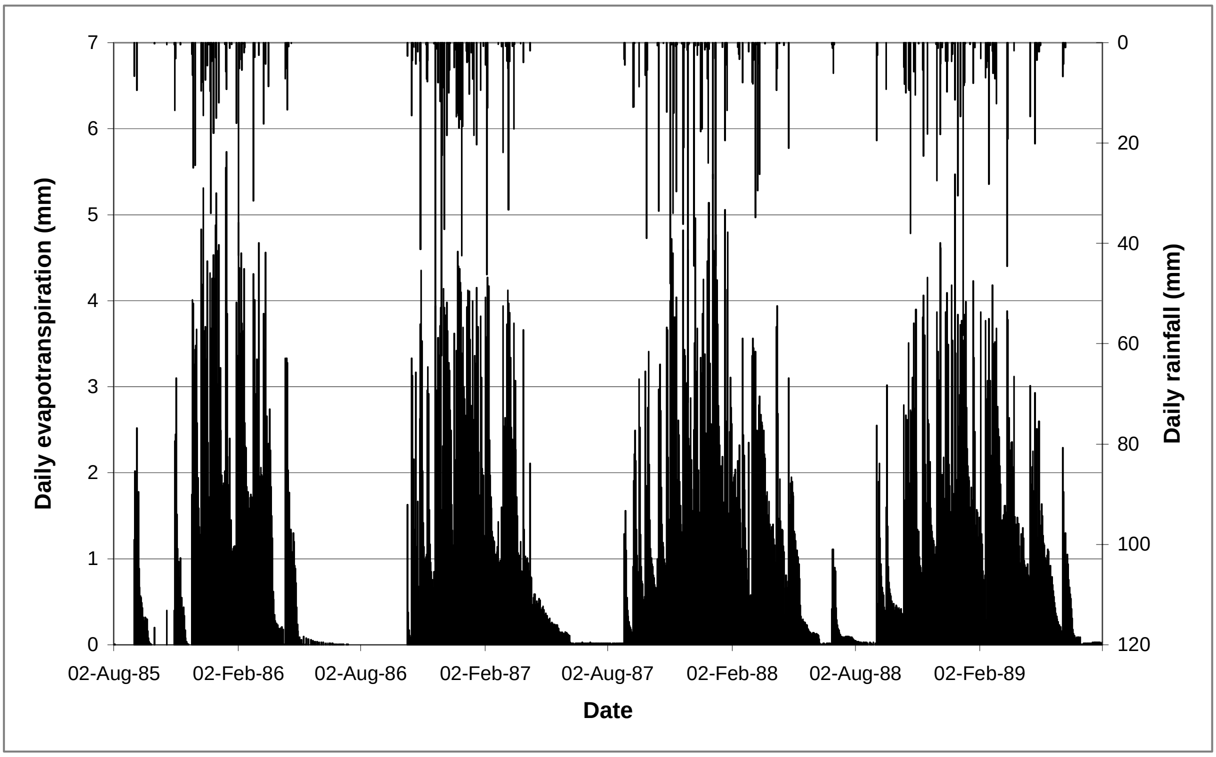

Figure v. **The pattern of daily evapotranspiration and daily rainfall simulated for savanna vegetation at Nylsvley, Limpopo Province.**

Table i. Correspondence between measured and simulated hydrological and structural properties pertaining to the Nylsvley savanna site.

			Simulated				
		Reported	85/86	86/87	87/88	88/89	Mean
Mean rainfall (mm yr^{-1})		623	419	766	809	598	648
Surface runoff (mm yr^{-1})		0	0	0	0	0	0
Rainfall interception by trees (mm yr^{-1})		35	36.8	12.2	29.6	27.5	26.5
Rainfall interception by grass (mm yr^{-1})		24	21.9	27.6	41.9	42.3	33.4
Maximum ET (mm day^{-1})		5.3	5.73	4.57	5.47	5.47	5.31
Soil evaporation loss (mm yr^{-1}) as a fraction of ET		0.50	0.43	0.65	0.49	0.45	0.51
Total ET (mm yr^{-1})		-	406	423	545	503	469
Peak LAI	(trees and grass)	1.2	1.28	0.69	1.23	1.10	1.08
	Trees	0.7	0.94	0.30	0.65	0.54	0.61
	Grass	0.5	0.34	0.39	0.58	0.56	0.47

A final example relates to a self-established stand of Wattle (*Acacia mearnsii*) that had invaded a riparian zone in the Wellington district of the Western Cape. Due to a constant supply of groundwater at this riparian site, and the substantial height (and therefore low aerodynamic resistance) of the dominant trees, the ET from this stand was highly correlated to an index combining day length and mean daylight vapour pressure deficit (VPD). Figure vi shows a plot of modelled whole-stand transpiration versus the daylength-VPD index. Superimposed is a non-linear regression line that describes the trend observed in the field data collected at this site.

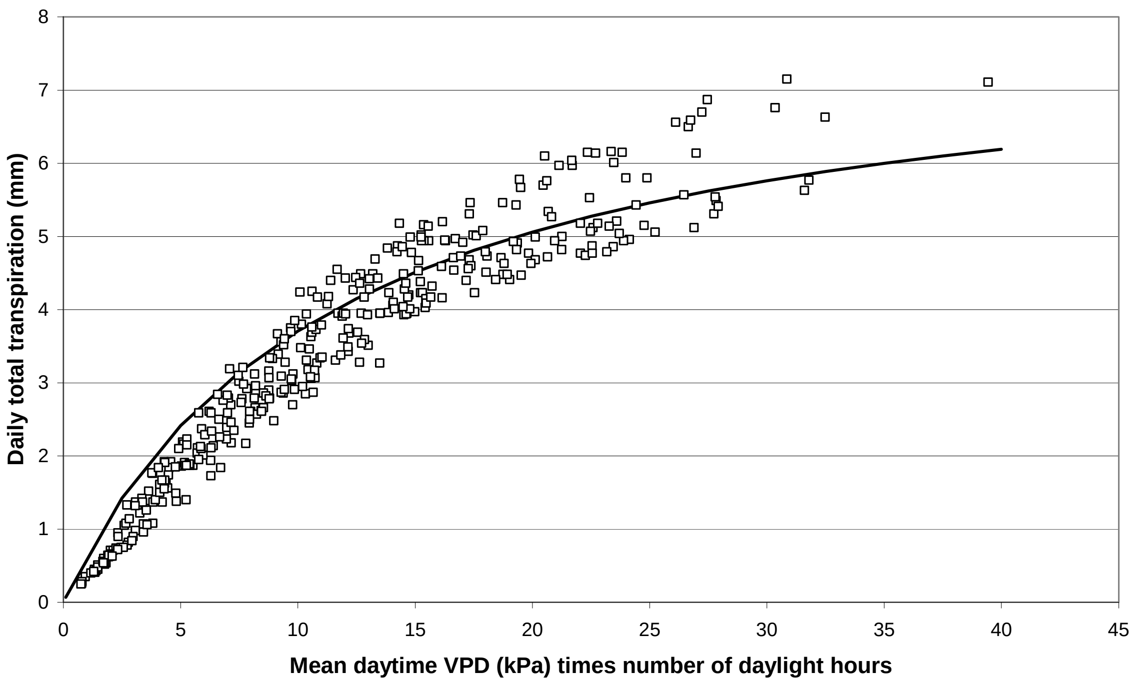

Figure vi. The relation between modelled whole-plot transpiration and the product of mean daily VPD and the number of daylight hours, simulated for the Wellington *A. mearnsii* site. The regression line indicates the trend observed in field data recorded at this site.

DISCUSSION

The aim of this project was to develop a relatively simple framework of understanding of annual ET patterns shown by a wide variety of land covers, and to translate this framework into a user-friendly form permitting predictions of vegetation ET by non-researchers. WAVES was designed specifically to portray the effects of land cover change on site water balances, and emphasis is placed on simulating the carbon balance of the vegetation and the water balance of the site. While the plant growth module is far simpler than that in many other process-based models, it allows the green leaf biomass to be adequately simulated over time, and models the various constraints imposed on both growth and transpiration.

A fundamental aim of this study was to identify and model the various biophysical limits imposed on crops, forest plantations and indigenous vegetation, which control rates of ET. While direct field measurements of ET and transpiration from various land covers are scarce, the few available data sets indicate that annual water use is strongly related to the proportion of the year in which a dense canopy of transpiring leaves is maintained. Thus, vegetation that is able to maintain a dense canopy of transpiring leaves throughout the year, such as the deep rooting *Eucalyptus grandis* stand and the Jonkershoek riparian Fynbos, exhibit a high annual ET. In contrast, grasslands maintain their maximum canopy cover of live leaves for a relatively short period of the year, even under conditions of sufficient soil water availability, and this greatly restricts their annual water use.

By comparison, the maximum rate of daily ET attained under favourable growth conditions is less variable among the various land covers, and commonly ranges from 5-8 mm d-1 in mid-summer. This maximum is generally close to the limit set by the availability of energy at the site. Plants have generally adapted their stomatal resistance to permit transpiration to occur close to this maximum rate. In the case of well-ventilated and aerodynamically rough tree canopies, aerodynamic resistance to diffusion of water vapour from leaves is low, and stomatal resistances are therefore relatively high. Conversely, plants of low stature are associated with a relatively high aerodynamic resistance, and so stomatal resistances are relatively low (Figure 6.6, Jones, 1983). WAVES accounts for these differences in aerodynamic resistance and canopy resistance.

Over most of South Africa, conditions for plant growth vary greatly over the different seasons. Soil water availability is a major limit to growth and transpiration due to seasonal rainfall. Process-based models such as WAVES are able to keep track of the site water balance, and can therefore predict the availability of soil water on any given day. Soil water depletion is often the principal limit to ET towards the end of a growing season, hastening the senescence and dieback of green leaves and shutting down transpiration.

The timing of rainfall in relation to season is of obvious importance. Growth and ET of non-riparian vegetation in the winter rainfall regions is largely confined to winter, since the summer is too dry to sustain active plant growth. ET is therefore constrained by short day lengths and reduced solar radiation, and also by relatively low VPD resulting from low temperatures and high relative humidity. The occurrence of frost and fire are also important limits to plant ET because both kill the transpiring leaves. The effects of these limits have been incorporated into WAVES.

The accuracy with which WAVES is parameterised depends to a large extent on the available field data. The Bellevue grassland study is an example of a situation where high quality field data for ET and weather conditions permits a rigorous model parameterisation process. In many of the other case studies, field data are less comprehensive, limiting the accuracy with which WAVES may be parameterised. In this study, we have recognized this limitation, but nevertheless evaluated whether our best estimates of the required model parameter values give rise to realistic patterns of ET and whole-year cumulative ET. WAVES has generally performed realistically despite the lack of rigorous parameterisation at most sites, and has met the requirement of providing a framework of understanding. It is hoped that further use and development of WAVES will lead to a greatly increased understanding of differences in ET over the full range of land covers in South Africa. A constant leaf mortality rate throughout a growing season is not always realistic, and seemed to be a particular problem in simulating poplar trees and sugarcane. This needs to be improved upon.

An important goal of this project was to design a user-friendly prediction tool to allow non-specialist modellers to assess the water use of various land cover types. The version of WAVES developed in this project is a CD-based product that is particularly user-friendly and simple to use. It is hoped that after a period of further testing, this product may be released for general use by South Africans.

RECOMMENDATIONS

It is believed that the new version of WAVES will be useful to a wide variety of researchers, water resource managers, conservationists and students. Inevitably, however, there is much scope for future testing, development and enhancements that would improve its usefulness. Some of these are identified below:

- More intensive model testing is required to identify possible programming bugs, and ensure flawless simulations under all possible set-up conditions.
- Development of additional graphical outputs and ET summaries, to permit easier comparison of different land cover scenarios.
- Investigate linking ET changes to streamflow in a spatial context.
- Parameterise more vegetation types for inclusion in the product. It appears that a high priority should be given to further species of alien invasive plants that are suspected of bringing about significant hydrological changes. The water use of aquifer-dependent vegetation in the drier parts of the country is also an important priority, in view of the scarcity of direct measurements of ET and the importance of regulating aquifer utilization to avoid permanent damage to such valuable ecosystems. The measurement of ET in the past has been fraught with technical difficulties, requiring a high degree of diligence and effort in maintaining equipment. The recent availability of scintillometer systems allows better quality ET data to be gathered. Two major advantages are that the instruments are less prone to mechanical and electronic problems, and they provide spatially averaged data from extensive beam paths. Their use in future ET studies should make the gathering of field data less complex and cheaper to undertake.
- Further studies of those aspects of the structure and physiology of South African vegetation types that relate to the processes of growth and transpiration are necessary to put WAVES (SA) simulations on a firmer footing. This will reduce the level of uncertainty regarding those parameter values that are presently poorly quantified, permitting

greater insights into plant functioning and improved predictive capability.

- There are also likely to be many subtleties in plant functional attributes that are not captured by the current plant parameter sets and model structure, which will require the attention of researchers in the future. Some of these problem areas (e.g. accelerated leaf senescence rates, pathogenic effects on canopy conductance, changes to the normal pattern of carbon allocation, the influence of deep roots in preventing extreme plant water deficits) are identified in the various simulations. We believe, however, that the current parameter sets for the various “plant functional types” serve as a useful statement of our present understanding of the constraints on plant growth and water use, and will encourage others to identify problem areas and improve on the current model predictive capability.

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List of Symbols and Acronyms

AIP	Alien invasive plants
b_0	Clear day transmissivity
b_1	Coefficients in the Bristow-Campbell equation
b_2	Coefficients in the Bristow-Campbell equation
C	Degrees centigrade
c_{dw}	Specific heat of dry wood
cp	Specific heat capacity of dry air at constant pressure
CMA	Catchment management agencies
DEM	Digital elevation model
E	Evaporation
EC	Eddy Covariance
e	Vapour pressure
e_s	Saturated vapour pressure
ET	Evapotranspiration
F	Mean vertical flux
G	Soil heat flux density
H	Sensible heat flux density
HPV	Heat pulse velocity
IRM	Integrated rate methodology
I_{ex}	Extraterrestrial daily radiant density
K_v	Diffusivity coefficient for latent heat transfer
K_h	Diffusivity coefficient for sensible heat transfer
LAI	Leaf area index
LAS	Large aperture scintillometer
MAMSL	Metres above mean sea level
MAP	Mean annual precipitation
MAR	Mean annual runoff
M_d	Molecular mass of dry air
M_w	Molecular mass of water
mm	Millimetres
m_c	Moisture fraction of sapwood
P	Atmospheric pressure
R_n	Net radiation
s	Flux entity
SFRA	Streamflow reduction activity
SLA	Specific leaf area
SLS	Surface layer scintillometer
SR	Total daily solar radiation
t	Time delay for the temperatures at points Xu and Xd to become equal

T_i	Daily total atmospheric transmittance
T_{max}	Maximum daily temperature
T_{min}	Minimum daily temperature
U	Heat pulse velocity
$u^{/}$	Corrected heat pulse velocity
VPD	Vapour pressure deficit of the air
w	Vertical wind velocity
X_u	Distance upstream from the heat pulse source (HPV technique)
X_d	Distance downstream from the heat pulse source (HPV technique
Z	Distance between two points
λ	Latent heat of vaporisation
β	Bowen ratio
ε	Ratio of molecular weights of water vapour and air
ρ_a	Density of air
ρ_b	Dry wood density
y	Psychrometric constant

1. INTRODUCTION

1.1 Policy context

Water is a scarce resource in South Africa, and requires increasingly sophisticated management to ensure that water availability keeps pace with growing demand. There is already a high degree of utilization of surface and groundwater resources in many catchments. Planning for an equitable allocation of these resources amongst a growing list of water users is complicated because of the great spatial and temporal variation in water availability. Large areas of South Africa are semi-arid, where median annual runoff is less than 60 mm (Schulze, 1997). These areas are characterised by a high degree of reliance on groundwater and riparian water resources. In the higher rainfall areas of the country, median annual runoff is higher, but only exceeds 100 mm in restricted areas of highest rainfall, often associated with seaward-facing mountain or escarpment slopes, or high-rainfall coastal regions. Year-to-year variation in rainfall and river flows is high throughout South Africa, and the frequency of critical periods of lowest flows, which may have a profound limiting effect on economic activity, are difficult to predict accurately. The challenging water supply situation is made more complex by forecast climate changes (Schulze and Perks, 2000), some of which are predicted to result in lower rainfall in certain regions of the country.

An important area where Man can modify the water yield from catchments is in the management of vegetation. Since the early 1900s, South Africa has witnessed one of the most hydrologically extreme changes in land use to be found anywhere in the world, which has demonstrated how influential land cover is altering the proportions of “green water” (water evapotranspired by plants) and “blue water” (stream water). South Africa is poor in indigenous forest resources, and so plantations of exotic timber species (mainly pines, eucalypts and wattle) have been the main source of timber. The first forest plantations were established in 1876 (Van der Zel, 1995). Since that time, there has been a steady conversion of natural grassland and shrublands to forest plantations in the higher rainfall areas of South Africa. These plantations now occupy a total of nearly 1.5 million hectares. The original vegetation replaced during this afforestation programme was mostly seasonally dormant grasslands and Fynbos shrublands, with an annual ET of approximately 700-800 mm (Bosch and von Gadow, 1990). By contrast, evergreen and deep-rooting forestry species are characterised by a much higher cumulative annual ET, commonly in the region of 1100 mm or more, depending on available rainfall and soil water. Catchment water yields may therefore decline by several hundred millimetres following afforestation. Experience throughout South Africa has shown that streams and rivers are significantly reduced when catchment areas are afforested with exotic plantation species (Malherbe, 1968). This issue of forestry and water supplies was discussed in detail at the 1935 Empire Forestry Conference held in South Africa. Out of this conference arose an initiative to establish hydrological research catchments in various parts of the country. These catchments yielded much information over the years, which is summarised in a series of publications, the latest and perhaps the most comprehensive of these being a report authored by Scott et al. (2000). Results demonstrated unequivocally that land cover change may have a very large influence on catchment water yields.

In more recent times, many developments have ensured a continued interest in the water use of vegetation, and how changes in land use are likely to affect catchment water yields. Some of these are listed below:

- Water demand in South Africa is rising steadily in response to population growth, rising standards of living, and increasing industrial and agricultural development. Many catchments are now regarded as water stressed, where water supplies are close to fully committed.
- Alien invasive plant (AIP) species are a significant threat to South Africa's biodiversity, and are thought to occupy a total of about 10 million hectares, representing 6.82% of the total area of South Africa and Lesotho (Versfeld et al., 1998). Much of this affected area lies in the higher rainfall regions that are a vital source of water to the rest of the country. The water use of AIPs, many of which are vigorous tree species, is believed to be high (Calder and Dye, 2000), and water saving is a major perceived benefit arising from a large-scale national programme of eradication of these plants (the Working for Water Programme).
- There is a need to look at more diverse "baseline" vegetation for hydrological scenario studies. Proposed changes in land use need to be evaluated against a baseline land cover, to determine the net increase in ET and likely reduction in catchment water yield. This is not always grassland, Fynbos or agricultural land, for which most information is currently available, but may comprise many forms of forest, woodlands, and other types of indigenous vegetation, for which water use information is scarce.
- A recent controversy has developed over the proliferation of golf estates in the southern Cape. A major concern is the high water requirement of these estates, since water is already scarce in this region. Comparative information on evapotranspiration (ET) from well-watered turf and the indigenous vegetation of the area is an essential component in environmental assessments of such proposed estates.
- The water use of artificially established grasslands on gold tailings storage facilities, coal dumps and fly ash dumps is becoming a critical issue in developing sustainable solutions to the problem of acid mine drainage and the seepage of contaminants into adjacent farm lands, residential areas and rivers. There is a significant health threat from some of these contaminants, and so it is important to understand if vegetation established along the sides and tops can take up and transpire a significant proportion of the rainfall, thereby reducing the rate of recharge into the dump, and decreasing the seepage problem.
- There is increasing concern in South Africa for the danger of over-utilisation of aquifers in areas where valuable groundwater-dependent ecosystems occur. In order to quantify the aquifer dynamics of such systems, it is necessary to determine the rate of water use by the overlying vegetation, and the fraction of water that is available for aquifer recharge.
- Similarly, the water use of riparian vegetation has been the subject of recent study, especially in the Mpumalanga lowveld. Water levels in lowveld rivers have declined in recent years due to increasing abstraction upstream for agricultural activity. This has

prompted investigations of the quantity of water required to maintain the health and survival of the riparian vegetation.

- The National water law introduced the concept of streamflow reduction activities (SFRA). Declared SFRAs are subject to restrictions on further expansion. Authorities are faced with difficulties when called upon to evaluate relatively new crops which may be high users of water, but for which relevant information is lacking. A recent case involving plans to plant bamboo on a large scale along riparian zones in Limpopo Province is a good example.
- Much effort and expense has been expended on bush clearing programmes in various woodland and savanna regions of the country. The degree of reduction in ET and potential benefit to groundwater recharge, for example, is an important outcome that, however, has been difficult to quantify.
- Forestry companies and small-scale forest growers have come under new pressure from forest certification authorities to demonstrate the hydrological consequences of their forest management practices, especially where a major change such as change of species or management (e.g. long-rotation saw timber to short rotation pulpwood) is envisaged. Information on a regional and local scale is generally required for these assessments, but is mostly unavailable.
- The water use of areas of high conservation value such as wetlands, montane grasslands and indigenous forests remains of great interest, since their impact on hydrological systems is believed to be more favourable than alternative land use systems.
- The government is in the process of setting up 19 Catchment Management Agencies to manage the major catchment areas of South Africa. These agencies will be representative of all the water use sectors in each region, and will be responsible for managing the catchment water resource. Decisions on land usage will need to be made, and these are likely to be controversial where different and competing options for land use are proposed. Realistic comparative water use figures will be required to evaluate the efficiency with which competing land covers use water. Their effects on overall catchment water yield will also need accurate assessment. Catchment hydrological modelling will be required to synthesize information and provide guidance on the optimum allocation of water resources. Sophisticated catchment hydrological models are available, but there is still appreciable uncertainty about the water use of natural vegetation types which provide important baseline scenarios against which to compare other forms of land use. Basin-scale hydrological models such as ACRU, HSPF and SWAT have been widely applied in South Africa. Estimation of land-cover ET by these models is generally adequate for crops, but is less reliable for other land covers. Improvements in ET estimation would lead to greater accuracy in predictions of catchment water balances.
- There is a growing need for environmental impact assessments and strategic environmental assessments to guide numerous development initiatives around the country. Potential changes in evapotranspiration are a vital aspect that requires attention, but again, good information is seldom available.

In summary, there are many examples of the need for realistic information on vegetation water use, but in most cases, accurate data are unavailable. Where information is available, such as for the forest plantation-grassland-Fynbos land use changes, the validity of extrapolating results to other localities is often questionable. To date, relevant information has been gathered from too few experimental sites to allow adequate extrapolation over the full range of sites and growing conditions. Such factors as rainfall, temperature, aspect and slope, soil depth, texture, degree of stoniness, fertility and depth to a water table vary widely over South Africa, and all may be significant in influencing ET patterns.

2. PROJECT AIMS

The stated aims of the project are:

"To develop a framework of understanding about major controls of evapotranspiration in different types of vegetation and crops in South Africa. This work will lead to:

1) *a better understanding of when a change of land cover may have a significant impact on surface water yields from an area of land,*
2) *recommendations for simple models to use in assessing these impacts, easing the task of simulating water use in a wide variety of vegetation, both indigenous and alien, existing in South Africa".*

The development of a user-friendly water use prediction tool for general use by non-specialists was regarded from the outset as an important output of this project. It was recognized that this framework would necessarily focus on the soil-plant-atmosphere system, and not include catchment-scale spatial aspects such as variation in climate, soil water and streamflow generation.

3. THE "LIMITS" CONCEPT AS A FRAMEWORK FOR UNDERSTANDING CONSTRAINTS ON VEGETATION WATER USE

Calder (1996, 1998, 1999) described the concept of recognizing overriding limits to ET, and using these to develop simpler water use models for a range of land cover types. This concept, which provided the main impetus for this project, arose from his experiences of hydrological research (mainly on forests and agricultural crops) in different countries that included wet and dry climates of both temperate and tropical regions. Calder (1996) suggested that ET could be interpreted in terms of six types of controls and limits on the evaporation process: advection, solar radiation, physiological, soil water, tree size and raindrop size (Table 1).

Table 1. Principal limits and controls on evaporation for different land uses in different climates as proposed by Calder (1996).

Principal limits on evaporation: temperate climate		
Land use	**DRY**	**WET**
Tall crop	Physiological Soil water	Advection
Short crop	Soil water Solar radiation	Solar radiation Physiological
Principal limits on evaporation: tropical climate		
Land use	**DRY**	**WET**
Tall crop	Soil water Tree size	Raindrop size Solar radiation
Short crop	Soil water	Solar radiation

This concept was thoroughly explored in the early phase of work in this project, but many uncertainties and a lack of information, particularly on many of the indigenous vegetation types, forced a reconsideration of its practicality, especially for use on a diversity of natural vegetation showing many structural and physiological complexities. A big concern was the emphasis on physical processes, and the omission of the many and varied physiological constraints to ET that are evident in natural vegetation. It was also considered to be significant that no further applications of this concept could be found in the literature.

It was then decided to retain the concept of a relatively simple modelling framework, but to search for a suitable biophysical processes model that could capture the main constraints on growth and water use experienced by the wide range of "plant functional types" that exist in South Africa.

Modelling indigenous vegetation in South Africa is particularly challenging, since the diversity of plant life is enormous, encompassing great variation in structure and physiology. We required a model with sufficient flexibility to be applicable to a wide variety of crops, forest, woodland, savanna, shrublands, and grasslands, growing in diverse biomes and responding to a wide variety of site factors. The model needed to take account of many physiological factors influencing growth and water use, such as seasonal patterns of leaf area development, canopy conductance, photosynthesis rates, carbon allocation and translocation patterns, respiration rates, and rooting depths. A review of international literature was conducted to examine the suitability of various process-based models as a possible general framework for understanding and predicting ET from a wide range of South African vegetation types.

The following criteria were used to assess models for their suitability:

- Model availability
- Proven scientific credibility and application in hydrological studies
- Good documentation
- Balance between simplicity and realism. All important hydrological processes need to be simulated, but not necessarily in great detail
- Suitability for linkage to a user-friendly interface to permit model use by non-specialist users.
- Applicability to a wide range of vegetation types. The ability to model two canopy vegetation types (overstorey and understorey) was considered to be essential.
- The model had to take account of the important limits and controls constraining water use by South African vegetation. The ability to describe seasonal patterns of green leaf development, and the effects of soil water availability, soil nutrition, temperature and light in reducing ET, were considered essential.

Against these criteria, the WAVES model was judged to be the most suitable model.

4. DESCRIPTION OF THE WAVES MODEL

The WAVES model (**Wa**ter, **V**egetation, **E**nergy, **S**olute) was considered to best meet the project requirements. It 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).

4.1 Model strengths

The primary strengths of WAVES are the following:

- It has the flexibility to be used on a wide range of plant functional types. This flexibility arises from:

  modelling two canopy layers (overstorey and understorey components) separately. This is particularly necessary for forests, woodlands and savannas.

  Many physical differences displayed by vegetation types are explicitly taken into account. These include differences in albedo, aerodynamic resistance, canopy resistance, carbon allocation patterns, specific leaf area, light extinction coefficient, initial biomass, and root carbon distribution with depth.

  Annual crops may be simulated in the conventional way by specifying planting date, cumulative heat units to maturation, and average shoot/root ratios.

- It simulates a wide range of factors limiting plant growth and water use.

  Soil water availability is the most important limitation to growth and water use in South African vegetation, dryland crops and forest plantations. 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.

The effects of solutes in soil solution and groundwater in limiting water uptake by plants may be explicitly modelled. Only the osmotic effect is taken into consideration. An important assumption in the model, however, is that chloride salts are assumed to occur. In situations where sulphate-dominated salts occur, such as in many sites influenced by acid mine drainage in South Africa, salinity effects may not be accurately modelled.

The integrated rate methodology of Wu et al. (1994) is used to describe the effects of temperature, soil water availability and a soil fertility index in limiting plant growth on a given day. This index is flexible, and additional limits such as the CO_2 concentration in the air may be added if required.

- WAVES is relatively simple by process-based model standards, and lends itself to interfacing through user-friendly Windows screens to permit model use by non-specialists. Required weather input data are minimal. Daily maximum and minimum temperatures, and daily rainfall are the minimum input requirements. If unavailable, the additional weather data required by WAVES (VPD and solar radiation) may be estimated from temperature and rainfall data using the well-known GENCLIM programme.
- Availability and support

The WAVES developers are available to offer support and advice.

A detailed and comprehensive manual is readily available on the Internet.

The CSIRO was agreeable to making the FORTRAN source code available to serious users for enhancements to be made.

Sets of parameter values for a range of crops, pasture and woodlands are available in the manual and in the WAVES literature.

4.2 Description

In view of the excellent and very comprehensive electronic manual available on the WAVES website, only a brief overview of the model is provided here.

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.

4.3 Model applications and validation

WAVES has been thoroughly tested at experimental test sites in France and the USA (Zhang et al., 1996), Australia (Zhang et al., 1999b; Salama et al. 1999; Zhang et al., 1999b); Slavich et al., 1998; Green et al., 1997a and Green et al., 1997b) and in China (Wang et al., 1997). Test crops and vegetation types have included grasslands, forests, mixed agricultural areas, *Eucalyptus* woodlands and a variety of different crops (e.g. wheat, oats, Lucerne, pastures).

5. MODIFICATIONS TO WAVES

A review of WAVES identified areas of weakness if the model were to be used as a general model of vegetation/crop water use by non-specialist users. These are listed below, together with actions taken to overcome these shortcomings.

5.1 User-friendly interface

The successful uptake of this modelling tool by non-specialist modellers is dependent on a simple user-interface that is unambiguous and intuitively easy to use. The project team developed such a user interface, written in Microsoft Visual Basic.Net, and using the Microsoft concept of a Wizard to guide users in specifying the various inputs required by the model. Features include:

- Point and click approach to providing all necessary inputs. Where the same repeated inputs are required in multiple rows, such as soil texture classes and carbon allocation fractions, these may be copied down easily.
- The provision of tool tips on all input and output headings to fully identify variables and constants, and their units.
- Information icons are provided at various positions on the menus to offer tips and clarifications.

5.2 Link to climate database for South Africa

Providing the required weather data input to a model is often a tedious process that is open to a variety of errors. We decided to provide the necessary databases of rainfall and temperature together with the model, and to make the selection of rainfall and temperature stations as simple as possible. Permission was obtained from the BEEH School of the University of KwaZulu-Natal to make use of a nation-wide 50-year database of daily rainfall, and daily maximum and minimum air temperatures (1950 to 2000). These databases are described by Lynch (2003) and Schulze and Maharaj (2004). Appropriate rainfall and temperature stations may be selected from a list, or by using a Map Objects Lite GIS module that displays the stations on a map of South Africa. The list option allows the user to quickly select the most appropriate temperature or rainfall station, if the station ID, name, or latitude and longitude are known. Sub-sets of stations may be sorted by altitude as well to make final selection easier. The GIS option displays all rainfall and temperature stations on a map of South Africa. These are shown against background coverages of provinces, towns, roads, railways, dams, quaternary catchments and a DEM. The standard GIS features (e.g. zoom in, zoom out, grab, etc) are available. When a cursor is positioned over a station, a tool tip appears to identify the station and list the altitude, MAP and MAT. This is to aid the selection of a station that best matched the site to be simulated. Selected rainfall and temperature data may be perused on a daily, monthly or annual time period, and exported in

Excel or text format. A facility is available to allow importation of weather data, should these be more appropriate than those available in the databases. After rainfall and temperature stations are selected, WAVES automatically estimates the total daily solar radiation (SR) and mean daily VPD.

Daily SR is an important WAVES input, yet is recorded at only a few weather stations in South Africa. There are numerous algorithms that permit one to estimate daily SR from daily maximum and minimum temperatures. Most are based on the premise that SR received on the surface of the Earth is strongly linked to daily temperature extremes. Clear-sky conditions result in high day-time air temperatures and lower night-time air temperatures due to the greater SR load during the day and reduced long wave emissivity from the atmosphere during the night. Conversely, overcast conditions result in reduced air temperature during the day and higher air temperatures during the night, due to increased interception of SR by clouds during the day and greater emissivity from clouds at night (Donatelli and Campbell, 1998).

Abraha (2003) has recently made a detailed comparison of 10 such models, comparing model output to observed daily SR measurements at four weather stations situated at Cedara, Ukulinga, Seven Oaks and Durban, all in KwaZulu-Natal. The models were calibrated against observed data recorded at an experimental site at Seven Oaks in the Natal midlands.

Two of the 10 evaluated models proved to yield the best estimates of SR from daily maximum and minimum temperatures. These two models - Bristow-Campbell (1984) and Donatelli and Campbell (1998) - were found to have the highest index of agreement and smallest RMSE. The Bristow-Campbell (BC) model was chosen for use in WAVES in view of its widespread use in many other agricultural and forestry models. The estimated coefficients based on measurements of SR at Seven Oaks were found to be as follows: $b_0 = 0.76$; $b_1 = 0.13$; $b_2 = 2.00$.

The form of the B-C equation contained within the RadEst tool (beta v3.00) (ISCI-Crop Science, 2002; Donatelli et al., 2003) was incorporated into WAVES:

$$SR = t_i * I_{ex} \tag{1}$$

$$t_i = b_0 (1-\exp(-b_1 \Delta T^{b2} / DT_{min})) \tag{2}$$

where

SR (MJ m^{-2}) = the estimated daily total SR
t_i = the daily total atmospheric transmittance
I_{ex} (MJ m^{-2}) = the extraterrestrial daily radiant density
b_0 = the clear day transmissivity
b_1 and b_2 = empirical coefficients that display the physics involved in the relationship
DT_m (^{o}C) = the monthly air temperature range
ΔT (^{o}C) = the diurnal air temperature range given as:

$$\Delta T_{(i)} = T_{max(i)} - ((T_{min(i)}+T_{min(I+1)})/2),\ \text{if } \Delta T_{(i)} <= 2 \text{ then } \Delta T_{(i)} = 2 \quad (3)$$

where T_{max} and T_{min} are the daily maximum and minimum air temperatures respectively, and (i) and (i+1) represent the current day and the day after. The mean of the two consecutive daily minimum air temperatures is used to reduce the effect of large-scale warm and cold air masses in temperate regions where advection is common.

Solar radiation estimated in this way was found to be in error for coastal sites experiencing a strong maritime influence. Daily temperature extremes at these sites are moderated by the presence of the sea, and give rise to underestimates of true daily solar radiation. This problem remains to be solved.

WAVES requires estimates of mean VPD over daylight hours. Long-term VPD data sets are rare, but daily maximum and minimum temperatures are commonly used by modellers to estimate mean daily VPD. The most commonly used equation is as follows:

$$VPD = \frac{e_s(_{T\max}) - e_s(_{T\min})}{2} \quad (4)$$

where

$e_s\ (_{Tmax})$ = the saturated vapour pressure at the daily maximum temperature

$e_s\ (_{Tmin})$ = the saturated vapour pressure at the daily minimum temperature

This equation is derived from two equations (12 and 14) described by Alan et al. (2004) relating to the estimation of saturation vapour pressure from daily maximum and minimum temperatures, as well as estimation of actual vapour pressure from daily minimum temperature when this is equated to dewpoint temperature.

There are two assumptions underlying this relationship. The first is that T_{min} coincides with dew point temperature. This is often the case in moist, high rainfall sites, but becomes increasingly inaccurate as rainfall decreases and ambient air humidity declines. The second assumption is that there is no change to the absolute humidity of the air during the course of the day. This is a reasonable assumption on most days, but may be in error when passing weather fronts introduce a different air mass to the site during the course of the day.

WAVES requires mean **daytime** VPD, since it is only during daylight hours that significant leaf stomatal opening and transpiration occurs. This adds a further source of potential error in using equation 4 to estimate the required daily VPD.

In an earlier test of equation 4 using five years of 2-hour hair thermohygrograph data recorded in the forestry region close to Sabie on the Mpumalanga escarpment, Dye (2001) showed that true VPD is significantly underestimated by equation 4 (Figure 1), especially on days of high VPD.

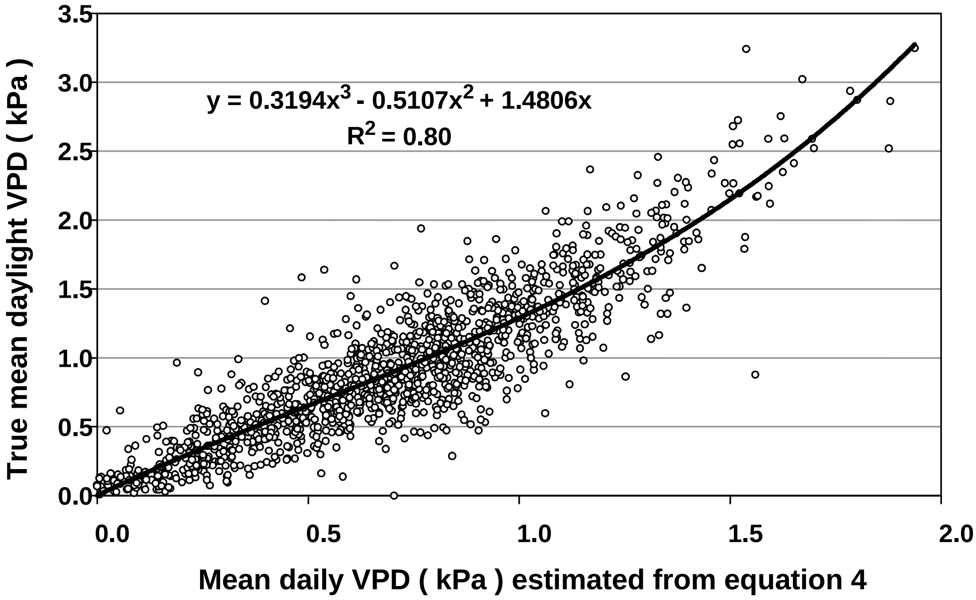


Figure 1. **The relation between VPD estimated from equation 4, and true daylight VPD calculated from five years of 2-hr thermohygrograph data recorded near Sabie, Mpumalanga.**

A further test of equation 4 was performed using one year of data recorded at an automatic weather station situated at Seven Oaks in the KwaZulu-Natal midlands. Mean daytime VPD was calculated for 20-minute intervals between 06h00 – 18h00 for each day during 2002, using ambient temperature and relative humidity. These values were compared to mean daily VPD calculated from daily T_{max} and T_{min} (equation 4). Figure 2 illustrates the correlation between these two estimates of mean daily VPD. The fitted polynomial function for the Seven Oaks data is compared to the previous function fitted to the Sabie data. The trends are very similar, suggesting that such correction functions may apply over many other regions.

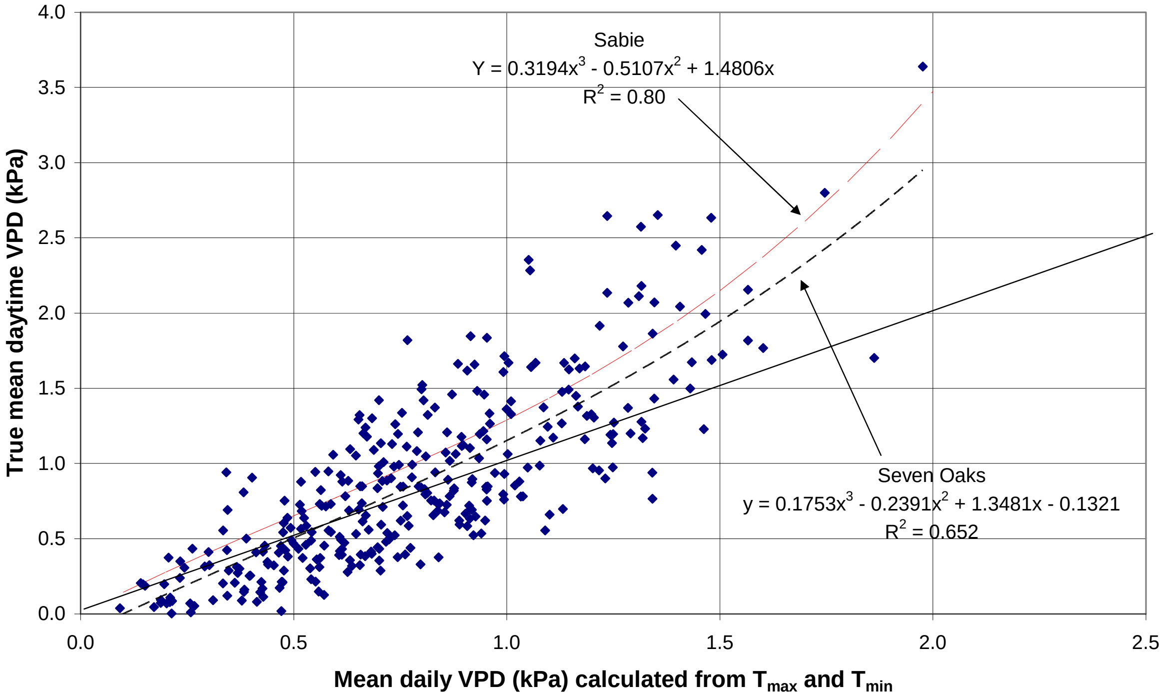


Figure 2. **The relation between VPD estimated from equation 4, and true daylight VPD calculated from 20-minute measurements of temperature and relative humidity at Seven Oaks.**

The following function describes a mean trend between the two fitted curves, and is used to correct mean daily VPD calculated with equation 4:

$$Y = 0.2473x^3 - 0.3749x^2 + 1.4143x \qquad (5)$$

Rainfall duration is a further input variable required by WAVES, and is used to estimate the average rainfall intensity on every rain day. If this rate exceeds the infiltration rate of the soil, overland flow is generated. A default rainfall duration of 0.25 of a day is assumed, unless more specific data are available.

5.3 Modification to carbon balance simulation

5.3.1 Flexible carbon allocation strategies

The original version of WAVES allowed the modeller to specify a particular shoot – root ratio, and then assumed that of the carbon allocated to shoots, one third went to growing leaf area and two thirds went to stem. This strategy works reasonably well for a variety of annual crop species that exhibit predictable allocation strategies, but is not realistic for certain categories of indigenous vegetation such as grasslands and savannas. In grasslands, for example, early shoot growth largely consists of leaves, with stems only appearing later, and growing in importance as the growing season advances. In savanna trees, the carbon allocation pattern has been shown to change markedly over the course of a growing season (Rutherford, 1984). Initially, most newly assimilated carbon goes to increasing leaf biomass, but later in the season, this switches to mainly support root growth.

Carbon allocation patterns are specified by weekly allocation fractions that direct daily net carbon to roots, stem or leaves. These allocation fractions may be described over a one year or two year carbon allocation cycle. This is designed to accommodate annual growth patterns (common in most annual and perennial vegetation) or two-year growth cycles, as is typical of sugarcane. It is possible to repeat these growth cycles as often as required.

In the case of forest plantations and indigenous vegetation (e.g. Fynbos) with longer developmental cycles, WAVES does not yet cater for longer-term changes in carbon allocation patterns. In such cases, vegetation parameter sets need to apply to a particular age or developmental stage (e.g. mid-rotation or 4-year post-fire).

5.3.2 Spring translocation of carbon

A feature of many grasses and deciduous trees is that warmer conditions in spring initiate translocation of carbohydrates from storage organs in roots or stem towards new leaves. This process is necessary to simulate in order to initiate a new growth cycle. A simple procedure has been added to WAVES to model this process.

- The modeller first enters the number of days required for the calculation of a moving average of daily T_{min}.
- A threshold T_{min} is then specified, above which translocation takes place.
- A threshold IRM value is also specified which prevents translocation from taking place when growth conditions (e.g. soil water availability) are too unfavourable for carbon translocation to occur.
- A daily rate of carbon translocation from root to leaf is specified for non-woody plants.
- A daily rate of carbon translocation from woody stems to leaf may be set for woody plants.
- Finally, the level of leaf carbon at which translocation stops is defined.

Coloured points are added to the green leaf biomass graph (described below) to indicate when translocation is initiated, and when it ceases.

5.4 Graphical check on simulated growth patterns

An important addition to the new WAVES user interface is a series of stacked graphs that illustrate the simulated patterns of leaf area index, green leaf dry mass, stem dry mass, litter dry mass and total root mass. An example of these is shown in Figure 3.

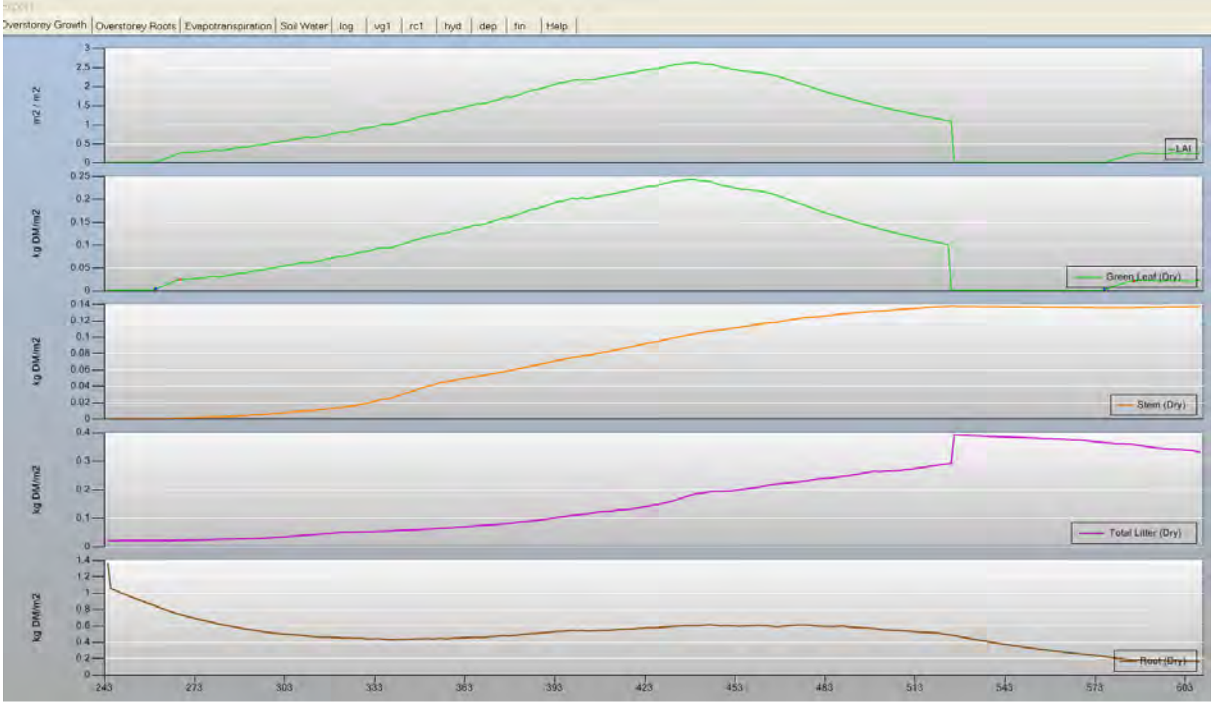


Figure 3. **An example of a WAVES output screen illustrating the trends in green leaf area, green leaf mass, stem mass, dry leaf/dry stem/litter and root mass over the simulation period.**

The purpose of these graphs is to allow the user to check that the model is generating realistic biomass trends, and that in particular, the simulated green leaf area/mass is acceptable. The quantity of green leaf is a particularly important determinant of evapotranspiration rate. If LAI is unrealistic, then the modeller is encouraged to return to the vegetation tab and modify the vegetation parameter values to produce a more realistic output.

For the purpose of the biomass graphs, it was decided to depart from the WAVES convention of describing only the carbon content of biomass. This was because most of the information available from biomass studies reported in the literature is based on dry matter measurement. A factor of 2.22 is assumed in WAVES conversions of kg C m^{-2} to kg dry matter m^{-2}.

5.5 Pre-defined vegetation parameter sets

The vegetation parameter sets are crucial to the correct simulation of vegetation biomass and ET, and represent one of the more complex components of WAVES. Pre-defined parameter sets are provided for the various vegetation/crop categories so that the non-specialist modeller avoids this complexity. Any of these vegetation/crop types may be used as a template in the construction of a parameter set for a new category of vegetation.

5.6 Display of output files

The standard WAVES output files are generated in parsed format for easy evaluation of trends over time. These files are accessed by clicking on labelled tabs. Output files may be exported in Excel or text format for further manipulation and graphical analysis.

5.7 Burning/mowing/harvest intervals

A facility has been added to allow the periodic removal of aboveground biomass due to burning, mowing or harvesting. The frequency and time of biomass removal can be specified after clicking on the site tab. All above-ground biomass is assumed equal to zero after such events. Grazing intensity and timing may be determined on the same tab.

5.8 Frost effects

An important limit to evaporation in many areas of South Africa is the occurrence of the first frosts in autumn. Frosts of sufficient intensity kill off green leaves and halt transpiration losses from these leaves. The user has the option in the vegetation tab of specifying a threshold minimum temperature that kills all green leaf and converts it to litter.

5.9 Fixed soil node depths and maximum soil depth

Earlier experience with WAVES revealed that the model would not run when node depths were spaced too far apart, since convergence and stability of the Richards' equation numerical solutions is not achieved. To minimize this problem, fixed node depths are specified, and these are close enough to avoid the non-convergence problem. As mentioned earlier, copying soils data across multiple nodes is easily accomplished.

A maximum soil depth of 4 m (which includes 31 node depths) has been set in the code. This is believed to be sufficient for most applications, but may be increased in future if required.

6. DESCRIPTION AND SIMULATION OF SELECTED VEGETATION TYPES

6.1 Selection of vegetation types

The aim of this project was to provide a general framework for predicting the water use of a wide range of natural vegetation, crops and forest plantations. It was therefore important to select a broad range of plant functional types to demonstrate that the prediction tool has wide applicability.

The choice of vegetation types was determined by the following considerations:

- A wide diversity of plant functional type was required
- Availability of field data for parameterising WAVES and demonstrating the realism of simulations
- A clear need for water use information, often for comparison to an alternative land cover
- Emphasis has been given to land cover types that are characteristic of higher rainfall parts of South Africa. It is in the better-watered catchments that a change of land cover may have a significant effect on catchment water yields. This is well demonstrated by Figure 4 that illustrates global trends in evapotranspiration calculated from over 250 catchments dominated by either forests or grassland/crops (Zhang et al., 1999a). The trend lines show that a change of cover from forest to grassland in an area where MAP equals 600 mm leads to much less reduction in absolute ET than the same conversion in an area experiencing an MAP of 2000 mm. The absolute reduction in ET will in most cases translate into a gain in catchment water yield. The potential effects of land use change on water resources are therefore greater in high rainfall environments than in lower rainfall environments.

The following categories and examples of land covers were included in this study:

- Plantation forestry (*Eucalyptus grandis, Pinus patula, Populus deltoides, Acacia mearnsii*)
- Baseline vegetation in hydrological studies

  C_3 grassland

  C_4 grasslands

  Fynbos

  Indigenous evergreen forest

  Savanna

  Valley thicket

- Wetlands (*Phragmites* reeds, riparian grassland, riparian Fynbos)
- Alien invasive trees (*Hakea drupacea, Acacia longifolia, Acacia mearnsii*)
- Dryland crops (sugarcane, wheat)

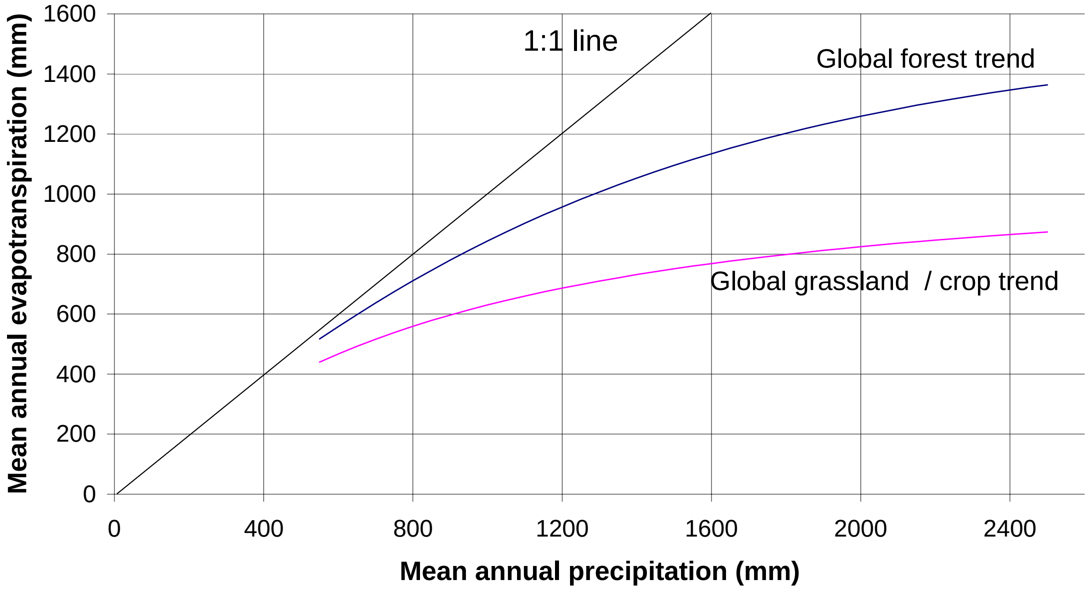
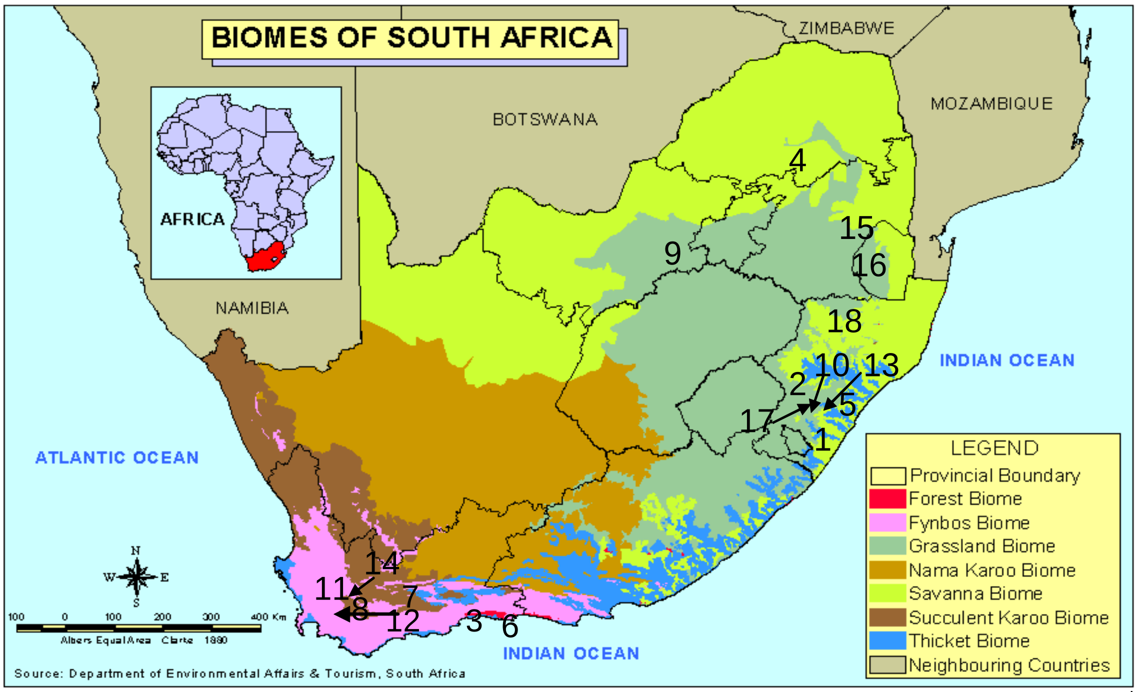


Figure 4. **Global trends in mean annual evapotranspiration from catchments dominated by forests and grassland/crops, as calculated by Zhang (1999) from a global review of catchment data from over 250 catchments.**

The location of these simulation sites is shown in Figure 5.



1 *Diheteropogon* grassland, Pietermaritzburg
2 *Themeda* grassland, Cathedral Peak
3 C_3 grassland, George
4 *Burkea* savanna, Nylsvley
5 *Acacia* valley thicket, Noodsberg
6 *Podocarpus* indigenous forest, George
7 *Protea* Fynbos, Somerset West
8 *Pteridium* riparian Fynbos, Stellenbosch
9 *Phragmites* reeds, Orkney
10 *Andropogon* wetland, Karkloof
11 Riparian invasive wattle, Wellington
12 Invasive *Hakea drupaceae*, Somerset West
13 Sugarcane, Seven Oaks
14 Wheat, Riebeeck Wes
15 *Eucalyptus grandis*, Sabie
16 *Pinus patula*, Usutu
17 *Acacia mearnsii*, Seven oaks
18 *Populus deltoides*, Piet Retief

Figure 5. A map of biomes of South Africa showing the location of WAVES simulation sites included in this study.

6.2 Simulation strategy

The modelling strategy involved obtaining field data describing the pattern of ET over as much of a full year as possible. Using rainfall and temperature data selected from an appropriate weather station where the vegetation being modelled is well represented, WAVES parameter values were then adjusted according to the best sources of information for that particular vegetation, and finally "tuned" to best resemble the measured seasonal pattern of ET. This process was governed as far as possible from knowledge of the vegetation in question, and parameter values were constrained within realistic limits set out in the WAVES manual. It is inevitable, however, that this process was somewhat subjective given the lack of required parameter data for many of the vegetation types. The vegetation parameter sets are nevertheless considered to provide credible estimates of the broad annual pattern of ET and growth in any year that WAVES is run. The reasonableness of the WAVES outputs is evaluated from the general shape of the trend of ET in different seasons of the year, the maximum ET in different seasons of the year, and the cumulative annual ET simulated for the site. Available biomass data is also used in some simulations to further validate the output.

Estimating the amount of water stored in the soil at the start of the simulation is a potential source of error that can affect the subsequent pattern of ET through a growing season. This error was minimized as far as possible by starting simulations in the dry season at a time when most soil water would be depleted.

Cumulative ET was considered to be a particularly important model output, since it is the long term effect of vegetation on catchment water balances that is commonly required in South Africa, rather than the accuracy of daily ET predictions. Cumulative ET graphs are therefore shown in preference to scatter diagrams of daily data.

It is not envisaged that the general user need make any changes to the vegetation parameter sets. Future improvements in model predictive capability will, however, undoubtedly be possible as more relevant plant physiological and structural information is gathered for the various vegetation types. This will reduce the level of uncertainty regarding those parameter values that are presently poorly quantified, permitting greater insights into plant functioning and improved predictive capability.

There are also likely to be many subtleties in plant functional attributes that are not captured by the current plant parameter sets and model structure, which will require the attention of researchers in the future. Some of these problem areas (e.g. accelerated leaf senescence rates, pathogenic effects on canopy conductance, changes to the normal pattern of carbon allocation, the influence of deep roots in preventing extreme plant water deficits) are identified in the various simulations. We believe, however, that the current parameter sets for the various "plant functional types" serve as a useful statement of our present understanding of the constraints on plant growth and water use, and will encourage others to identify problem areas and improve on the current model predictive capability.

6.3 Field measurement techniques

Some field hydrological and vegetation structural data are reported for most target categories of vegetation described and simulated below. The purpose of these data was to assist in the model set-up, and to demonstrate that model results exhibit a realistic pattern of ET and structure. A variety of different field techniques has been used in these studies, and these are described below.

6.3.1 Scintillometry

Scintillometry is a relatively new technique for estimating evaporation rates from land surfaces. The basic principle underlying this technique is as follows. When an electro-magnetic (EM) beam of radiation propagates through the atmosphere, it is distorted by various processes that cause some removal of energy from the beam, and an attenuation of the signal. The most influential phenomenon that causes signal attenuation is small fluctuations in the refractive index of the air. These fluctuations, caused largely by turbulent eddies of air generated by heat absorption near the surface, lead to intensity fluctuations that are known as scintillations (Figure 6). A scintillometer is an instrument that can measure the quantity of scintillations by emitting a beam of light over a horizontal path. The scintillations seen by the instrument can be expressed as the structure parameter of the refractive index of air (C_n^2), which represents the turbulent strength of the atmosphere. The turbulent strength describes the ability of the atmosphere to move heat, water vapour, dust particles and other atmospheric gases. The greater the proportion of solar energy heating the air, vegetation and soil surface, the greater the generation of wind eddies, and the greater the number of scintillations and degree of disturbance to the refractive index of the air. The significance of this measurement of so called “sensible heat” is that the difference between net radiation (the amount of solar energy absorbed at the surface) and sensible heat, is the quantity of latent heat used in converting liquid water to vapour, and from which the rate of evapotranspiration can be calculated. Soil heat flux is accounted for in the course of these calculations. A correction term involving calculation of the Bowen Ratio (the ratio of sensible heat flux to latent heat flux) is also used to account for the effect of humidity fluctuations on measured scintillations.

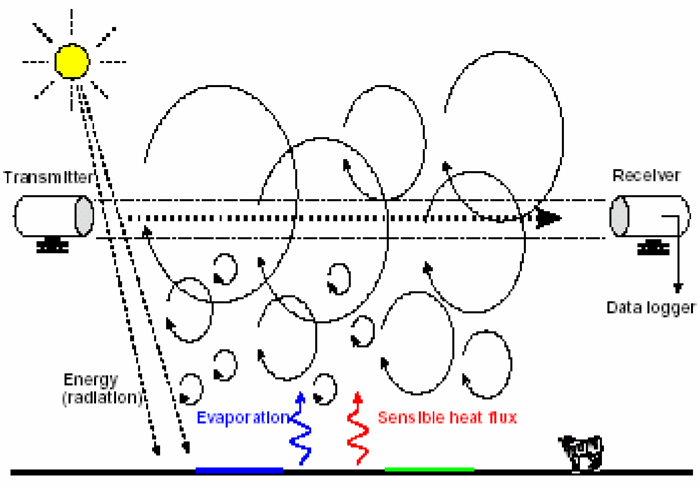


Figure 6. **Diagrammatic representation of a scintillometer beam subject to turbulent influences.**

Two varieties of scintillometer have been deployed in evaporation studies mentioned in this report. The LAS (large aperture scintillometer) system employs an infra-red beam to measure the path-averaged structure parameter of the refractive index of air (C_n^2) over horizontal path lengths from 250 m to 4.5 km. Measurements of C_n^2 together with standard meteorological observations, especially air temperature, wind speed and air pressure, are used to derive the surface sensible heat flux (H). The SLS system (surface layer scintillometer) has been used to measure evaporation rates from grassland (Savage et al. 2004). This instrument is characterised by a laser beam. Horizontal path lengths are typically shorter with this instrument, of the order of 50 to 250 m.

There are several significant advantages to scintillometer systems.

- They produce a spatial average of sensible heat, from which an ET rate can be derived.
- Their 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 rain, 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 weatherproof enclosure, and may be left in the field for extended periods.
- Data analysis is relatively simple and rapidly accomplished.

Unexpected problems were experienced at two sites (*Acacia longifolia*, *Hakea drupacea*) in the Western Cape, at which regular scintillometer measurements were performed. Signal quality deteriorated during the early morning or late afternoon, creating gaps in the data. A great deal of effort was expended in attempts to identify the source of the problem. Opinions were sought from colleagues in South Africa and specialists in Holland. The problem appeared to occur at times when the angle of sunlight was low. Several possible causes were identified and investigated. These included reflection of sunlight from the vegetation canopies, ineffective filters in front of the light receptors, and a non-optimum beam height that is too close to the canopies. Various solutions were tested, but none were really effective. Expert opinion from researchers in the Netherlands suggested that the problem may be related to sensor electronics.

6.3.2 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:

$$R_n - G - \lambda E - H = 0 \tag{6}$$

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.

$$\lambda E = (\lambda \rho_a \varepsilon K_v / P)\ ((\bar{e}_1 - \bar{e}_2) / (z_1 - z_2)) \tag{7}$$

$$H = \lambda \rho_a K_h (T_1 - T_2)/(z_1 - z_2)) \tag{8}$$

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

$$\beta = H/\lambda E \tag{9}$$

$$\beta = \gamma\ ((T1 - T2)/(e1 - e2)) \tag{10}$$

where γ is the psychrometric constant.

Using the simplified surface energy balance (equation 6) and the computed Bowen ratio (equation 10), Bowen (1926) showed the sensible and latent heat flux densities (equation 7 and 8) to be

$$H = \beta\ (Rn – G)/(\beta+1) \tag{11}$$

and

$$\lambda E = (R_n - G)/(\beta + 1) \tag{12}$$

where $\beta \neq -1$.

The Bowen ratio total evaporation is solved as

$$\lambda ET = (R_n – G) / (\beta + 1) \tag{13}$$

where λ is the latent heat of vaporisation.

The net radiation is measured with a net radiometer, installed above the vegetation under study (Figure 7). 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 grass 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.

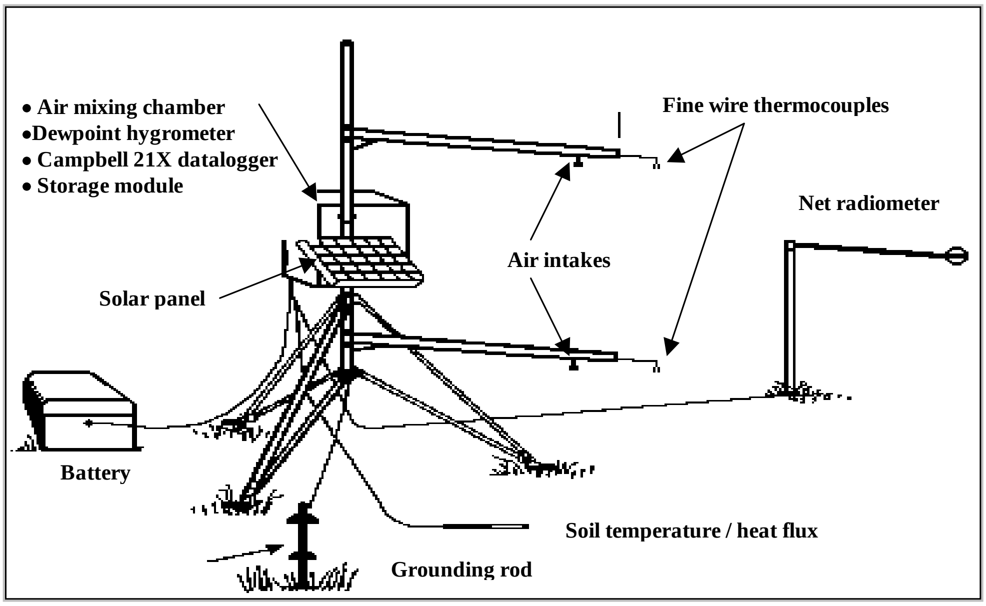


Figure 7. A diagrammatic representation of the Bowen ratio system

6.3.3 Eddy Covariance

The Eddy Covariance system is based on very high frequency measurements of water vapour and CO_2 above vegetation canopies (10Hz). 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

$$F = \overline{\rho_a w s} \tag{14}$$

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:

$$w = \overline{w} + w', \qquad s = \overline{s} + s', \qquad \rho_a = \overline{\rho_a} + \rho_a' \tag{15}$$

where the prime symbol denotes an instantaneous departure from the mean. These expressions can be substituted into Equation (15) and if we neglect fluctuations in density, the mean vertical flux *F* reduces to:

$$F = \overline{\rho_a w s} + \overline{\rho_a w' s'} \tag{16}$$

or

$$F = \rho_a \overline{w s} + \rho_a \overline{w' s'} \tag{17}$$

The first term on the right-hand side of Equation (17) 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 (17) reduces to

$$F \approx \rho_a \overline{w' s'} \tag{18}$$

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

$$H = \rho_a C_p \overline{w'T'} \tag{19}$$

and

$$E = \frac{\varepsilon}{P} \rho_a \overline{w' e'_a} \tag{20}$$

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.

A number of complex corrections are required during the course of these calculations. An example is trend correction, where variables such as temperature and radiation show slow changes during the course of a day that are not related to the much faster changes due to air turbulence which govern evaporation rates. Another data correction is known as 3-D coordinate rotation, and is used to adjust for sloping ground and also for sensor misalignment. Most of these corrections are now performed by the data analysis software obtained with Eddy Covariance systems.

A typical Eddy Covariance system is shown diagrammatically in Figure 8.

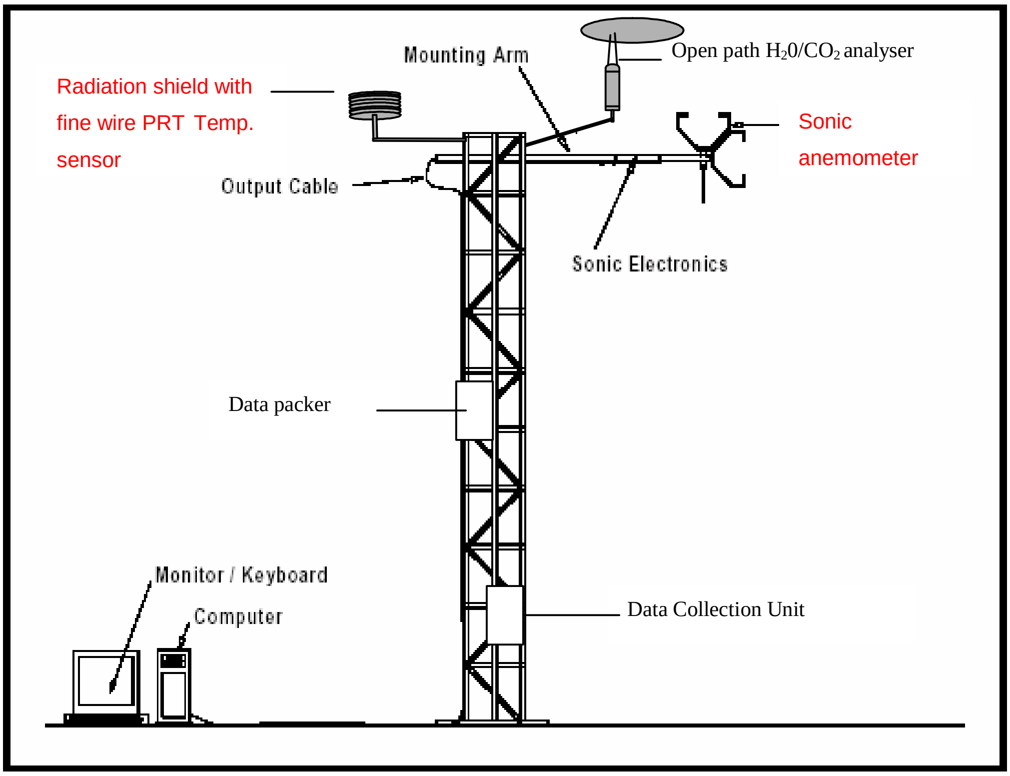


Figure 8. **Diagrammatic representation of an Eddy Covariance system.**

6.3.4 Heat pulse velocity

The heat pulse velocity technique allows measurement of sap flow rates through woody stems, and is widely used in studies of transpiration rates of trees and shrubs. The technique is well described in the literature, and has been reviewed by Smith and Allan (1996). There are many variations on this technique, and the description below outlines the method adopted in the sap flow studies referred to in later sections.

Three vertically aligned holes are drilled radially into the sapwood at several positions around the trunk, using a 1.85 mm drill bit guided by a 20 mm-thick drilling jig strapped firmly to the tree. The purpose of the jig is to ensure that the holes were exactly parallel to each other. A line heater is inserted into the central hole, while temperature-sensing probes are implanted 10 mm above and 5 mm below the heater. The line heater consisted of a steel tube with an outside diameter of 1.8

mm. Temperature probes consists of a single thermistor sealed within a Teflon tube of similar diameter. Each sensor probe pair thus gives a point estimate of sapwood temperature. Each thermistor pair is connected in a Wheatstone bridge configuration and automatically zeroed before each heat pulse initiation. The logger is programmed to apply a current of 30 amps lasting 1.0 s to each heater probe. HPV (*u*), (uncorrected for wound effects) is measured for each probe set using the compensation technique (Huber and Schmidt, 1937; Swanson, 1974). The temperature rise is measured at distances X_u upstream and X_d downstream from the heater, and *u* is calculated as follows:

where *t* is the time delay for the temperatures at points X_u and X_d to become equal.

The heat pulse velocity is calculated from the time taken for the pulse to travel the distance of 2.5 mm, i.e. the distance between the heater and a point midway between the thermistors.

$$u = (X_u + X_d) / 2t \qquad (21)$$

Heat pulse velocities are corrected for sapwood wounding caused during the drilling procedure. Swanson and Whitfield's (1981) wound correction coefficients are used to derive corrected heat pulse velocities (*u'*). The correction takes the form:

$$u' = p + qu + r(u)^2 \qquad (22)$$

where *p, q* and *r* are the correction coefficients appropriate to the measured wound size, diameter of Teflon probes, and probe separation distances, respectively.

The corrected heat pulse velocities are converted to sap flux (*v*) using the following equation (Marshall, 1958):

$$v = \rho_b (m_c + c_{dw})\, u' \qquad (23)$$

where ρ_b is dry wood density, m_c is the moisture fraction of sapwood, and c_{dw} is the specific heat of dry wood, assumed constant at 0.33 (Dunlap, 1912). Total sap flow is then calculated as the product of mean sap flux density and sapwood area.

At the conclusion of each experiment, trunk segments containing the drilled holes are removed to the laboratory for measurement of sapwood properties required to calculate sap flow from null-balance times. The sections of the tree trunk containing the probe implantation holes are excised and re-cut longitudinally at the particular radial depth below the cambium where the thermistor was originally positioned. The exposed, fresh face is shaved smooth using a microtome to allow precise measurement of probe separation distances and wound widths. These are typically -5 mm between the heater probe and the lower thermistor, and 10 mm between the heater probe and the upper thermistor probe, yielding a X_u-X_d/2 = 2.5 mm. Measurements of wound widths are taken midway between the line heater position and both the upper and lower thermistors. An average width is applied to the probe set.

Measurements of sapwood moisture fraction are generally obtained by chiselling sapwood samples from non-sample trees at each site. A portable electronic scale is used to record fresh mass of each sapwood sample immediately after its removal from the trunk. The immersed weights of the samples are also recorded in the field in the following manner. A small container of water of a size sufficient to hold the sapwood samples is placed on the balance. A laboratory clamp stand is set up next to the balance, and a sharp pointed seeker is clamped to position its point 2-3 mm below the water surface. The balance is then zeroed. The seeker is unclamped and impaled into the sapwood sample, and then replaced to completely immerse the sapwood sample under water. No part of the sample is allowed to touch the sides or bottom of the water container. A new weight is immediately recorded, and using Archimedes' principle, taken to be equivalent to the weight of water displaced. Assuming a specific gravity of water of 1000 kg m^{-3}, the immersed weight in grams is assumed equal to the sample volume in cubic centimetres. The sapwood samples are then brought back to the laboratory, where they are oven-dried to constant weight, before their dry mass is recorded. Moisture fraction is calculated as (fresh weight - dry weight) / dry weight, while basic wood density is calculated as dry weight / volume of a freshly excised section of wood. The sapwood in most species is clearly distinguished from the heartwood by a difference of colour. The sapwood ring is traced onto paper, the area of which is then measured with a LI-COR area meter.

The following data analysis procedure is adopted. The raw data are first examined using a custom-developed Visual Basic analysis programme to identify probes with missing or faulty data, those with long null-balance times, and those exhibiting poor correlation with other probe sets. Missing data are patched using data from another probe set with which it was most highly correlated. Long null-balance times that indicate slow sap flow rates are sometimes recorded by the deepest probes, indicating close proximity to heartwood. These probes are excluded where the number of missing data points is high. Patched files are saved and subsequently read again during the calculation of sap flow. The analysis programme calculates hourly sap flow for the tree, and then saves the output in three files containing the hourly sap flow rates, daily total sap flow, and the parameters used in the calculations. The daily data files are concatenated using a text editor, partial days at the start and end of files are joined appropriately, and the complete data record converted to an Excel file. These files are then checked as follows:

- The whole-year pattern is examined to check for unusually high and low values, and marked discontinuities.
- Readings taken at times when transpiration rates were not reduced by soil water deficits are plotted against mean daily VPD. High non-linear correlations are typical under these conditions, and suspect data points are immediately apparent. These data points are removed and the gaps patched using data from adjacent probes.

6.3.5 Weather monitoring

In the more recent studies of ET, weather data are routinely recorded to provide a description of the weather conditions during the periods when evaporation or transpiration is being measured. The basic weather variables are solar radiation, air temperature, ambient relative humidity, wind speed, wind direction and rainfall.

6.3.6 Leaf area index

Measurements of leaf area index (LAI) are very valuable in modelling ET. LAI has on occasion been measured directly on clipped grassland material harvested from sample quadrats, or from harvested trees. The green leaf component in grassland clippings is separated out from the shoot material, and passed through an area meter to record total projected area. In the case of grasses where leaves have a strong tendency to fold, the projected area is doubled to yield the total (one-sided) projected area.

LAI may also be estimated from readings of light interception by plant canopies. The LI-COR canopy analyser was deployed in a number of the studies described below.

6.3.7 Soil water

The CS615 time domain reflectometer probe is routinely installed in close proximity to Bowen ratio systems, to provide a continuous record of volumetric soil water in the surface soil horizon.

6.4 Grassland biome

Natural grassland is a very widespread and important biome in South Africa, covering more than 336500 km^2 or 26.5% of the total area of South Africa (Low and Rebelo, 1998). It is the original indigenous vegetation in many of the high rainfall regions of the country where much of our river water originates. Information from hydrological research catchments has shown that the annual water use of grasslands is comparatively low, leading to relatively high catchment water yields (Bosch and Gadow, 1990; Dye, 1996). Table 2 and Figure 9 illustrate the trend in annual ET in a variety of grassland-dominated catchments in KwaZulu-Natal that span a wide rainfall gradient. It is significant that grassland ET increases very slowly in response to increasing rainfall. This is believed to be a result of the strongly seasonal nature of shoot growth, and the fact that maximum leaf area and transpiration rate is only attained relatively late in the growing season, and maintained for only a short period before senescence becomes significant. Figure 9 also illustrates the steep increase in the difference between annual ET and annual precipitation (the difference between the grassland ET trend line and the 1:1 line), in response to increasing rainfall. On an annual time scale, this difference is approximately equal to streamflow, and illustrates the importance of high rainfall grassland catchments in feeding rivers.

A large proportion of the high rainfall grassland biome has been afforested, bringing about a significant increase in ET, and causing marked declines in catchment water yield (Malherbe, 1968). These grasslands are also susceptible to encroachment by alien invasive trees, which may also bring about a marked reduction in catchment water yield. For all these reasons, information on the water use of grasslands is important in planning for the optimum use of catchment water resources, and justifying the protection of grasslands in high rainfall regions for water conservation.

Table 2. A summary of measured mean annual precipitation (MAP), measured mean annual runoff (MAR) and estimated mean annual ET (MAP-MAR) for catchments in the Natal Drakensberg and adjacent areas (Schulze, 1979; Smithers and Schulze, 1994).

Weir	Catchment area (km^2)	MAP (mm)	MAR (mm)	Estimated annual ET (mm)	Years of record used
V1M01	4176	991	226	765	26
V1M02	1689	1036	388	648	14
V1M09	196	697	105	592	17
CP1	0.49	1381	552	829	25
CP3	1.39	1515	652	863	24
CP4	0.95	1376	632	744	27
CP6	0.68	1219	523	696	22
CP7	0.45	1305	535	770	20
CP9	0.65	1216	535	681	20
CP10	0.73	1293	506	787	20
V2M02	937	986	378	608	25
T5M03	140	1084	382	702	19
T5M04	545	1126	433	693	25
T5M07	3586	1010	263	747	13
T3M02	2101	895	154	741	18
T3M04	1029	733	102	631	21
V1H015	1.03	915	114	801	15
V1H019	14.64	798	87	711	15
V1H028	0.41	848	141	707	15
V7H003	0.43	858	203	655	15

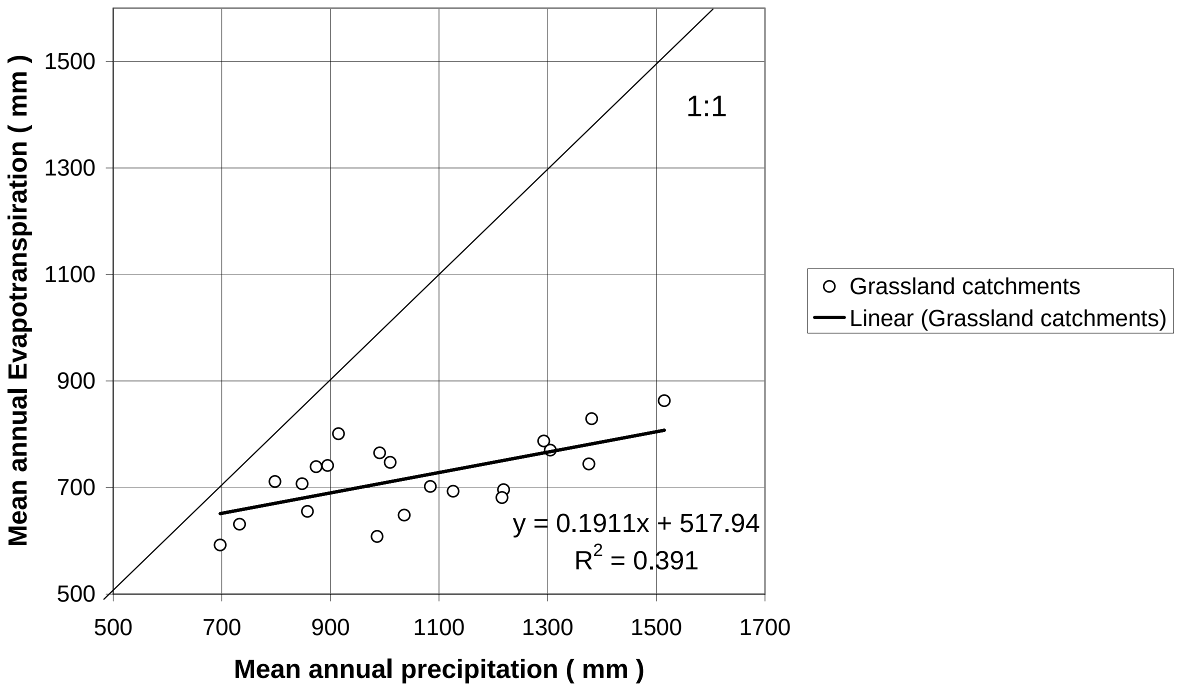


Figure 9. The relation between estimated mean annual ET and MAP for a selection of predominantly grassland catchments in the Drakensberg and adjacent uplands areas of KwaZulu-Natal.

6.4.1 *Diheteropogon amplectans – Themeda triandra* (Pietermaritzburg)

A natural grassland site adjacent to the suburb of Bellevue in Pietermaritzburg was used to evaluate a new scintillometer technique for estimating evapotranspiration from vegetation (Savage et al., 2004). The site is located at 29.6348^{o}S and 30.4329^{o}E, and lies at an altitude of 670 m.a.m.s.l. Mean annual precipitation is 782 mm, while the mean annual temperature is 18.3^{o}C. The ground slopes gently towards the southeast. The soils are derived from Dwyka Tillite, and the lithology is classified as C-Pd (ICFR, 2003). A typical soil profile consists of a loam textured A horizon in the first 300 mm below the surface. A clay texture is then characteristic of the B1 and B2 horizons that extend down to approximately 1000 mm.

The research conducted on this site is comprehensively described in WRC report 1335/1/04 (Savage et al., 2004). Briefly, ET was measured over a full year using a surface layer scintillometer, Bowen Ratio and Eddy Covariance systems. Additional instrumentation recorded solar radiation, air temperature, air humidity, wind speed, wind direction, soil heat flux and rainfall.

Fortnightly shoot harvesting took place over the 2003/2004 growing season to describe the changes in shoot biomass and green leaf area. A botanical description of the site was also undertaken. The nearest neighbour technique was employed, and the results of this survey are summarised in Table 3.

Table 3. The species composition of the Bellevue grassland site, expressed as a percentage nearest neighbour to 200 sample points.

Species	Percentage nearest neighbour
Diheteropogon amplectens	16.5
Themeda triandra	12.5
Tristachya leucothrix	11.5
Cymbopogon excavatus	11
Hyparrhenia hirta	8.5
Aristida junciformis	7.5
Heteropogon contortus	7
Herbs	6.5
Eragrostic capensis	4
Brachiaria serrata	2.5
Eragrostis plana	2.5
Sporobolus pyramidalis	2
Diheteropogon filifolius	2
Urelytrum agropyroides	2
Trachypogon spicatus	1.5
Sporobolus africanus	1.5
Setaria pallide-fusca	1.5
Elionurus muticus	1.5

An area of 50 m by 50 m was demarcated adjacent to the scintillometer beam. The top and bottom margins of this block were marked off with steel pegs at 2 m intervals. Starting on 11 November 2003, 10 quadrats, each 0.5 m by 0.5 m, were located at randomly defined positions within the sample block. A random number specified a particular row, and a second random number specified a particular distance along the tape measure. All rooted material within the quadrats was clipped and immediately stored in plastic bags. These sealed bags were then returned to the laboratory where their fresh mass was recorded. The contents of each bag were then separated into grass leaf, forb leaf and a remainder category that included dead leaf, stems, inflorescences and seeds. Live leaf samples were passed through a Li-Cor area meter to record the cumulative projected area of the samples. The cumulative area of the grass leaf samples was estimated by doubling the cumulative projected area, since the grass leaves were invariably strongly folded along the leaf midrib. The leaf area of forbs was assumed to be the same as the projected area measured in the area meter. All the material from each bag was then oven-dried to constant weight and weighed. The dry mass of green leaf, forb leaf and remainder material was also recorded. Shoot harvesting was repeated at approximately 2-week intervals through the growing season, ending on 21 April 2004 (Table 4).

For each sample date, leaf area index was calculated as the mean projected plant leaf area per unit area of ground. A specific leaf area was also calculated on each sample date. This was defined as the live leaf area (m^2) per kg of leaf carbon, which was assumed to be 45% of the total dry mass of the green leaves (Scholes and Walker, 1993).

Table 4. Harvest dates, green leaf area, green leaf mass, and specific leaf area (based on both dry mass and leaf carbon) recorded on each harvest date. Sample quadrat size was 0.25 m^2.

Harvest date	Mean green leaf area (m^2)	Mean green leaf dry mass ($kg\ m^{-2}$)	Specific leaf area ($m^2\ kg^{-1}$ DW)	Specific leaf area ($m^2\ kg^{-1}$ Carbon)
11 Nov 2003	0.071	0.009	7.9	17.5
26 Nov 2003	0.094	0.009	10.7	23.8
9 Dec 2003	0.141	0.014	10.3	22.9
22 Dec 2003	0.275	0.024	11.4	25.3
6 Jan 2004	0.143	0.022	6.7	14.9
20 Jan 2004	0.160	0.027	6.4	14.2
3 Feb 2004	0.219	0.030	7.5	16.7
18 Feb 2004	0.290	0.031	9.6	21.3
2 Mar 2004	0.220	0.030	7.5	16.7
16 Mar 2004	0.242	0.032	7.2	16.0
30 Mar 2004	0.277	0.034	8.3	18.4
21 Apr 2004	0.113	0.032	3.7	8.2
Mean	0.187	0.024	8.1	18.0

The measured trend in green LAI over the 2003/4 growing season is shown in Figure 10. Figure 11 illustrates the annual pattern of ET recorded at the site. It is calculated as the average of the Scintillometer, Eddy Covariance and Bowen Ratio measurements. Savage et al. (2004) report very good agreement in ET estimation amongst the three techniques, and none were judged to be consistently superior to the others. Spring-time ET starts from a low daily rate, but increases progressively during the summer to peak at around 5 mm per day around the summer solstice. Daily ET then declines steeply in autumn as the soil water is depleted and the green leaf fraction declines into winter. The build up of shoot biomass was noticeably slower in the 2003 season, due to very hot and dry spring conditions.

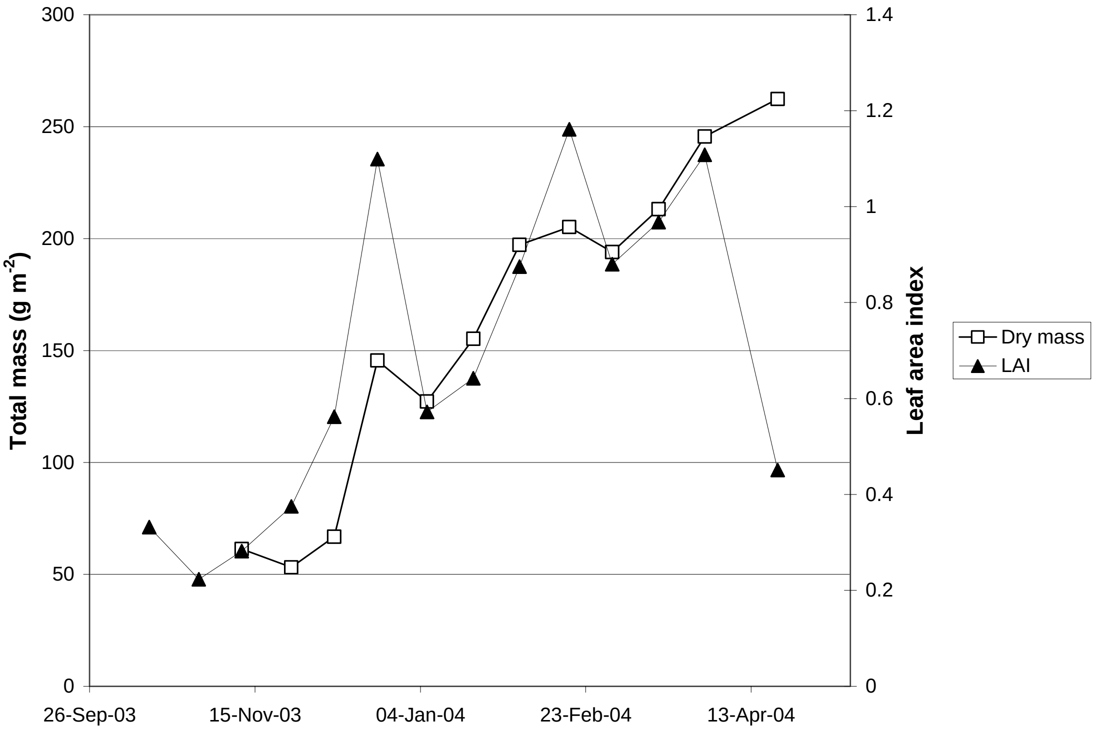


Figure 10. **Trends in dry shoot mass and leaf area index recorded at the Bellevue grassland site over the 2003/2004 growing season.**

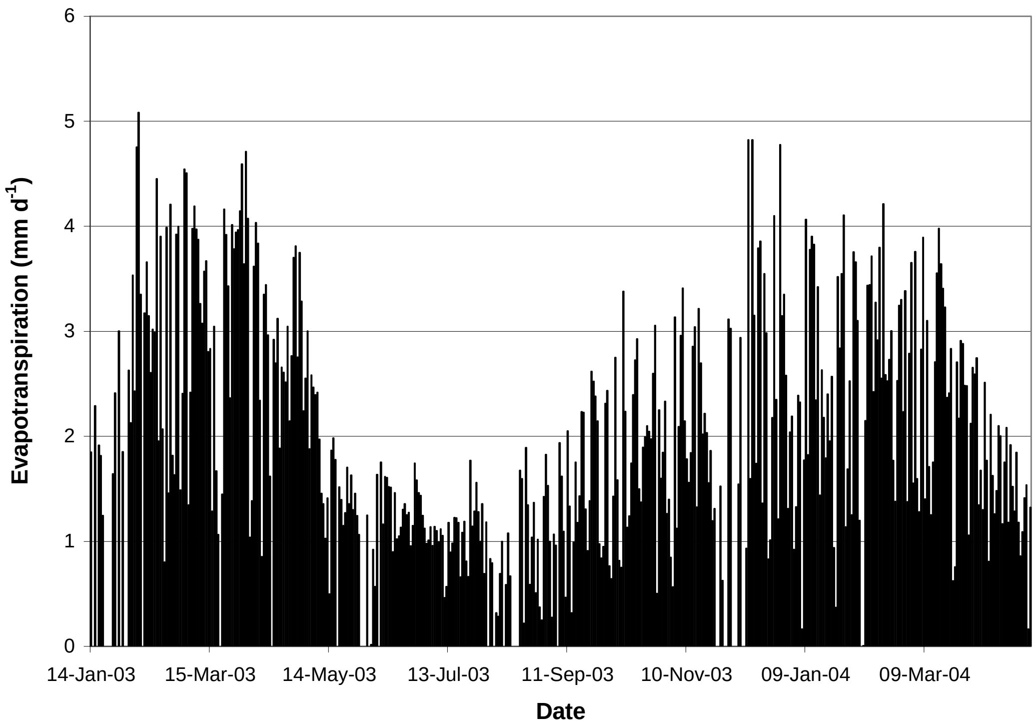


Figure 11. **Daily evapotranspiration recorded at the Bellevue grassland site from 14 January 2003 to 1 May 2004. Cumulative evapotranspiration over this period totalled 909 mm.**

The simulation period was set to start on 14 January 2003 and end on 1 May 2004. Daily rainfall and daily maximum and minimum temperatures were obtained from the Weather Bureau for Pietermaritzburg (station 0239698-5). Solar radiation and mean daily VPD were automatically calculated by WAVES in the manner described earlier.

Appendix 1 lists the parameter values adopted for the Bellevue grassland simulation. Initial root carbon was estimated using information provided by Jackson et al. (1996) on global trends in root mass beneath grasslands. These authors describe the cumulative root fraction with depth below the surface. Table 5 shows the calculations performed in estimating the root carbon mass at the various node depths. The first column lists the standard node depths down to 1.2 m. The second column converts these depths into cumulative fractions of the maximum depth. The third column provides the estimates of the cumulative fraction of the total root mass associated with each node depth. This is calculated from the $Y = 1-\beta^d$ equation provided by Jackson et al. (1996) for grasslands, where Y is the cumulative root fraction from the soil surface to depth d, and β is a fitted "extinction coefficient". Assuming a total root dry mass of 1.4 Kg m^{-2} listed by Jackson et al. (1996) as appropriate for temperate grasslands, column 4 lists the cumulative root dry mass with depth. Column 5 provides the equivalent cumulative root carbon with depth, assuming carbon comprises 45% of root dry matter). The final column lists the mass of root carbon associated with each node depth.

Table 5. Estimation of grassland root carbon mass (kg m-2) at each node depth in the soil profile. See text for a full explanation of calculations performed.

Depth (m)	Cumulative fraction of maximum depth	Cumulative fraction of total root mass (Jackson et al., 1996)	Cumulative root dry mass (kg m^{-2})	Cumulative root carbon (kg m^{-2})	Difference (kg C) in each horizon
0.001	0.0005	0.005	0.07	0.003	0.003
0.002	0.001	0.010	0.014	0.006	0.003
0.005	0.0025	0.024	0.034	0.015	0.009
0.01	0.005	0.048	0.067	0.030	0.015
0.02	0.01	0.094	0.131	0.059	0.029
0.05	0.025	0.218	0.305	0.137	0.078
0.1	0.05	0.389	0.544	0.245	0.107
0.2	0.1	0.626	0.877	0.394	0.150
0.3	0.15	0.771	1.080	0.486	0.092
0.4	0.2	0.860	1.204	0.542	0.056
0.5	0.25	0.915	1.280	0.576	0.034
0.6	0.3	0.948	1.327	0.597	0.021
0.7	0.35	0.968	1.355	0.610	0.013
0.8	0.4	0.980	1.373	0.618	0.008
0.9	0.45	0.988	1.383	0.622	0.005
1	0.5	0.993	1.390	0.625	0.003
1.2	0.6	0.997	1.396	0.628	0.003

Figure 12 illustrates the match between measured and modelled cumulative ET over the period from 14 January 2003 to 1 May 2004. This type of comparison is an efficient means of assessing the correspondence of modelled to observed rates throughout the simulation period. It clearly reveals any difference in annual cumulative ET, which is often of more interest to model users than differences in daily or monthly totals. The measured (909 mm) and modelled (935 mm) cumulative ET differs by only 26 mm. Peak leaf area index predicted by WAVES during the 2003/4 growing season is 1.25 compared to the measured value of 1.17, while predicted combined peak shoot mass (0.26 kg m^{-2}) is similar to the measured peak shoot mass (0.24 kg m^{-1}).

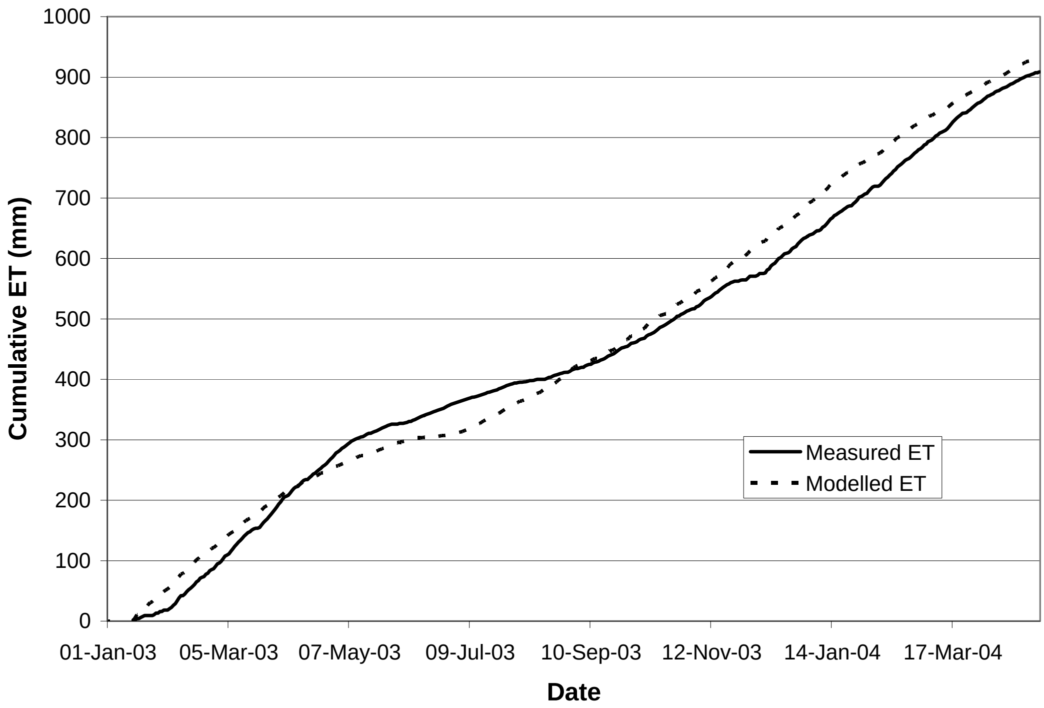


Figure 12. A comparison of modelled versus measured cumulative ET from the Bellevue grassland over the period from 1 January 2003 to 1 May 2004.

6.4.2 *Themeda triandra – Tristachya leucothrix* (Cathedral Peak)

The pattern of water use by a montane grassland in the Cathedral Peak area of the Natal Drakensberg (29° 00′ S, 29° 15′ E) was reported by Everson et al. (1998) and Everson (2001). Various hydrological processes were monitored within a 0.677 km^2 research hydrological catchment (catchment VI) dominated by *Themeda triandra* and *Tristachya leucothrix.* The catchment received a regular biennial spring burn treatment. Grass growth was strongly seasonal, exhibiting a temperature-linked spring flush in September (Everson and Everson, 1987), and dying back in May with the first frosts. The elevational range varied from 1860 m.a.m.s.l. at the basin outlet to 2070 m.a.m.s.l. at the highest point. The mean catchment slope was 19%. Soils classified as lateritic red and yellow earths, grading into heavy black soils (Katspruit and Champagne) in saturated zones (Granger, 1976). These soils are derived from basalt, and are characteristically acidic, highly leached and structureless. The topsoil has a friable consistency, permitting rapid infiltration of rainfall into the dry soil. Subsoils have very high clay contents and exhibit low hydraulic conductivity. From soil texture data reported by Everson (1979) for the nearby catchment IX, it was assumed that the top 300 mm is a clay loam, which is underlain by clay to the limit of the rooting zone set at 1.4 m.

Figure 13 shows a typical whole-year pattern of ET recorded with a Bowen Ratio system over the year 1993/1994. ET was found to be very low in winter when the grass was dormant and the previous season's shoot growth had died back. Following warmer spring weather, leaf area slowly builds up, reaching a peak in December/January. This is tracked by a similar ET pattern. There is a slow decline in ET into autumn, as day length shortens and the shoots mature and senesce. A rapid decline in early winter occurs in response to the first frosts. Annual ET over the whole year amounted to 651 mm.

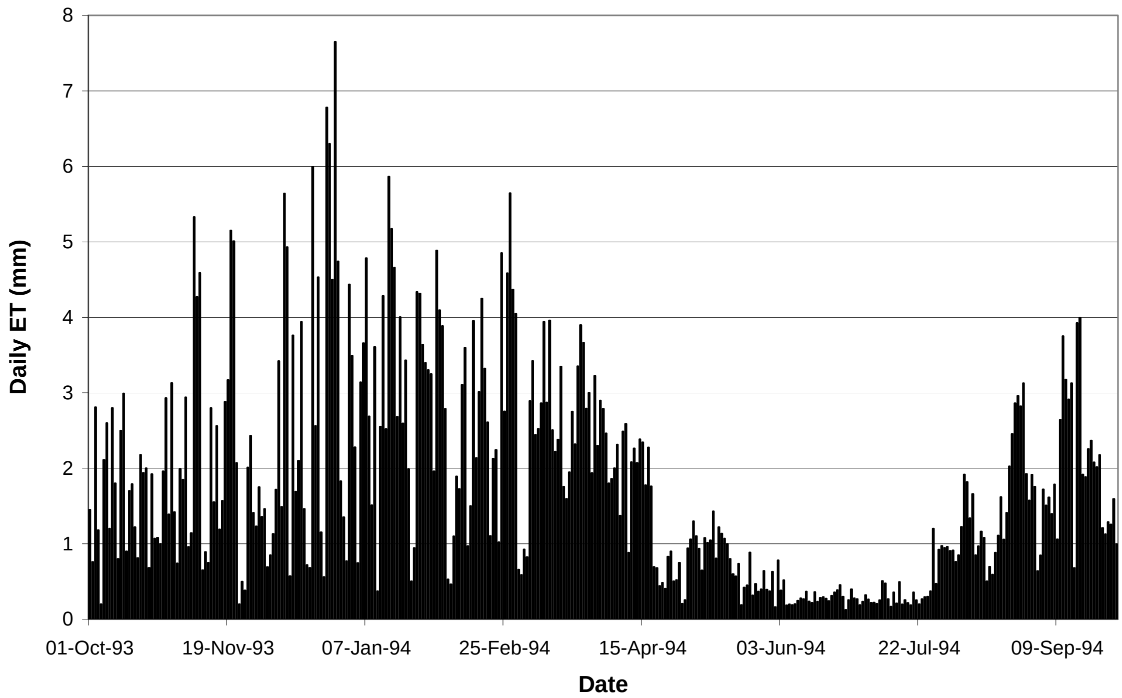


Figure 13. The annual pattern of daily ET recorded for montane grassland for the year 1993/1994 at catchment VI, Cathedral Peak.

WAVES was set up to simulate grass growth and water use over the period 1 October 1993 to 30 September 1994. Daily rainfall and temperature data were obtained from the weather station at the Cathedral Peak Forestry Office (0299419-W). The altitude of this station is 1879 m.a.m.s.l. Vegetation parameter values are shown in Appendix 1. The site was assigned an arbitrary slope of 30% and an aspect of 270^{o}. The soil texture was considered to be a clay loam to a depth of 0.3 m, thereafter changing to a clay to the limit of the soil profile at 2 m. Free gravity drainage of excess soil water was specified below the rooting zone. Initial root carbon mass per node depth was assumed to be the same as shown in Table 5. Springtime translocation of carbon from roots to leaves was activated when the 10-day moving average of minimum temperature exceeded 10

^{o}C, and ceased when the shoot carbon content reached a value of 0.01 kg C m^{-2}. Frost killed all green leaves when daily minimum temperature dropped below 1 ^{O}C. This makes allowance for the fact that minimum temperatures are recorded at approximately 1.5 m above the soil, where minimum temperatures are generally slightly warmer than at ground level. An annual burn was simulated in July to remove all shoot and litter biomass. No grazing was simulated.

A comparison of modelled to measured cumulative ET for the entire year is shown in Figure 14. Correspondence is excellent over most of the growing season, but modelled ET exceeds measured ET at the end of the growing season. This possibly reflects the inability of WAVES to increase the rate of leaf mortality at this time when leaf senescence occurs.

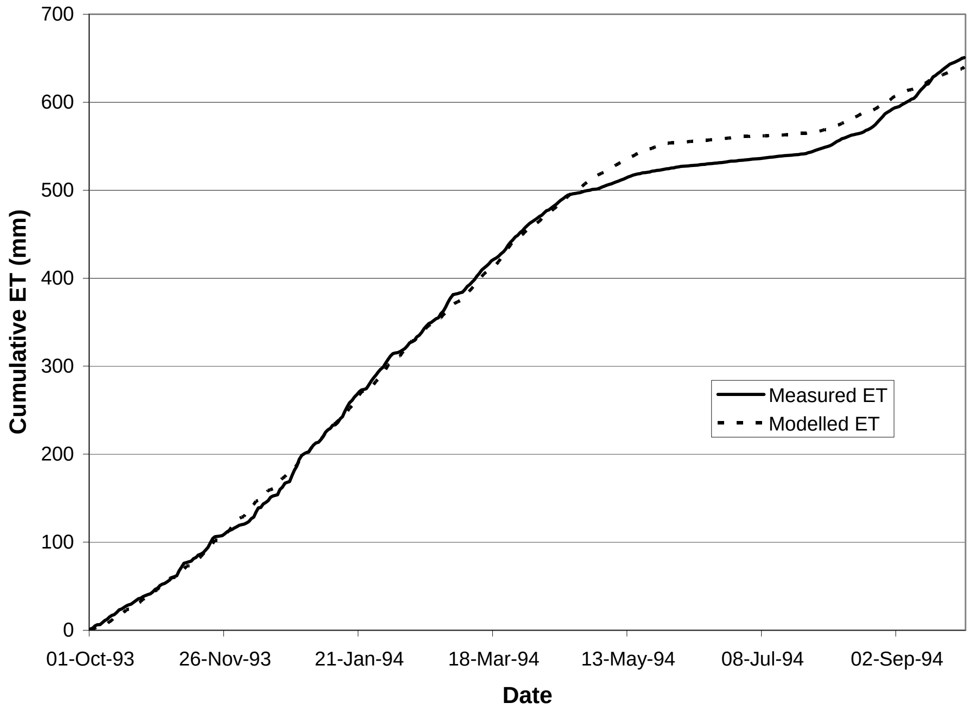


Figure 14. A comparison of modelled versus measured cumulative ET from Cathedral Peak montane grassland over the period from 1 October 1993 to 30 September 1994.

6.4.3 C_3 perennial grasslands

Tainton (1999) has described how fire is widely used as a management tool in the Western and Southern Cape to create an herbaceous plant community of moderate grazing value. The grass component of this plant community consists mostly of both exotic and indigenous winter-green temperate and sub-tropical C_3 species, which experience very different growth conditions to grasslands in the summer rainfall regions. Rainfall in the southern Cape coastal belt, for example, occurs in all seasons of the year. Air humidity is relatively high throughout, and temperatures are moderate. Consequently these grasslands do not exhibit pronounced seasonal dormancy. In view of these differences, it was believed to be useful to simulate ET from such grasslands. The recent concern over the establishment of numerous golf estates in the Cape coastal regions, and their influence on local water resources, provided added reasons for investigating this type of grassland.

WAVES was set up to simulate ET from dryland C_3 grass over a four year period from 1 August 1985 to 31 July 1989. Daily rainfall and temperature data were obtained from the weather station at George (0028838-W). Vegetation parameter values are shown in Appendix 1. The site was assigned an arbitrary slope of 10% and an aspect of 180^{o} from north. The soil texture was considered to be a sandy loam throughout the rooting zone to a depth of 0.9 m. These soil characteristics are common in this region, according to data from ISCW summarised by Schulze (1997). Free gravity drainage of excess soil water was specified below the rooting zone. A burn was simulated in January 1987. Additional physiological parameters were mostly sourced from the C_3 perennial pasture parameter values listed in the WAVES V3.5 user manual. The pattern of modelled daily ET is shown in Figure 15.

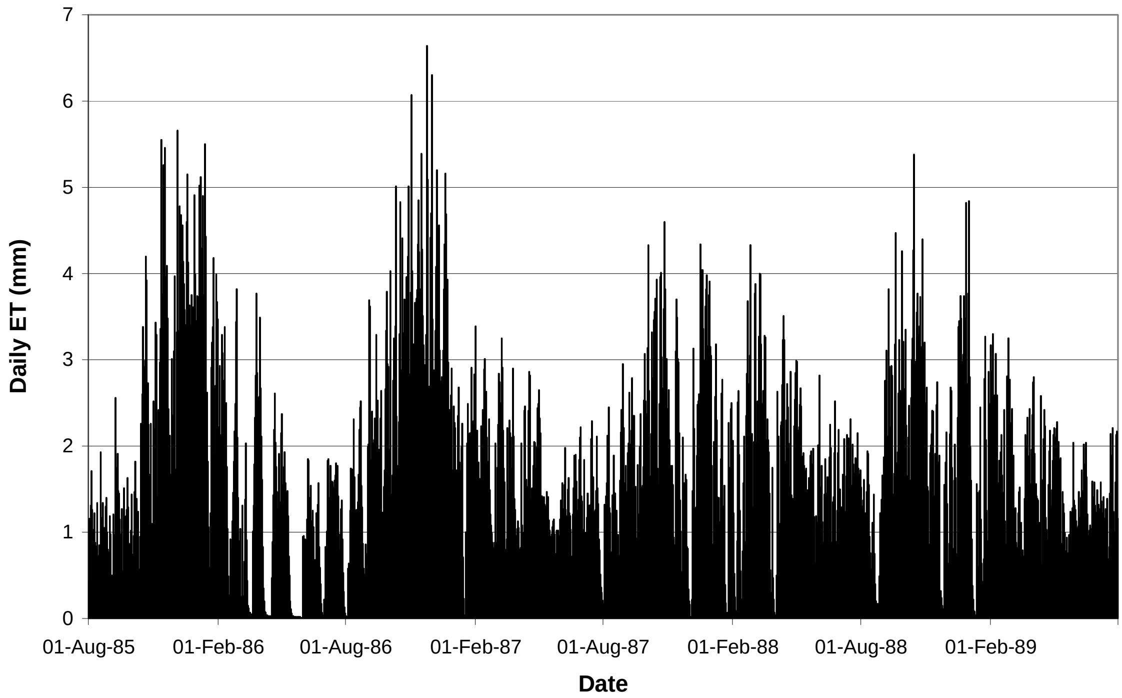


Figure 15. The pattern of daily ET for a C_3 grassland simulated at George for the period 1985 to 1989.

Peak LAI occurred in the second year after a burn (3.02 in year 2; 2.67 in year 4). Seasonal growth patterns appear to be more variable than in the previously described summer-rainfall grasslands, with frequent periods of reduced ET due to extended periods of dry weather. Simulated annual ET for the four years was estimated to be 612, 719, 661 and 614 mm, respectively, averaging 652 mm. There are unfortunately no field measurements of ET for grassland in the George area against which these ET estimates can be compared. However, a relation between mean annual ET and MAP for a global selection of hydrological catchments reported by Zhang et al. (1999a) predicts that an annual ET of 590 mm may be expected from a grassland site with an MAP of 880 mm. The mean ET predicted by WAVES is reasonably close to this figure.

6.5 Savanna biome

Savanna is a major biome covering 426216 km^2 or 33.6 % of South Africa (Low and Rebelo, 1998). The example site selected for simulation represents one of the higher rainfall forms of savanna. Nylsvley falls within the Mixed Bushveld category, which covers 66647 km^2 or 5.25 % of the total area of South Africa.

6.5.1 *Burkea africana – Eragrostis pallens* (Nylsvley)

A great deal of useful information on the *Burkea africana/Eragrostis pallens* ecosystem at the Nyslvley Nature Reserve is reported by Scholes and Walker (1993). The area is situated at 24^0 39$^/$ S and 28^0 42$^/$ E. The geology is described as Waterberg Sandstone, and gives rise to gentle slopes with the occasional rocky outcrops. Soils are generally sandy in texture, average 1 m in depth, and are relatively nutrient poor. Typical soil profiles are described in Table 6.

Table 6. Soil characteristics associated with three major horizons comprising a typical soil profile.

Depth	0-250 mm	250-570 mm	570-920 mm
Coarse sand (%)	16.9	16.6	10.1
Medium sand (%)	37.6	40.3	40.4
Fine sand (%)	28.7	25.6	29.5
Silt (%)	10.5	10.1	12.7
Clay (%)	4.5	12.4	10.2
BD (g cm^{-3})	1.6	1.6	1.6
Texture	Loamy sand	Loamy sand	Loamy sand
Porosity	0.471	0.397	0.397
Residual water content	0.008	0.008	0.008
K_{sat} (10^{-6} m s^{-1})	12.38	12.87	12.87

Mean annual rainfall recorded over 56 years is 623 mm. Infiltration rates into the surface soil horizons are high, producing virtually no surface runoff. Profile storage capacity averages 120 mm. Deep drainage from the profile is estimated to be 6 mm or approximately 1% of mean annual rainfall, but is zero in most years. Evapotranspiration in this broad-leafed savanna is estimated by Moore (1980) to vary from 1.6 to 5.3 mm per day during periods when soil water availability to plants is high. Canopy interception of rainfall has been quantitatively described by De Villiers (1977, 1981). However, a useful rule of thumb is that a fixed loss of 2 mm per rainfall event can be assumed, regardless of event size. Interception loss by the trees is estimated as ~ 35 mm per annum, amounting to 6% of mean annual rainfall. Rainfall interception by grasses amounts to about 1 mm per storm, and 1-2 mm from the litter layer. On an annual basis, the average annual loss is estimated to be 24 mm from grass and 50 mm from litter, totalling 109 mm or 18.5% of mean annual rainfall.

Pendle (1982) investigated soil evaporation with microlysimeters, and showed that evaporation occurred from the top 200 mm of soil. This loss accounted for about half of the total water loss from this savanna.

Regarding the annual energy balance at this site, extraterrestrial radiation at the latitude of Nylsvley is 11915 MJ m^{-2}. However, 39% is absorbed by the atmosphere, leaving 7316 MJ m^{-2} of incoming radiation to reach the plant canopies (Harrison, 1984). About 12.5% of this is reflected by the plant canopies and the soil surface (albedo), leaving 6401 MJ m^{-2} intercepted by leaves. Of this intercepted radiation, 4132 MJ m^{-2} is net radiation.

Peak total leaf area index approaches 1.2 at the height of the growing season, in January. Tree LAI peaks at approximately 0.7, while grass LAI peaks at approximately 0.5. Tree LAI remains close to the maximum value over most of the growing season (from November to May), whereas the grassland peak LAI is maintained for a relatively short period centred on January. The tree species are deciduous, and the leaves fall in response to drying soil, or to severe frosts. Leafing out in spring is in response to rising temperatures. The rates of water use by trees and grasses are approximately proportional to their leaf areas, since transpiration rates per unit leaf area are quite similar.

Specific leaf area (m^2 / kg dry matter) has been reported for various species at Nylsvley, and is shown in Table 7.

Table 7. The specific leaf area and fraction of total leaf area reported for dominant species at Nylsvley

	Fraction of total LA of woody or herbaceous stratum (%)	**m^2 kg^{-1} dry matter**
Burkea africana	36.5	7.1
Ochna pulcra	29.0	7.8
Terminalia sericea	12.5	6.1
Eragrostis pallens	70	3.8

WAVES requires a specific leaf area expressed as m^2 per kg carbon. The carbon content of various plant components has been reported for Nylsvley vegetation, and is summarised in Table 8.

Table 8. The percentage carbon content of various plant components of woody plants and grasses at Nylsvley. Data from Nelson and Sommers (1975).

	Carbon content (%)	
Plant part	**Minimum**	**Maximum**
Woody plants		
Stem wood	45.01	46.96
Current twigs	42.73	44.73
Coarse roots	42.69	42.69
Fine roots	40.00	40.08
Flowers	40.00	40.00
Fruit and seeds	40.00	45.26
Live leaves	45.78	45.90
Leaf litter	42.00	44.49
Grasses		
Live leaf	43.4	45.15
Standing dead	40.23	40.80
Fine roots	27.20	44.83
Crown	40.21	41.75

Information on the distribution of roots with depth has been reported by Knoop and Walker (1984). This study confirms that both tree and grass roots extend to a depth of 1 m and exploit the same soil volume, but that root lengths per unit volume of soil are much lower for tree roots than for the grasses. Tree roots were found to extend laterally up to seven times the canopy radius, and effectively sampled the entire soil volume. The overall root mass assumed at the start of the simulation (Table 9) was calculated from data pertaining to the global trend in root mass reported for tropical grasslands/savannas (Jackson et al., 1996).

Table 9. Estimation of root carbon mass (kg m^{-2}) at each node depth in the soil profile.

Depth (m)	Cumulative fraction of maximum depth	Cumulative fraction of total root mass (Jackson et al., 1996)	Cumulative root dry mass (kg m^{-2})	Cumulative root carbon (kg m^{-2})	Difference (kg C) in each horizon
0	0	0	0	0	0
0.001	0.001	0.003	0.004	0.002	0.002
0.002	0.002	0.006	0.008	0.004	0.002
0.005	0.004	0.014	0.020	0.009	0.005
0.01	0.008	0.028	0.039	0.018	0.009
0.02	0.017	0.055	0.077	0.035	0.017
0.05	0.042	0.132	0.185	0.083	0.049
0.1	0.083	0.247	0.346	0.156	0.072
0.2	0.167	0.433	0.607	0.273	0.117
0.3	0.250	0.573	1.803	0.361	0.088
0.4	0.333	0.679	0.950	0.428	0.066
0.5	0.417	0.758	1.062	0.478	0.050
0.6	0.500	0.818	1.145	0.515	0.038
0.7	0.583	0.863	1.208	0.544	0.028
0.8	0.667	0.897	1.256	0.565	0.021
0.9	0.750	0.922	1.291	0.581	0.016
1	0.833	0.942	1.318	0.593	0.012
1.2	1.000	0.967	1.354	0.609	0.016

One assumption behind the WAVES model is that the canopies of both overstorey and understorey components are uniform both vertically and horizontally. While this may be a reasonable assumption for the understorey grass layer, it does not hold for the tree overstorey. The extent to which this affects model realism is unknown at this stage, but needs to be borne in mind for future detailed investigation.

A simulation was set up for an arbitrary four-year period extending from 1 August (day 213) 1985 until 31 July (day 212) 1989. In view of marked differences in annual rainfall in such semi-arid environments, it was considered important to evaluate model output over more than one year. Daily rainfall and temperature data were sourced from the Nyslvley weather station (0590370-W). The soil texture was specified as loamy sand, extending down to the maximum rooting depth of 1.2 m. Burning was simulated annually on day 182 of each year. The translocation option was activated for both the overstorey and understorey canopies, to initiate growth in early spring. Specific leaf areas of understorey (24) and overstorey (12) plants are similar to values reported on a dry mass basis in Table 7. Carbon allocation coefficients and maximum assimilation rates were adjusted to return realistic seasonal patterns of above- and below-ground standing biomass and litter. Table 10 demonstrates the degree of similarity between model output and the hydrological information reviewed above.

Table 10. Correspondence between measured and simulated hydrological and structural properties pertaining to the Nylsvley savanna site.

	Reported	Simulated				
		85/86	86/87	87/88	88/89	Mean
Rainfall (mm yr^{-1})	623	419	766	809	598	648
Surface runoff (mm yr^{-1})	0	0	0	0	0	0
Rainfall interception by trees (mm yr^{-1})	35	36.8	12.2	29.6	27.5	26.5
Rainfall interception by grass (mm yr^{-1})	24	21.9	27.6	41.9	42.3	33.4
Maximum ET (mm day^{-1})	5.3	5.73	4.57	5.47	5.47	5.3
Soil evaporation loss (mm yr^{-1}) as a fraction of ET	0.50	0.43	0.65	0.49	0.45	0.51
Total ET (mm yr^{-1})		406	423	545	503	469
Peak LAI (trees and grass)	1.2	1.28	0.69	1.23	1.10	1.08
Trees	0.7	0.94	0.30	0.65	0.54	0.61
Grass	0.5	0.34	0.39	0.58	0.56	0.47

The patterns of daily rainfall and total daily ET simulated by WAVES are shown in Figure 16.

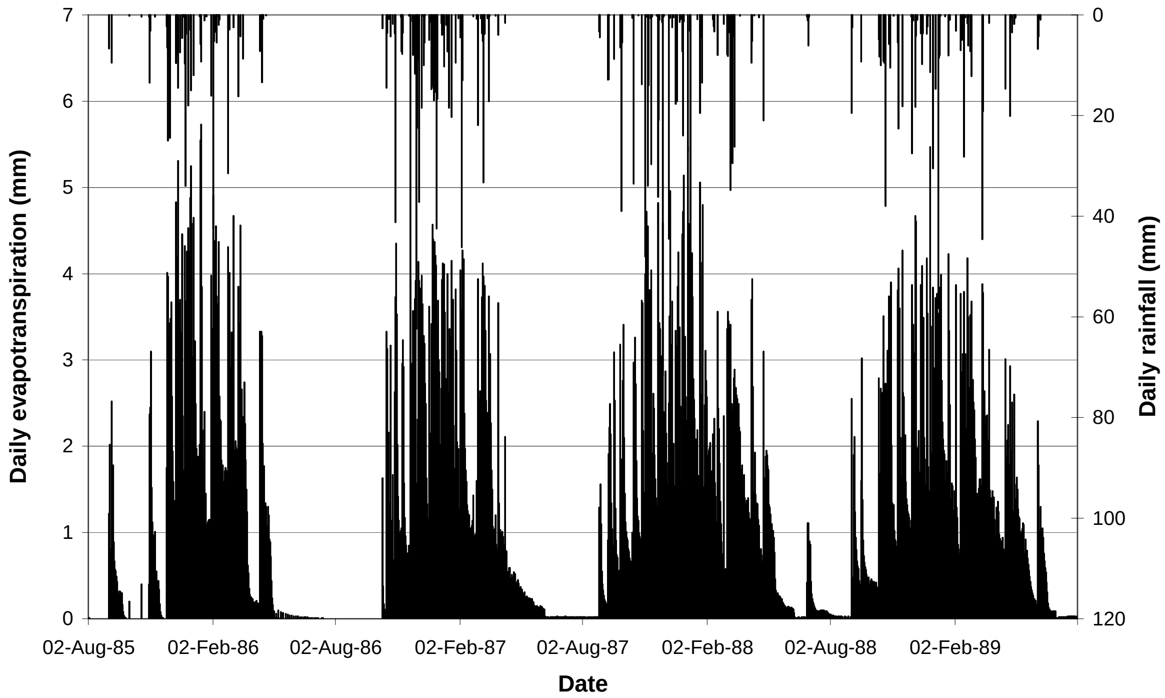


Figure 16. The pattern of daily evapotranspiration (lower bars) and daily rainfall (upper bars) simulated for savanna vegetation at Nylsvley.

6.6 Thicket biome

Subtropical thicket is described by Low and Rebelo (1998) as vegetation ranging from a closed shrubland to low forest. The Valley Thicket vegetation covers a total area of 22616 km^2, or 1.78 % of the total area of South Africa, and is represented by the Noodsberg site.

6.6.1 Valley thicket (Noodsberg)

Jarmain et al. (2004) describe a study of ET from a 0.25 km^2 patch of Valley Thicket vegetation located on a private farm near Noodsberg (29° 19’ S; 30° 49’ E). The altitude of the site is 838 m.a.m.s.l., and the mean annual precipitation is 843 mm. The soil is classified as of the Cartref soil form, and is characterised by a high sand fraction. The fractions of sand, silt and clay at four depths in the profile are illustrated in Table 11.

Table 11. The percentage of sand, silt and clay at four depths in the soil profile at the Noodsberg site.

Depth (mm)	% sand	% silt	% clay
Surface	87.5	8.5	4.0
500	87.5	9.9	2.3
2000	76.6	13.0	10.4
3000	68.9	15.2	15.9

Analysis of aerial photographs of the site revealed that approximately 62 % of the area was covered by tree clumps, and 38 % by open grass. *Acacia sieberiana* was the dominant tree species.

ET was recorded with a Bowen Ratio system from 25 May 2002 to 11 March 2003. Measured days were intermittent for the most part, due to frequent instrument problems, as well as periods where 20-minute data were rejected due to small or reversed gradients in temperature and vapour pressure deficit.

The simulation period was determined by the availability of weather and evaporation data. A one year period was chosen, ranging from 18 June 2002 to 17 June 2003. Much of the necessary weather data were recorded on site by instruments comprising an automatic weather station. Gaps also exist in this data set due to instrument malfunctions and battery problems. These gaps were patched with data from a weather station maintained by SASSEX in the Wartburg district.

Soil depth was defined to be 3-m deep, consisting of sand in the upper 900 mm, and underlain by a sandy clay loam. A 3-m soil pit revealed no signs of mottling or saturated soil water in any part of the profile. The vegetation parameters employed at this site were similar to those used for the Nylsvley savanna site. Spring translocation was activated for both the overstorey and understorey canopy layers. A fire was simulated on DOY 182 (1 July).

Simulated daily ET is shown in Figure 17, with observed daily ET superimposed as points, and daily rainfall shown along the X2 axis. It is evident that measured daily ET is generally higher than simulated daily ET. It was found to be impossible to match the high daily ET without simulating an extra source of water. Examination of the 3-m soil pit at the site revealed no evidence of groundwater or even seasonal accumulation of water at this depth. Lateral movement of soil water from upslope areas is also believed to be unlikely, in view of the position of the site in the catchment, and the absence of any signs in the profile of saturated soil conditions. It is therefore unlikely that ET at this site can exceed net rainfall. The WAVES-generated site water balance is summarised in Table 12. Total ET (668 mm) comprises most of the gross rainfall (710 mm) recorded at the site, since losses from the soil due to overland flow, deep drainage or lateral flux of soil water are negligibly low.

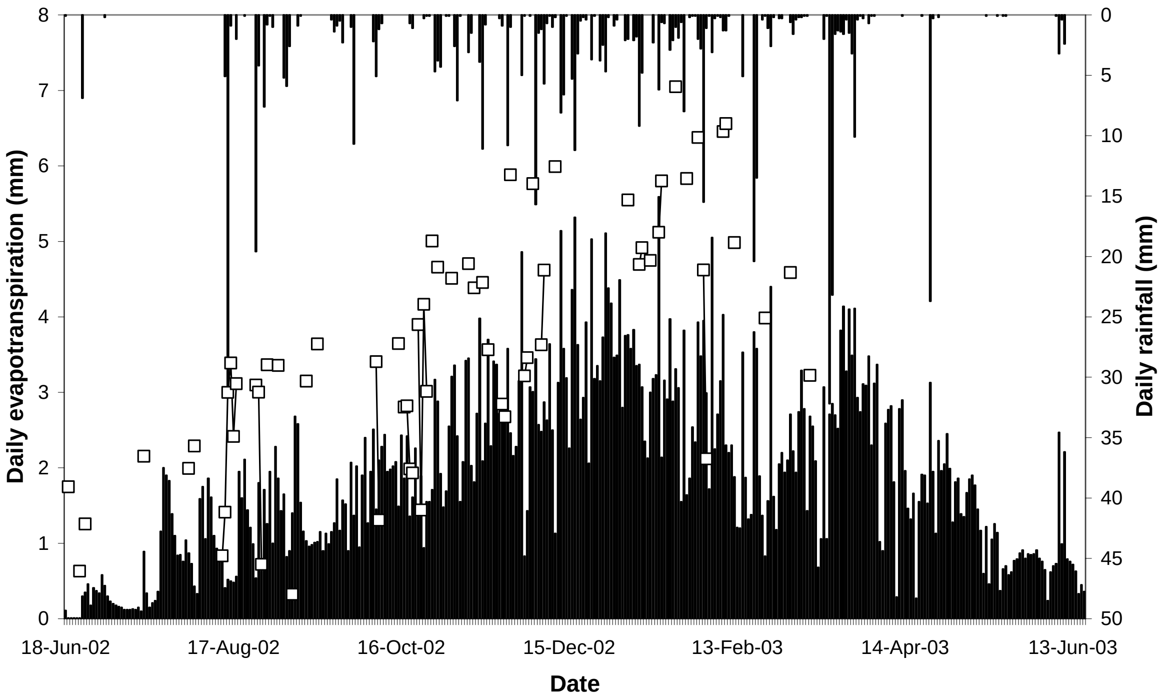


Figure 17. A comparison of modelled (bars) and measured (□) daily evapotranspiration at the Noodsberg Valley Thicket site. Daily rainfall is referenced to the X2 axis.

Table 12. The site water balance calculated by WAVES for the Noodsberg Valley Thicket site

Water balance component	mm	% of gross rainfall
Gross rainfall	710	100
Overstorey rainfall interception	30	4.2
Understorey rainfall interception	51	7.2
Total rainfall interception	81	11.4
Throughfall	629	88.6
Soil evaporation	147	20.7
Overstorey transpiration	248	34.9
Understorey transpiration	192	27.0
Total transpiration	440	61.9
Total evapotranspiration	668	94.1
Lateral flux	0	0
Overland flow	0	0
Change in soil water storage	42	5.9

Jarmain et al. (2004) experienced similar problems in modelling ET at this site using the ACRU, SWAT and SWAP models. All three models underestimated ET at this site. Possible reasons for these discrepancies were listed by Jarmain et al. (2004) as follows:

- The structurally complex vegetation was insufficiently described by the relatively simple vegetation parameters required by the three models.
- Effects of scale differences between field measurements and modelled sub-catchments.
- Discontinuous measured ET data sets.

However, the fact that the more physiologically-explicit, two-canopy WAVES model also underestimated measured ET suggests that model simplicity may not be the problem. Likewise, the one-dimensional WAVES model provides a detailed description of a relatively small site, and so the difference in scale between the site measurements and the WAVES simulation is not significant. The problem of discontinuous measured data could become important, especially if the Bowen Ratio measurements of ET were biased in favour of particular weather conditions, such as warm dry days.

Soil water storage effects could potentially account for some of the discrepancy. The site was modelled for just a 12 month period, and an assumption had to be made concerning the initial soil water available in the rooting zone at the start of the simulation. This was assumed to be low, in view of the dry season start, and the absence of any sign of saturated conditions at the bottom of the 3 m soil profile. Underestimated initial soil water is therefore not considered to be an important source of error.

In view of all these considerations, it is unclear whether the discrepancy between measured and modelled ET at this site is due to unrealistic parameter values, or whether the Bowen Ratio measurements of ET failed to adequately represent the ET from the structurally complex tree/grass thicket vegetation at this site. A current WRC project (K5/1567) is aimed at evaluating methodologies for evaporation measurements, and this may provide a comparison of Bowen Ratio and scintillometer estimates of evaporation from thicket/savanna vegetation.

6.7 Forest biome

Afromontane forests are the largest category of indigenous forest in South Africa, and cover an area of 5964 km^2 or 0.47 of the total area of the country (Low and Rebelo, 1998). They occur in areas of relatively high rainfall (greater than 525 mm MAP in the winter rainfall region, and higher than 725 in the summer rainfall region; Rutherford and Westfall, 1994). These forests are viewed by many as highly valuable ecosystems, owing to their rarity, beauty, species richness and valuable timber and non-timber resources, and have great tourism potential. Because they are often found in areas that have seen large-scale establishment of forest plantations, their comparative influence on water resources has been much debated. Unfortunately, few relevant data have been available to clarify forest ET and their effect on catchment water yields. The data reported below for the Groenkop forest situated near to the town of George is the first direct measurement of large scale ET from indigenous forest in South Africa, and is part of an ongoing study of the water use and water use efficiency of indigenous trees in South Africa (WRC Project K5/1462).

6.7.1 *Podocarpus latifolius – Curtisia dentata – Burchellia bubalina* platform forests (Saasveld)

The Groenkop forest is situated a short distance east of the Saasveld campus of the Nelson Mandela Metropolitan University, which lies north-east of the town of George in the southern Cape. The forest is a good example of the southern Cape evergreen indigenous forests.

A variety of instrumentation (Eddy Covariance, Bowen Ratio, LAS scintillometer) was set up to record ET from a central location within the Groenkop forest. Figure 18 illustrates the position of the Eddy covariance and Bowen ratio instrumentation (circle) and the path length of the LAS system. The Saasveld campus is visible in the bottom left corner of the image. The circled site lies in a 40 ha block in the north-central portion of the forest that is reserved for research purposes, and many studies have been conducted there over the years (Geldenhuys, 1998).

Consequently, much is known of the species composition, population dynamics, litter fall rates, vertical microclimate gradients, rainfall interception, soil structure, and other relevant features of the forest. Many of these studies are described or referenced in the milestone report "Review of past research and implementation of alternative indigenous forest and woodland systems in South Africa" submitted to the WRC in January 2004 (Project K5/1462).

The forest is predominantly underlain by Table Mountain sandstone, which commonly includes bands of conglomerate and shale. According to Lübbe and Versfeld (1991), the underlying geology of the research site is pre-Cape Phyllite, Silver River formation, of the Kroonstad form. The area receives rainfall throughout the year, but most falls between September and April. Mean annual rainfall recorded at Saasveld is 860 mm (Geldenhuys, 1998). Strong dry and warm berg winds occasionally blow from the north-west during winter and may fan intense and destructive fires. The northern portion of the research block was affected by such a fire during 1996 (Geldenhuys, 1998).

Figure 18/…

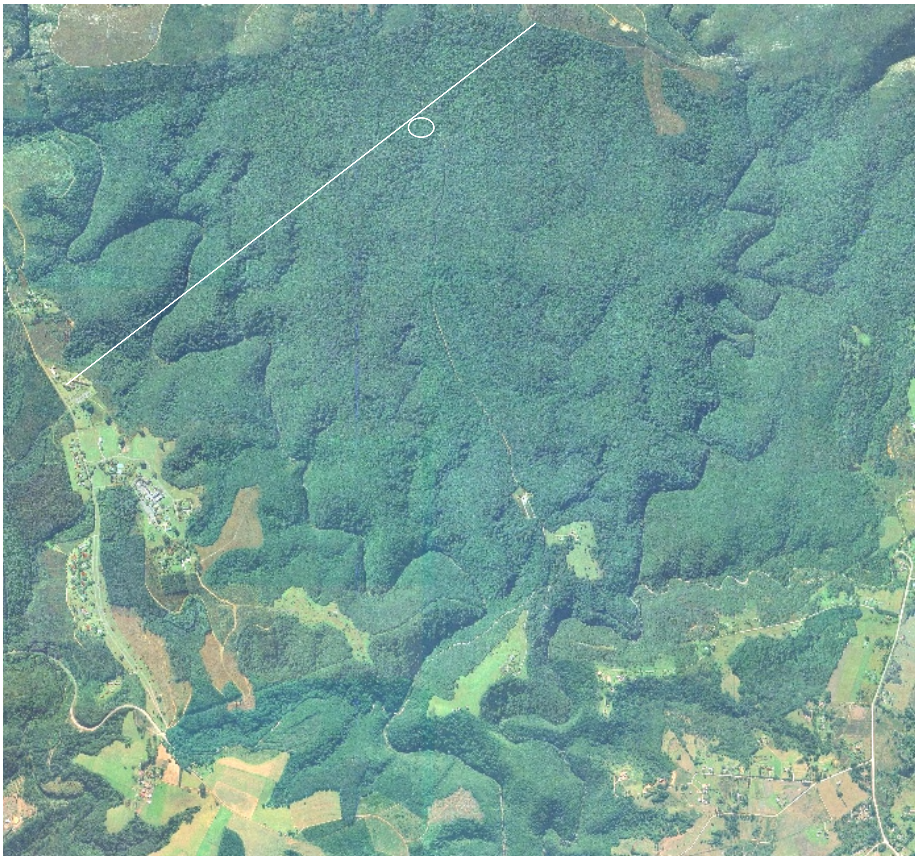


Figure 18. **Aerial photograph of the Groenkop indigenous forest, showing the Saasveld campus in the southwest quadrant. The superimposed line shows the path of the LAS beam (3.1 km), while the circle shows the position of the Eddy Covariance system.**

The forest appears to be approaching an ecological equilibrium, supporting a high standing biomass, and exhibiting a low mean annual volume increment (4 m^3 ha^{-1} y^{-1}; Geldenhuys, 2005). Species composition is relatively stable, and a closed, high canopy is formed by the dominant, mature trees. Mean canopy height is believed to be approximately 22 m. The distribution of stem size shows a strong skew, with many smaller sub-canopy trees dominated by relatively few larger canopy 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 forests. A total of 35 tree species have been recorded in the Groenkop forest study site. The overstorey canopy is seldom dense, and contains numerous gaps that allow sunlight to penetrate to the understorey vegetation. The leaf area index is believed by the authors to be roughly 2 for the overstorey, and 2 or more for the understorey.

Micrometeorological instrumentation was transported to the site on three occasions and set up to record sensible and latent heat over a period of approximately 7 to 10 days. Although the three techniques provided broadly comparable results, the evaporation estimates provided by the LAS system are believed to be the most reliable, since they are spatial averages over 3 km.

Results recorded by the LAS system over the three field campaigns are shown in Figures 19, 20 and 21.

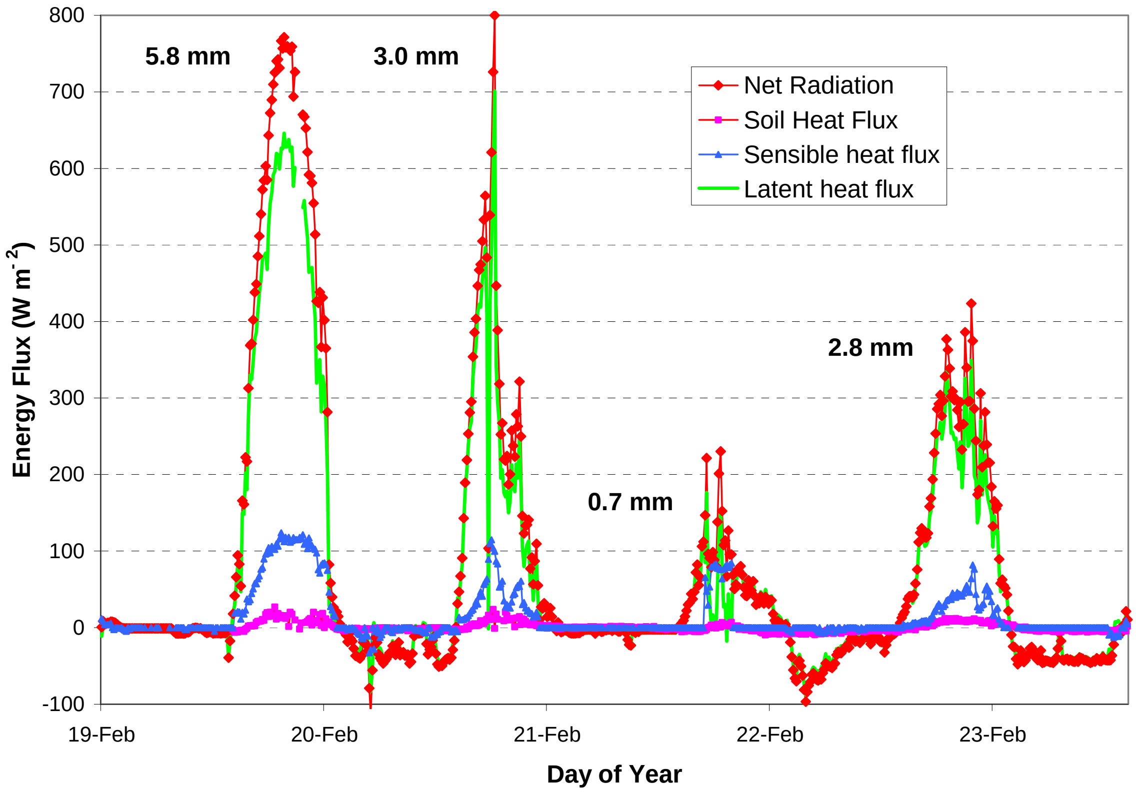


Figure 19. Energy balance components estimated with the LAS system for the Groenkop indigenous forest over the first field campaign (16 to 27 February 2004). Total daily ET is indicated on each day.

Cloudless weather occurred on day 51 (Figure 19), 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 5.8 mm. An approaching low-pressure front caused day 52 and day 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. A daily evaporation total of 5.8 mm is close to the maximum rate recorded in different plantation forests in South Africa and elsewhere (Dye et al., 1997; Dye et al., 2001; Campion et al., 2004).

Data collected during the second field campaign (Figure 20) showed two days of fine to partly cloudy berg wind weather 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.

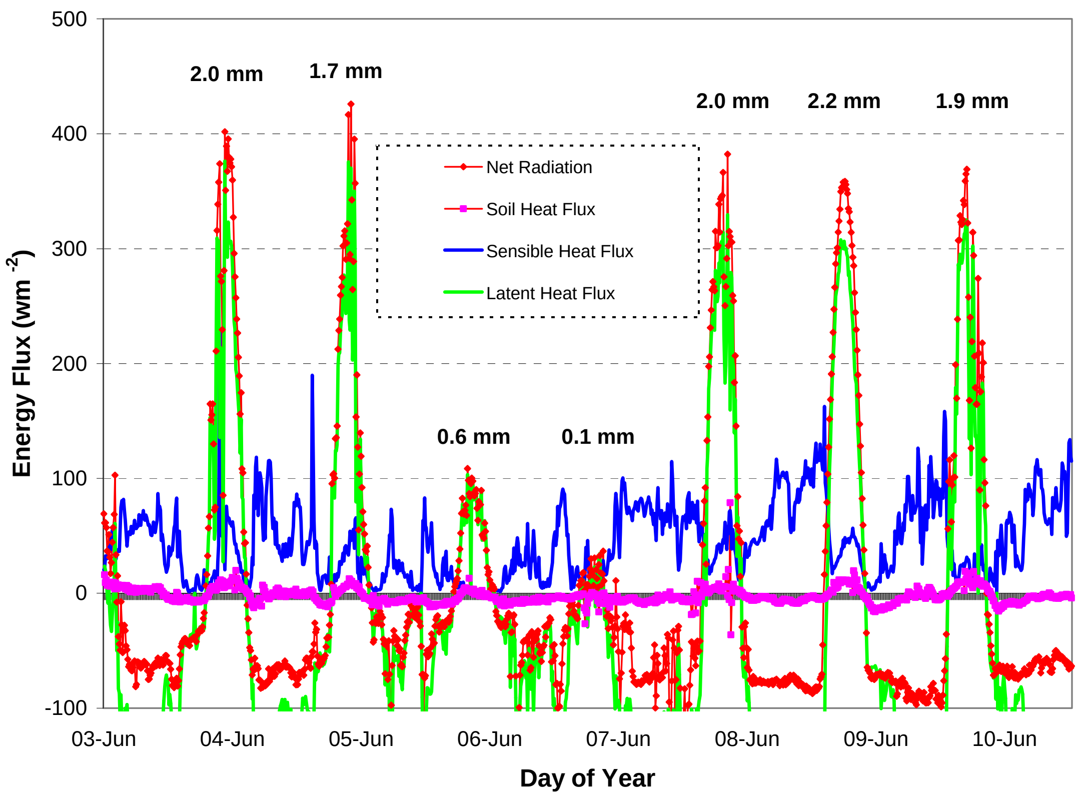


Figure 20. **Energy balance components estimated with the LAS system for the Groenkop indigenous forest over the second field campaign (31 May to 11 June 2004). Total daily ET is indicated on each day.**

Data collected during the third field campaign are shown in Figure 21.

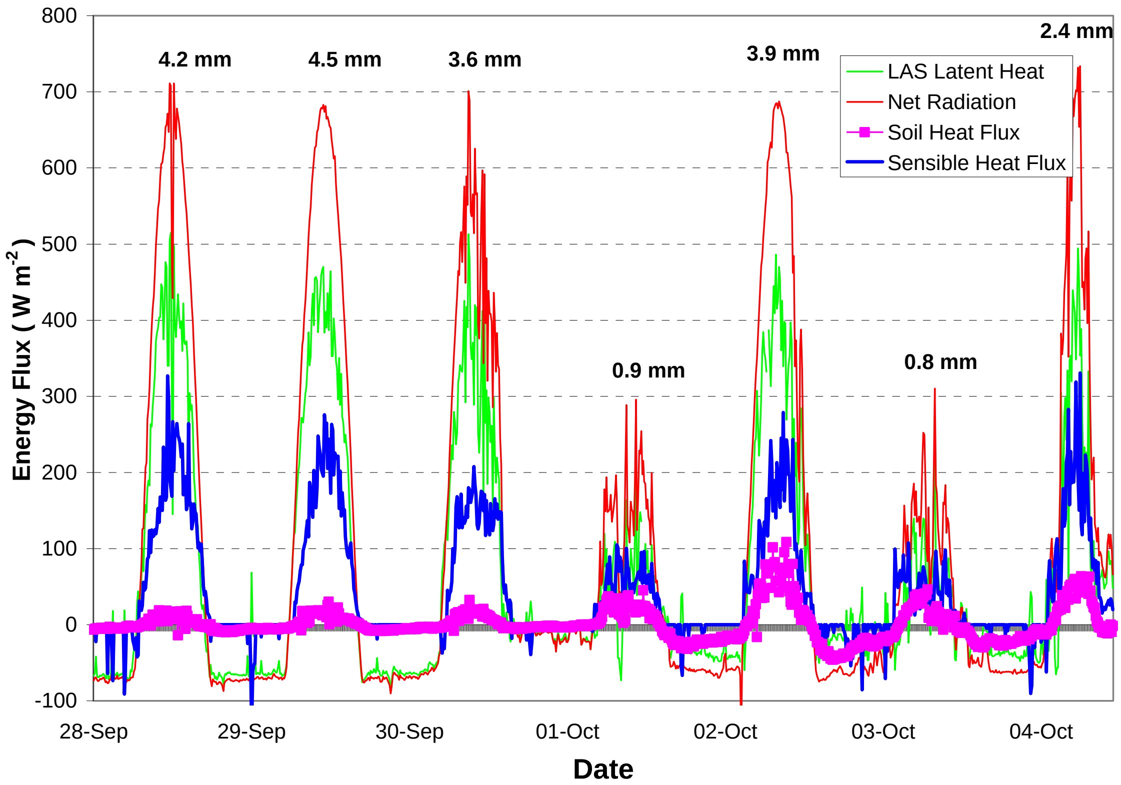


Figure 21. **Energy balance components estimated with the SAS system for the Groenkop indigenous forest over the third field campaign (25 September to 8 October 2004). Total daily ET is indicated on each day.**

Total daily ET recorded on each of the 18 sample days is shown in Figure 22. Weather conditions varied widely over these sample days, causing ET to vary from 0.1 to 5.8 mm day^{-1}.

The relation between daily solar radiation and total daily evapotranspiration (Figure 23) illustrates a reasonably close correlation. It is clear, however, that daily ET recorded during the summer months (February 2004) appears to be somewhat higher at a given daily solar radiation, than days of similar solar radiation recorded in June and September/October. Differences in temperature and soil water availability to the trees could be responsible for this seasonal effect. It may also arise from enhanced physiological activity in the leaves during the summer months. This phenomenon has been described before in *Eucalyptus grandis* (Dye, 1993) and may be linked to the occurrence of flushes of new leaves developing in the warmer months. A study of litter fall (comprising 80% leaves) in the Groenkop Forest Study Site showed peak litter fall occurs between November and February (Geldenhuys and Theron, 1994). This follows extensive production of new leaves in spring. It is possible, therefore, that the leaves during the summer months are generally younger and more physiologically active than the older leaves that predominate during the winter months.

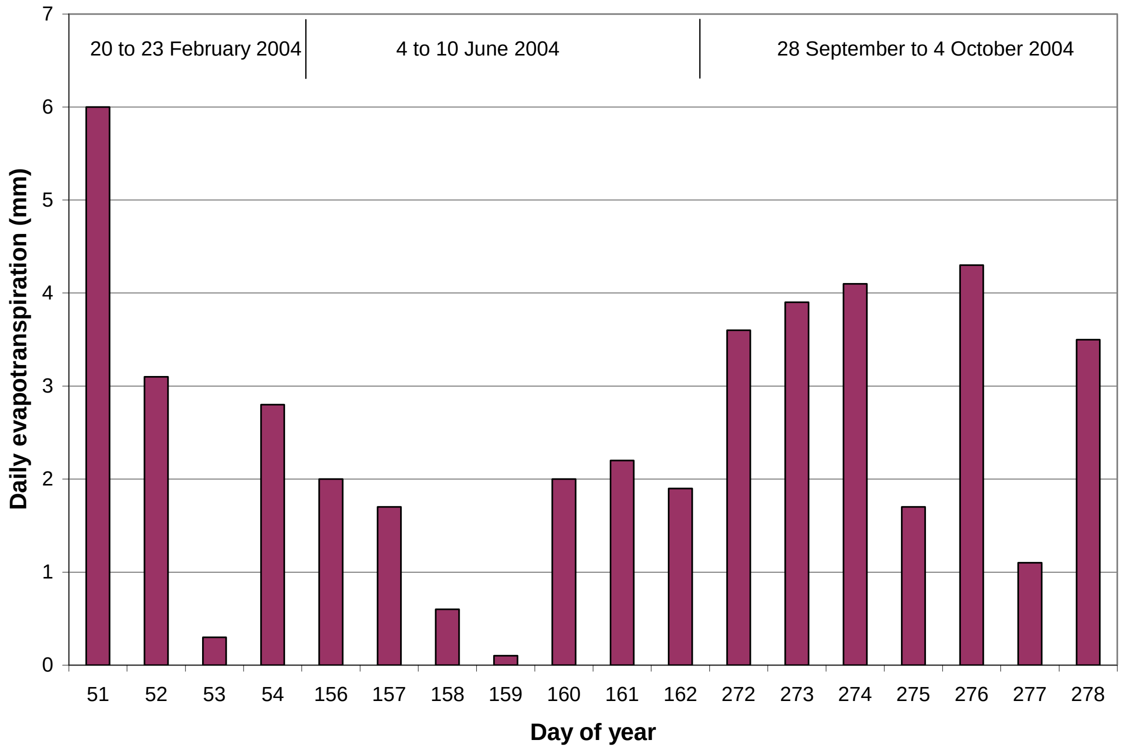


Figure 22. Daily evapotranspiration recorded in the Groenkop forest over three measurement periods during 2004.

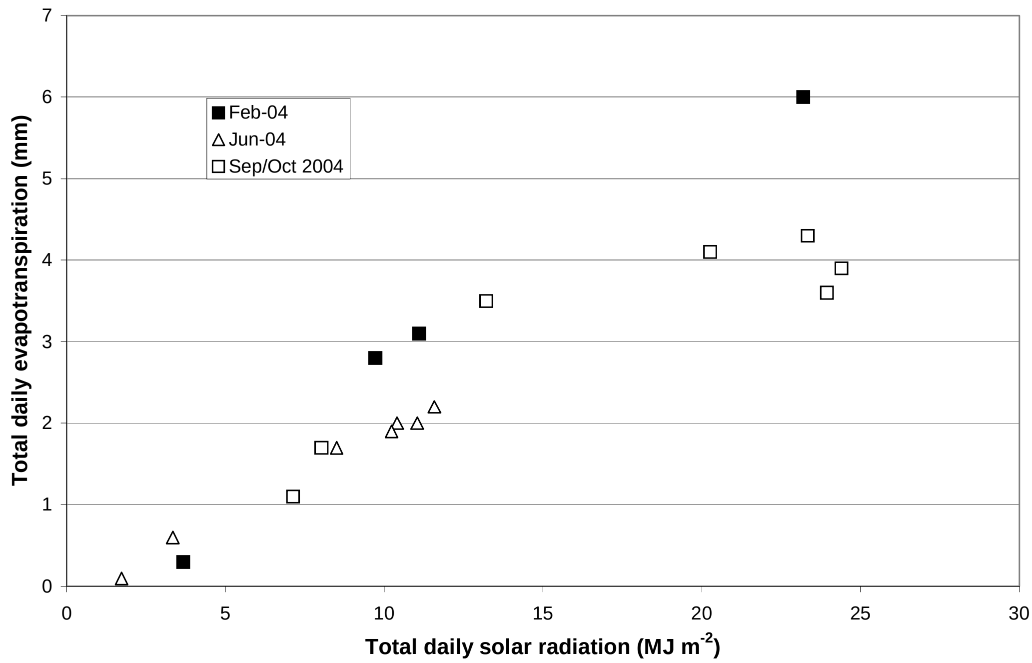


Figure 23. The relation between total daily solar radiation and total daily evapotranspiration recorded over three different times of the year in the Groenkop forest.

Both solar radiation and vapour pressure deficit are estimated by the WAVES model from daily maximum and minimum temperatures. Since the site was potentially affected by the maritime influence on temperature, as well as strong orographic effects against the Outeniqua Mountains, it was considered necessary to check these estimates against the available measured data recorded during the three field visits.

Daily weather data recorded at a weather station situated at George (0012661 7, George Wo) was obtained from the Weather Bureau for the period 1 January 2003 to 31 December 2004. Figure 24 shows the correlation between solar radiation measured at the Groenkop forest and WAVES-estimated daily solar radiation based on the George temperature data. This station is situated at a similar altitude (191 m) to the Groenkop forest. There is significant scatter on a daily basis (perhaps not unexpected in view of the high degree of cloud and topographical variation in this area), but the general trend is close to the 1:1 line, suggesting that temperature-based estimates of solar radiation would suffice for extended periods of modelling. Figure 25 illustrates the relation between observed and estimated VPD, the latter again based on daily temperature extremes recorded at the George weather station. Clearly estimation of VPD from daily temperature in this area is problematic. In view of this, daily VPD at the George station was calculated from the mean of daily measurements of relative humidity (RH) taken at 08h00 and 14h00. This involved calculating mean daily saturated vapour pressure (SVP) from mean daily temperature (the average of maximum and minimum temperatures). Vapour pressure (VP) was then calculated as SVP-(RH/100), and finally, VPD was estimated as SVP-VP. The WAVES climate file was altered to replace the temperature-based VPD with daily VPD based on the RH readings.

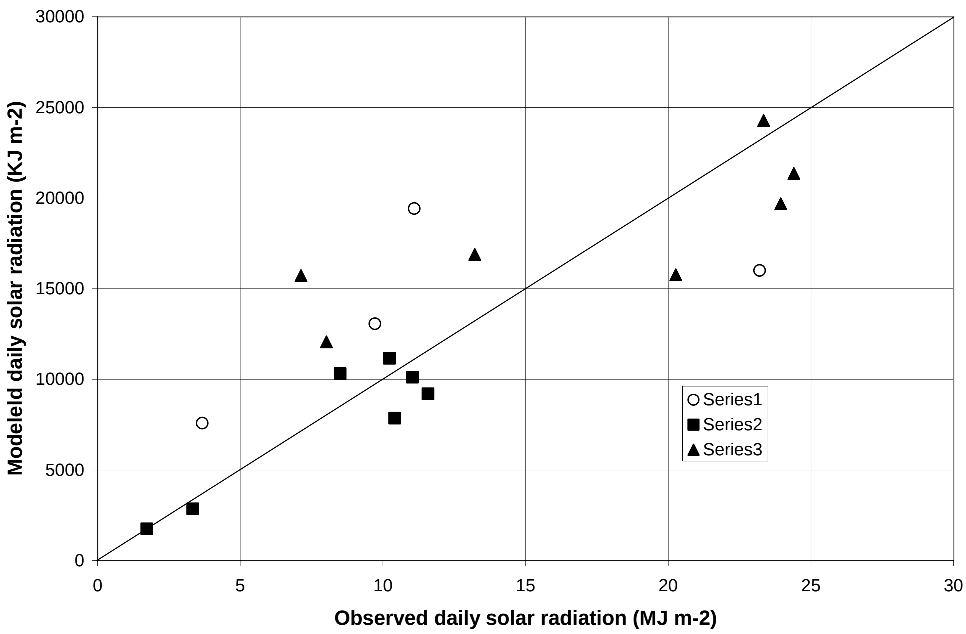


Figure 24. **A comparison of solar radiation measured over the three field campaigns (series 1, 2 and 3 represent the first, second and third field campaigns, respectively) at the Groenkop site, to modelled solar radiation calculated by WAVES on the basis of daily maximum and minimum temperatures recorded at the George weather station.**

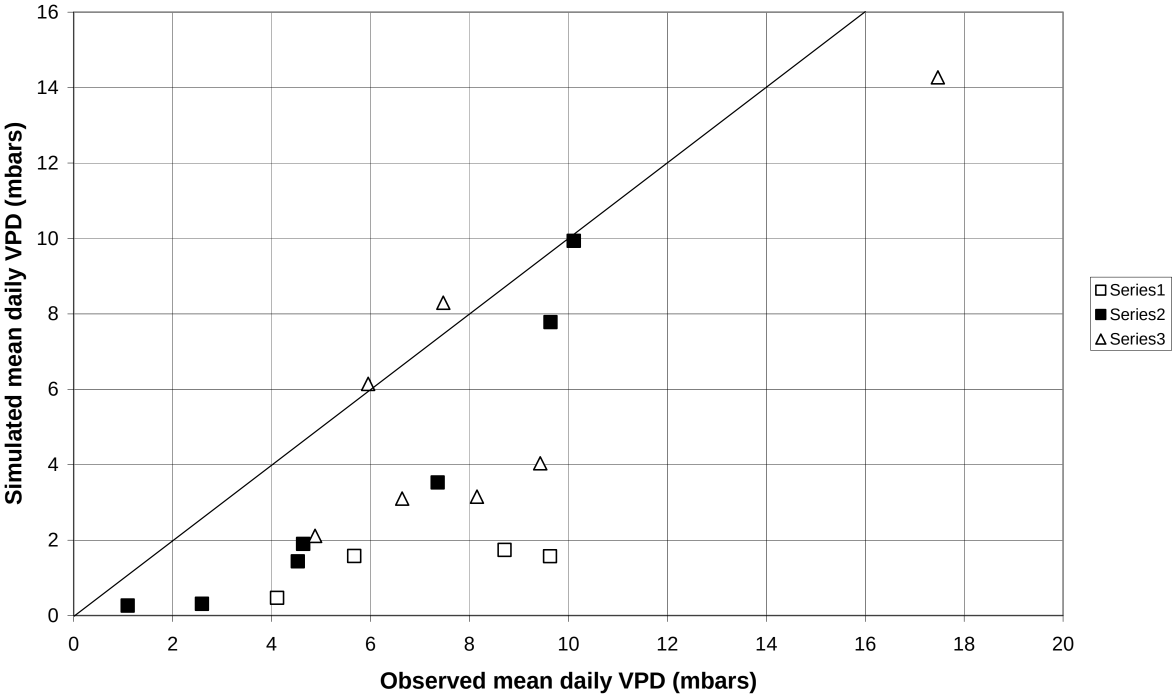


Figure 25. **A comparison of mean daily VPD measured over the three field campaigns (series 1, 2 and 3 represent the first, second and third field campaigns, respectively) at the Groenkop site, to modelled VPD calculated by WAVES on the basis of daily maximum and minimum temperatures recorded at the George weather station.**

The WAVES model was set up as follows. 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) for each. 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 m^3 ha^{-1} y^{-1}).

- Leaf stomatal conductances recorded with a porometer on sample trees of *Podocarpus henkelli*, *Nuxia floribunda* and *Rapanea melanophloeos* were found to be low in comparison to exotic tree species such as *Eucalyptus grandis* and *Acacia melanoxylon* (Figure 26).

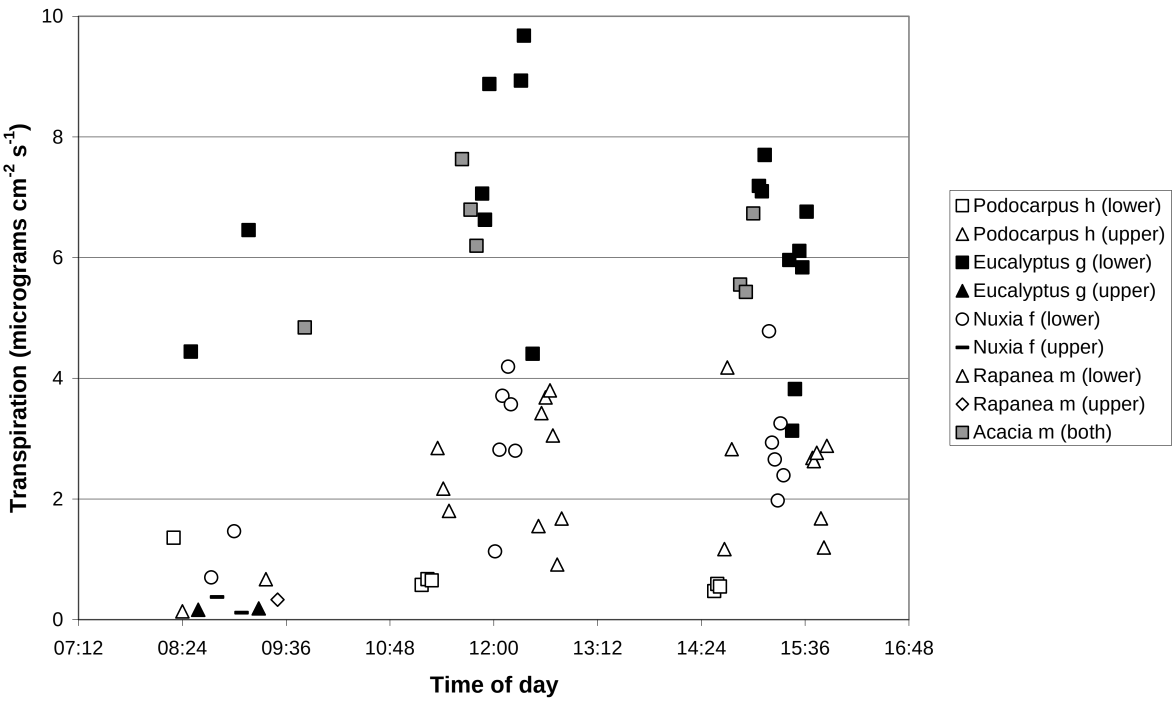


Figure 26. A comparison of leaf conductance rates recorded with a porometer for selected indigenous and exotic trees situated on the grounds of the Saasveld campus. Species measured were *Podocarpus henkelli*, *Eucalyptus grandis*, *Nuxia floribunda*, *Rapanea melanophloeos* and *Acacia melanoxylon*.

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 a 35-45 cm sandy loam topsoil which overlies a 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 to the upper level of the pronounced clay layer. 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. The additional water is believed to originate on 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.

The influence of fog drip in augmenting the store of soil water in the forest should also be borne in mind. 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. The treated site consisted of a 1 ft high wire mesh frame mounted above the raingauge which had four *Podocarpus latifolius* branches, each with approximately 30 leaves, inserted over it. The control gauge measured 1321 mm, while the treated site measured 2401 mm (an increase of 81.7%).

The bedrock below the subsoil is assumed to be impermeable. A slope of 20% and an aspect of 180^o were judged to be typical of the Groenkop forest along the scintillometer beam path. The distribution of initial root mass with soil depth is shown in Table 13. Observations of root systems reported by Kotze and Geldenhuys (1992) confirm a concentration of roots in the topsoil, and a maximum rooting depth varying from 700 mm to 1400 mm.

Table 13. Estimation of forest root carbon mass (kg m^{-2}) at each node depth in the soil profile.

Depth (m)	Cumulative fraction of maximum depth	Cumulative fraction of total root mass (Jackson et al, 1996)	Cumulative root dry mass (kg m^{-2})	Cumulative root carbon (kg m^{-2})	Difference (kg C) in each horizon
0.001	0.0005	0.004	0.019	0.009	0.009
0.002	0.001	0.008	0.038	0.017	0.008
0.005	0.0025	0.019	0.094	0.042	0.025
0.01	0.005	0.038	0.186	0.084	0.041
0.02	0.01	0.075	0.365	0.164	0.081
0.05	0.025	0.176	0.863	0.388	0.224
0.1	0.05	0.321	1.574	0.708	0.320
0.2	0.1	0.539	2.642	1.189	0.481
0.3	0.15	0.687	3.367	1.515	0.326
0.4	0.2	0.788	3.860	1.737	0.222
0.5	0.25	0.856	4.194	1.887	0.150
0.6	0.3	0.902	4.421	1.989	0.102
0.7	0.35	0.934	4.575	2.059	0.069
0.8	0.4	0.955	4.679	2.106	0.047
0.9	0.45	0.969	4.750	2.138	0.032
1	0.5	0.979	4.798	2.159	0.022
1.2	0.6	0.990	4.853	2.184	0.025

The remaining vegetation parameters (Appendix 1) were assigned values according to the best available data, and constrained within limits recommended in the WAVES manual. The resulting simulations for the two-year period showed a stable leaf area index of approximately two for both the overstorey and understorey canopies. The pattern of daily evapotranspiration and rainfall are shown in Figure 27.

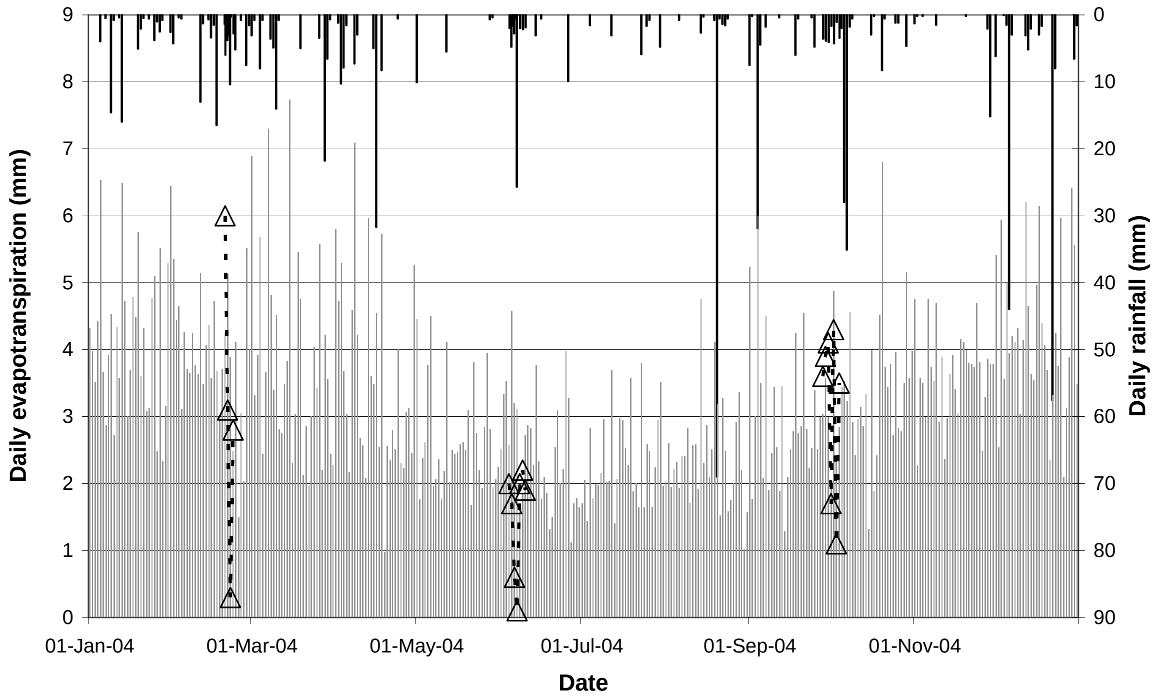


Figure 27. The pattern of daily evapotranspiration modelled for the year 2004. Measured daily ET during the three field campaigns is indicated with triangular symbols. Daily rainfall is also shown along the X2 axis.

Most observed data points fall within the range modelled by WAVES. However, one point in March and two points in June are particularly low. Rainfall was measured on all three days, and the modelled ET includes the rainfall interception component. WAVES deducts rainfall interception on the day of the rainfall, whereas in reality, leaves that become wet due to late afternoon or evening rainfall are likely to stay wet until a following day when evaporative conditions improve. Thus the rainfall interception component of daily ET may be lagged by a day or more. This may have a particularly pronounced effect on estimated daily ET, in view of the high LAI of the forest and high canopy storage capacity. Consequently, we believe that the daily range in modelled ET is of less significance than the longer-term trend.

Another potential problem relating to the accuracy of daily ET on rain days is that the scintillometer may record reductions in signal strength along the 3 km beam path when rain or fog reduce visibility, leading to over-estimates of ET at such times.

The summary soil water balance produced by WAVES for this simulation period is reproduced in Table 14.

Table 14. A summary of the Groenkop site water balance as simulated by WAVES over a two-year period. Transpiration and ET are not expressed as a % of gross rainfall due to the postulated additional groundwater use.

Water balance component	mm	% of gross rainfall
Gross rainfall	1575	100
Overstorey rainfall interception	211	13.4
Understorey rainfall interception	213	13.5
Total rainfall interception	424	26.9
Net rainfall	1151	73.1
Overland flow	83	5.3
Soil evaporation	59	3.7
Overstorey transpiration	1216	-
Understorey transpiration	652	-
Total transpiration	1868	-
Total evapotranspiration	2351	-
Additional groundwater used	776	-

According to Geldenhuys (1998), the estimated mean annual rainfall for the site is 850 mm. The total rainfall recorded over the two year simulation period is 1575 mm (828 mm in 2003, 747 mm in 2004), which is therefore only 125 mm short of the two year mean of 1700 mm. The rainfall interception loss due to both the overstorey and understorey canopies totals 424 mm, or 26.9% of gross rainfall. This is the same percentage as recorded by Lübbe and Versfeld (1991) in the Groenkop forest.

The results of this modelling work suggests that the annual ET of the Groenkop moist high forest is around 1175 mm per annum, and that, given the long-term average MAP of 850 mm, a further 325 mm per year is obtained from groundwater originating from upslope regions of the catchment. Additional groundwater would be required to feed the streams that arise in the area. The inference is that annual water use of moist high forest exceeds MAP, and that these forests will be limited to areas where additional groundwater is available. Significantly, von Breitenbach (1974) observes that moist high forest in the southern Cape is found on eastern and southern slopes, and on soils that remain moist throughout the year.

6.8 Fynbos biome

The dominant category of Fynbos in the relatively high rainfall areas of the western and southern Cape is Mountain Fynbos, which covers an area of 27 462 km^2 (Low and Rebelo, 1998). This vegetation is of immense conservation value in view of its species richness and attractiveness. Significant areas of this vegetation have been converted in the past to *Pinus radiata* forest plantation, and the consequences of this land cover conversion have been extensively investigated in hydrological research catchments (Scott et al., 2000). These studies have provided catchment average ET estimates, but little information is available on ET at smaller scales. The water use of Fynbos remains an important baseline against which the hydrological effects of alien invasive trees and plantation forestry need to be compared.

6.8.1 *Protea repens* and *P. nerrifolia* Fynbos (Helderberg)

The original aim of the Western Cape field component of this project was to find a single site, or similar sites close-by each other, where evaporation from Fynbos could be compared with evaporation from stands of invasive *Hakea* and *Acacia* species. Suitable invaded areas were found on the Vergelegen Farm to the east of Somerset West but no suitable Fynbos stands could be found either on this farm or on the adjacent farms (Knorhoek and Lourensford). The nearest location with a suitable stand of mature, *Protea*-dominated Fynbos proved to be in the Helderberg Nature Reserve that is situated on the southwest facing slopes of Helderberg, north of Somerset West. The vegetation at this site is younger but otherwise very similar to the proteoid Fynbos described by Van Wilgen (1981, 1982). The site is about 10 km from the *Hakea* site on Vergelegen Farm. The vegetation was in good condition and had obviously been well managed and kept free of invasive species.

The climate of the site is similar to the well-documented climate of the Jonkershoek valley, about 12 km to the north (Van Wyk, 1987; Versfeld et al., 1992; Scott et al., 2000). There are no long-term records of mean rainfall from the site itself, but it is likely to be about 1000 - 1200 mm per year. Most of the rain falls during winter. Temperatures are generally mild with occasional frosts in winter, but given the location of the site on a slope, minimum temperatures probably remain above freezing. Summer daily maximum temperatures can exceed 30°C. The site is directly exposed to the strong, warm and dry south-easterly winds that are characteristic of the Cape summers. The south-westerly aspect means that the site is sheltered from the late-afternoon and evening sun, especially during the winter.

The soils on the site are derived from deeply weathered, coarse granites and talus from the Peninsula Formation sandstones. The texture is typically loamy and the percentage of clay increases down the profile. No soil classification has been undertaken yet, but the soils would probably be classified as Hutton or Clovelly forms. They are very similar to the well-studied soils of the Jonkershoek catchments and can be expected to have very high infiltration rates and little or no surface runoff like those studied at Jonkershoek (Versfeld 1981). A thick litter layer also served to promote rainfall infiltration at this site.

The vegetation is dominated by tall, seed-regenerating shrubs of the Proteaceae family, mainly *Protea repens, P. coronata* and *P. neriifolia*. The vegetation is approximately 8-10 years old and the mean canopy height is 2.5 - 3.5 m, with some shrubs reaching 4.5 m. The canopy cover of the Proteas ranges from 60-100%. Higgins et al. (1987) report that *Protea* shrubs in a mountain fynbos site in the Jonkershoek valley had deep tap roots extending beyond 3-m below the surface. They report root-shoot ratios of 0.2 for *Protea nerrifolia* and *Protea repens*. The understorey comprises fine-leaved shrubs, herbaceous sub-shrubs, sedges and grasses and the cover of this layer ranges from low (<10%), where the overstorey is dense, to 90-100% in the openings.

ET was recorded with a LAS (scintillometer) during four window periods spaced between 8 September 2004 and 3 May 2005 and covering all four seasons. The mean slope across the site was approximately 35%, and the distance between the transmitter and receiver was 760 m. The slope is convex with the steepest part occurring towards the upper end. There is an area of very rocky talus to the west of the measurement transect, near the lower end, which is dominated by *Protea neriifolia*. The LAS transmitter was located at 34^{o} 3' S and 18^{o} 53' E. The altitude at the transmitter and receiver positions was 405 and 244 m.a.m.s.l. respectively.

Only a single overstorey canopy was modelled. The simulation period started on 27 June 2004 and ended on 28 June 2005 after a full year. Rainfall and temperature data recorded at the site were imported into WAVES, while solar radiation and vapour pressure deficit were estimated in the usual way. Root mass distribution with depth was based on Jackson et al. (1996) and is shown in Table 15. No groundwater table was simulated for the site. Initial leaf mass was set at 0.1 kg C per m^2, with a specific leaf area of 18 m^2 leaf area per 1 kg leaf carbon, equivalent to an initial LAI of 1.8.

Figure 28 illustrates the pattern of ET recorded in spring, early summer, late summer and autumn, which is compared to modelled daily ET over the entire year. Modelled daily ET is generally consistent with measured ET, and also with the pattern of rainfall measured at the site. Modelled ET reproduces the range of measured values reasonably well in each season, although there is a tendency, particularly noticeable in the second half of the simulation period, for simulated ET to drop below measured ET, approaching zero in some cases. The effect of rainfall distribution on ET over the summer months is clearly seen in the simulated pattern. The second measurement window coincided with a dry spell of reduced ET, and modelled ET reproduces this pattern. Measured and modelled daily ET match reasonably well in the third measurement window, where the effect of declining soil water availability on the pattern of daily ET is clearly seen. A noticeable deviation is seen towards the end of this period, when measured ET remains at a higher level than modelled ET. The reason for this deviation is not known, but may involve some water abstraction by the deepest roots.

The overall pattern of ET is consistent with the expected controls on evaporation in this winter rainfall region. Daily ET in winter is constrained by shorter day length, lower solar radiation, lower temperatures and higher air humidity. The potential rate of evaporation in the summer months is high, but is reduced by soil water deficits during these generally dry months. There is rapid response by plants to any episodes of rainfall that may occur.

The total ET simulated over the simulation period is 757 mm which equals the rainfall recorded over the same period. Simulated leaf area index varied from 1.8 to 2.75 over the year.

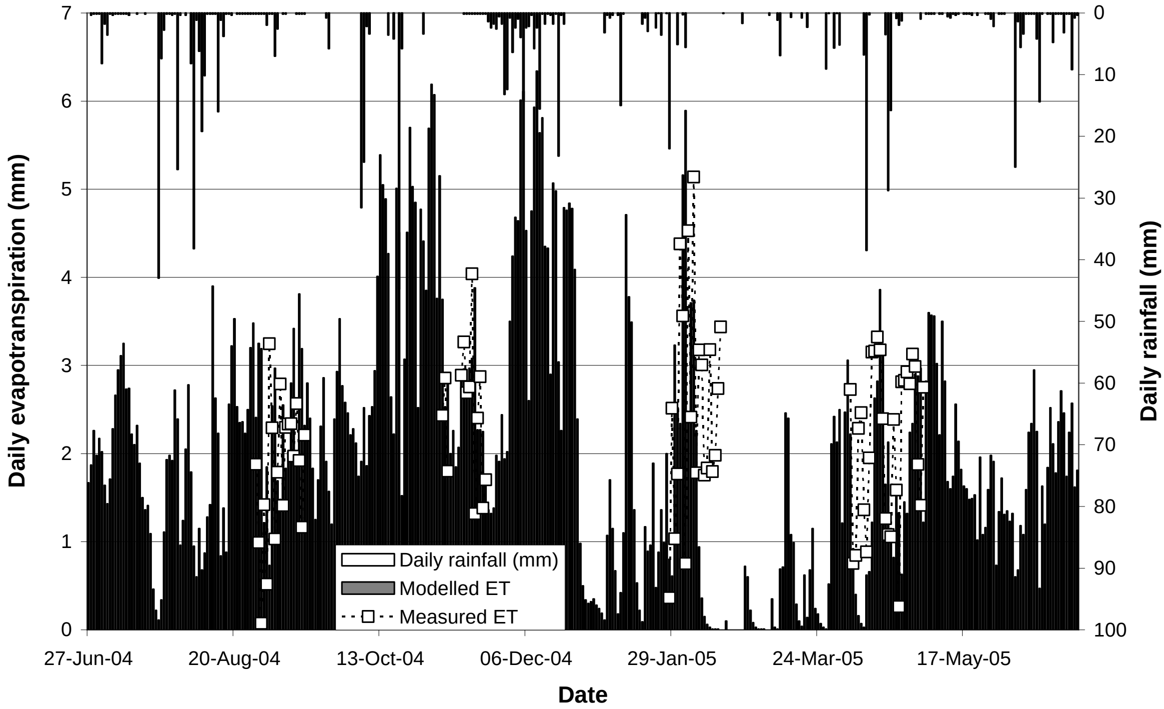


Figure 28. **The pattern of daily ET recorded with a LAS system, and modelled with WAVES, over four different seasons at the mature Fynbos site in the Helderberg Nature Reserve in the Western Cape. Daily rainfall is also shown along the X2 axis.**

An additional check on the realism of the simulated ET rates is shown in Figure 29, which depicts cumulative ET for both simulated and observed ET. The cumulative measured ET at the start of each measurement window was fixed at the corresponding cumulative ET value at that time. The degree to which simulated cumulative ET follows the cumulative measured ET over the remainder of the measurement window is a useful check of the longer-term accuracy with which WAVES simulates the site water balance. Agreement over these four periods is excellent. Marked changes in ET rate recorded over the third and fourth measurement periods are faithfully reproduced by WAVES.

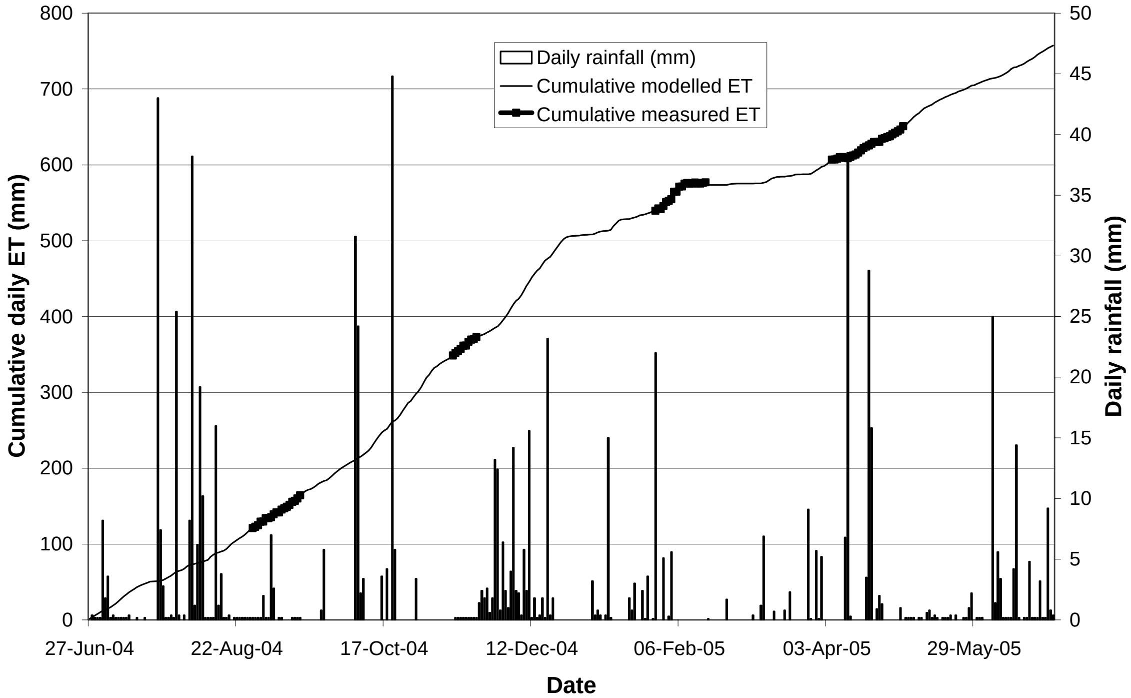


Figure 29. A comparison of cumulative modelled and measured ET at the Fynbos site. The start of each period of measured ET is set at the corresponding value of simulated ET. Daily rainfall is also shown along the X2 axis.

Table 15. Estimation of Fynbos root carbon mass (kg m^{-2}) at each node depth in the soil profile.

Depth (m)	Cumulative fraction of maximum depth	Cumulative fraction of total root mass (Jackson et al., 1996)	Cumulative root dry mass (kg m^{-2})	Cumulative root carbon (kg m^{-2})	Difference (kg C) in each horizon
0.001	0.0005	0.004	0.018	0.008	0.008
0.002	0.001	0.007	0.035	0.016	0.008
0.005	0.0025	0.018	0.087	0.039	0.023
0.01	0.005	0.036	0.173	0.078	0.039
0.02	0.01	0.071	0.339	0.153	0.075
0.05	0.025	0.167	0.804	0.362	0.209
0.1	0.05	0.307	1.473	0.663	0.301
0.2	0.1	0.520	2.494	1.122	0.459
0.3	0.15	0.667	3.202	1.441	0.318
0.4	0.2	0.769	3.693	1.662	0.221
0.5	0.25	0.840	4.032	1.815	0.153
0.6	0.3	0.889	4.268	1.921	0.106
0.7	0.35	0.923	4.431	1.994	0.073
0.8	0.4	0.947	4.544	2.045	0.051
0.9	0.45	0.963	4.623	2.080	0.035
1	0.5	0.974	4.677	2.105	0.024
1.2	0.6	0.988	4.741	2.133	0.029
1.4	0.7	0.994	4.772	2.147	0.014
1.6	0.8	0.997	4.786	2.154	0.007
1.8	0.9	0.999	4.793	2.157	0.003
2	1	0.999	4.797	2.159	0.002

6.8.2 *Pteridium aquilinum – Elegia capensis – Cannomois virgata* riparian Fynbos (Jonkershoek)

The water use of riparian vegetation is important to quantify. These zones are particularly prone to invasion by alien invasive plants (AIP), and so it is useful to know what change in ET occurs following removal of AIP and their replacement by indigenous vegetation.

Year-long evaporation was measured at a Fynbos riparian site in the upper reaches of the Jonkershoek valley (Stellenbosch district, 33^{o} 59$^{/}$ S; 18^{o} 57$^{/}$ E). This study formed a component of a WRC project (K5/808) investigating the water use patterns of a variety of indigenous and alien riparian plant species. The site lies at an altitude of 325 m.a.m.s.l, and mean annual precipitation is 1324 mm. A Bowen ratio system was set up at a location close to the Eerste River where the instruments were surrounded by riparian vegetation. The wind fetch over this vegetation exceeded 100 m both up and down the valley in the prevalent wind directions. Dominant plant species included *Pteridium aquilinum*, *Elegia capensis*, *Cannomois virgata* and *Ischyrolepis gaudichaudiana*. Projected canopy cover of the plant community was approximately 95%, with a mean plant height of 0.5 to 0.75 m. Good quality data were collected from August 1998 to July 1999.

The geology can be described as Quaternary alluvium derived from a mix of the Table Mountain sandstones and Cape Granite of the higher slopes. There is a considerable depth of alluvial material that is sandy and organic, overlying a basement of large, rounded river rocks and stones. The soil profile is between 0.8 m and 1.5 m deep with very few rocks and stones in the upper half. Soil forming is dominated by the accumulation of the organic material as a result of high water levels over much of the year. However, there were no signs of permanent wetness in the upper 1 m of soil. Organic material is fairly well broken down and the profile is black. The soils are of the Rietfontein family of the Champagne form (Ch2200; Soil Classification Working Group, 1991) with a mineral fraction of coarse sand.

Figure 30 shows the annual pattern of daily ET recorded at this site. Gaps in the data record were caused primarily by problems with the BREB Dew10 humidity sensor. A good correlation was observed between total daily ET and total daily solar radiation (Dye et al., 2001), and this correlation was used to patch the missing days. Towards the end of the data record (July and August), solar radiation data were also lost. Daily ET over this period was estimated as an average daily rate calculated from a period before and after the gap. The cumulative annual ET calculated from the complete patched data set was 1332 mm. This high annual water use reflects the evergreen vegetation at this site, and the permanently wet conditions under which these plants grow.

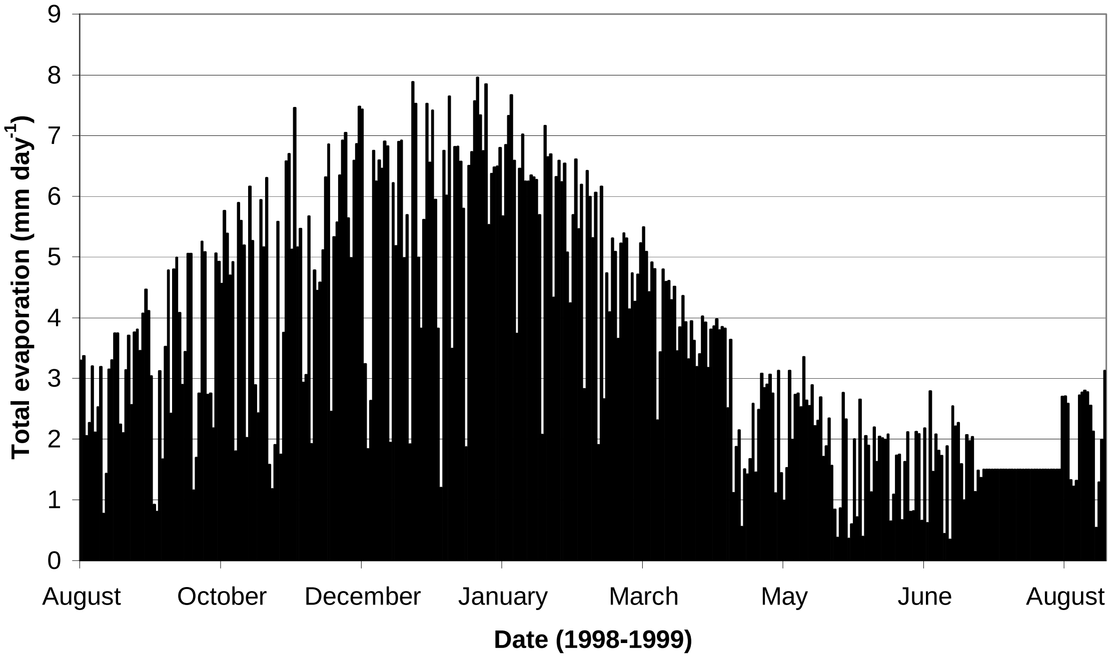


Figure 30. The annual pattern of total evaporation from a riparian Fynbos plant community in the Jonkershoek valley, Western Cape for the period 26 August 1998 to 25 August 1999. A period of constant total evaporation contains patched data based on mean daily total evaporation on either side of the data gap.

WAVES was set up to simulate ET over the same 12 month period over which measurements tool place in the field. Daily rainfall and temperature data were taken from stations close to the site in the Jonkershoek valley. A depth to water table of 1.1 m was assumed, and a high root mass was specified from the surface to the water table.

Figure 31 illustrates the excellent correspondence between cumulative measured ET and cumulative modelled ET. It demonstrates that WAVES duplicated realistic rates of ET throughout the year and in all seasons.

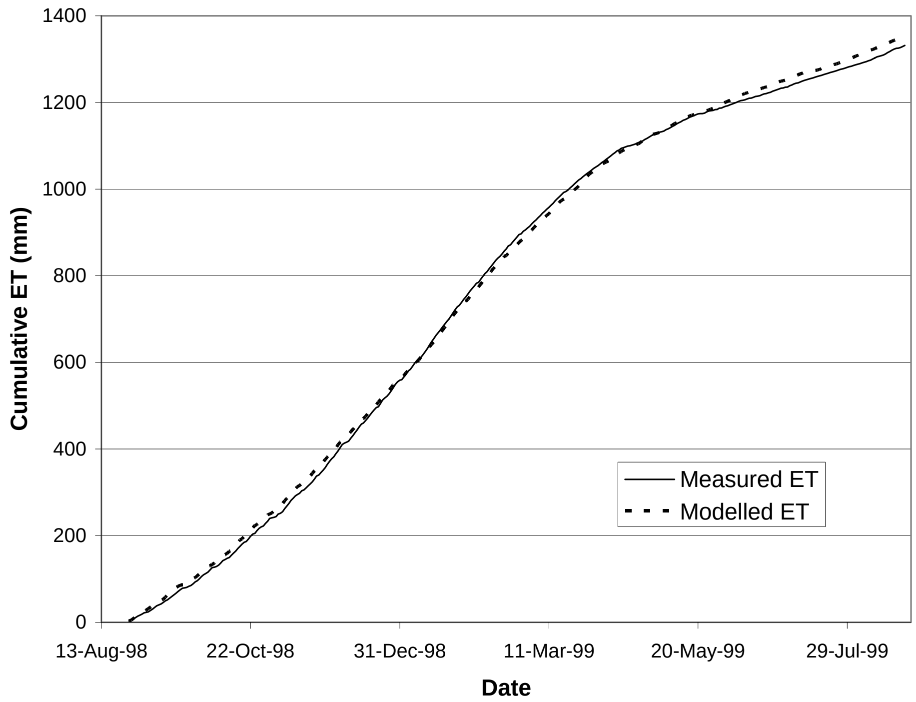


Figure 31. A comparison of measured and modelled cumulative ET from riparian fynbos vegetation in the Jonkershoek valley, Stellenbosch district.

6.9 Wetlands

The role of wetlands in retarding soil erosion, improving water quality, and moderating water flow is well described and widely accepted, but the quantitative influence of such systems on the catchment water balance is less clearly understood. The high availability of soil water and the high LAI often exhibited by wetland vegetation creates the potential for a high annual water use. Wetlands are generally flat and productive sites if drained, and many have been altered to permit agricultural activity or other developments. Their conservation is viewed by many as an urgent issue, and it has become important to obtain a better understanding of their hydrological influences, so that claims of their positive effect on local water resources may be fully tested.

6.9.1 *Phragmites communis* reedbed (Orkney)

AngloGold Ashanti Ltd and the Department of Trade and Industry are funding the University of the Witwatersrand, Johannesburg, to assess the use of vegetation to control acid mine drainage (the Mine Woodlands Project; Weiersbye, 2002). As part of this project, the CSIR is measuring water use from natural vegetation types occurring on acid mine drainage sites. In 2003, ET was measured from a *Phragmites communis* reed bed in the Orkney district (Jarmain, 2005). The water use of *Phragmites* reeds (as well as of natural grassland and indigenous woodland) is an important baseline against which to assess the predicted higher water use of plantation trees.

ET of *Phragmites* was recorded at a site (27°01'S, 26°41'E) within the R.G. William Reserve in the Vaal River mining district east of Orkney. The altitude of this highveld site is 1280 m.a.m.s.l. A plume of contaminated mine seepage water flows through the reed bed. The site is burnt annually in late winter, and is lightly grazed by game and cattle through the year. ET was measured from December 2003 until the end of January 2005, using a Bowen Ratio system. Towards the end of 2003, a sonic anemometer was installed at this site. This permitted direct measurement of sensible heat flux, which together with measurements of net radiation and soil heat flux, provided an additional back-up method of estimating latent heat flux and daily evaporation rates.

The WAVES simulation was set up for a two-year period, starting on day 181 (1 July 2003) and ending on 30 June 2005. Daily rainfall and daily maximum and minimum temperatures recorded on site were imported into WAVES, with solar radiation and mean daily VPD calculated by WAVES in the standard manner. A slope of 10% and an aspect of 270^{o} was assumed. The depth to the water table was set at 1.5 m below the surface. Soil texture was determined to be a clay loam throughout the rooting zone, which extended to 1.2 m below the surface. Initial soil water content at the start of the simulation was assumed to be dry. Spring translocation was activated to initiate leaf growth at the start of the growing season. The nutrient index was set at 0.6. All green leaf mass was converted to litter at the time of the first frost (when the daily minimum temperature dropped to 0^{o}C). A burn was simulated on day 180 (29 June) at which time all above-ground mass is removed.

Some useful additional information on *Phragmites* model parameters were obtained from a recent detailed study of this genus reported by Soetaert et al. (2004) under estuarine conditions in Holland. The carbon content of leaves, stems, panicles and roots rhizomes were measured, and confirmed to vary from 0.41 to 0.45 g C g DW^{-1}. Leaf mortality rate was calculated to be 0.0074 during the growth phase, although this increased to 0.1 during senescence at the end of the growth cycle. Shoot biomass was reported to typically peak at around 1000 g DW m^{-2}. During the period of active growth, 45% of assimilates were found to return to the rhizome/root system (Allirand and Gosse, 1995). A complete list of plant parameter values adopted in the simulation is shown in appendix 1.

Figure 32 illustrates the annual trend in ET recorded at this site. During the second half of the 2003/4 summer, simulated daily ET closely followed measured daily rates. A high degree of variation from day to day is typical, and is due to the alternation of cloudy, humid days with sunny and drier days. In late autumn, this variation disappears with the return to generally cloudless stable conditions that are typical of the Highveld winter. Simulated ET drops to zero at the time that the first frost is recorded. This has the effect of converting all green leaf area to litter (which must be viewed as including standing dead material). A fire is also simulated at the site on day 180, and this removes all shoot material. Curiously, ET measurements around this time registered between 0.5 and 1.5 mm per day. Given the visibly dry soil surface conditions, and the absence of green leaf, it is difficult to explain where this water could come from. The possibility of poor resolution of ET measurements under these dry conditions should be borne in mind. Spring growth is then initiated through translocation of carbon from roots to leaf and stem, once a critical threshold of 10-day moving average of minimum daily temperature exceeds 9^{o}C. Daily ET increases steadily over the first half of summer as the leaf area builds up to its mid-summer maximum. The total ET simulated over 411 days from 18 December 2003 to 31 January 2005 is 1387 mm, whereas the annual total from 18 December 2003 to 17 December 2004 is 1174 mm.

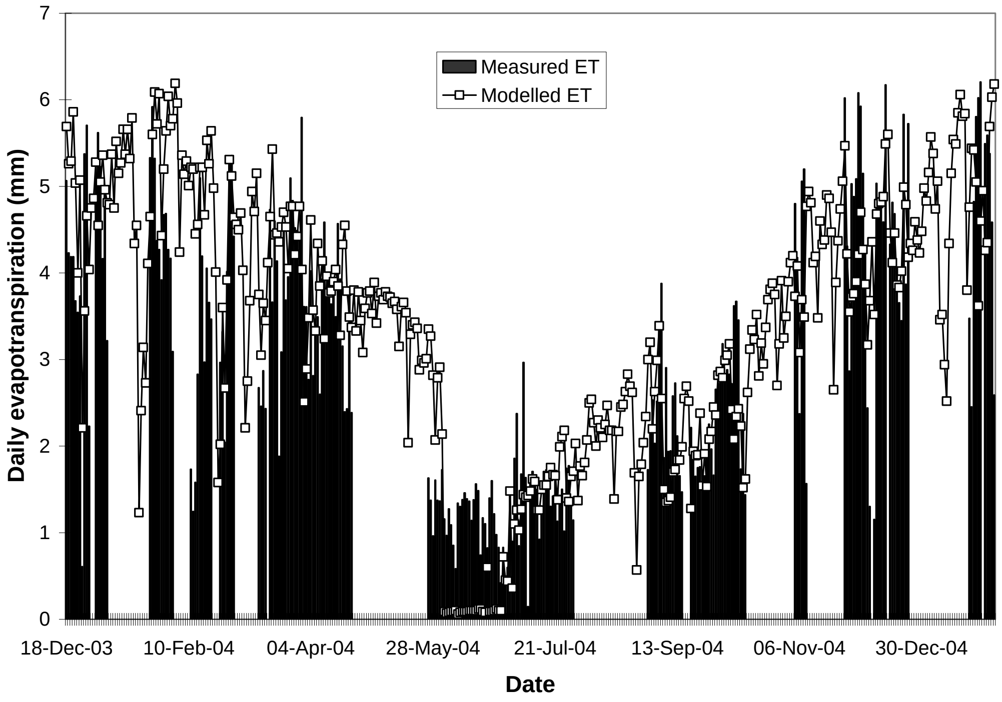


Figure 32. A comparison of measured and simulated ET pertaining to the *Phragmites* reed site at Orkney, for the period 18 December 2003 until 31 January 2005.

6.9.2 *Andropogon appendiculatus – Helictotrichon turgidulum* moist grassland (Gilboa)

A Bowen ratio system was installed in a high-altitude wet grassland site situated on the edge of a wetland. This site is located on the Mondi property Gilboa, which lies at the top of the Karkloof hills north of Howick in the KwaZulu-Natal midlands. The altitude of the site is 1532 m.a.m.s.l, and the mean annual precipitation is 867 mm. The Bowen ratio system was erected near the centre of the Inyamvubu vlei (30^{o} 15$^{/}$ E; 29^{o} 15$^{/}$ S). This vlei is flat and extensive, providing a wind fetch in excess of 150 m in all directions. The soil surface remained wet throughout the summer, with occasional shallow inundation after heavy rainfall, but dried during the winter months. The predominant plant species in the vicinity were *Andropogon appendiculatus*, *Helictotrichon turgidulum*, *Tristachya leucothrix*, *Harpechloa falx*, *Helichrysum aureonitens* and *Aristida congesta*. The system was operational from early spring of 1998/99. Because of persistent technical problems during this summer, monitoring was extended into the 1999/2000 growing season. Missing data were filled with average daily rates calculated on measured days on either side of the gaps.

Figure 33 illustrates the pattern of ET recorded over a complete summer growing season. The pattern resembles the grassland patterns described earlier for the Bellevue and Cathedral Peak sites. Factors limiting ET appear to be negligible green leaf area in winter, a slow green leaf development in early summer, and an obvious and steep decline in autumn. Annual ET was estimated to be 836 mm (Dye et al., 2001).

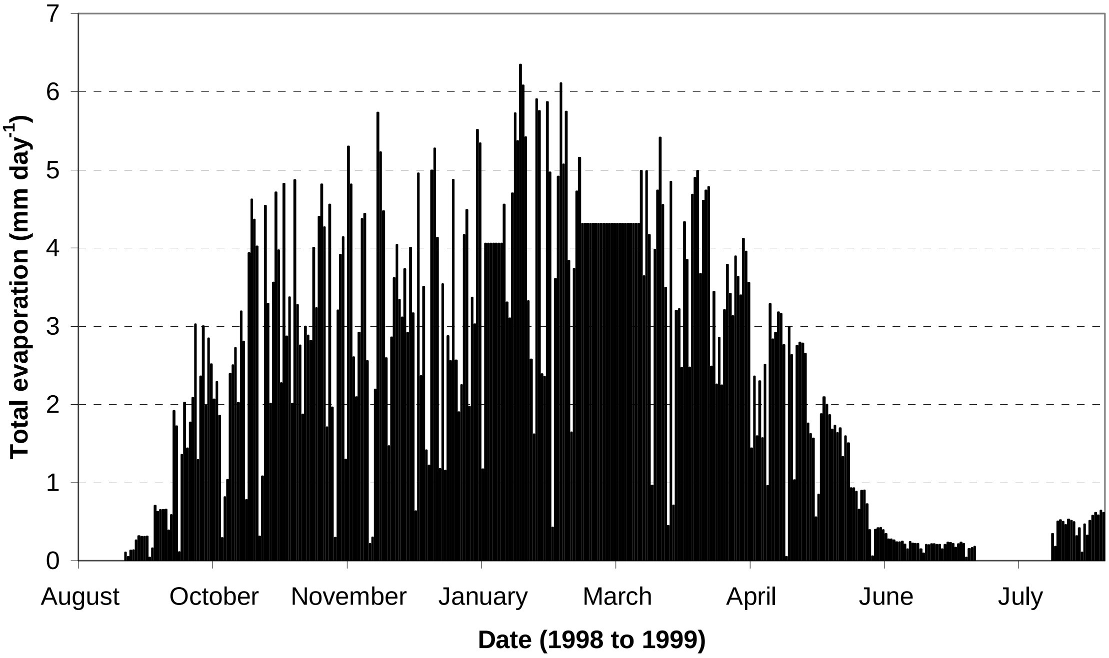


Figure 33. **Daily total evaporation from a seasonally wet grassland at Gilboa, KwaZulu-Natal Midlands for the period 15 August 1998 to 31 August 1999. Two periods of constant total evaporation contain patched data based on mean daily total evaporation on either side of the data gap.**

The simulation period was defined as starting on 1 September 1998 and ending on 31 August 1999. Daily rainfall and daily maximum and minimum temperatures were selected from a climate station at Neteni, Rietvlei (0269493-A) at an altitude of 1387 m.a.m.s.l. MAP at this station is 1013 mm, and MAT is 15.4^{o}C. Soil texture was defined as sandy loam extending from the surface down to 1.4 m. The soil nutrient index was set at 0.7 to reflect the moderately fertile wetland soil. A water table was defined at 1.2 m below the surface, with roots extending down to 1.4 m. Initial root carbon is shown in Table 5. The water content of the soil profile was assumed to be dry at the start of the simulation period on 1 September 1998. Root to leaf translocation was activated to start leaf growth in early spring.

The realism of simulated ET at this site is demonstrated in a comparison of cumulative measured and simulated ET (Figure 34). Modelled total ET over the entire simulation period (831 mm) closely matched measured ET (836 mm).

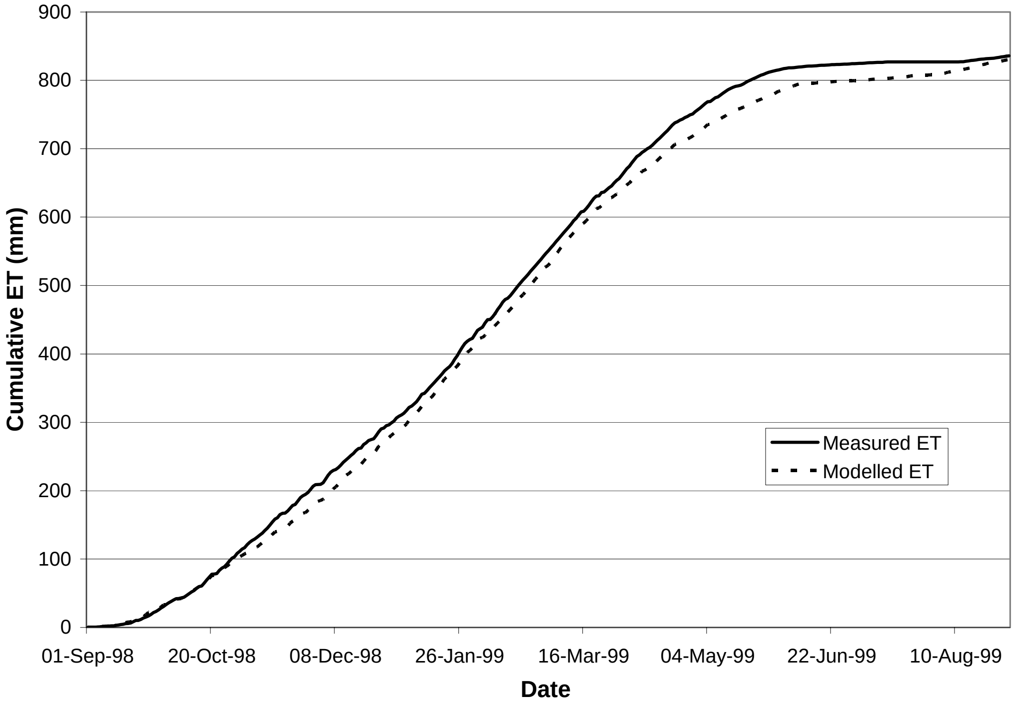


Figure 34. A comparison of measured and simulated cumulative ET pertaining to the Gilboa moist grassland site.

6.10 Alien invasive trees

There are numerous species of alien invasive trees that pose a major problem throughout South Africa (Versfeld et al., 1998). Many of these species form dense stands, maintain high leaf areas, and are particularly numerous in riparian zones. Their rate of water use is therefore believed to be relatively high and to result in substantial decreases in catchment water yields. The presumed water yield benefits of clearing alien invasive plants are a major justification of the Working for Water Programme that receives approximately R400 million of Government funds per year.

6.10.1 *Acacia mearnsii* riparian thicket (Wellington)

A closed-canopy, mature, self-established riparian wattle thicket was located on the farm Oaklands (33^{o} 26.084$^{/}$ S; 19^{o} 04.892$^{/}$ E), which lies northeast of the Western Cape town of Wellington, and east and south of the Groenberg, a free-standing mountain formed from the Malmesbury Shale Formation. Mean annual rainfall in the area is 1050 mm, and the altitude is 345 m.a.m.s.l (Prinsloo and Scott, 1999). Locally, the soils are derived from the decomposition of massive sub-greywacke. The soils of the valley bottom are a complex of surface deposits of very coarse alluvial gravels, deposited in lenses of variable size and thicknesses of up to 1-m, on deeply weathered and much finer grained *in situ* shales. Where no recent gravels have been deposited, the soil is a well-drained deep Clovelly (Brereton family, Cv1200 clay loam) of at least

2-m depth. Below the yellow subsoil there is a further metre or more of deeply weathered parent material. The recent alluvial deposits consist mainly of stones with mean diameters in excess of 20 mm (probably in excess of 80% by volume), and the remainder is a mixture of coarse sand and finer gravel. Apart from the recent gravel lenses, which are all surface deposits of up to 1 m depth, there are remarkably few rocks in the profile (<5% by volume).

The entire farm was infested with *A. mearnsii*, with particularly dense stands along the riparian zones. Following a survey of tree diameters in a sample plot of 301 m^2, six sample trees were selected to represent each of six diameter classes of trees. Heat pulse velocity (HPV) probes were implanted into each sample tree to record sap flux densities at depths of 4, 9, 15 and 23 mm beneath the cambium. In the smallest size class, only two probe sets were implanted to depths of 4 and 9 mm beneath the cambium. The largest tree received six probe sets, with additional probes at 26 and 34 mm.

Hourly heat pulse velocities were recorded over a period of seven months, starting in August 1997 and ending prematurely in February 1998 when the trees and instruments were destroyed by a wildfire. Measurements of sapwood area, sapwood moisture fraction and density, and probe separation distances were used to convert heat pulse velocities to whole-tree sap flow. Wound widths were assumed to be 3 mm (Smith et al., 1992), since resin staining around the drilled holes in this long-term study obscured the transition between functional and non-functional sapwood. An automatic weather station was sited approximately 50 m from the sample trees on a grassland hill slope. Hourly means of air temperature and relative humidity were recorded over the entire study period, and used to calculate hourly vapour pressure deficit (VPD). Periodic spot measurements of relative humidity were taken with a sling psychrometer to check for possible drift in the response of the Coreci capacitance chip to relative humidity. The sapwood moisture fraction of nearby trees was measured at monthly intervals.

Figure 35 shows days when good quality HPV data were recorded from all six sample trees. These data display a typical seasonal pattern of daily transpiration, with highest values in mid-summer due to long day lengths and high temperatures and high vapour pressure deficits (VPD). The data suggest periodic incursions of cold and humid air, followed by extended periods of recovery to high sap flow rates. Daily sap flow in every sample tree was found to be closely correlated to the product of mean daily VPD and the number of daylight hours (Dye et al., 2001). Daylight hours were calculated from the number of hours where solar radiation exceeded zero. Daily plot transpiration was calculated by scaling the sample tree sap flows by the number of trees in the diameter class, and summing across all diameter class totals. Whole-plot sap flow was also closely correlated to the product of mean VPD and the number of daylight hours (Figure 36). No seasonal differences could be discerned in this scatter plot, implying that the trees had access to adequate soil water throughout the monitoring period, which included extremely hot and dry late-summer weather. The sapwood moisture fraction showed no seasonal trend, averaging 0.91 over the monitoring period.

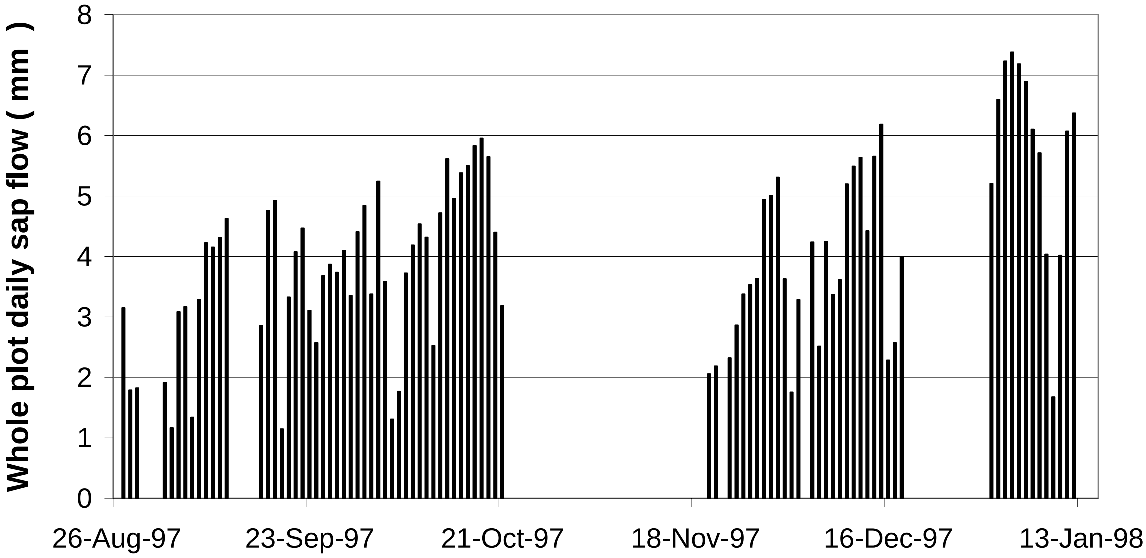


Figure 35. Whole-plot daily sap flow (transpiration) recorded at the Wellington *A. mearnsii* site. Gaps indicate periods of missing data for one or more of the sample trees.

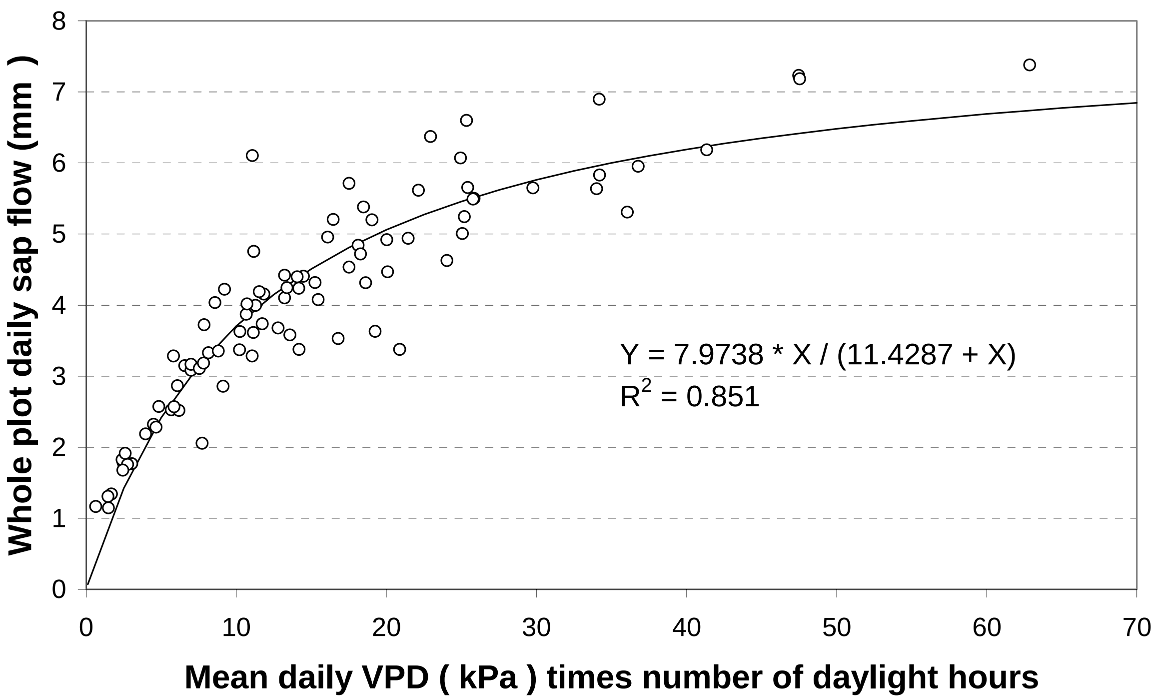


Figure 36. The relation between whole-plot sap flow and the product of mean daily VPD and the number of daylight hours, recorded at the Wellington *A. mearnsii* site.

A one year simulation was set up for this site, starting on 1 August 1997 and ending on 31 July 1998. Daily rainfall data for this simulation were obtained from a station (Bainskloof Tweede Tol, 0022214-W) located to the south of the simulation site, but at a similar altitude (343 m.a.m.s.l.) and with an MAP of 892 mm. Although the MAP at this station is about 160 mm lower than at the simulation site, this was considered not to be important in view of the fact that the riparian trees are believed to have access to groundwater throughout the year (Dye et al., 2001). Daily temperature data were sourced from the Welvanpas station (0022098-A) which is also situated at a similar altitude (320 m.a.m.s.l.) to the simulation site. The soil was specified to be a sandy clay loam, with roots stretching down to a water table at 1 m.

In view of the gaps in the original data, the realism of the WAVES simulation was checked by comparing the relation shown in Figure 36 to a comparable graph using daylength, mean daily VPD and total daily transpiration generated by WAVES. This relation is shown in Figure 37 (square symbols), and closely resembles the trend in measured data (trend line) recorded at this site. The simulated annual ET (including evaporation of intercepted water) was 1165 mm.

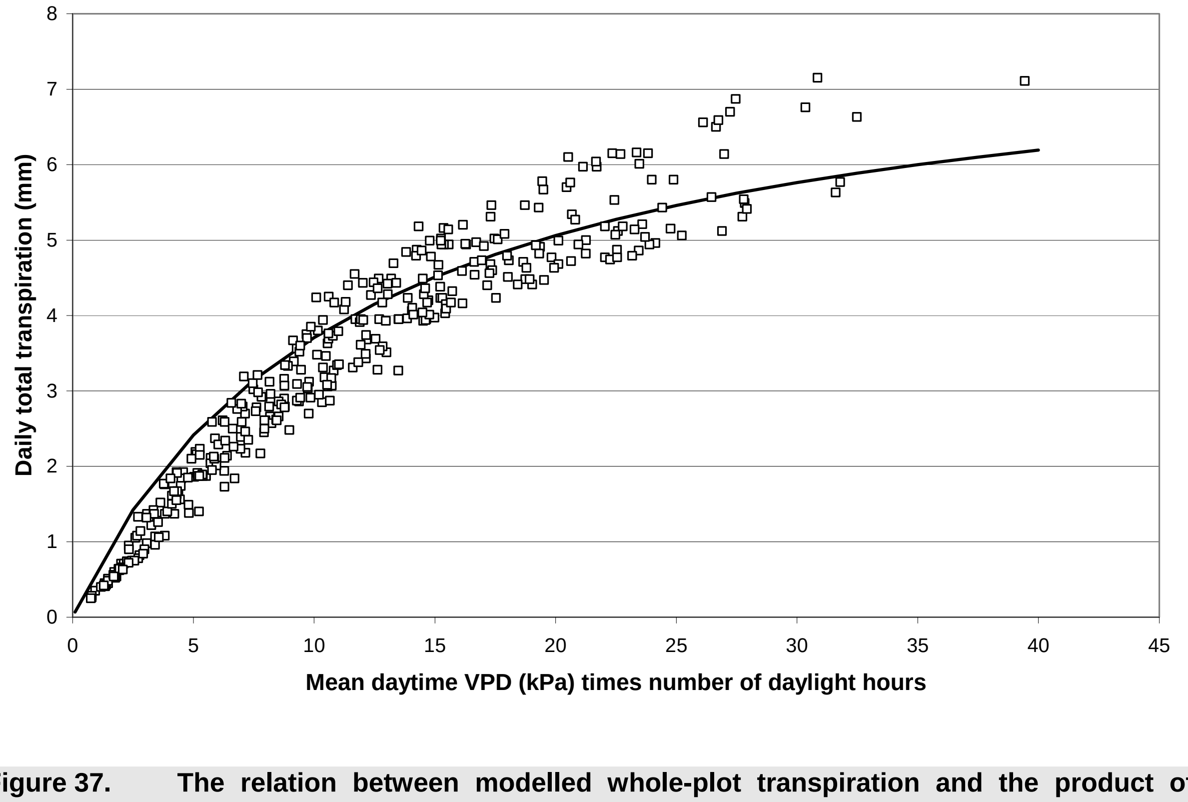


Figure 37. The relation between modelled whole-plot transpiration and the product of mean daily VPD and the number of daylight hours, simulated for the Wellington *A. mearnsii* site (square symbols). The regression line indicates the trend observed in the field data.

6.10.2 *Acacia longifolia* (Somerset West)

A suitable riparian site invaded by *Acacia longifolia* was identified on Vergelegen farm in the basin formed by the Hottentots-Holland, Stellenbosch and Helderberg Mountains. The stand is located along a tributary of the Lourensford River and varies in width from about 50-100 m. The site is situated in a wide valley and has a gentle slope of about 2%. The trees are approximately 10 years old and form a dense, 2-5 m tall, almost completely mono-specific stand with essentially no understorey vegetation. The vegetation on either side of the *Acacia* stand is a mixture of typically weedy shrubs, semi-herbaceous sub-shrubs and grasses that may originally have been a pasture when Vergelegen farm was run as a commercial dairy.

The soils are derived from granites, have a loamy texture and provide good growing conditions for plants. The rainfall has not been measured at this site but is probably about 1 000 mm per year. Temperatures are generally moderate. The daily maxima can reach more than 30°C in February and March and mild frosts occasionally occur in the winter months. The site is exposed to the dry, warm and strong south-easterly winds that are characteristic of the Cape summer months.

A scintillometer was set up and run at this site, but there were ongoing technical problems with this instrument. These were reviewed in a presentation (Jarmain, C. and Everson, C. 2005. A comparison of the total evaporation of natural and invaded vegetation in South Africa using a large aperture scintillometer) delivered at the 5th Annual Meeting of the European Meteorological Society (EMS) and 7th European Conference on Applications of Meteorology (ECAM), Utrecht, Netherlands, 12 - 16 September 2005. The nature of the problem caused the scintillometer beam from the transmitter to saturate the receiver under certain conditions and times of day. Problem days tended to be those associated with high temperatures and high solar radiation. In view of the very limited reliable data that were recorded at this site, it was decided not to attempt a WAVES simulation. The few data that were recorded are shown in Figure 38 together with ET data from a nearby site dominated by *Hakea dupracea* (next section).

6.10.3 *Hakea drupacea – Hakea sericea* – Pinus spp. (Somerset West)

Areas with dense *Hakea* stands were identified using data compiled for the forthcoming Protea Atlas, which were kindly supplied by Dr Tony Rebelo of the S.A. National Botanical Institute. Although there are still extensive areas with dense *Hakea* in the southern Cape, there were relatively few suitable stands in the mountains near Stellenbosch. Most of these have been burnt within the past few years and were too young for our purposes, or not extensive enough. After an exhaustive search, a suitable stand of mature, exceptionally dense *Hakea drupacea* (Sweet Hakea) was found on the farm Vergelegen near Somerset West. Smaller numbers of *Hakea sericea* were also present. The stand is situated on a west-facing aspect on the lower slopes of the Hottentots-Holland Mountain Range. There is a farm dam below the site. *Hakea drupaceae* is an important invader of Fynbos. It is not as widespread or as aggressive an invader as *H. sericea,* but is similar enough in size, growth-form, canopy structure and leaf characteristics to be a suitable substitute. The site is approximately 3 km from the *Acacia longifolia* site described above.

The current vegetation is dominated by *Hakea drupaceae,* a 2-4 m tall shrub with a fairly dense and upright canopy. The upright leaves are arranged in clusters around the erect branches. Each leaf is divided into round, needle-like sections, rather like a coarse feather and each “needle” has a sharp tip. The total canopy cover of the *Hakea* is about 60-70%. Emergent *Pinus radiata* trees, about 5-10 m tall, are scattered throughout the *Hakea* stand, especially in the lower part of the measured transect. Their total canopy cover is about 5-10%. There are a few *Hakea sericea* trees and occasional indigenous *Protea* species. The understorey is generally sparse because of the dense canopy and comprises a mixture of shrubs, herbs and grasses. On the northern side of the transect, towards its lower end, there is a mixture of *Acacia longifolia* and *Hakea drupaceae*. The area was last burnt in 1995, which means that the vegetation was 10 years old at the time of the study.

The soils are derived from deeply weathered granites and overlain by talus from the higher lying Peninsula sandstone formation. They are very similar to the well-studied soils found in the experimental catchments at Jonkershoek, which is about 15 km to the north. The topsoils are moderately fertile loams and the percentage of clay increases with depth. No soil classification has been done yet but the soils would probably be classified as Hutton or Clovelly forms. They probably have high infiltration rates and little or no surface runoff, like those recorded for Jonkershoek (Versfeld 1981) and allow for the development of deep root systems.

The climate is similar to the well-documented climate of the Jonkershoek valley, about 12 km to the north (see Van Wyk 1986, Scott et al. 2000). There are no records of the long-term annual rainfall at the site, but it is likely to be about 1000-1200 mm with about 60-70% of the rainfall occurring during the winter half of the year. Temperatures are generally moderate. The daily maxima can reach more than 30°C in February and March and mild frosts occasionally occur in the winter months. The summers are characterised by strong, warm and dry, south-easterly winds. This site was the windiest of the Western Cape sites, with winds blowing in a predominantly east-west direction.

A LAS system was set up to record sensible heat along a path length of 487 m. The transmitter was located at 34.09189 ^{o}S and 18.94227$^{/}$ E, at an altitude of 328 m.a.m.s.l.. The receiver was located at 34.09018 ^{o}S and 18.93748 $^{/}$E, at an altitude of 245 m.a.m.s.l. The mean slope over the beam transect is ± 10 %. The curve of the slope is concave and the steepest slopes are found near the top.

ET from the *Hakea drupacea* stand was measured during four window periods, scheduled in four different seasons of the year, and spanning the period from 11 August 2004 to 3 April 2005. An unresolved problem with the LAS system at this site has resulted in data loss. Figure 38 nevertheless illustrates the broad pattern of ET recorded in each season, and is shown in relation to reference evaporation and rainfall events. Calculation of reference ET is based on algorithms described by Allen et al (1998), but modified by Professor M. Savage to apply to periods of less than a day (Savage, 1999). On the majority of sample days shown in Figure 38, some data loss (1-4 20 minute periods) was experienced in the early morning prior to about 10h00. The daily ET is therefore underestimated, but not by a large amount, since good data were recorded over the remainder of each day when evaporative conditions were highest.

Evapotranspiration from *Hakea drupacea* in mid winter of August 2004 was similar to reference ET. By October, however, it was markedly lower, despite some high rainfall in the preceding weeks. By January 2005, there is evidence of further reduction of ET below reference evaporation rates. Together with the small degree of variation from day to day, this suggests that there is tight control of stomata apertures to limit transpiration. This was most likely brought about by hot and dry summer conditions. January rainfall was recorded, but the amounts were relatively small and insufficient to wet up the soil profile. Daily ET in March/April 2005 remained below reference ET levels, most likely because of continuing poor rainfall at this time. Simulated annual ET amounted to 694 mm. The overall pattern suggests that water use by *Hakea dupracea* at this non-riparian site is severely limited by the availability of soil water, and is far lower than reference evaporation. The species is obviously adapted to this situation, however, and does not exhibit obvious drought symptoms such as leaf drop or leaf wilting. It is significant that the 2004/5 period was exceptionally dry in the Western Cape, and that greater water use by these species is likely in years of normal rainfall.

The available data recorded at the *Acacia longifolia* site are also shown in Figure 38. The annual pattern of ET is broadly similar to the *Hakea* pattern, despite its location along a watercourse, suggesting that this was not a truly riparian habitat. Due to the very dry conditions that prevailed during this summer, a stream that flows down the site was reduced to a trickle.

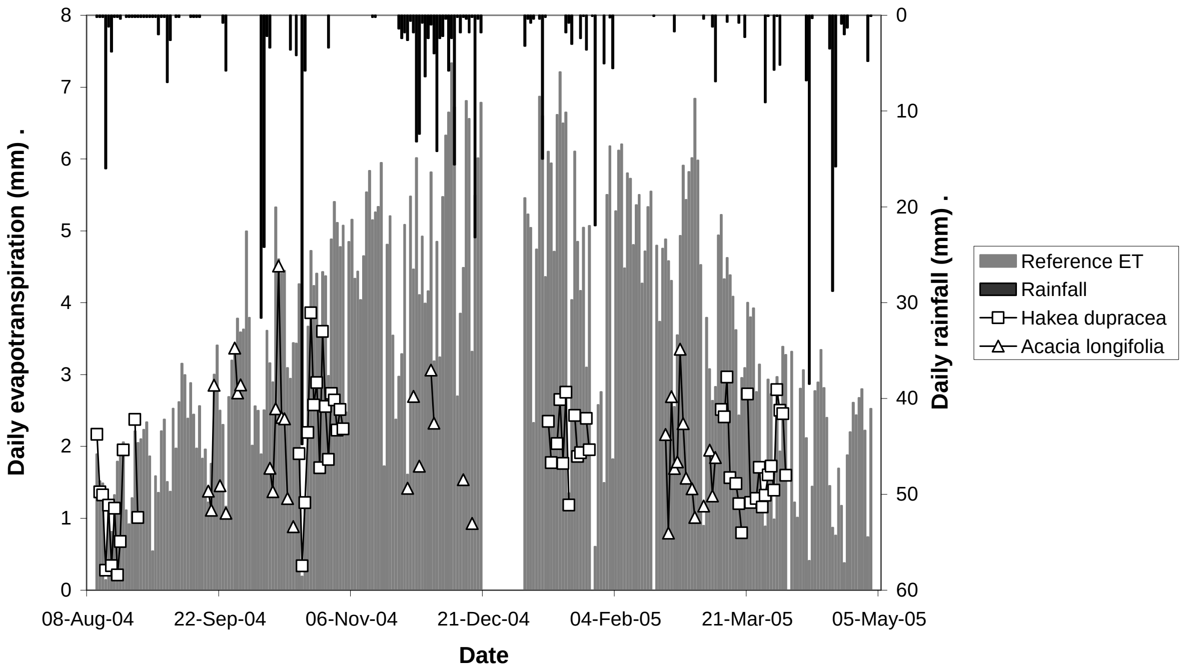


Figure 38. **The pattern of daily evapotranspiration (square symbol) recorded with a LAS system in four different seasons at a mature *Hakea drupacea* stand on the farm Vergelegen near Somerset West, Western Cape. Grey bars illustrate the daily reference evaporation calculated over this period. Rainfall is plotted along the X2 axis. The limited data from the *Acacia longifolia* stand (triangles) are also shown on this graph.**

WAVES was set up to simulate a west-facing *Hakea* site with a 10% slope and a fairly poor soil nutrient index of 0.5. A single overstorey canopy was assumed, and a constant above-ground allocation fraction of 0.5 was specified. The soil profile was set to reflect dry soil water conditions at the start of the simulation. The soil was assumed to be a loam throughout its 1 m depth, and to be underlain by impermeable rock. The maximum rooting depth was assumed to be 1 m. No water table was simulated at the start. Vegetation parameters are listed in appendix 1.

The simulation period extended from 1 August 2004 to 31 July 2005. A two week data gap exists from 21 December to 3 January when logger problems were experienced. Daily temperature data for this period were assumed to remain unchanged from the last full day before the gap, but no suitable replacement rainfall data could be found. Zero rainfall was therefore assumed over this period. Figure 39 illustrates the trends in observed (square symbols) and modelled (triangular symbols) daily ET, as well as reference ET (bars). Daily rainfall is plotted along the X2 axis. Simulated LAI varied from 1 at the start of the simulation to 2.1 at the end.

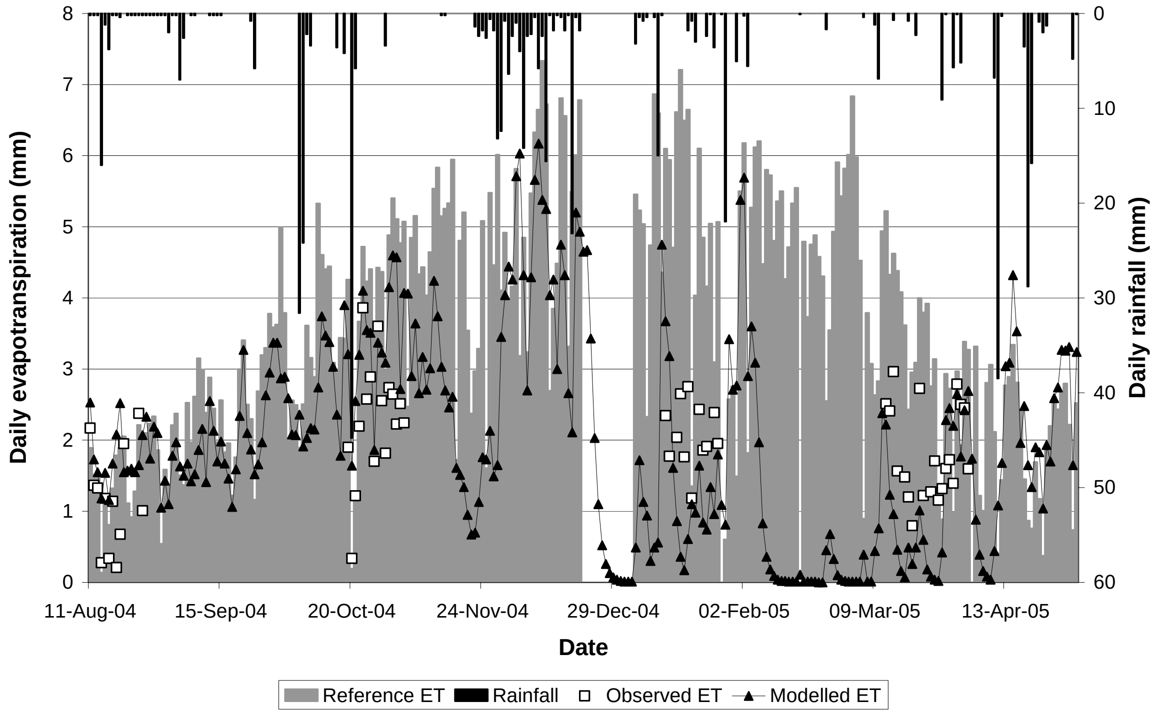


Figure 39. The pattern of daily evapotranspiration observed (square symbols) and modelled (triangular symbols) pertaining to the *Hakea dupracea* site. The grey bars indicate calculated daily reference evaporation, while the bars along the X2 axis indicate daily rainfall.

Modelled daily ET follows reference ET for those periods when rainfall has occurred and when soil water is available to the trees. However, in dry spells of weather, available soil water rapidly declines, causing modelled ET to drop rapidly to very low values. Recovery is rapid following further rainfall (e.g. December 2004). Modelled daily ET during January 2005 is lower than observed in the field, and this is very likely a consequence of the gap in the rainfall record towards the end of December, when zero rainfall was assumed over a two week period. Rainfall was recorded on either side of this data gap, and it is likely that some rainfall did fall over this period. The March/April measured daily ET rates are of similar magnitude to the modelled rates, but it is noticeable that modelled minimum daily ET is lower than the observed rates. This difference may arise from the tendency of many plants to extract sufficient soil water from deepest strata, with a limited number of deep roots, in order to keep tissues alive and functioning until the next rains.

6.11 Crops

6.11.1 Sugarcane (Seven Oaks)

Burger (1999) and Jarmain and Everson (2002) describe a study of ET above a dryland sugarcane crop in the Seven Oaks district of KwaZulu-Natal. The site is designated as compartment DS15 (30.67 ^{o}S, 29.194 ^{o}E), covers an area of 9.23 hectares, and is situated at an altitude of approximately 1100 m.a.m.s.l. The compartment was planted with the N12 variety, with a row spacing of 1.1 m. The sugarcane canopy was uniform with a fetch distance greater than 100 m in all directions. The crop was planted during November 1989, and Bowen ratio evaporation measurements commenced in August 1997. The crop (third ratoon) was harvested at the end of August 1998 and the following ratoon in April 2000. LAI was estimated every 2-4 weeks during the crop cycle with a LI-COR LAI 2000 canopy analyser, and varied from 4 to 8 (Burger, 1999). ET measurements continued until July 2001. Figure 40 illustrates the trends in ET, which are shown in relation to daily rainfall.

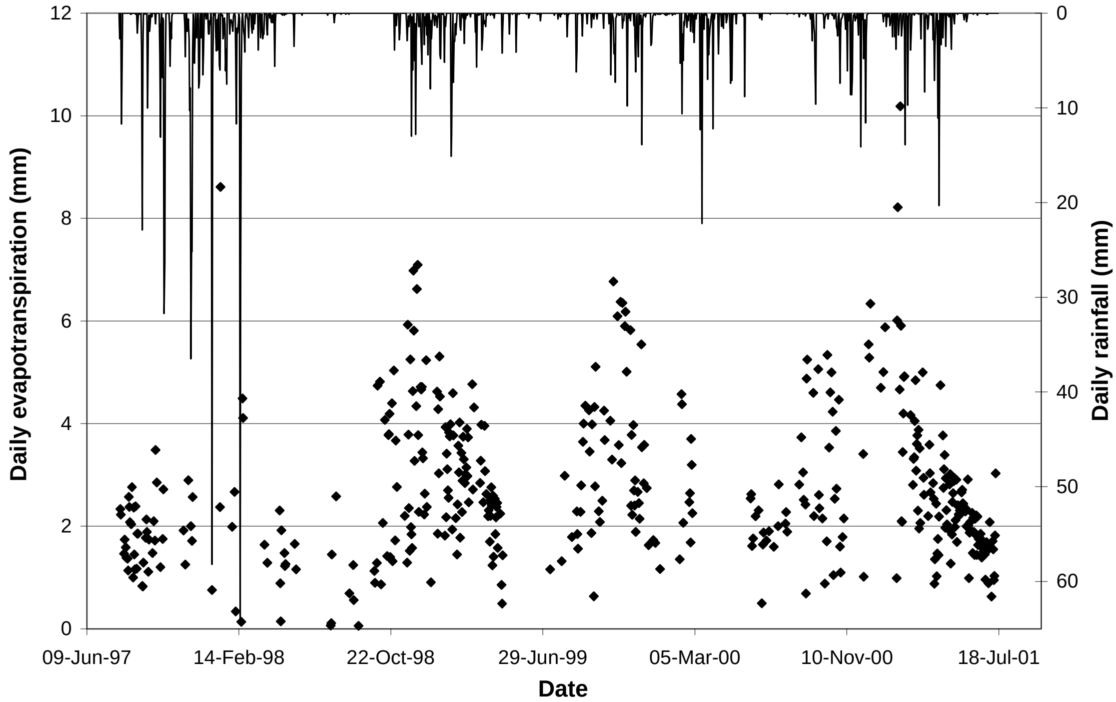


Figure 40. Daily evapotranspiration rates recorded at the sugarcane site from July 1997 to June 2001. Daily rainfall is plotted along the X2 axis. The crop was harvested in August 1998, and again in April 2000.

Dryland sugarcane at this site demonstrates pronounced seasonal variation in ET, peaking above 6 mm in mid-summer, and declining below 1 mm in the winter months due to shorter day lengths, lower temperatures, lower soil water availability, reduced physiological activity of the older leaves, and harvesting at the end of the growth cycle. The sensitivity of sugarcane to spells of dry weather is clearly seen in Figure 40. In February 2000, a period of dry weather is correlated to a rapid decline in daily ET, which recovers with the arrival of further rainfall.

Leaf area index was recorded at intervals using a Li-Cor Canopy Analyzer. The pattern of these readings over time is shown in Figure 41. LAI recorded at the end of the growth cycle in the winter of 1998 exceeded 6. Similar high values for LAI have been found in other studies of sugarcane (Keating et al., 1999). LAI in the second crop (1998 to 2000) did not attain the same level, and this is believed to be the result of a violent hail storm that removed the leaves from the crop and also flattened a significant proportion of the stems.

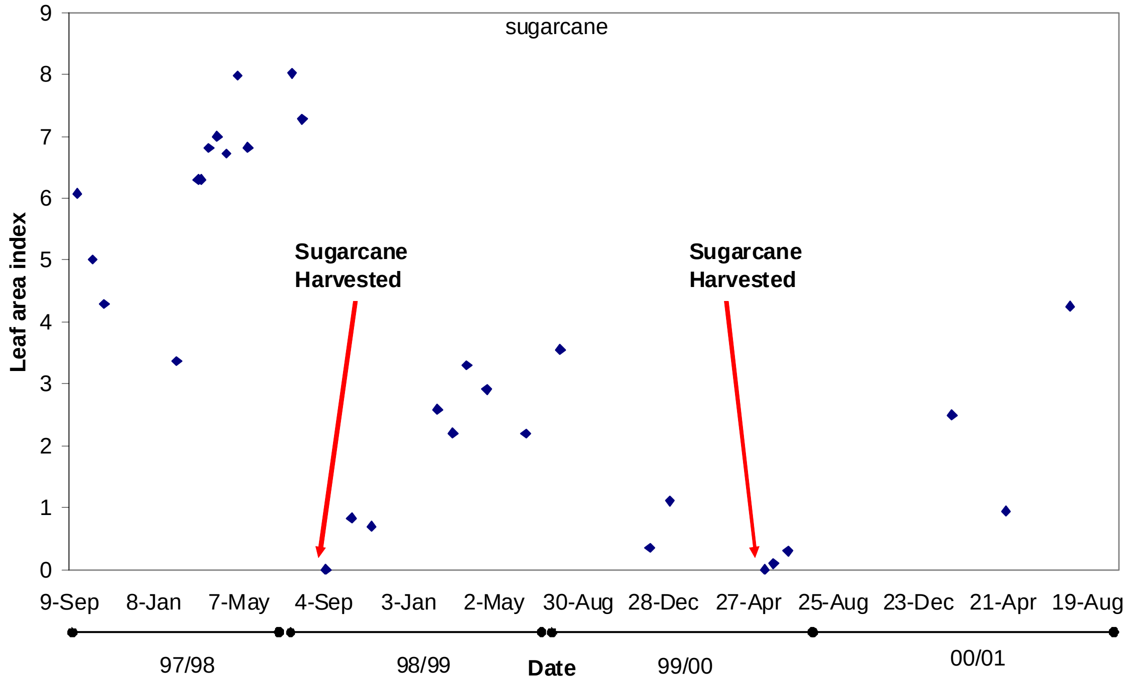


Figure 41. The four-year trend in LAI (leaf and stem) recorded with a Li-Cor Canopy Analyser in a sugarcane site at Seven Oaks.

WAVES was set up to simulate a two-year period, stretching from 1 September 1998 to 31 August 2000. Daily weather data were obtained from the WAVES weather database for the Seven Oaks weather station (0270164-S; MAP = 910 mm). Model parameter values for sugarcane are shown in Appendix 1. Keating et al. (1999) reviewed 35 sugarcane datasets from Australia, Hawaii, South Africa and Swaziland, and shows peak LAI to vary between 6 and 8. A light extinction coefficient of 0.38 is assumed. These authors found above-ground green biomass generally ranges from 3000 to 8000 g m^{-2} over a 12-month growth cycle. The fraction of total biomass comprising the root system was approximately 0.3 at emergence, and 0.2 at flowering. According to Thompson (1976), sugarcane is able to extend roots to 2 m below the soil surface. Rooting depth was therefore set to the maximum soil depth of 1.4 m.

Figure 42 shows the pattern of ET modelled by WAVES over the two-year period. It was found to be very difficult to reproduce the high yields of above-ground stem growth. Measured LAI towards the end of the 1998 growing season peaked at just under 3. The only way the required high growth rate could be achieved was to increase the daily maximum assimilation rate to 0.12 kg carbon m^{-2}. This is considerably higher than the usual range of 0.01 to 0.04 quoted in the WAVES manual as applicable to most crops, but is possible given the very high productivity of sugarcane. In view of some uncertainty with this parameter, the water use efficiency of the simulated crop over the first 12 months after planting was tested using a relation reported by Thompson (1976) which links annual yield and total evaporation in the following manner:

$$Y_{sc} = 9.53(E_{an}/100) – 2.36 \quad (26)$$

where Y_{sc} = annual sugarcane yield (t ha^{-1})
E_{an} = annual total evaporation (mm)

According to the WAVES output, E_{an} equalled 717 mm over the first 12 months, which translates into a yield of 66 t ha^{-1}. The modelled stem yield (what is finally harvested is largely stem) at the end of the 12 months was 59.7 t ha^{-1}. It appears therefore that a maximum assimilation rate of 0.12 kg carbon m^{-2} d^{-1} is necessary to produce a realistic yield. Approximately 20% of actually assimilated carbon would be translocated below-ground (Keating et al., 1999), and additional respiratory losses would occur in all live tissue. Experimental evidence in support of this high maximum assimilation rate is required.

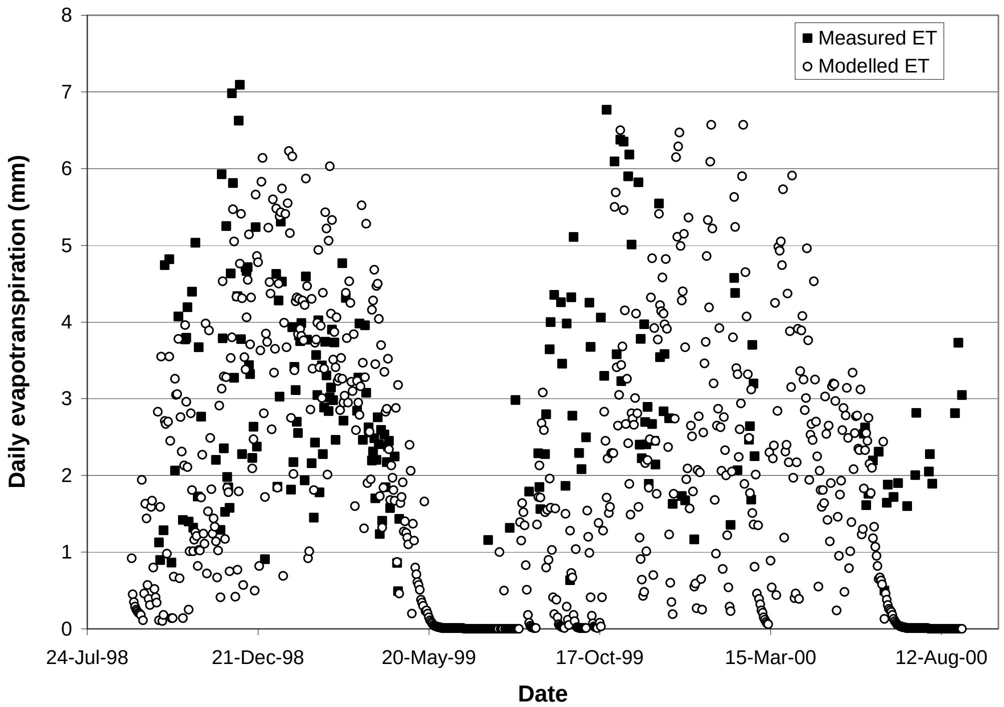


Figure 42. The patterns of measured and modelled evapotranspiration for the sugarcane crop simulated at Seven Oaks.

There is reasonable correspondence in the seasonal rise and fall of measured and modelled ET. However, in both years, the simulated rise in daily ET during early summer increases more slowly than for the measured values, while in late summer/autumn, the simulated ET rates decrease more slowly than the measured rates. A possible reason for this discrepancy is that WAVES does not take into account within-season variation in leaf mortality and senescence. Leaves produced early in the growing season have a very low mortality rate, and are physiologically very active, whereas later in the growing season, leaf physiological activity decreases, and the mortality rates of leaves increase. Late summer ET is consequently over-predicted, and this would explain why winter ET declines to zero in response to the complete depletion of available soil water, whereas measurements suggest that they remain around 1 mm or more. Reduced ET over late summer and autumn would conserve soil water, permitting continuation of ET at a low rate during winter. Similarly, the overprediction of ET during the pronounced dry spell in early 2000 may reflect the fact that too little soil water was removed from the soil in the first half of summer, leaving an excess to allow the sugarcane to maintain high rates of ET during the dry weather.

This simulation has demonstrated the usefulness of models such as WAVES in offering insights into constraints on rates of growth and transpiration. Further information on the carbon balance of this crop and certain key physiological parameters could enhance the realism of model predictions. Modifications to WAVES to account for changing leaf mortality rates and physiological activity are likely to also improve predictions.

6.11.2 Dryland Wheat (Western Cape)

Dryland wheat is grown extensively in the Western Cape. A site located in the wheat belt near the town of Riebeeck-Wes is currently being intensively researched as part of a WRC project on land use impacts on water resources in the Western Cape. We decided to make use of the descriptive climatic and soil data from this site to simulate a crop of wheat.

Daily rainfall data were obtained from rainfall station 0041681-W (MAP = 571 mm), and daily maximum and minimum temperature from station 0041651-A. A wheat parameter set was synthesized from Australian information reported by Slavich et al. (1998). A few changes to these parameter values were drawn from the international literature. These included setting the mean specific leaf area at 19 m^2 kg^{-1} dry matter (Van den Boogaard et al., 1997), and the optimum temperature for growth at 22^{o}C (Wang and Engel, 2002). A list of physiological parameter values is shown in appendix 1. The soil depth was set at 2 m, with a uniform sandy clay loam soil texture. A maximum rooting depth of 1.5 m was selected.

Growth was assumed to start from a low initial value on day 91 (1 April) of each year. The length of the growing season was specified by entering a value (25000) of degree-daylight hours. Harvest was assumed to occur on day 274 (1 October) of each year. Patterns of shoot and leaf area growth simulated over three seasons (1997 to 1999) and were compared to data reported by Wang and Engel (2002) and Asseng et al. (2004).

The modelled changing pattern of LAI over the season is typical of examples described by Wang et al. (2002) for wheat in three localities in Europe. LAI increased to a peak of approximately 5.5 at about 140 days after sowing, after which it declined as the plants senesced. Figure 43 shows the pattern of simulated ET for the period 1 January 1997 to 31 December 1999. Cumulative annual ET from time of planting to time of harvest for each year was 331, 320 and 384 mm for the years 1997, 1998 and 1999, respectively. Unfortunately no direct measurements of evapotranspiration from wheat in the Western Cape could be sourced for comparison to model simulations. However, the total ET simulated for each of the three growing seasons is similar to comparable results reported in the literature. For example, Ward et al. (2002) reported cumulative annual ET of around 380 mm for dryland winter wheat in south-western Australia at a site receiving a mean annual rainfall of 483 mm during the winter months.

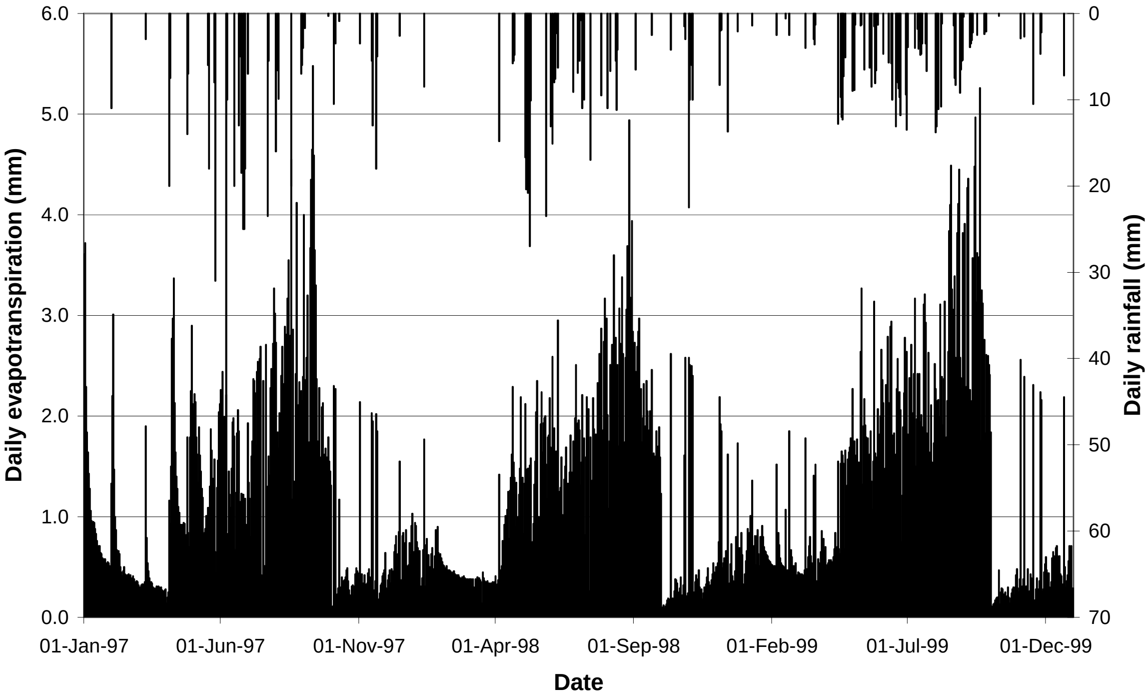


Figure 43. **The three-year pattern of daily evapotranspiration simulated for a wheat crop growing in Riebeeck Wes (Western Cape).**

6.12 Plantation forests

6.12.1 *Eucalyptus grandis* (Sabie)

Transpiration from four *Eucalyptus grandis* trees was reported from an experimental site in the vicinity of Sabie, Mpumalanga (Lat. 24^{o} 49' S, long. 30^{o} 43' E, alt. 950 m. a. m. s. l.). The purpose of the experiment was to investigate the relationship between soil water availability and transpiration rates of *E. grandis* plantations, and was initiated in June 1992 in a stand of three-year-old trees planted at a spacing of 3.5 m by 3.5 m. LAI of the stand was measured at intervals during the course of the experiment, and averaged 4. The well-drained soil is of granitic origin and is classified as a Hutton (Soil Classification Working Group, 1991). Deep drilling showed the subsoil at this site to extend beyond 30 m (Dye, 1996; Dye et al., 1997). The A horizon soil texture is a sandy clay loam, grading into a sandy clay with depth. The mean annual rainfall is 1459 mm, most of which falls in the summer months. The mean annual temperature is 18.1 ^{o}C. Plastic sheeting was laid out in a 30 m by 30 m area centred on four sample trees, with the aim of preventing soil water recharge and inducing a progressive drying of the soil by tree roots. See Dye (1996b) and Dye et al. (1997) for further details. An automatic weather station was mounted on the highest frame of a scaffolding tower erected near the centre of the experimental plot. The height of the tower was periodically increased to a maximum height of 23 m, to maintain it at approximately 1 m above the tallest adjacent tree.

A significant fact recorded at this site was that the trees experienced no water stress at any time of the year. This was demonstrated by regular measurements of the pre-dawn water potential of the sample trees (Dye et al., 1997). This absence of water stress is attributed to the observed abstraction of soil water down to 8 m by these trees, and the probable deeper abstraction of soil water by the root systems. The whole-year pattern of transpiration (Figure 44) illustrates a relatively high rate of evaporation (~2.5 mm) during the dry winter months, and this is the main cause of the high annual transpiration (~1200 mm) recorded at this site. A steep spring-time increase in transpiration was recorded in response to rising temperatures, while peak daily transpiration rates around midsummer reached 6-7 mm. Transpiration declined thereafter in response to shorter day lengths, lower temperatures and lower VPD. The relation of leaf area to dry mass was investigated and reported to be 3.161 m^2 kg^{-1} (Dye and Olbrich, 1993).

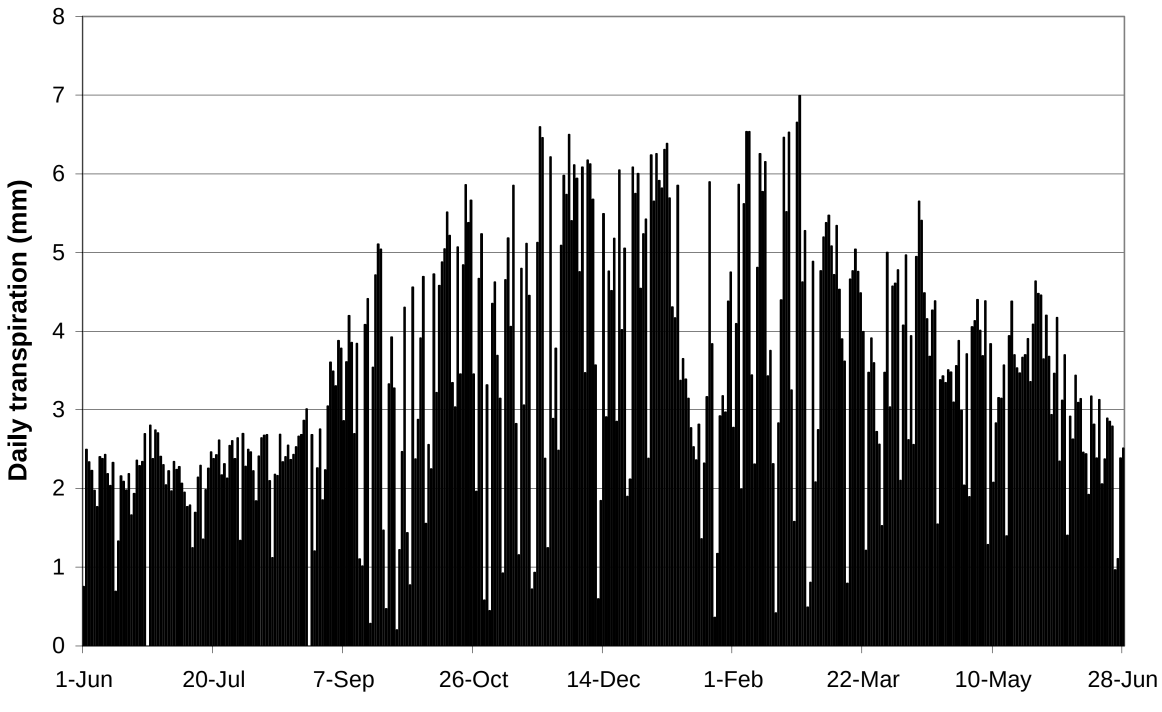


Figure 44. **Mean daily transpiration recorded in four *Eucalyptus grandis* trees in Frankfort plantation in the Sabie district of Mpumalanga for the period June 1992 to June 1993 (Dye et al., 1997).**

Since a maximum rooting depth of 4 m has been set in the new version of WAVES, the unusually deep root system of these trees could not be directly modelled. Instead, a 3.0 m water table was specified to ensure that the trees had sufficient soil water throughout the simulation period. Rainfall and temperature data were those recorded at the D.R. de Wet Forest Research station (0555663-A) which is situated a short distance from the site. The value chosen for Initial leaf carbon (0.4 kg m^{-2}) ensured a realistic starting LAI of around 4.0. A nutrient index of 0.8 was appropriate for the relatively fertile soils of the site. A slope of 15% and an aspect of 180^o were specified to resemble the site. The soil texture was specified as a sand loam throughout its depth. Initial root carbon assumed the temperate coniferous pattern reported by Jackson et al. (1996).

Figure 45 illustrates the correspondence between measured and simulated cumulative transpiration over the period 1 June 1992 to 30 June 1993 (13 months). A brief divergence appears in January 1993, and corresponds to a noticeable drop in daily transpiration visible in Figure 44. This divergence is then maintained at the same level for the remainder of the sample year. The cause of the apparent decline in transpiration over this period is unknown, since it cannot be attributed to overcast and humid weather, or to a decline in pre-dawn xylem pressure potential. A possible explanation lies in the fact that the probes lie progressively deeper in the sapwood as the tree grows outward. In a fast growing species of tree such as *Eucalyptus grandis*, the probes have to be re-implanted every few months to reposition them at their correct depth beneath the cambium. It is quite possible that by January 1993, the probes lay too deep in the older section of the xylem, thus not sampling the younger, outer and more active zones of the sapwood, and therefore underestimating total sap flow. The probes were repositioned in February, and a normal pattern of transpiration was recorded thereafter. Leaf area index remained relatively constant over the simulation period, starting at 4.0, and varying seasonally between 3.3 and 4.2. This is believed to be a realistic pattern. Cumulative transpiration over the first 12 months of the 13 month simulation period amounted to 1347 mm.

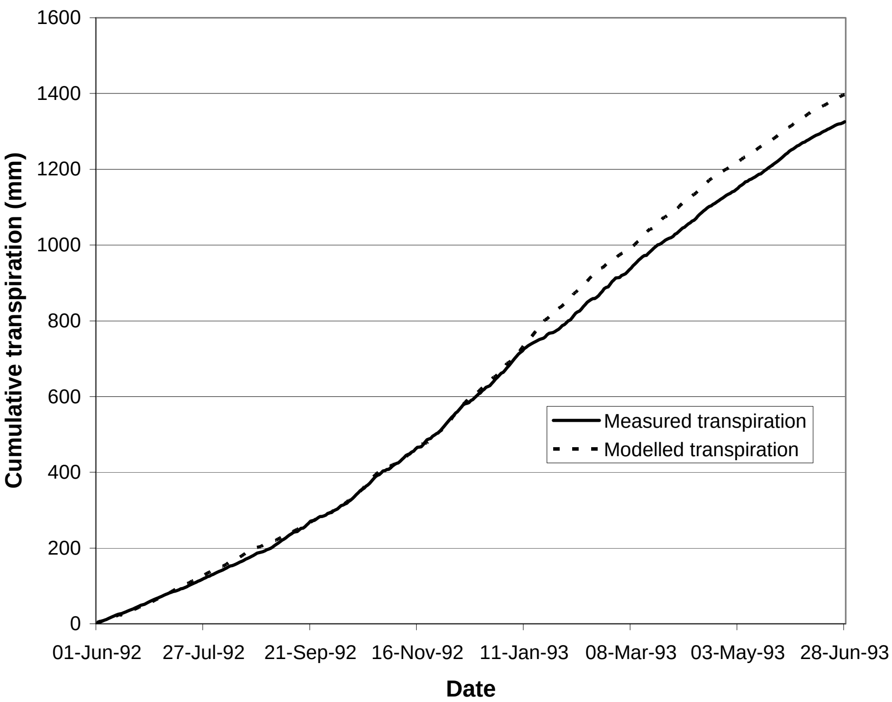


Figure 45. Measured and simulated daily transpiration at the *Eucalyptus grandis* site (Sabie) over the period 1 June 1992 to 30 June 1993.

6.12.2 *Pinus patula* (Usutu)

In 1981, an espacement trial was established in compartment C7 (26^o 25' S; 31^o 00' E) of Usutu forest, Swaziland. The altitude of the site is 1440 m.a.s.l, and estimated mean annual rainfall is 1124 mm. The well-drained granite-derived apedal soil (classified as Hutton / Clovelly; Soil Classification Working Group, 1991) is greater than 1000 mm in depth, and is predominantly a sandy clay loam, with a clay percentage of approximately 25 % in the A horizon and 30 % in the B horizon. The estimated site index for *P. patula* (based on height at age 15) is 19.2, and MAI_{10} is 23.4 m^3 ha^{-1} yr^{-1}. Growth of *P. patula* in plots planted at five different initial espacements (820, 950, 1116, 1333 and 1600 trees per hectare) were compared. A row spacing of 2.74 m was adopted in all plots, but within–row spacing of trees was 4.45, 3.84, 3.27, 2.74 or 2.29 m, depending on the planting density. Plots comprised 5 rows with 10 trees per row (50 trees). Regular annual growth measurements in each plot were performed on an inner block of 3 by 8 trees. The trial was terminated in 1995 when the 15-year-old trees were felled. Further details are available in Morris (1995a) and Morris (1995b). Tree growth in the plots initially planted at 1116 stems per hectare (SPH) was simulated in this study.

A nearby biomass trial provided useful data on the age-sequence pattern of growth and allometric relationships that are characteristic of this species (Morris, 1992). This source of data has been particularly valuable in parameterizing the model to produce realistic patterns of biomass accumulation (Dye, 1998).

No water use data are available for this *P. patula* site. The aim of the simulation was therefore to match the available biomass data, and to evaluate the resultant pattern of ET.

Rainfall data from a nearby station (Mushroom-Hlabanyati; 0482087-W) was chosen in view of the similarity of its MAP (1123 mm) to the estimate for the site supplied by SAPPI Forests. Temperature data were selected for Mbabane (0482229-W). As this station was at a lower altitude (1219 m.a.m.s.l.) than the simulation site (1440 m.a.m.s.l.), an altitude correction was specified in WAVES (SA).

The trees were planted in 1981. The simulation was set to start at age six and end at age seven. This age range was chosen to ensure that the canopies are fully developed. Table 16 lists the mean DBH, height and stand density (SPH – stems per hectare) at the start and end of the one year simulation period. These data were extracted from a report on the trial (Morris, 1995). Mean tree volume was calculated using a segmented polynomial model described by Kotze (1996). The remaining calculations were based on information contained in Morris (1992).

Model parameters were adjusted so that the simulated mass of foliage, stem (plus branches and bark), and roots matched the data in Table 16. Morris (1991) recorded only roots with a diameter greater than 20 mm. Bearing in mind that an appreciable fraction of carbon allocated to tree roots supports the fine root fraction which also has a high turnover rate (Cannell, 1985), the higher simulated root mass is not considered to be unrealistic.

Table 16. Steps leading to the calculation of the mass of foliage, stem and roots at the start and end of the one year simulation period of *Pinus patula*.

		Age 6	**Age 7**
Mean height (m)		10	11.4
Mean diameter at 1.3 m (cm)		15.6	17.0
Mean stem volume (m^3 $tree^{-1}$)		0.07818	0.1059
SPH		1058	1058
Stand stem volume (m^3 ha^{-1})		82.71	112.04
Wood basic density (t m^{-3})		0.305	0.305
Stand stem mass (t ha^{-1})		25.23	34.17
Fraction of branches + bark		1.2	1.2
Stem mass	(t DM ha^{-1})	55.51	75.17
	(kg DM m^{-2})	5.55	7.52
	(kg carbon m^{-2})	2.50	3.38
Leaf mass	(t DM ha^{-1})	10	10
	(kg DM m^{-2})	1	1
	(kg carbon m^{-2})	0.45	0.45
Root mass	(t DM ha^{-1})	6	7
	(kg DM m^{-2})	0.6	0.7
	(kg carbon m^{-2})	0.27	0.45

Figure 46 illustrates the pattern of evapotranspiration calculated for the stand of trees over the full year of simulation. It is characterised by very low rates of ET during the dry winter months, high rates over the summer months, and a pronounced mid-summer decline in ET. This decline corresponds to a dry spell of weather which is evident from the superimposed cumulative rainfall graph. Annual ET amounts to 944 mm, which is reasonably close to a figure of 1034 mm predicted by a global relationship developed by Zhang (1999a) for a site receiving 1357 mm of rainfall.

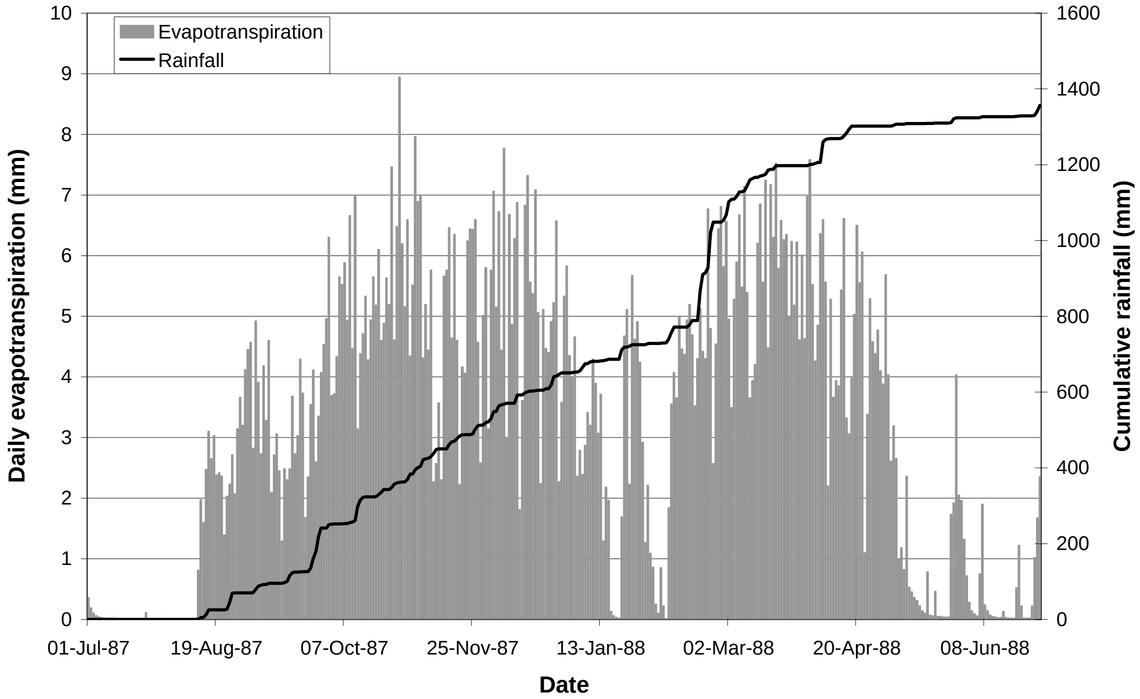


Figure 46. **The simulated pattern of daily evapotranspiration from *Pinus patula* at Usutu forest over the period 1 July 1987 to 30 June 1988.**

6.12.3 *Acacia mearnsii* (Seven Oaks)

Burger (1999) describes a study of ET from an *Acacia mearnsii* plantation in the Seven Oaks district of KwaZulu-Natal. The trees were planted in compartment B27 (44.7 ha) (30.647 ^{o}S, 29.183 ^{o}E) of the Mondi-owned Mistley Camera estate, at an altitude ranging from 1000 to 1100 m.a.m.s.l. The shortest distance from the Bowen ratio system (mounted on a tower to position the sensors above the tree canopies) to the edge of the compartment was greater than 500 m. The trees were planted in June 1996 at an initial espacement of 0.45 m. When ET measurements commenced in August 1997, the average canopy height was 1.1 m. Burger et al. (1999) reports that the leaf area index, as estimated with a Li-Cor Canopy Analyser, ranged from 2 to 3 over most of the study period. Figure 47 illustrates the pattern of ET recorded over the entire four-year monitoring period. Daily ET for periods of missing data was calculated on the basis of estimated canopy resistances and the Penman-Monteith equation. Winter-time ET rates are significant, and suggest an ability by the growing roots to abstract sufficient soil water to maintain high ET rates during the largely rainless winter months. Occasional summer-time peak daily ET rates in excess of 9 mm were recorded in all years, but rates were more commonly in the range of 7-8 mm d^{-1}.

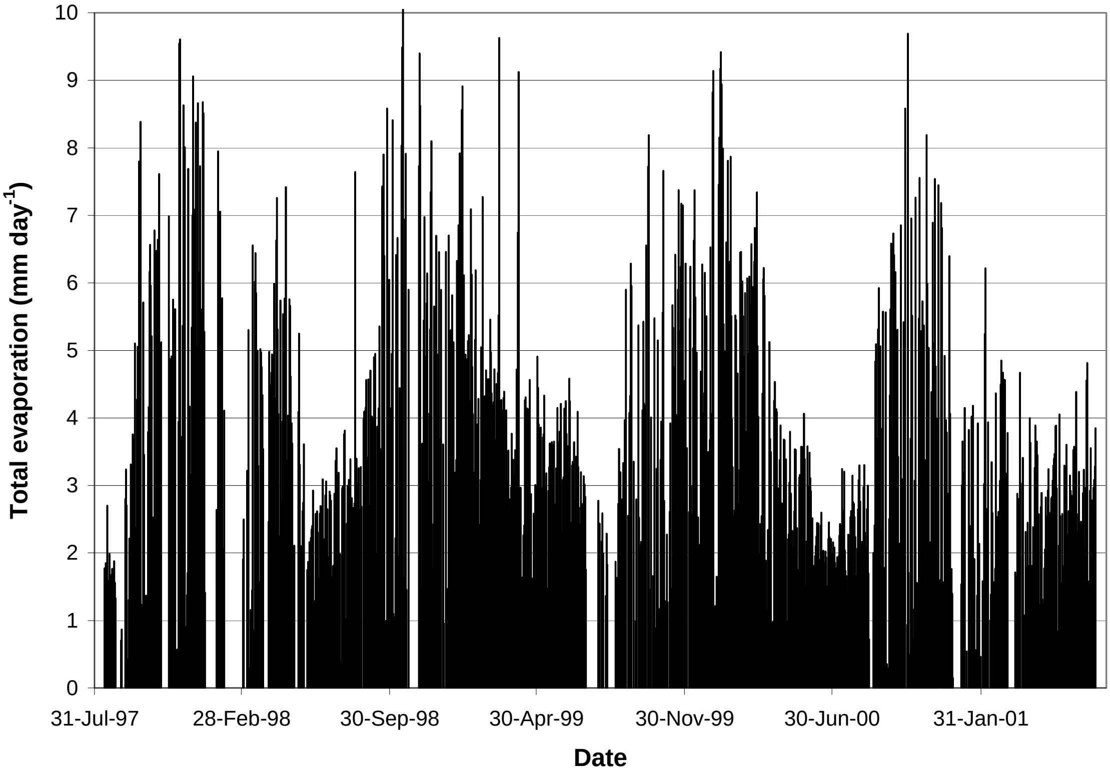


Figure 47. Patterns of daily ET recorded for an *Acacia mearnsii* plantation in the Seven Oaks district, KwaZulu-Natal, for the period 1 August 1997 to 30 July 2001.

The simulation period extended from August 1997 to August 2000, since no climate data beyond August 2000 were available in the WAVES climate database. Rainfall data were first sourced from Mistley Groenekop (0270282-W). However, it was discovered that no rainfall data were recorded between 27 October 1999 and 31 December 1999. This was considered to be most unlikely, given that December is well within the summer rainfall season. Rainfall for this same period was recorded at the Seven Oaks-Ryhill station. In view of this, rainfall and temperature data were both sourced from the Seven Oaks-Ryhill station (0270194-W).

Soil depth was assumed to extend down to 4 m, and consists predominantly of sandy clay loams. The leaf area index of the developing stand of trees was recorded at regular intervals over all three years, and varied from about three in the first half of summer to around two at most other times of the year.

It was immediately obvious that simulated winter ET dropped close to zero each year when the trees were reliant only on rainfall recharging the soil profile. Soil water accumulated during the summer months was rapidly depleted in autumn, effectively curtailing significant ET until further rains in spring. This pattern contrasted with the measured daily ET values that were consistently around 2-3 mm (Figure 47) during winter. The only way that this pattern could be approximated in WAVES (Figure 48) was to introduce a water table at 3.75 m below the surface near the bottom of the soil profile, and to ensure that the modelled root system extended down to this depth. This resulted in a higher simulated annual ET (Table 17) which exceeded annual rainfall, but still fell short of the annual ET based on Bowen Ratio measurements reported by Jarmain and Everson (2002).

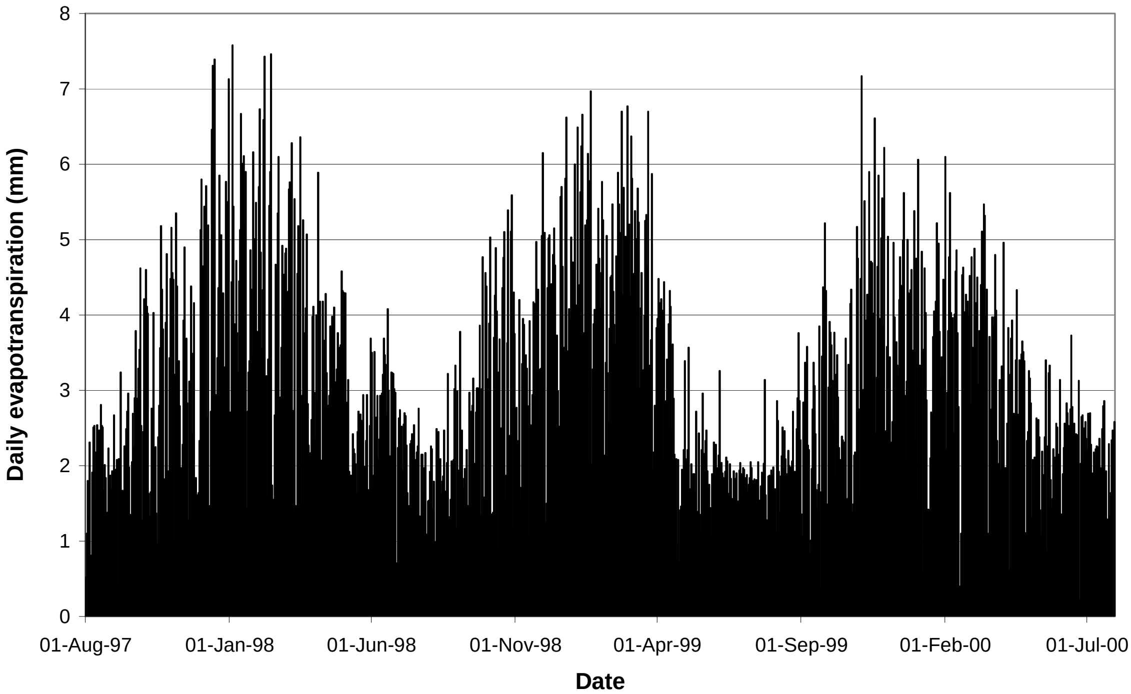


Figure 48. Patterns of daily ET simulated for an *Acacia mearnsii* plantation in the Seven Oaks district, KwaZulu-Natal, for the period 1 August 1997 to 30 July 2000.

Table 17. A comparison of annual rainfall, simulated ET and measured ET (based on Bowen Ratio measurements) over three years. Each year begins on 1 August and ends on 31 July.

	1997/1998	1998/1999	1999/2000
Rainfall(Seven Oaks)	834.5	592.7	658.4
Simulated ET	1118.5	1093.4	1062.4
Estimated from BR measurements	1240	1364	1239

This result is Intriguing, since it suggests either that the Bowen Ratio measurements were overestimating at times, or that the trees had access to a significant amount of additional water, over and above what fell as rain. The site is situated close to the crest of a hill, and therefore the potential for lateral influx of water from higher areas is considered to be small. There is a possibility that in earlier years before trees were planted on this site, the grassland or sugarcane crop would have used less water, resulting in greater deep drainage to deeper subsoil levels. This could have become accessible to the deep-rooting trees which were extending to greater depths early in their growth cycle. In view of indications of a similar discrepancy between Bowen Ratio measurements and model simulated ET at the Noodsberg thicket site, comparisons between Bowen Ratio and scintillometer or Eddy Covariance ET data recorded over forest plantations and woodlands are highly desirable.

The period from March to July 1999 was noted by Burger et al. (1999) as being unusually hot and dry. This is evident in Figure 48, where the trend in daily ET drops noticeably over this period.

6.12.4 *Populus deltoides* (Greytown)

Dye et al. (1996) describe a study of sap flow in five Poplar sample trees growing on the property Sheepmoor Estate (Lion Match) in the vicinity of Piet Retief. The altitude of the site is approximately 1500 m.a.m.s.l. The study site was located in compartment 2A at a position close to a perennial stream. The trees were planted in 1976, and were 20 years old at the time of the study. The initial planting espacement was 4 m X 4 m, and the stand was thinned once to 330 stems per hectare. Six sample trees considered representative of the compartment were chosen for continuous sap flow monitoring through the growing season. Mean DBH of the five sample trees was 353 mm, while the mean height of two of the sample trees which were felled was 22.4 m. Sap flow rates were monitored continuously from 9 September 1995 to 21 February 1996. Four probes sets were implanted into each sample tree, to depths of 8, 15, 22 and 31 mm below the cambium. Hourly sap flow rates recorded between 05h00 and 19h00 each day. Two sample trees were felled at the conclusion of the study to determine the various sapwood characteristics required to derive sap flow from heat pulse measurements. The sapwood cross-section revealed a dark-stained central heartwood, surrounded by a slightly discoloured ring of wood with a smooth texture and without clearly defined rings of vessels. Both these zones stained lightly with methyl orange, indicating the presence of tyloses. The outermost 45 mm was light coloured and characterized by well defined narrow rings of large vessels. The latter portion of the cross-section was taken to be the functional sapwood, which averaged 45 mm in width.

The mean daily sap flow of all six sample trees, for the greater part of the growing season, is shown in Figure 49. The pattern reveals a rapid increase in daily water use in early spring as the leaves emerge and rapidly enlarge to their full size. The data show that substantial sap flow rates occur even before the leaves were observed to be fully expanded. Peak rates of daily water use occurred in late November and December, when the rainfall equivalent for the stand as a whole exceeded 8 mm per day. This is equivalent to a mean daily sap flow of approximately 250 litres per day. A steep decrease in daily sap flow commenced in early January. This is attributed to the development of pathogenic rust on the leaves. The fungal hyphae grow through the stomata and reduce the rate of evaporation of water from the leaves. Sap flow rates appear to have stabilized by the end of January at a relatively low rate, but it is expected to slowly decline as the leaves senesce and are ultimately shed at the start of winter. The total mean water use over the period of measurement was 735 mm. The dashed lines in figure 49 indicate the estimated mean water use before (20 mm) and after (63 mm) the period of measurement. The total seasonal water use was thus estimated to be 818 mm. The water use of the stand as a whole will have been somewhat higher, in view of the dense understorey of grass and small shrubs that occupied the site.

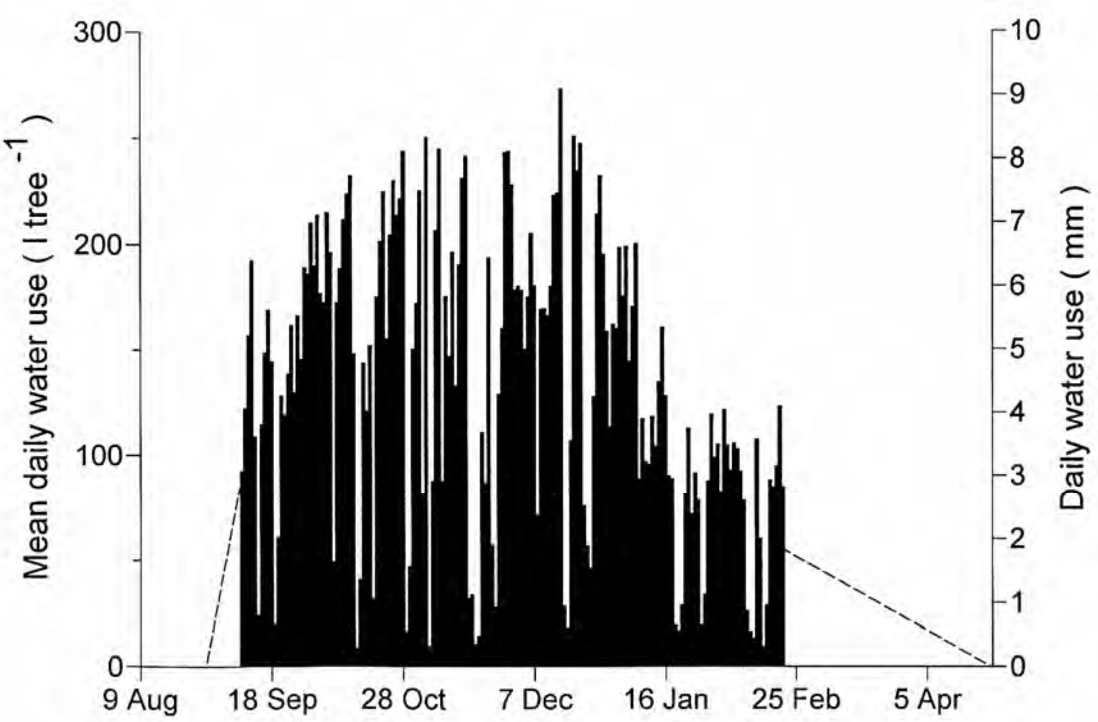


Figure 49. **The seasonal trend in mean daily transpiration recorded in six sample trees of *Populus deltoids* growing on Sheepmore estate during the 1995/96 season.**

Additional measurements were performed on sample trees of this species on Redclyffe plantation in the vicinity of Greytown (Dye et al., 1995). The site altitude was 975 m.a.m.s.l. The sample trees (clone 60/129) were planted in 1973, and were thus 22 years old at the time of first sap flow measurements, and of a similar age and appearance to the stand on Sheepmoor Estate. The planting espacement was 3.65 m, and the stand was thinned in October 1985 to 300 stems per hectare (sph). Mean DBH and height of the five sample trees was 48 cm and 33 m, respectively. The fresh leaf mass stripped from a harvested tree was found to be 70.5 kg. The area and fresh mass of leaves was determined for a 268 g sub-sample of leaves (petioles removed) and showed that 1 kg of leaves was equivalent to a leaf area of 4.89 m^2. Thus, 1 kg of carbon is equivalent to approximately 11 m^2 of leaf area.

Figure 50 illustrates the pattern of daily transpiration simulated by WAVES for this species. Rainfall and temperature data were taken from a station at Piet Retief (0444540-W). A clay loam soil profile, a water table at 2 m beneath the surface, and no understorey canopy were additional assumptions.

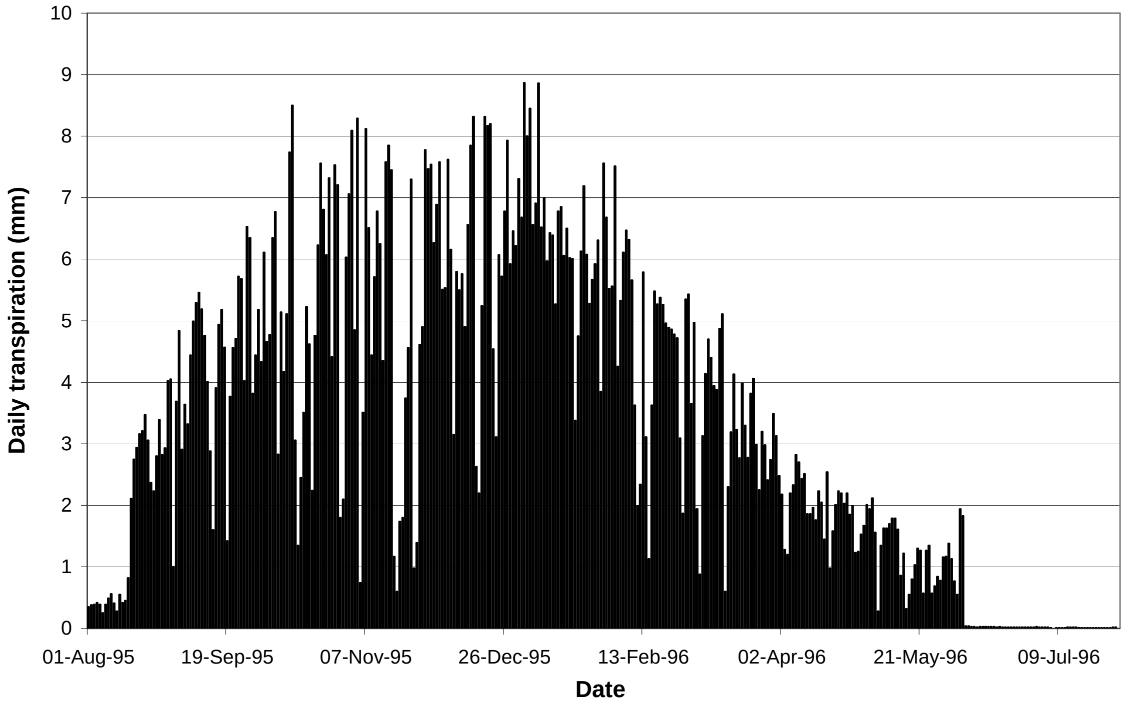


Figure 50. **Simulated daily ET from *Populus deltoids* over the period 1 August 1995 to 31 July 1996.**

The overall modelled pattern matches the observed pattern (Figure 49) to a reasonable degree. There is a rapid build-up of leaf area in early spring that is supported by translocation from stem to leaf. Maximum daily transpiration over the period October to January lies in the range of 6-8 mm per day, which is relatively high because of a high leaf area (peaking at 5) and a high canopy conductance (peaking at 0.03 m s^{-1}, ignoring occasional “spikes”). A short period of low daily transpiration in November is visible in both figures 34 and 35, and is due to humid, overcast weather. A comparison of cumulative transpiration was not possible because of the loss of the original field data.

The simulation did, however, highlight two shortcomings in the WAVES simulation: It was difficult to simulate the rapid decline in transpiration and leaf area at the end of the growing season. WAVES uses a constant leaf mortality rate, whereas in the case of deciduous trees like Poplar, leaf mortality should increase greatly at the end of the season.

A noticeable feature of the data in Figure 49 is the step down in daily transpiration to 3 mm d^{-1} that occurs in January. As noted above, this is believed to be caused by a rust fungus that appeared at this time in the season, and reduces stomatal conductance by blocking the stomata. This is a good example of how transpiration patterns can be modified by the presence of pest organisms.

7. DISCUSSION AND CONCLUSIONS

7.1 The project aim

The aim of this project was to develop a relatively simple framework of understanding of annual ET patterns shown by a wide variety of land covers in South Africa, and to translate this framework into a user-friendly form permitting predictions of vegetation ET by non-specialist users. After a period of investigation of the various possible options, it was decided to use the WAVES ecohydrological model for this purpose. This model was designed specifically to portray the effects of land cover change on site water balances, and emphasis is placed on simulating the carbon balance of the vegetation, and the water balance of the site. While the plant growth module is relatively simple compared to many other plant growth models, it nevertheless allows the quantity of green leaf to be adequately simulated over time, and models the various constraints imposed on both growth and transpiration. WAVES has generally performed realistically despite the lack of rigorous parameterisation at most sites, and has met the requirement of providing a framework of understanding. It is hoped that further use and development of WAVES will lead to a greatly increased understanding of differences in ET over the full range of land covers in South Africa.

7.2 Controls on ET

A fundamental requirement of this study was to identify the various biophysical limits imposed on crops, forest plantations and indigenous vegetation that control rates of ET. While direct field measurements of ET and transpiration from various land covers have been relatively few in South Africa, available data sets indicate that annual water use is strongly related to the proportion of the year in which a dense canopy of transpiring leaves is maintained. Thus, vegetation able to maintain a dense canopy of transpiring leaves throughout the year, such as the deep rooting *Eucalyptus grandis* stand and the Jonkershoek riparian Fynbos, exhibit a high annual water use. In contrast, grasslands maintain their maximum canopy cover of live leaves for a relatively short period of the year, even under conditions of sufficient soil water availability, and this greatly restricts their annual water use.

The maximum rate of daily ET attained under favourable growth conditions is less variable among the various land covers than the period of active growth and transpiration, and commonly ranges from 5-8 mm d^{-1} in mid-summer. This maximum is generally close to the limit set by the availability of energy at the site. Plants have generally adapted their stomatal conductances to permit transpiration to occur close to this maximum rate. In the case of well-ventilated and aerodynamically rough tree canopies, aerodynamic resistance to diffusion of water vapour from leaves is low, and stomatal resistances are relatively high. Conversely, plants of low stature are associated with a relatively high aerodynamic resistance, and so stomatal resistances are correspondingly low (Figure 6.6, Jones, 1983). WAVES accounts for the differences in aerodynamic resistance and canopy resistance.

Over most of South Africa, conditions for plant growth vary greatly over the different seasons. Soil water availability is a major limit to growth and transpiration due to seasonal rainfall. Process-based models such as WAVES are able to keep track of the site water balance, and can therefore predict the availability of soil water on any given day. Soil water depletion is often the principal limit to ET towards the end of a growing season, hastening the senescence and dieback of green leaves and shutting down transpiration.

The timing of rainfall in relation to season is of obvious importance. Growth and ET of non-riparian vegetation in the winter rainfall regions is largely confined to winter, since the summer is too dry to sustain active plant growth. ET is therefore constrained by short day lengths and reduced solar radiation, and also by relatively low VPD resulting from low temperatures and high relative humidity. The occurrence of frost and fire are also important limits to plant ET, both killing off live, transpiring leaves. The effects of these limits have been incorporated into WAVES.

WAVES is designed to take into account the effects of high soil salinity in reducing plant growth and water use. High levels of salinity are characteristic of sites affected by acid mine drainage. It is important to realise that the WAVES model assumes that the dominant salt is chloride

7.3 The need for more field data

The accuracy with which WAVES is parameterised depends to a large extent on the available field data. The Bellevue grassland study is an example of a situation where high quality field data for ET, weather conditions and biomass accumulation permits a more rigorous model parameterisation process. In many of the other case studies, field data are less comprehensive, limiting the accuracy with which WAVES may be parameterised. In this study, we have recognized this limitation, but nevertheless evaluated whether our best estimates of the required model parameter values give rise to realistic patterns of ET and whole-year cumulative ET.

8. RECOMMENDATIONS

It is believed that the new version of WAVES will be useful to a wide variety of researchers, water resource managers, conservationists and students. Inevitably, however, there is much scope for future testing, development and enhancements that would improve its usefulness. Some of these are identified below:

- More intensive model testing is required to identify possible programming bugs, and ensure flawless simulations under all possible set-up conditions.
- Development of additional graphical outputs and ET summaries, to permit easier comparison of different land cover scenarios.
- Investigate linking ET changes to streamflow in a spatial context.
- Parameterise more vegetation types for inclusion in the product. It appears that a high priority should be given to further species of alien invasive plants that are suspected of bringing about significant hydrological changes. The water use of aquifer-dependent vegetation in the drier parts of the country is also an important priority, in view of the scarcity of direct measurements of ET and the importance of regulating aquifer utilization to avoid permanent damage to such valuable ecosystems. The measurement of ET in the past has been fraught with technical difficulties, requiring a high degree of diligence and effort in maintaining equipment. The recent availability of scintillometer systems allows better quality ET data to be gathered. Two major advantages are that the instruments are less prone to mechanical and electronic problems, and they provide spatially averaged data from extensive beam paths. Their use in future ET studies should make the gathering of field data less complex and cheaper to undertake.
- Further studies of those aspects of the structure and physiology of South African vegetation types that relate to the processes of growth and transpiration are necessary to put WAVES (SA) simulations on a firmer footing. This will reduce the level of uncertainty regarding those parameter values that are presently poorly quantified, permitting greater insights into plant functioning and improved predictive capability.
- There are also likely to be many subtleties in plant functional attributes that are not captured by the current plant parameter sets and model structure, which will require the attention of researchers in the future. Some of these problem areas (e.g. accelerated leaf senescence rates, pathogenic effects on canopy conductance, changes to the normal pattern of carbon allocation, the influence of deep roots in preventing extreme plant water deficits) are identified in the various simulations. We believe, however, that the current parameter sets for the various “plant functional types” serve as a useful statement of our present understanding of the constraints on plant growth and water use, and will encourage others to identify problem areas and improve on the current model predictive capability.

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APPENDIX 1:
WAVES vegetation parameter values

Vegetation type		**Grassland**		
District		**Pietermaritzburg**	**Cathedral Peak**	**George**
Dominant genus		***Diheteropogon***	***Themeda***	**Unspecified**
Parameter	**Units**			
1-albedo of the canopy		0.75	0.85	0.85
1-albedo of the soil		0.85	0.85	0.85
Rainfall interception coefficient	m LAI^{-1} d^{-1}	0.0003	0.0003	0.0003
Light extinction coefficient		-0.6	-0.65	-0.65
Maximum carbon assimilation rate	kg C m^{-2} d^{-1}	0.017	0.03	0.015
Slope parameter for conductance model		1	1.1	0.9
Maximum plant available soil water potential	m	-200	-150	-150
IRM weighting of water		2.1	3.0	2.0
IRM weighting of nutrients		0.5	0.5	0.5
Ratio of stomatal to mesophyll conductance		0.8	0.8	0.2
Temperature when growth is ½ of optimum	^{o}C	15	15	10
Temperature when growth is optimum	^{o}C	30	25	25
Year day of germination	d	-	-	-
Degree-daylight hours for growth	^{o}C hr	-	-	-
Saturation light intensity of sunlit leaves	µmol m^{-2} s^{-1}	1500	1200	1000
Maximum rooting depth	m	1.4	1.4	1.2
Specific leaf area	m^2 $(kg C)^{-1}$	18	24	24
Leaf respiration coefficient	kg C kg C^{-1} d^{-1}	0.0002	0.0001	0.001
Stem respiration coefficient	kg C kg C^{-1} d^{-1}	0.0004	0.0001	0.0001
Root respiration coefficient	kg C kg C^{-1} d^{-1}	0.00012	0.00001	0.001
Leaf mortality rate	kg kg^{-1} d^{-1}	0.001	0.015	0.01
Above-ground partitioning factor		-	-	-
Salt sensitivity factor		1	1	1
Aerodynamic resistance	s m^{-1}	50	50	70
Soil nutrient index		0.6	0.7	0.5
Weekly carbon allocation		√	√	√
Spring carbon allocation		√	√	√
Frost effect		√	√	X

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	^oC	15	15	15	15	10	10
Temperature when growth is optimum	^oC	30	30	30	30	25	25
Year day of germination	d	-	-	-	-	-	-
Degree-daylight hours for growth	^oC hr	-	-	-	-	-	-
Saturation light intensity of sunlit leaves	µmol m^{-2} s^{-1}	1200	1800	1200	1200	1800	1000
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

Vegetation type		Fynbos		Wetlands		AIP
District		**Helderberg**	**Jonkershoek**	**Orkney**	**Gilboa**	**Wellington**
Dominant genus / species		***Protea***	***Pteridium***	***Phragmites***	***Andropogon***	***Acacia mearnsii***
Parameters	**Units**					
1-albedo of the canopy		0.85	0.85	0.85	0.85	0.85
1-albedo of the soil		0.75	0.85	0.85	0.85	0.85
Rainfall interception coefficient	m LAI^{-1} d^{-1}	0.0001	0.0003	0.0003	0.0003	0.0003
Light extinction coefficient		-0.85	-0.5	-0.5	-0.65	-0.5
Maximum carbon assimilation rate	kg C m^{-2} d^{-1}	0.01	0.02	0.03	0.02	0.015
Slope parameter for conductance model		1	1	1	1.1	1
Maximum plant available soil water potential	m	-300	-150	-150	-150	-200
IRM weighting of water		2.0	2.1	2.1	3.0	2.1
IRM weighting of nutrients		0.5	0.5	0.5	0.5	0.5
Ratio of stomatal to mesophyll conductance		0.2	0.2	0.2	0.2	0.2
Temperature when growth is ½ of optimum	^{o}C	10	10	15	15	15
Temperature when growth is optimum	^{o}C	25	25	30	25	30
Year day of germination	d	-	-	-	-	-
Degree-daylight hours for growth	^{o}C hr	-	-	-	-	-
Saturation light intensity of sunlit leaves	µmol m^{-2} s^{-1}	1500	1200	1800	1200	1200
Maximum rooting depth	m	4.0	1.6	1.2	1.5	4.0
Specific leaf area	m^2 (kg C)$^{-1}$	18	10	10	24	15
Leaf respiration coefficient	kg C kg C^{-1} d^{-1}	0.0005	0.005	0.0001	0.0001	0.0001
Stem respiration coefficient	kg C kg C^{-1} d^{-1}	0.0001	0.00001	0.00005	0.0001	0.00001
Root respiration coefficient	kg C kg C^{-1} d^{-1}	0.0002	0.0002	0.0002	0.00001	0.00002
Leaf mortality rate	kg kg^{-1} d^{-1}	0.001	0.001	0.0074	0.015	0.001
Above-ground partitioning factor		-	0.7	-	-	-
Salt sensitivity factor		1	1	1	1	1
Aerodynamic resistance	s m^{-1}	30	40	40	50	15
Soil nutrient index		0.7	0.8	0.6	0.7	0.7
Weekly carbon allocation		√	X	√	√	√
Spring carbon allocation		√	X	√	√	X
Frost effect		X	X	√	√	X

Vegetation type		**AIP**	**Dryland crops**	
District		**Somerset West**	**Seven Oaks**	**Riebeek Wes**
Dominant species		***Hakea dupracea***	***Saccharum officinarum***	***Triticum aestivum***
Parameters	**Units**			
1-albedo of the canopy		0.85	0.85	0.85
1-albedo of the soil		0.75	0.85	0.85
Rainfall interception coefficient	m LAI^{-1} d^{-1}	0.0001	0.0003	0.0003
Light extinction coefficient		-0.85	-0.38	-0.65
Maximum carbon assimilation rate	kg C m^{-2} d^{-1}	0.015	0.12	0.025
Slope parameter for conductance model		1	1.2	1.1
Maximum plant available soil water potential	m	-200	-150	-200
IRM weighting of water		1.5	2.1	2.1
IRM weighting of nutrients		0.5	0.5	0.5
Ratio of stomatal to mesophyll conductance		0.2	0.8	0.2
Temperature when growth is ½ of optimum	^oC	10	15	10
Temperature when growth is optimum	^oC	25	30	23
Year day of germination	d	-	-	91
Degree-daylight hours for growth	^oC hr	-	-	25000
Saturation light intensity of sunlit leaves	µmol m^{-2} s^{-1}	1200	1650	1200
Maximum rooting depth	m	1.0	1.4	1.5
Specific leaf area	m^2 $(kg\ C)^{-1}$	12	10	42
Leaf respiration coefficient	kg C kg C^{-1} d^{-1}	0.0005	0.0001	0.0001
Stem respiration coefficient	kg C kg C^{-1} d^{-1}	0.0001	0.00001	0.00001
Root respiration coefficient	kg C kg C^{-1} d^{-1}	0.0002	0.0002	0.0002
Leaf mortality rate	kg kg^{-1} d^{-1}	0.001	0.002	0.001
Above-ground partitioning factor		0.5	-	-
Salt sensitivity factor		1	1	1
Aerodynamic resistance	s m^{-1}	10	40	50
Soil nutrient index		0.5	0.8	0.6
Weekly carbon allocation		X	√	√
Spring carbon allocation		X	√	X
Frost effect		X	√	X

Vegetation type		**Plantation forest**			
District		**Sabie**	**Usutu**	**Seven Oaks**	**Greytown**
Dominant species		***Eucalyptus grandis***	***Pinus patula***	***Acacia mearnsii***	***Populus deltoides***
Parameters	**Units**				
1-albedo of the canopy		0.85	0.85	0.85	0.85
1-albedo of the soil		0.85	0.85	0.85	0.85
Rainfall interception coefficient	m LAI^{-1} d^{-1}	0.0003	0.0003	0.0003	0.0003
Light extinction coefficient		-0.5	-0.5	-0.5	-0.5
Maximum carbon assimilation rate	kg C m^{-2} d^{-1}	0.04	0.03	0.015	0.04
Slope parameter for conductance model		0.9	1	1	1
Maximum plant available soil water potential	m	-150	-150	-200	-150
IRM weighting of water		2.1	2.1	2.1	2.1
IRM weighting of nutrients		0.5	0.5	0.5	0.5
Ratio of stomatal to mesophyll conductance		0.2	0.2	0.2	0.2
Temperature when growth is ½ of optimum	^{o}C	15	15	15	15
Temperature when growth is optimum	^{o}C	30	30	30	30
Year day of germination	d	-1	-1	-1	-1
Degree-daylight hours for growth	^{o}C hr	-1	-1	-1	-1
Saturation light intensity of sunlit leaves	µmol m^{-2} s^{-1}	1200	1200	1200	1200
Maximum rooting depth	m	4	3	4	2.0
Specific leaf area	m^2 $(kg\ C)^{-1}$	10	12	15	11
Leaf respiration coefficient	kg C kg C^{-1} d^{-1}	0.001	0.0001	0.0001	0.0001
Stem respiration coefficient	kg C kg C^{-1} d^{-1}	0.00001	0.00001	0.00001	0.0001
Root respiration coefficient	kg C kg C^{-1} d^{-1}	0.00002	0.001	0.00002	0.0001
Leaf mortality rate	kg kg^{-1} d^{-1}	0.001	0.001	0.001	0.02
Above-ground partitioning factor		-	-	-	-
Salt sensitivity factor		1	1	1	1
Aerodynamic resistance	s m^{-1}	15	10	15	10
Soil nutrient index		0.8	0.7	0.6	0.8
Weekly carbon allocation		√	√	√	√
Spring carbon allocation		X	X	X	√
Frost effect		X	X	X	√