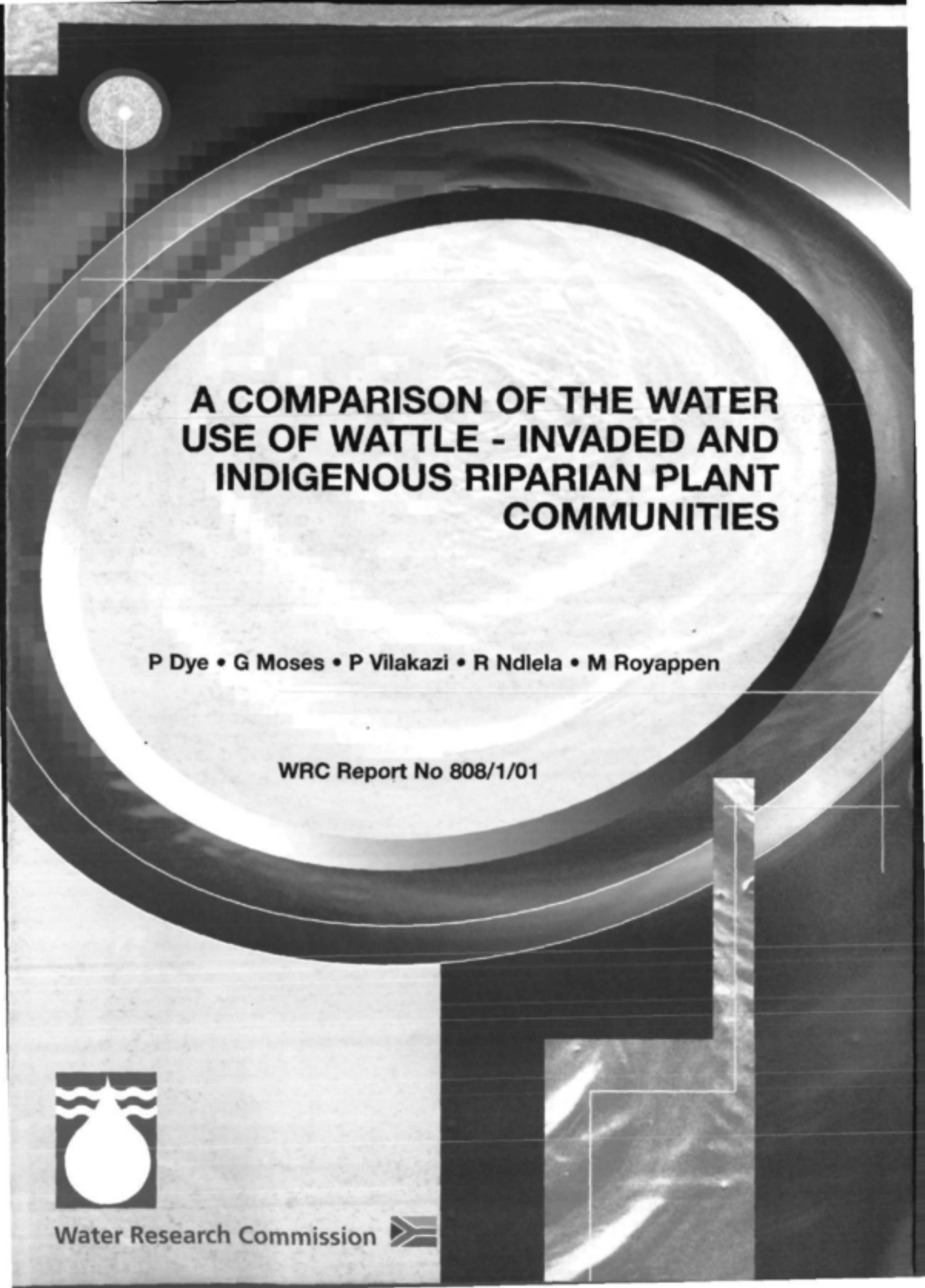

A COMPARISON OF THE WATER USE OF WATTLE - INVADED AND INDIGENOUS RIPARIAN PLANT COMMUNITIES

P Dye • G Moses • P Vilakazi • R Ndlela • M Royappen

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Water Research Commission

A COMPARISON OF THE WATER USE OF WATTLE-INVADED AND INDIGENOUS RIPARIAN PLANT COMMUNITIES

REPORT TO THE WATER RESEARCH COMMISSION

by
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EXECUTIVE SUMMARY

INTRODUCTION

Several recent developments in South Africa have highlighted the need for better information on the water use of trees in riparian zones. The declaration of plantation forestry as a streamflow reducing activity (SFRA) has served to maintain interest in the issue of forest water use, and the extent to which their impact on catchment water yields may be minimized. One long-recognized option is to remove plantations a set distance away from streams, and promote indigenous, preferably herbaceous vegetation in its place. The trend towards forest certification has further encouraged growers to adopt this practice as a means of minimizing the hydrological impacts of their forests on catchment yields, and promoting the sustainability of their forestry enterprise.

It is, however, the problem of self-established alien invasive trees that has received the most publicity in recent years. Large scale funding by both the Government and the private sector continues in support of the Working For Water programme, which is active in many regions of the country. One justification for this programme of alien tree removal is the streamflow enhancement that is believed to follow the replacement of dense stands of invasive trees by indigenous, largely herbaceous or shrub-dominated plant communities. Often the densest stands of invader trees occur within riparian zones, where removal of trees in close proximity to stream channels is believed to strongly enhance streamflow.

Few data are available to quantify these assumptions. Portable weir experiments (Dye and Poulter, 1995; Prinsloo and Scott, 1999) document streamflow enhancement immediately following the clearance of trees, but do not take into account water use by the indigenous plant community that with time subsequently develops on the site. Scott and Lesch (1995) report changes in streamflow following clearance of riparian trees in four research catchments. Their paper illustrates how variable streamflow response may be to this treatment, and how important the characteristics of the post-felling vegetation are in determining this response.

Results from a number of research catchments have consistently shown that catchment-wide afforestation significantly decreases streamflow where the pre-afforestation vegetation was seasonally dormant mountain grassland or fynbos (Versfeld, 1994). The net difference in evapotranspiration (ET) between **riparian** thickets or plantations of alien trees and indigenous **riparian** vegetation may be quite different, however, due to the yearlong availability of soil water and enhanced plant growth in riparian zones, and the occurrence of many different types of indigenous riparian vegetation. The water use characteristics of thickets of alien self-established trees in South Africa remains largely unknown, adding further uncertainty to the effect of alien tree removal on streamflow.

OBJECTIVES

The objectives of this study were:

- To record the annual pattern of water use of the most widespread alien invasive tree species occurring in riparian zones in both the summer and winter rainfall regions of the country.
- To record the annual pattern of water use of indigenous riparian plant communities with which to compare to the alien invasive communities.
- To summarise the annual reduction in water use by riparian vegetation that can be achieved through the removal of alien invasive trees.

METHODOLOGY AND RESULTS

A riparian fynbos site was chosen in the upper reaches of the Jonkershoek valley, close to the Eerste River that flows past Stellenbosch. A 12-month record of 20-minute evaporation rates from this site was recorded using the Bowen ratio energy balance (BREB) technique. A closed-canopy, mature stand of self-established wattle in the Wellington area of the Western Cape was selected to provide comparative water use data. The heat pulse velocity technique was used to record hourly sap flow rates in six sample trees representing the range of tree sizes in the thicket. Total daily sap flow in all sample trees was closely correlated to a daily air humidity index defined as the product of mean daily vapour pressure deficit (VPD) of the air and the number of daylight hours. A wildfire destroyed the sample trees after seven months of data collection. However, the daily sap flow/VPD index relation was found to be constant over the entire data record, which spanned both wet conditions in late winter, and very hot and dry conditions in late summer, indicating an absence of stress due to soil water deficits. It was assumed therefore that the same relationship would hold throughout an entire year, and could be used to predict wattle transpiration at the Jonkershoek site using the VPD data recorded there by the BREB system.

A replacement *A. mearnsii* riparian site was chosen on the slopes of the Groot Drakenstein mountains close to Pniel in the Stellenbosch district. Hourly sap flow was monitored in six sample trees over a period of seven months, until the experiment was terminated by another wild fire. Daily sap flow over the entire period of measurement showed a distinct and progressive reduction over the second half of the dry summer, which is shown to be caused by stress due to soil water deficits. Sap flow rates recorded over the period prior to the commencement of transpiration reduction were found to be very similar to those recorded at the Wellington site. Both data sets were used to develop a simple model of daily sap flow (under conditions of no water stress) for this species on the basis of tree DBH and the product of mean daily VPD and the number of daylight hours.

This model of daily sap flow by *A. mearnsii* was used to predict the annual transpiration of a thicket of this species at the Jonkershoek site. Rainfall interception by the canopies was predicted from the number of rain days recorded at Jonkershoek, and daily rainfall interception estimates for this species provided by Schulze *et al.* (1995)

In the summer rainfall region, the annual ET of riparian grassland at Gilboa forest plantation in the Karkloof hills of the KwaZulu-Natal midlands was estimated from 20 minute Bowen ratio data over a full growing season. Six months of hourly sap flow data were recorded in five sample trees growing within a riparian zone situated in a mature *A. mearnsii* compartment on Mistley-Canema plantation in the Seven Oaks district. Instrument problems at the Gilboa site caused gaps in the data record during the mid-summer period. A model of daily ET based on daily solar radiation and an empirical leaf area function provided satisfactory patching. Problems were experienced with the heat pulse measurements at Seven Oaks. Sap flow measurements declined with time to unusually low levels. Examination of sectioned stems at the conclusion of the monitoring period revealed heavy resin impregnation of the region surrounding the probe positions. Comparison of sap flow rates recorded over the first four to eight weeks (presumed to be the least affected by the wound reaction), to those recorded in the Western Cape, showed the Seven Oaks trees to be transpiring at relatively low rates. Possible reasons for this are discussed, and the most likely is believed to be the result of heavy defoliation of the canopies by a high population of bagworm observed in the area.

In view of the difficulties associated with the Seven Oaks plantation data, the *A. mearnsii* model developed from the Western Cape sites was used, together with daily mean VPD data from Gilboa, to predict annual transpiration of *A. mearnsii* at this site. Rainfall interception by the canopies was again estimated from the number of rain days recorded at the site, and daily rainfall interception estimates for this species provided by Schulze *et al.* (1995)

Table I summarises the annual ET recorded or modelled at each site.

TABLE I: A summary of transpiration and rainfall interception estimates recorded or modelled at the study sites.

Locality	***Vegetation***	***Annual water use (mm)***			
		Transpiration	***Rainfall Interception***	***ET***	***Difference***
Jonkershoek	*A. mearnsii*	1304	171	1475	143
	Fynbos			1332	
Gilboa	*A. mearnsii*	1188	183	1371	535
	Grassland			836	

CONCLUSIONS AND RECOMMENDATIONS

The principle conclusions and recommendations arising from this project are as follows:

- Reduction in annual ET following removal of *A. mearnsii* from riparian zones is potentially large, but is also highly variable, depending on the characteristics of the pre- and post-clearing plant communities, and climate regime. The results of this research cannot be extrapolated to other sites without taking careful account of these factors.

- Assuming that soil water availability remains high throughout the year in riparian habitats, annual ET will be greatest in vegetation that maintains a high state of physiological activity and green leaf area through the year, and lowest where water use is curtailed by seasonal dormancy or any other cause of low green leaf area.

- The impact on catchment water yield of clearing *A. mearnsii* from riparian zones will vary in proportion to the area of riparian zone present in the catchment.

- Where *A. mearnsii* is present in non-riparian areas of a catchment, the potential for streamflow enhancement following clearing is greatly magnified. However, the hydrological effects of clearing these areas will depend on the annual ET characteristic of the pre- and post-clearing plant communities. The more constrained this is by soil water deficits, the less scope there is for large differences in annual ET between pre- and post-clearing vegetation.

- Clearing alien invasive trees in different parts of the country will lead to different catchment yield responses. Local assessments of such responses are required for prioritising clearing efforts and evaluating the cost-benefit of such actions. Simple predictive models are required to make such assessments.

- This study has demonstrated that annual water use of diverse plant communities may be adequately modelled on the basis of the factors most limiting ET rates. This is the basis of the "limits concept" propounded by Calder (1999). Models described in this report for predicting the water use of riparian *A. mearnsii*, grassland and fynbos are examples of such models.

- We recommend that a research programme be initiated to provide a simple modelling framework for assessing the annual water use of a wider range of vegetation types occurring in areas of the country invaded by alien invasive plants.

- Difficulties were experienced in applying the heat pulse velocity technique to *A. mearnsii*. These are described in order to assist researchers in future HPV studies involving this species. Project funds supported the development of efficient analysis programmes for HPV and Bowen ratio data that will greatly assist in any future studies of alien invader trees involving these techniques.

- The significant effect of seasonal soil water deficit on the annual water use of *A. mearnsii* was demonstrated at the Groot Drakenstein site. We recommend that research into the possibility of using remote sensing data to map plant physiological activity and water use over time should be supported.

CAPACITY BUILDING

This project has been effective in building the technical capacity of previously disadvantaged members of the team. Mr Godfrey Moses gained much experience with meteorological and sap flow instrumentation, and attended a scientific symposium where a paper co-authored by him was presented. Mr Vilakazi and Mr Ndlela were trained in the installation and maintenance of heat pulse and Bowen ratio equipment, while Ms Royappen played a major role in analysing the heat pulse velocity data.

TABLE OF CONTENTS

LIST OF FIGURES

List of figures continued…

LIST OF TABLES

1. INTRODUCTION

Several recent developments in South Africa have highlighted the need for better information on the water use of trees in riparian zones. The declaration of plantation forestry as a streamflow reducing activity (SFRA) has served to maintain interest in the issue of forest water use, and the extent to which their impact on catchment water yields may be minimized. One long-recognized option is to remove plantations a set distance away from streams, and promote indigenous, preferably herbaceous vegetation in its place. The trend towards forest certification has encouraged this practice amongst growers, as a means of minimizing the hydrological impacts of their forests on catchment yields, and promoting the sustainability of their forestry enterprise.

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This report describes the results of a comparative study of ET between indigenous riparian plant communities and riparian wattle (*Acacia mearnsii*) stands, at sites in the Western Cape and KwaZulu-Natal midlands. The objectives of the project were:

1. To record the annual pattern of water use of the most widespread, exotic invading tree species in different climatic zones of the country.

2. To record the annual pattern of water use of post-clearing indigenous riparian plant communities.

3. To summarize the annual reduction in water use by riparian vegetation that can be achieved through the removal of exotic invader trees.

2. SELECTION OF STUDY SITES

A recent assessment of the extent of alien invading plants in South Africa listed *A. mearnsii* as the most pervasive invader in all parts of the country (Versfeld *et al.*, 1998). This species is perceived as having a large and negative impact on streamflow and catchment yields, because of its propensity to spread rapidly along riparian zones, quickly forming dense thickets characterised by high biomass and leaf area. For these reasons, *A. mearnsii* was chosen as the most appropriate alien invader species to focus this investigation upon. The widespread presence of *A. mearnsii* in both the winter and summer rainfall regions, and the different characteristics of native riparian vegetation in these regions, led to the decision to conduct water use comparisons in both areas of the country. Possible sites were investigated in reasonable proximity to the CSIR offices in Stellenbosch and Pietermaritzburg. Final choice of site was dictated largely by the occurrence of suitable mature, closed-canopy riparian wattle stands. Additional considerations were site accessibility and the required travel distance, risk of equipment theft and vandalism, and the degree to which the vegetation was representative of the general area. In the case of the native riparian plant communities, adequate wind fetch and unobstructed wind flow were further requirements. The final choice of sites is summarized in Table 1.

TABLE 1:

Sites chosen for the comparison of water use by invaded wattle and uninvaded native riparian vegetation in the Western Cape and KwaZulu-Natal midlands.

	Western Cape	*KwaZulu-Natal*
Wattle	Wellington	Seven Oaks
	Groot Drakenstein	
Native vegetation	Jonkershoek	Gilboa

3. METHODS

Two different methods were employed to record the annual water use at the study sites.

3.1 BOWEN RATIO ENERGY BALANCE (BREB) TECHNIQUE

The native riparian plant communities chosen in the Western Cape and KwaZulu-Natal comprised a complex assemblage of different species. The most appropriate and practical technique for measuring ET rates was judged to be the Bowen-ratio energy balance (BREB) method. This technique has been comprehensively described by Savage *et al.* (1997) and has been extensively deployed in previous experiments in South Africa (e.g. Everson *et al.*, 1998; Burger, 1999). The standard BREB sensors (net radiation, air temperature, air humidity, soil temperature, soil heat flux) were supplemented by a LI-COR PAR sensor (LI-190SB quantum sensor; LI-COR Inc., Box 4425, Lincoln, Nebraska 68504, USA) at the Jonkershoek site, and a Pyranometer sensor at the Gilboa site. A Campbell temperature and humidity probe (CS500, Campbell Scientific Inc., 815W. 1800 N. Logan, Utah 84321-1784, USA) was also installed at each site. The BREB arms supporting temperature sensors and air intake nozzles were positioned 1 m apart at both study sites, with the lower arm at a height of 1.3 m above the ground. Measurements of ET were recorded every 20 minutes over a full year. Volumetric soil water in the top 100 mm of soil was measured at fortnightly intervals from three sample cores removed from the vicinity of the BREB systems. Analysis of data was accomplished using a custom-developed Visual Basic programme (BOWCALC).

3.2 HEAT PULSE VELOCITY (HPV) TECHNIQUE

3.2.1 Heat pulse measurement

The water use by trees in the wattle stands was measured using the heat pulse technique, which has previously been shown by Smith *et al.* (1992) to provide valid estimates of sap flow in *A. mearnsii*. Three vertically aligned holes were 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 was to ensure that the holes were exactly parallel to each other. A line heater was inserted into the central hole, while temperature-sensing probes were 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 consisted of a single thermistor sealed within a Teflon tube of similar diameter. Each sensor probe pair thus gave a point estimate of sapwood temperature. Each thermistor pair was connected in a Wheatstone bridge configuration and automatically zeroed before each heat pulse initiation. The logger was programmed to apply a current of 30 amps lasting 1.0 s to each heater probe. HPV (u), (uncorrected for wound effects) was measured for each probe set using the compensation technique (Huber and Schmidt, 1937; Swanson, 1974). The temperature rise was measured at distances X_u upstream and X_d downstream from the heater, and u was calculated as follows:

$$u = (X_u + X_d) / 2t \qquad (1)$$

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

The heat pulse velocity was 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.

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

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

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

3.2.2 Sap flow calculation

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

$$v = \rho_b (m_c + c_{dw}) u' \qquad (3)$$

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 was 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 were removed to the laboratory for measurement of sapwood properties required to calculate sap flow from null-balance times. The four, six or eight sections of the tree trunk containing the probe implantation holes were excised and re-cut longitudinally at the particular radial depth below the cambium where the thermistor was originally positioned. The exposed, fresh face was shaved smooth using a microtome to allow precise measurement of probe separation distances and wound widths. These were 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 were taken midway between the line heater position and both the upper and lower thermistors. An average width was applied to the probe set.

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

3.2.3 Heat pulse data analysis procedure

The following data analysis procedure was adopted. The raw data were 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 were patched using data from another probe set with which it was most highly correlated. Long null-balance times that indicate slow sap flow rates were sometimes recorded by the deepest probes, indicating close proximity to heartwood. These probes were excluded where the number of missing data was high. Patched files were saved and subsequently read again during the calculation of sap flow. The analysis programme calculated hourly sap flow for the tree, and then saved 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 were concatenated using a text editor, partial days at the start and end of files were joined appropriately, and the complete data record converted to an Excel file. These files were then checked as follows:

- The whole-year pattern was 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 were plotted against mean daily VPD. High non-linear correlations are typical under these conditions, and suspect data are immediately apparent.

Where suspect data were identified, they were removed and replaced with patched data based on the mean daily sap flow for 10-day periods immediately before and after the period in question. Wound sizes could often not be discerned in excised wood samples, due to discoloration of the wood by the resin. On the basis of results reported by Smith *et al.* (1992), it was assumed to be 3 mm in all sample trees.

3.3 ARE THE BREB AND HPV DATA COMPARABLE?

The BREB and HPV methods are very different techniques, and it is important to consider their accuracy and to what extent they are comparable. The BREB method has received extensive scrutiny and validation, and is accepted as being capable of providing accurate estimates of total evaporation above plant canopies (Savage *et al.*, 1997). Accuracy is enhanced where the aerodynamic boundary layer is relatively low (especially above short vegetation), where flat land promotes laminar rather than turbulent air flow, and where the vegetation in question is uniform and sufficiently extensive to provide adequate aerodynamic fetch (Brittin and Heilman, 1989). These conditions were satisfied at the BREB sites in this study. Additional requirements are relatively constant radiation levels over the 20 minute sampling intervals, minimal advection of energy (Bertela, 1989) and relatively moist conditions (Angus and Watts, 1984). Variable radiation over the 20 minute measurement intervals is believed to be a possible source of error in this study, but one that is unlikely to bias annual ET.

The validity of HPV estimates of whole-tree sap flow has been tested on a variety of different species, and has been shown to be potentially accurate if sapwood properties and probe positions are carefully described (e.g. Swanson, 1983; Olbrich, 1991; Vertessy *et al.*, 1997). In a detailed analysis of sampling requirements in a *Eucalyptus populnea* stand, Hatton *et al.* (1995) concluded that the HPV method may legitimately be used to estimate stand level transpiration. Errors associated with the technique can be minimized by stratifying the sensors within sample stems by depth into the sapwood and aspect, and by stratifying the selection of sample trees within the stand by size class. Tree diameter at 1.3 m was shown to be an excellent scalar of flux at the stand level. With a sample size of six trees stratified by diameter, coefficients of variation (percent of true sap flow mean) in scaling to the stand level was approximately 5%. These sampling recommendations were adopted in this study.

The HPV method records transpiration in trees, and does not take into account evaporation of water intercepted by the canopy, and returned to the atmosphere. A canopy interception loss must be added to the HPV-based stand transpiration to arrive at a total evaporation estimate that can be compared to the BREB estimate.

4. *SITE DESCRIPTIONS AND INSTRUMENTATION*

4.1 WINTER RAINFALL SITES

4.1.1 Jonkershoek riparian fynbos site

Yearlong ET was measured at a fynbos riparian site in the upper reaches of the Jonkershoek valley (Stellenbosch district, 33° 59.336′ S; 18° 57.651′ E). The site lies at an altitude of 325 m.a.m.s.l, and mean annual precipitation is 1324 mm. 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. At the research site this is sandy and organic over a basement of large, rounded river rocks and stones. The 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 a coarse sand.

A BREB 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 BREB data were collected from August 1998 to July 1999. Maintenance visits occurred fortnightly.

4.1.2 Wellington A. mearnsii *site*

A closed-canopy, mature, self-established riparian wattle thicket was located on the farm Oaklands (33° 26.084′ S; 19° 04.892′ E), which lies northeast of Wellington, and east and south of the Groenberg, a free-standing mountain of the Malmesbury Shale Formation. Locally, the soils are derived from the decomposition of massive sub-greywacke. Mean annual rainfall in the area is 1050 mm, and the altitude is 345 m.a.s.l (Prinsloo and Scott, 1999). 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 1m, 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 of at least 2 m depth (Brereton family; Cv1200 clay loam). Below the yellow subsoil there is a further 1 m or more of deeply decomposed parent material. Despite the position of the study site in the drainage line, no signs of permanent wetness were observed. The recent alluvial deposits are comprised 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. Drainage through these gravels would be very high. The Clovelly soils have a high clay level that makes drainage through this profile much slower than through the gravels, but percolation nonetheless does appear to occur freely. 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 especially dense stands along the riparian zones. Following a survey of tree diameters in a sample plot of 301 m², six sample trees were selected to represent each of six diameter classes of trees (see Table 2). 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 equipment 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 hillslope. Hourly means of 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. No such correction was necessary at any site. The sapwood moisture fraction of nearby trees was measured at monthly intervals.

TABLE 2:

A summary of the six diameter size classes defined from an enumeration of all trees within a plot of 301 m^2 at the Wellington site. The diameter of sample trees chosen to represent e ach size class, the number of trees within each size class, and the number of HPV probe sets per sample tree are also shown.

	SIZE CLASS					
	1	*2*	*3*	*4*	*5*	*6*
Diameter range (mm)	21 - 50	51 - 100	101 - 150	151 - 200	201 - 250	251 - 300
Diameter of sample tree (mm)	29	55	127	145	210	274
No. of trees in size class	50	34	25	15	9	4
No. of heat pulse probe sets	2	4	4	4	4	6

4.1.3 Groot Drakenstein A. mearnsii *site*

Since only seven months of data were collected at the Wellington site, it was decided to conduct a further study at another Western Cape riparian wattle site. A new site was chosen on the slopes of the Groot Drakenstein mountains (33° 54.595′ S; 18° 58.530′ E) in the vicinity of Pniel, close to Stellenbosch. This site lies at an altitude of 275 m and is situated toward the upper side of a broad, evenly sloping footslope below the craggy Groot Drakenstein Mountains (nearby Drakenstein Peak has a height of 1500 m). Mean annual precipitation was estimated at 906 mm. The mountains are composed of quartzitic Table Mountain Sandstones and the adjacent slope is quaternary scree and piedmont and terrace gravels of the same sandstone source. The streams draining the high rainfall mountains split into many smaller and poorly defined drainage channels when they reach the gently sloping footslope. Much drainage is expected to be underground.

Wattle infestation in the area was severe, but was in the process of being cleared by Working for Water teams. A riparian study site was selected adjacent to a water course associated with dense *A. mearnsii* trees that were substantially taller than those in the surrounding area. Soils are of the Waterton family of Fernwood form (Fw2110) with coarse sands and a high rock and gravel content. Soils are especially variable spatially because of the complex of alluvial and colluvial sources of deposits. Occasional organic profiles are possible along the drainage lines, but generally the soils are too shallow, warm and dry for higher organic matter development. The soil indicates that the primary soil forming mechanism is elluviation of the seasonally saturated subsoil, which is a pale to medium grey colour and underlain by coarse gravels and rock of mixed alluvial and colluvial origin. The mineral soil fraction is coarse to very coarse, and the profiles are freely draining above the E-horizon.

A survey of tree diameters was performed in a plot measuring 30 by 10 m, orientated along the channel and including both banks of the channel. On the basis of 121 measurements, six size classes were defined (Table 3). Six sample trees representing each of these size classes was chosen for heat pulse monitoring.

A weather station was maintained at an exposed fynbos site within 100 m of the sample trees. VPD was calculated from hourly temperature and relative humidity readings. The latter were checked against spot readings of RH taken with a sling psychrometer at each visit. At the start of the monitoring period, water was flowing strongly in the channel, but flow ceased by January. The site was burnt out by wildfire in March 1999 after seven months of sap flow record.

TABLE 3:

A summary of the six diameter size classes defined from an enumeration of all trees within a plot of 300 m^2 at the Groot Drakenstein site. The diameter of sample trees chosen to represent each size class, the number of trees within each size class, and the number of HPV probe sets per sample tree are also shown.

	SIZE CLASS					
	1	*2*	*3*	*4*	*5*	*6*
Diameter range (mm)	0 - 40	41 - 80	81 - 120	121 - 160	161 - 200	201 - 240
Diameter of sample tree (mm)	38	62	114	122	177	223
No. of trees in size class	8	62	28	11	8	4
No. of heat pulse probe sets	2	4	4	4	4	6

4.2 SUMMER RAINFALL SITES

4.2.1 Gilboa riparian grassland

This site was situated on the Mondi property Gilboa, which lies on the top of the Karkloof hills north of Howick in the KwaZulu-Natal midlands. The altitude of the site is 1532 m.a.s.l, and mean annual precipitation is 867 mm. The BREB system was erected near the centre of the Inyamvubu vlei (29° 15′ S; 30° 15′ E). 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 arms of the BREB system were maintained a distance of 1 m apart. 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. Maintenance visits occurred every 2-3 weeks.

4.2.2 Seven Oaks A. mearnsii *site*

Great difficulties were experienced in finding self-established riparian wattle thickets in the Pietermaritzburg area. One site was located at the foot of the Karkloof range, but was subsequently abandoned following the theft of data logger batteries. A riparian stand of mature plantation *A. mearnsii* (compartment C07a; 29° 14′ S, 30° 36′ E) lying within a research catchment on the Mondi property Mistley-Canema, was then selected for comparison to the Gilboa site. The altitude of the Mistley site is 1067 m.a.s.l., and MAP is 941 mm.

The catchment is underlain by sandstone of the Natal group. The crest soils are uniformly shallow, with an effective rooting depth of 20 to 50 cm. Topsoils are coarse sandy clay loams, high in organic matter, and with clay contents averaging 25-30%. Profile gravel is mostly absent, and surface rock is absent. Infiltration into the soil is good, and soil water storage is high. As a result of the high degree of leaching, fertility is low. Exchangeable aluminium may be extremely high, while exchangeable bases are less than 4 milliequivalents. Soils vary from red (Hutton form, Inanda) to yellowish (Glen Rosa, Nomana, Magwa) where some leaching has occurred.

The riparian zone is very narrow, comprising old and recent alluvium. Soils are distinctly layered, with similar textures to upslope areas. The sand grade is medium to coarse throughout. Profiles are permeable to water, while lower soil hydromorphy exists at depth, giving rise to bright red or yellow mottles in a grey matrix. There is a fluctuating water table, but the soils are more dry than wet. The dominant soil type is of the Tukulu form, while sub-dominant soil forms are Dundee, Bloemdal, and Baynesvlei (Soil Classification Working Group, 1991).

The trees were planted in 1989 at an espacement of 1.5 by 3 m, and were aged 10 at the start of the monitoring period in May 1999. Following a diameter survey of a sample of trees growing within the riparian zone, four trees were selected to represent the different size classes. Thermistor probes were implanted to depths of 4, 9, 16 and 23 mm below the cambium. Data quality began to deteriorate after three months. It was later discovered that the stainless-steel heater pins had almost completely corroded inside the sapwood due the copious presence of the gum exuded into the drilled holes. The measurements were terminated, and the opportunity taken to fell the sample trees and examine a trunk cross-section close to the drilled holes. It was seen that the drilling had caused the stem to stop growing in the vertical plane of the holes, causing adjacent normal growth to produce a bulge on either side. Heat pulse measurements were no longer representative of the average sapwood of the tree.

Five replacement sample trees were then selected in the same general vicinity, but heater probes were now withdrawn at each fortnightly visit, and smeared with Vaseline to retard the corrosive effect of the gum. Any gum exuded at the surface was removed, since the greatest probe damage occurred at this position. The three largest sample trees each received eight probe sets, with thermistors positioned at depths of 5, 8, 11, 14, 17, 20, 23 and 26 mm beneath the cambium. The remaining two sample trees each received only one set of four probes, with thermistors positioned at 5, 10, 17 and 26 mm beneath the cambium (Table 4). Monitoring ceased in April 2000 prior to the felling of all the riparian trees. Growth distortions became apparent only towards the end of the study, and so fresh sample trees were not required.

TABLE 4:

A summary of the five diameter size classes defined from an enumeration of all trees within the riparian zone in the Seven Oaks research catchment. The diameter of sample trees chosen to represent each size class, the number of trees within each size class, and the number of HPV probe sets per sample tree are also shown.

	SIZE CLASS				
	1	*2*	*3*	*4*	*5*
Diameter range (mm)	130-179	180-229	230-279	280-329	330-379
Sample tree diameter (mm)	178	201	276	289	338
No. of trees in size class	7	19	6	13	3
No. of HPV probe sets	4	4	8	8	8

5. *RESULTS*

5.1 WINTER RAINFALL SITES

5.1.1 Jonkershoek riparian fynbos site

Figure 1 shows the pattern of daily ET measured through the year, and expressed in terms of mm equivalent depth of water. Gaps in the data record were caused primarily by problems with the BREB Dew10 humidity sensor failing to record dew point. Figure 2 shows the correlation between total daily ET and total daily solar radiation (estimated from the quantum sensor data assuming a conversion factor of 2200 μmol m^{-2} s^{-1} to 1000 W m^{-2} (Landsberg and Gower, 1997). The correlation was judged to be sufficiently good to patch the missing days. Greater scatter is evident below than above the fitted line, and is attributed to a degree of evaporation suppression caused by high humidity. Figure 3 shows the complete data set for the site. No solar radiation data were available over a period of missing data in July and August 1999, and so an average ET rate based on data on either side of the gap was assumed. The cumulative annual ET amounted to 1332 mm. Figure 4 illustrates the variation in daily ET for each month of the year.

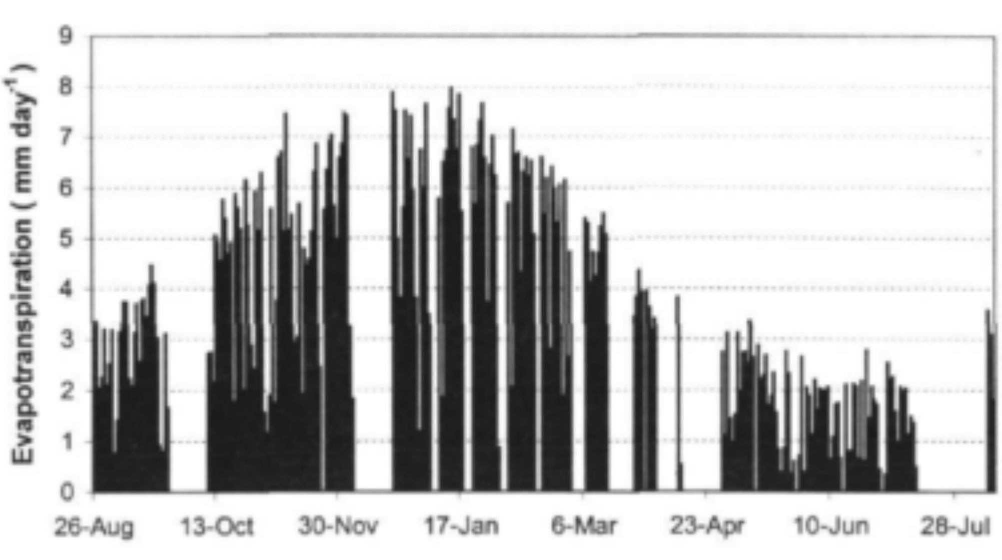

FIGURE 1: The annual trend in daily ET recorded at the Jonkershoek site.

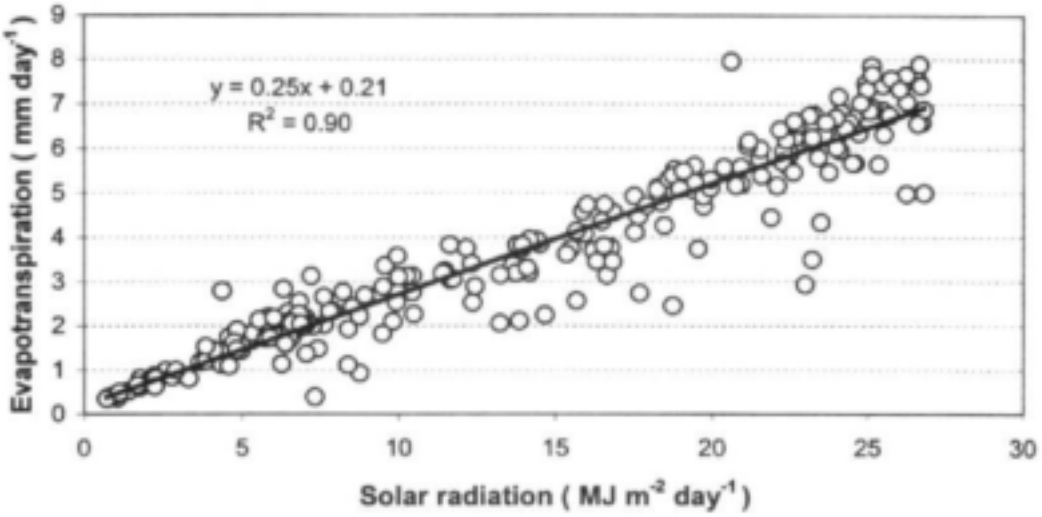

FIGURE 2: The relation between total daily solar radiation and total daily ET recorded at the Jonkershoek site.

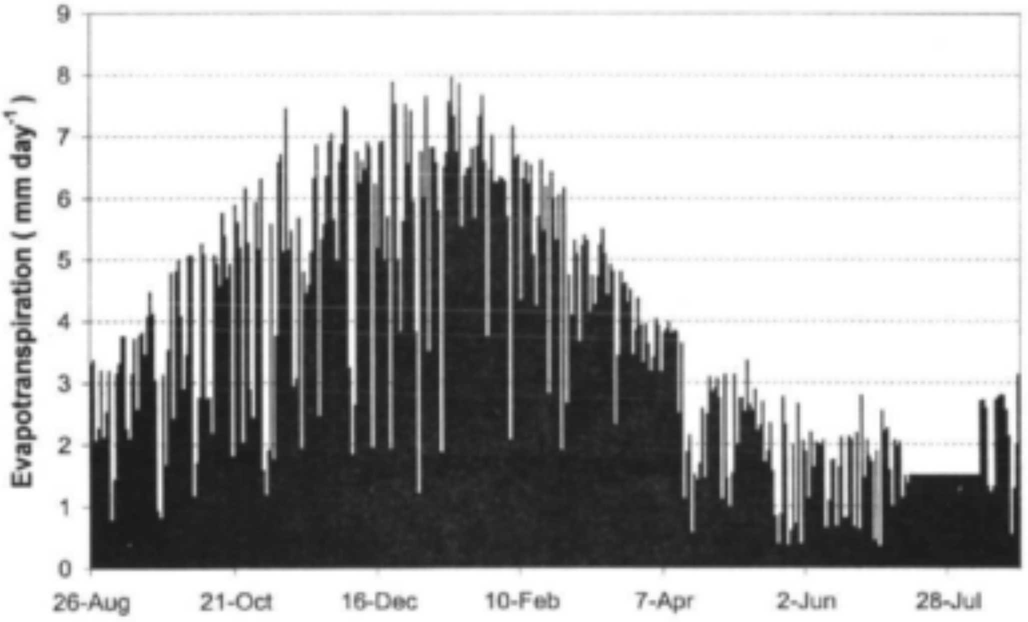

FIGURE 3: Daily ET recorded at the Jonkershoek site over a 12 month period. Missing data were patched using the relation depicted in Figure 2. No solar radiation data were available over a period of missing data in July and August 1999. An average rate based on data on either side of the gap was assumed.

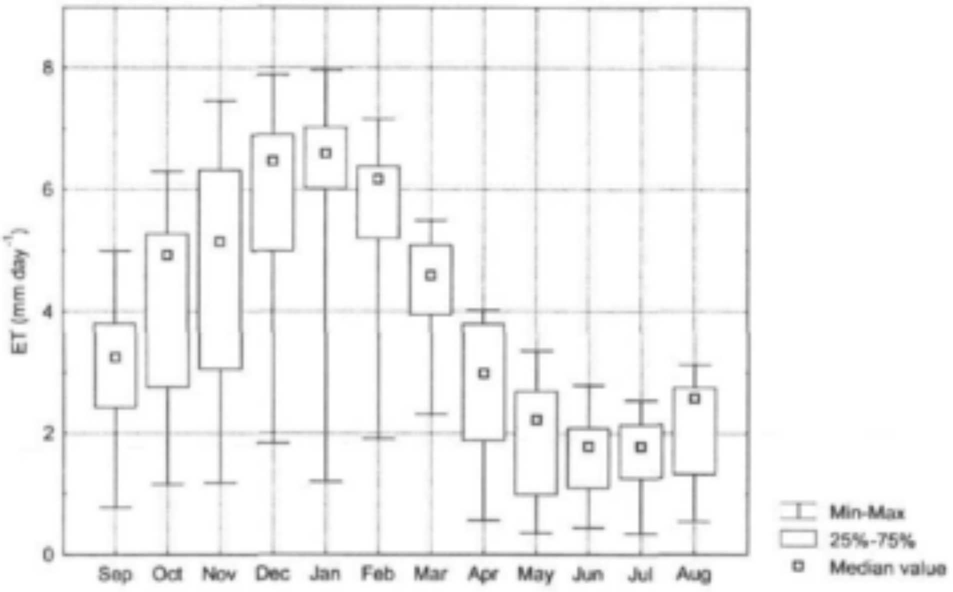

FIGURE 4: The median, upper and lower quartiles, and range of daily ET recorded in each month at the Jonkershoek site. Patched data were excluded from this analysis.

5.1.2 Wellington A. mearnsii *site*

Figure 5 shows the days when good quality HPV data were recorded from all six sample trees. These data display a typical seasonal pattern of daily ET, with highest values in mid-summer due to long day lengths and high 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 closely correlated to the product of mean daily vapour pressure deficit (VPD) and the number of daylight hours (Figure 6). Daylight hours were calculated on the basis of the number of hours where solar radiation/PAR exceeded zero, the sensors exhibiting a slight negative offset. Daily whole plot evaporation 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 closely correlated to mean VPD times daylight hours (Figure 7). 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. We concluded that the relationship shown in figure 7 could be used to infer whole-year wattle water use on the basis of the VPD data recorded at the fynbos site.

5.1.3 Groot Drakenstein A. mearnsii *site*

High quality sap flow measurements were recorded from August 1998 to February 1999. For each sample tree, total daily sap flow was scaled up by the number of trees of the same size category in the plot.

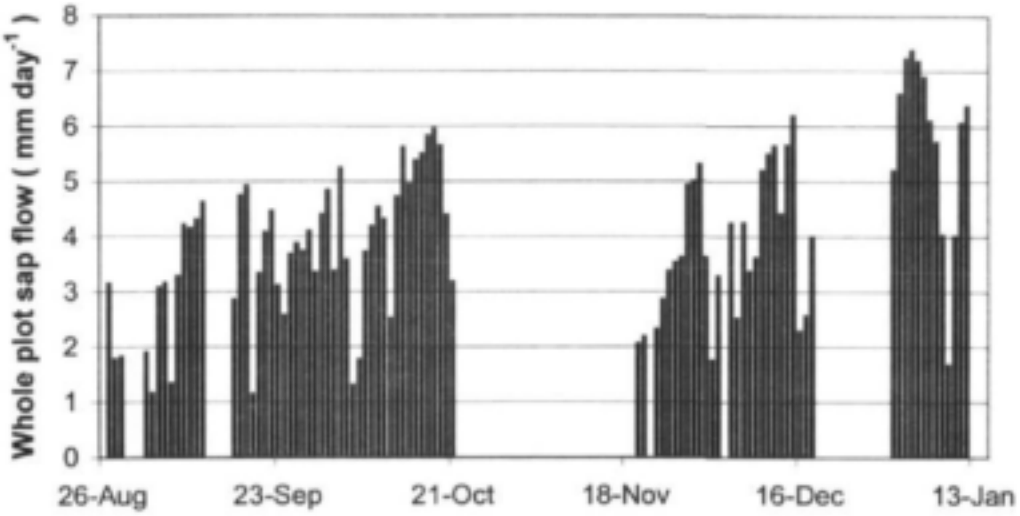

FIGURE 5: Daily whole plot sap flow recorded at the Wellington A. mearnsii *site. Gaps indicate periods of missing data for one or more of the sample trees.*

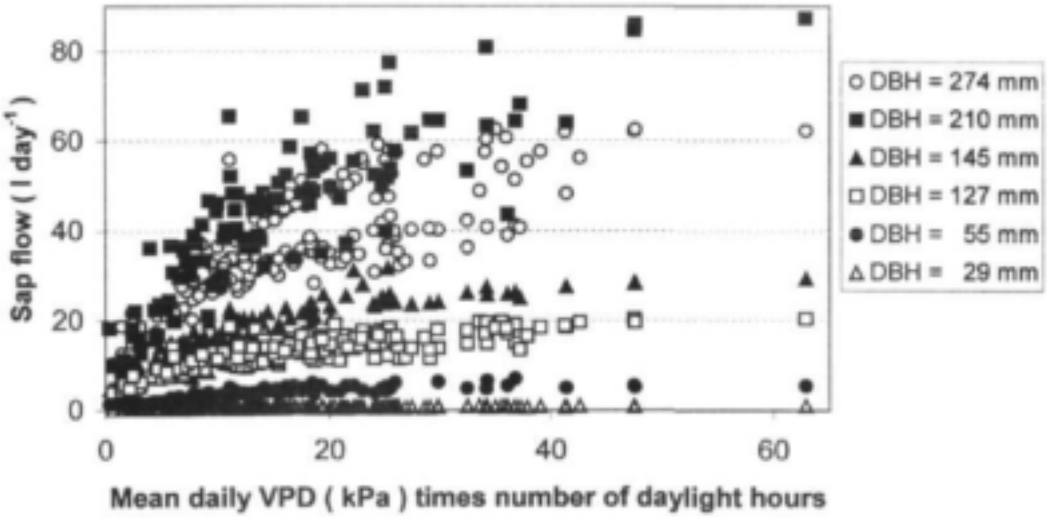

FIGURE 6: The relation between daily sap flow and the product of mean daily VPD and the number of daylight hours, recorded in all six sample trees at the A. mearnsii *Wellington site.*

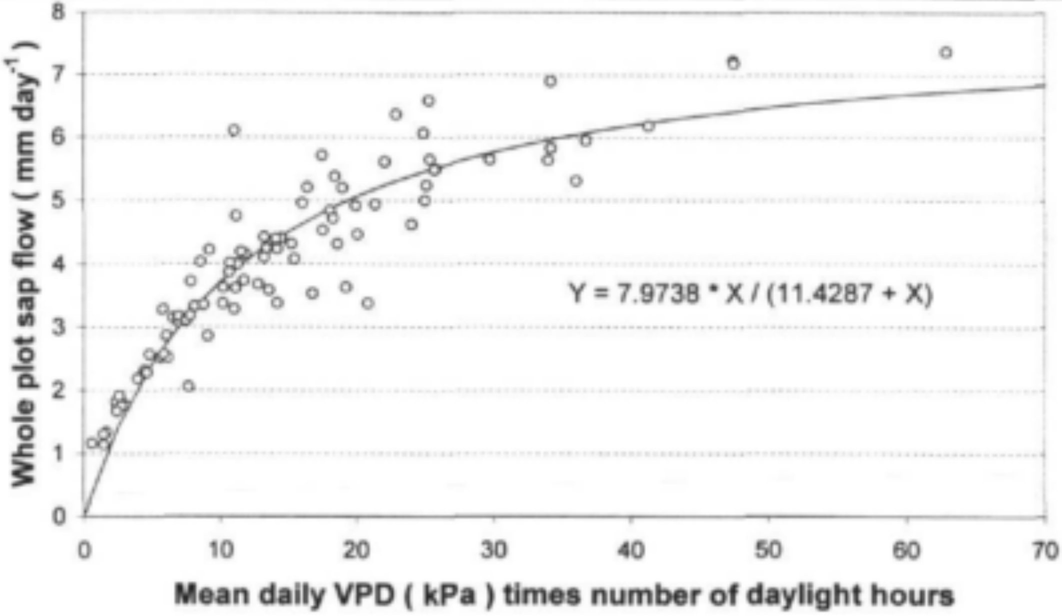

FIGURE 7: The relation between whole plot ET and the product of mean daily VPD and the number of daylight hours, recorded at the Wellington A. mearnsii *site.*

Figure 8 illustrates the trend in whole-plot sap flow over the monitoring period. There is a definite trend of declining daily sap flow from December onwards, which is not linked to day-length changes, and is therefore attributed to the depletion by the trees of a limited store of soil water. The stream stopped flowing during January 1999, and the trees were visibly wilting by February. The trend of sapwood moisture fraction also showed a marked decline from December onwards (Figure 9).

Daily sap flow for each of the six sample trees was examined up to the end of November, before stress became evident in the trees (Figure 10). These were again highly correlated to the product of VPD and number of daylight hours, exhibiting a very similar relation to that recorded at the Wellington site. Whole plot daily sap flow was calculated by scaling up each sample tree daily sap flow by the number of trees in the size class it represents. The relation between whole plot daily sap flow and the mean daily VPD times number of daylight hours, for the period up to the end of November, is shown in Figure 11.

The study was again terminated by a wildfire. This time, the annual sap flow could not be estimated, since the assumption of non-limiting soil water availability could not be made at this site. Water availability and sap flow could not be forecast with reasonable accuracy over the remaining five months to describe annual water use. The study was nevertheless valuable in illustrating the very important concept that annual water use of vegetation at a site may be significantly reduced by periods of soil water deficit. Accurate soil water budgeting is required to forecast annual water use at such sites.

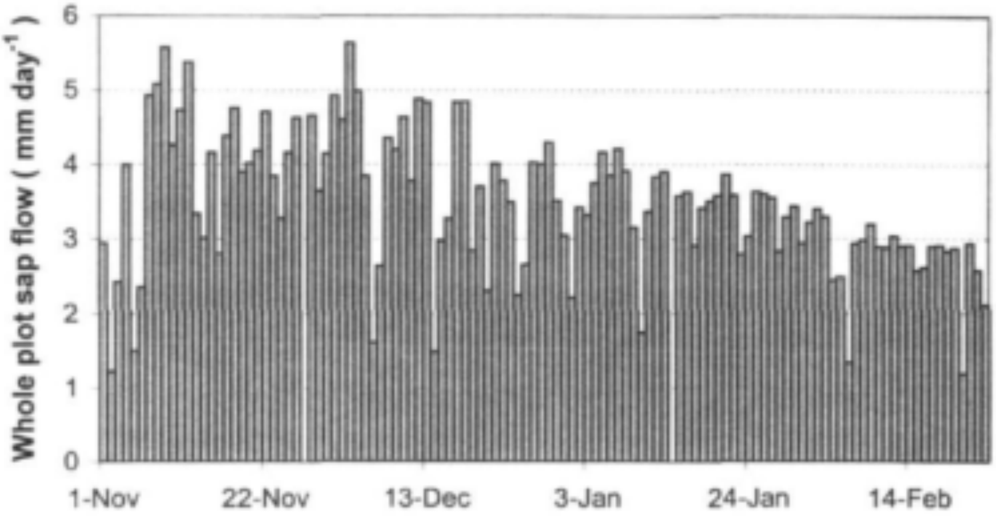

FIGURE 8: Daily whole plot sap flow recorded at the Groot Drakenstein A. mearnsii *site.*

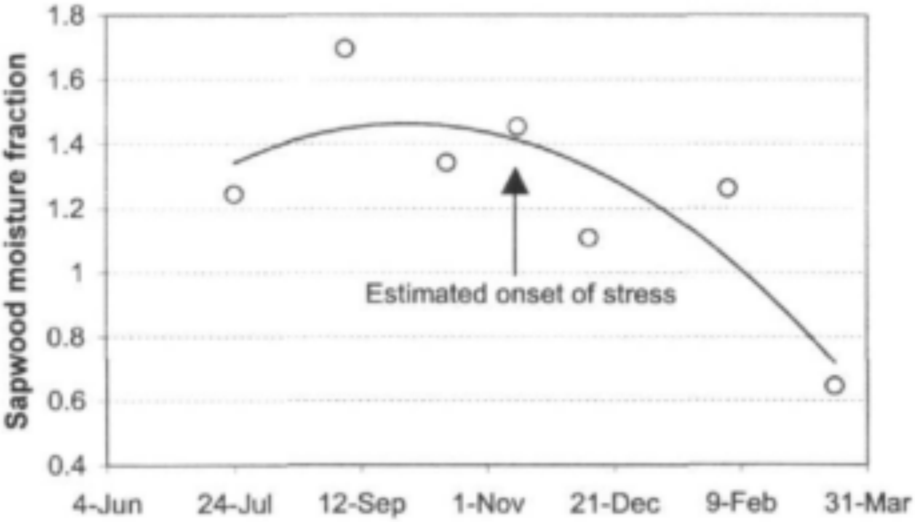

FIGURE 9: The trend in sapwood moisture fraction recorded at the Groot Drakenstein A. mearnsii *site.*

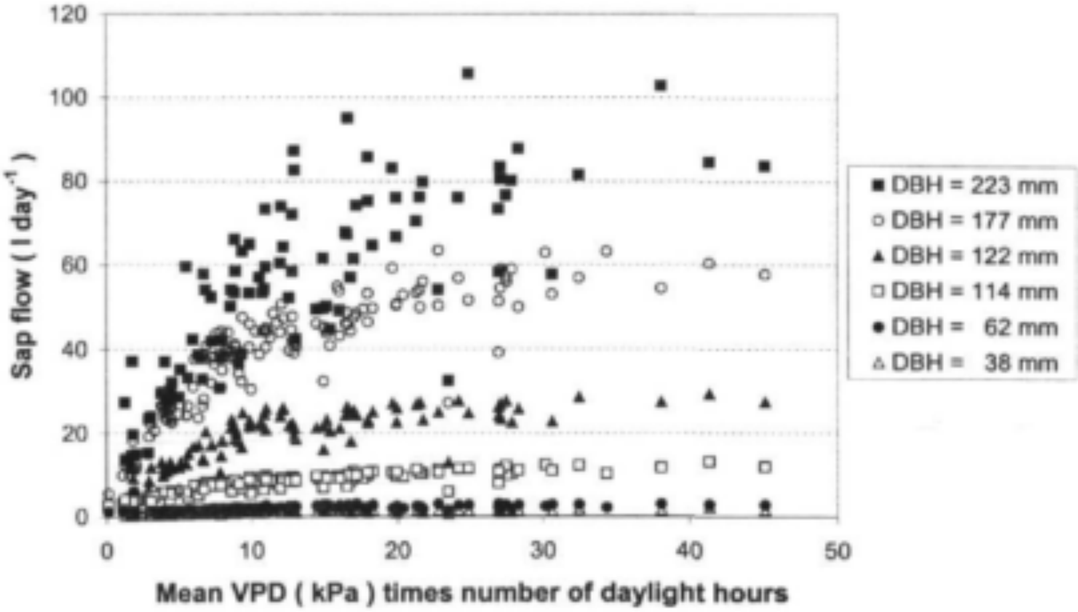

FIGURE 10: The relation between daily sap flow and the product of VPD and the number of daylight hours recorded at the Groot Drakenstein site up to the onset of stress at the end of November.

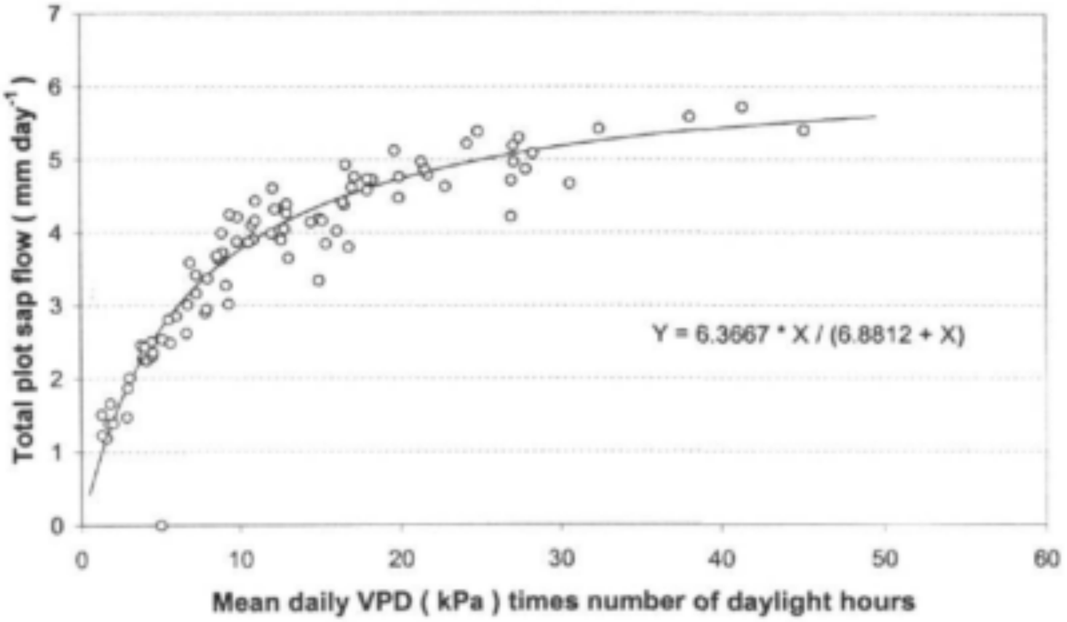

FIGURE 11: The relation between daily whole plot sap flow and the product of mean daily VPD and the number of daylight hours, measured at the Groot Drakenstein site before the onset of stress.

5.1.4 A model of sap flow in A. mearnsii

The studies at Wellington and Groot Drakenstein have shown that daily sap flow in unstressed *A. mearnsii* trees is correlated to tree size (as reflected by breast height diameter) as well as mean daily VPD scaled by the number of daylight hours. A number of different equations were tested for their ability to describe the curves shown in Figures 6 and 10, and incorporate the effect of tree size. The most suitable function was judged to be the saturation growth rate model, which has the following form:

$$Y = aX / (b+X) \qquad (4)$$

where a is the maximum Y value attained by the curve, and b describes the initial slope close to the origin of the graph. The function was fitted to the curves shown in Figures 6 and 10, and the calculated a coefficients plotted against the tree DBH (Figure 12). A power function was fitted to describe the trend.

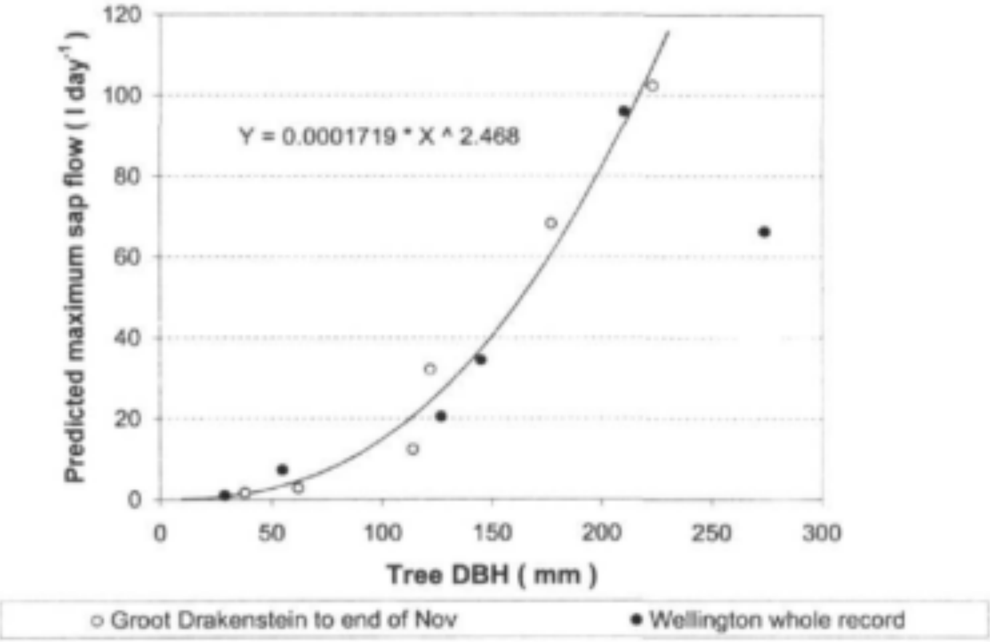

FIGURE 12: The relation between A. mearnsii *DBH and the maximum daily sap flow at the Wellington and Groot Drakenstein sites, predicted from a saturation growth rate function. A single outlying point was excluded from the curve fit.*

The fitted curves returned coefficient b values ranging from 3.6 to 15.8 (mean of 8.42), which vary with tree size and site (Figure 13). This variability is likely to reflect differences in sapwood conductivity to water brought about by differences in tree age and probably long-term soil water availability.

Total sap flow in a stand of unstressed *A. mearnsii* can be calculated by measuring the DBH of all trees in a representative sample plot, and estimating the coefficients a and b for each tree. These can then be used to estimate sap flow from mean daily VPD and number of daylight hours. This study has demonstrated that reliable VPD measurements may be derived from temperature and relative humidity data recorded by inexpensive Hobo sensors fixed to tree trunks and protected by a simple rain shelter.

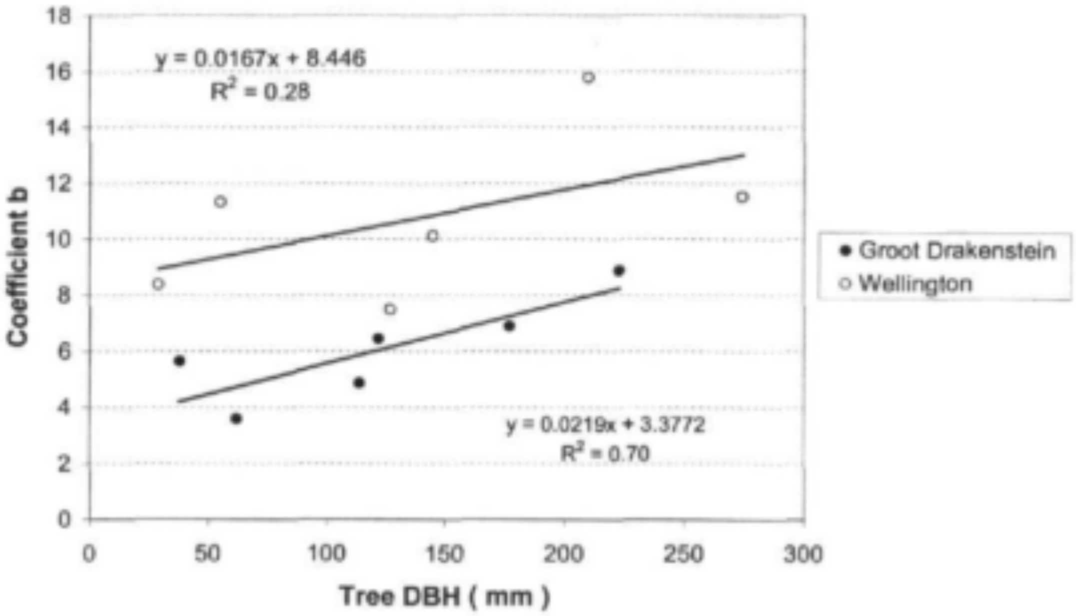

FIGURE 13: The relation between the coefficient b in the saturation growth rate equation and the tree DBH at the Wellington and Groot Drakenstein sites, as obtained by non-linear regression.

5.1.5 Comparison of annual water use by riparian A. mearnsii *and fynbos at Jonkershoek*

The annual sap flow in the *A. mearnsii* stand at Wellington could not be directly compared to the Jonkershoek fynbos ET for the following reasons:

- Weather conditions at the two sites were different over the study periods. Measurements took place in different years, and the sites were geographically dissimilar.
- The wattle stand measurements did not span a full year

- The BREB technique records total ET, whereas sap flow measurements reflect transpiration rates but not the interception loss component of ET.

To perform a valid comparison, the temperature and relative humidity data recorded at the Jonkershoek site were used to calculate mean daily VPD over periods where a positive PAR reading was recorded. These data were then used to estimate daily wattle sap flow using the equation shown in Figure 7. The calculated annual sap flow amounted to 1304 mm. Figure 14 illustrates the range of daily sap flow modelled for each month of the year.

To arrive at an estimate of ET (required for comparison with the BREB measurements above fynbos), the evaporation of water intercepted on the surfaces of leaves, branches and trunk had to be added to the transpiration component recorded by the HPV sensors. In the absence of any experimental data, this component was estimated using a table of daily interception losses provided for this species by Schulze et al. (1995; Table 20.5.5, key 24). Total interception loss was calculated on the basis of these daily losses and the number of sample period rain days recorded at a gauge situated close to the fynbos site. Where daily rainfall was less than the predicted daily interception loss, it was assumed that the interception loss equalled the daily rainfall. The estimated annual interception loss of 171 mm (14% of the rainfall total of 1212 mm) was added to the sap flow total to yield an estimated annual ET of 1475 mm. This compares to 1332 mm recorded above the riparian fynbos.

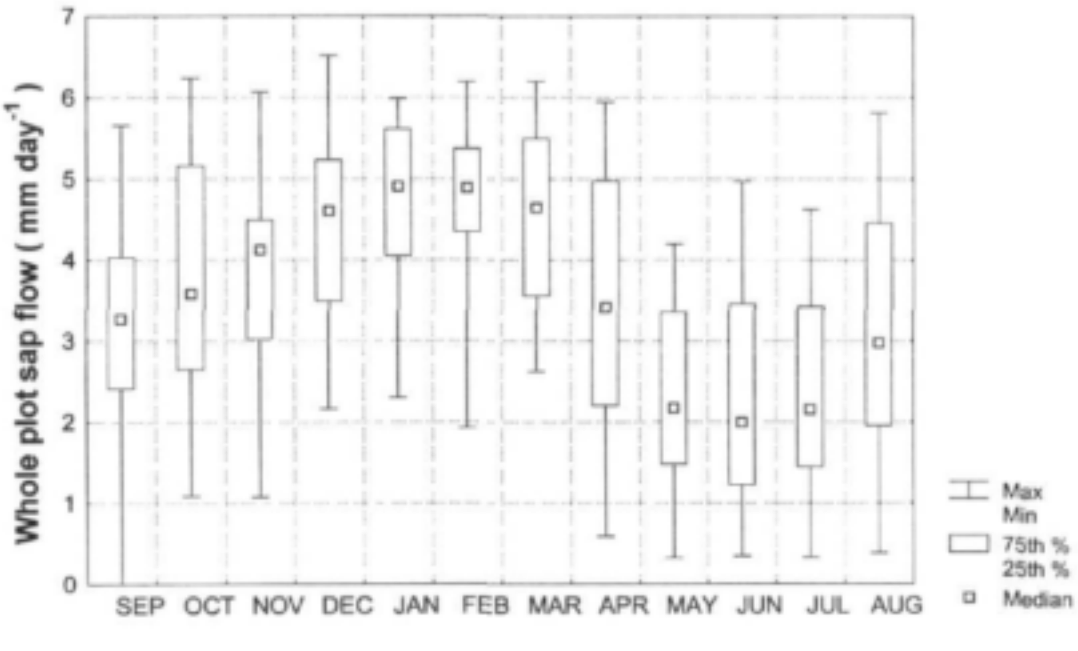

FIGURE 14: The median, upper and lower quartiles, and range of daily ET modelled for A. mearnsii *growing at the Jonkershoek site. Patched data were excluded from this analysis.*

5.2 SUMMER RAINFALL SITES

5.2.1 Gilboa riparian grassland site

Figure 15 shows the available data collected from this site from September 1998 until September 1999. Persistent problems with the Dew10 humidity sensor were experienced during the middle of the growing season. This was compounded by logger malfunction caused by a nearby lightening strike in January. Gaps in the data record were too long to patch on the basis of average ET rates immediately before and after the gap. A suitable model was required for this purpose.

The relation between daily solar radiation (SR, MJ m^{-2} day^{-1}) and measured daily ET (mm) was first investigated for all days for which measured ET data were available. Figure 16 shows that a large scatter in data points exists in this relation. High correlation to SR is shown by the ET data collected in March and April (closed symbols), when the plants were fully developed and still physiologically active. The remaining points falling below this maximum rate of ET indicate times of the year when ET is restricted by low green leaf area, either early (Sep) or late (Jun – Aug) in the growing season. The theoretical annual trend in maximum ET was calculated using the relation between SR and peak season ET. Actual ET was then expressed as a fraction of the maximum ET, to derive an empirical seasonal trend (Figure 17). This is believed to track changing green leaf area through the season. The first two months of the 1999/2000 season were added to the start of the 1998/99 data, to obtain a pattern of ET over a complete growing season. This pattern shows a steep increase in early spring as the green leaf area increases rapidly with rising temperature and spring rains. This increase continues at a reduced rate through the summer, reaching a peak in March/April. With autumn senescence, ET drops sharply to very low rates that continue through the winter. Figure 18 shows simulated ET over the complete growing season. Two significant gaps caused by an absence of SR data were patched by ET estimates based on the mean of 10 readings on either side of the gap. Simulation results were judged to be realistic on the basis of the following observations:

- The total ET amounted to 836 mm. This is somewhat greater than the four-year mean of 696 mm (ranging from 651 to 752 mm) recorded by Everson *et al.* (1998) for high altitude grasslands at Cathedral Peak. The difference is attributed to the lower altitude at Gilboa, and greater opportunity for soil evaporation from the periodically saturated soil surface. Research catchment data show annual ET of control catchments to range from 700 to 1000 mm (Bosch and von Gadow, 1990).

- The shape of the seasonal pattern of ET was judged to be realistic on the basis of data from the Cathedral Peak area. The single well-defined mid-season peak, as well as the steep increase and decrease at the start and end of the growing season, respectively, closely resemble the Cathedral Peak data.

- Peak daily rates of ET in mid-summer reached 6 mm, which is realistic for grasslands (Everson *et al.*, 1998).

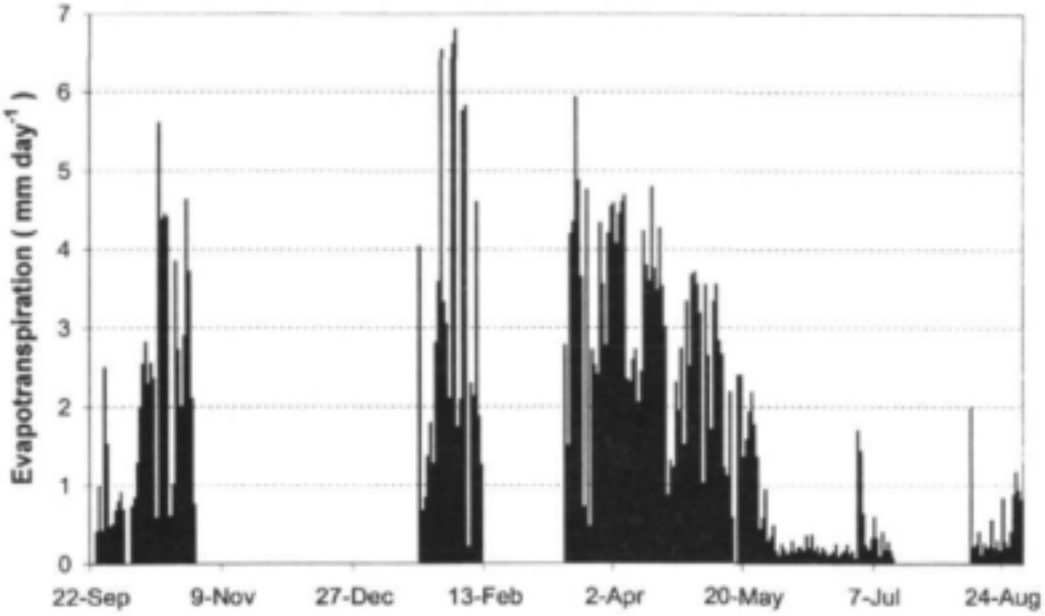

FIGURE 15: Available daily ET data recorded at the Gilboa riparian grassland site.

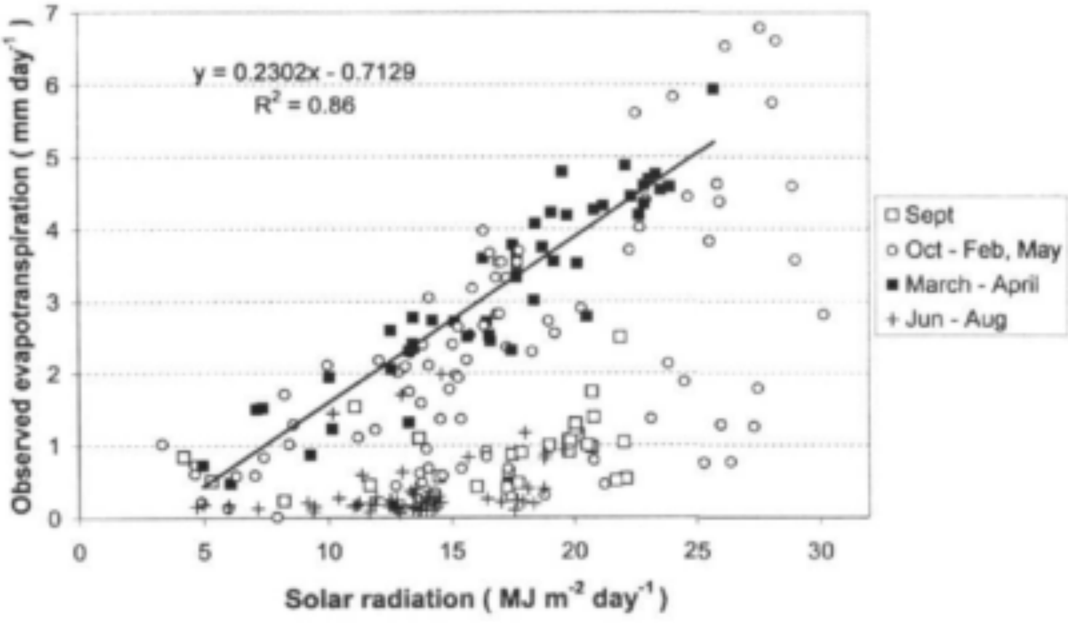

FIGURE 16: The relation between daily solar radiation and observed daily ET at Gilboa, for different periods of the year.

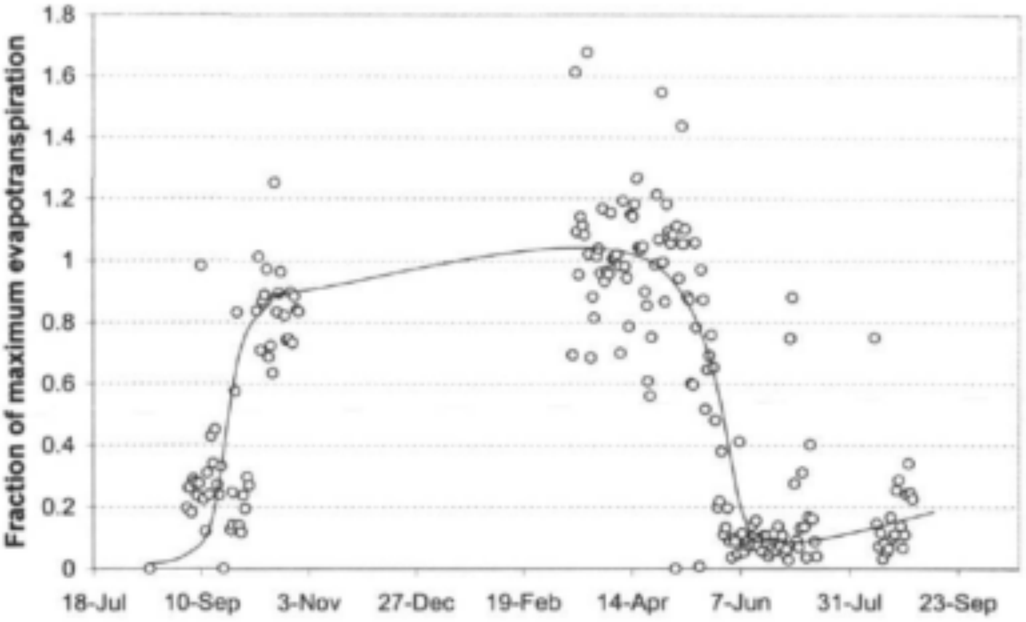

FIGURE 17: The trend in fraction of maximum daily ET fitted to data recorded at Gilboa.

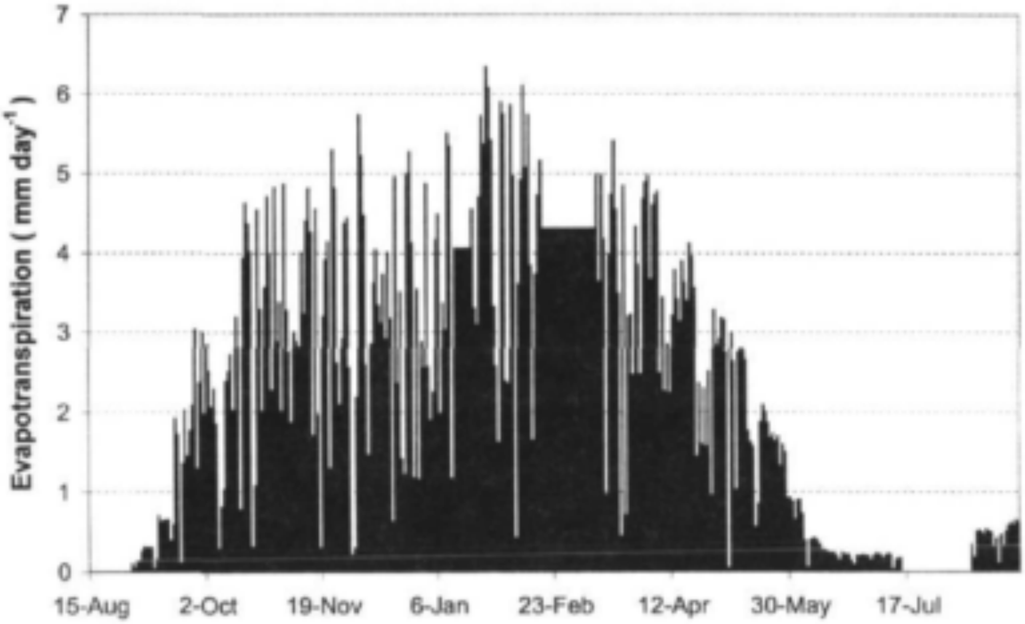

FIGURE 18: The pattern of daily ET modelled over the whole growing season at the Gilboa grassland site. Where solar radiation data are missing, ET is estimated as an average of values on either side of the data gap.

Figure 19 illustrates the range of daily ET modelled in each month of the year.

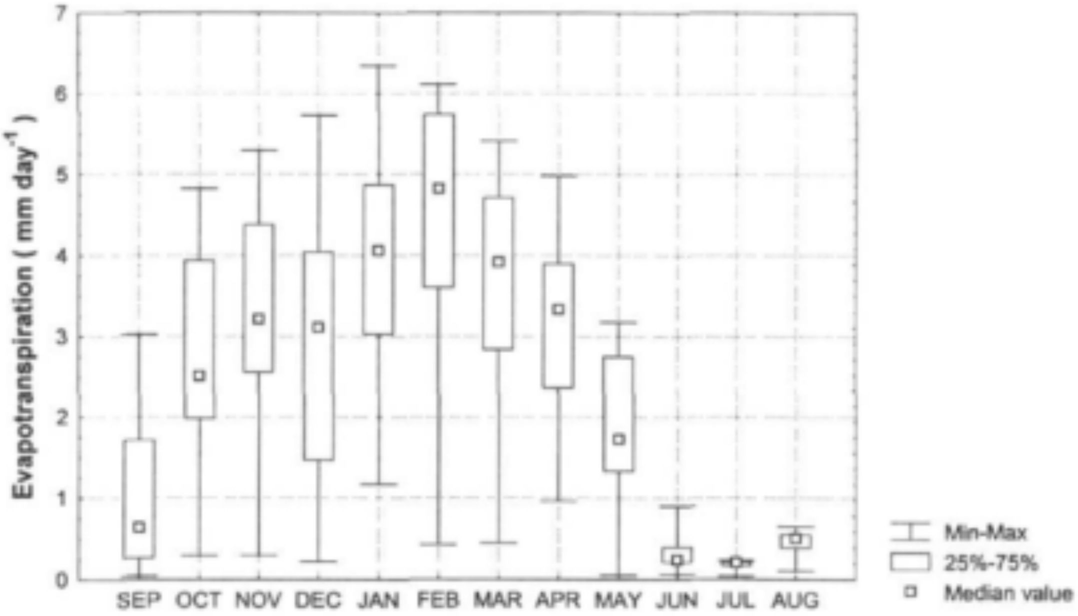

FIGURE 19: The median, upper and lower quartiles, and range of daily ET modelled in each month at the Gilboa grassland site. Patched data not based on measured solar radiation were excluded from this analysis.

5.2.2 Seven Oaks A. mearnsii *site*

Heat pulse sampling began during May 1999, and ended in December 1999. The largest sample tree exhibited a realistic pattern of a smooth decline through the winter months, followed by a recovery during spring and early summer (Figure 20). The remaining trees, however, showed a reduced recovery of sap flow rates after the winter. Examination of trunk cross-sections at the conclusion of the study showed no marked sapwood bulging, but very pronounced invasion of resin from the heartwood into the sapwood in the region of the probes (Figure 21). We believe that this may be responsible for the long-term reduction in heat pulse velocity recorded by the probes, as sap flow in the adjacent sapwood is progressively blocked. The daily sap flow for all sample trees was calculated, but only the data for the first two months after probe implantation (before wounding reactions became pronounced) were closely inspected. These all described the typical curve defining the relation between daily sap flow and mean daily VPD times the number of daylight hours (Figure 22). Although the range of calculated VPD times daylight hours is relatively small (being close to mid-winter), one can clearly see that the maximum sap flow rates are lower than the relation in figure 12 would predict. A comparison of the relation between DBH and sapwood area for all three wattle sites (Figure 23) showed that differences in sapwood area could not account for differing sap flow rates.

Soil water deficits could cause such reductions in expected sap flow rates, but this possibility is considered most unlikely, in view of the proximity of the trees to the channel, and the deep moist soil profile available to the roots. A more likely explanation lies in the severe bagworm infestation that was observed in the area. A large number of fallen bags littered the ground in the study area, and the tree canopies were observed to thin noticeably during the spring. A significant feature also observed in the vicinity of the sample trees was the large differences in canopy defoliation often seen among adjacent trees.

Because of the uncertain basis for extrapolation, and the presence of a well-developed understorey vegetation, we did not attempt to estimate a relationship for whole-plot sap flow.

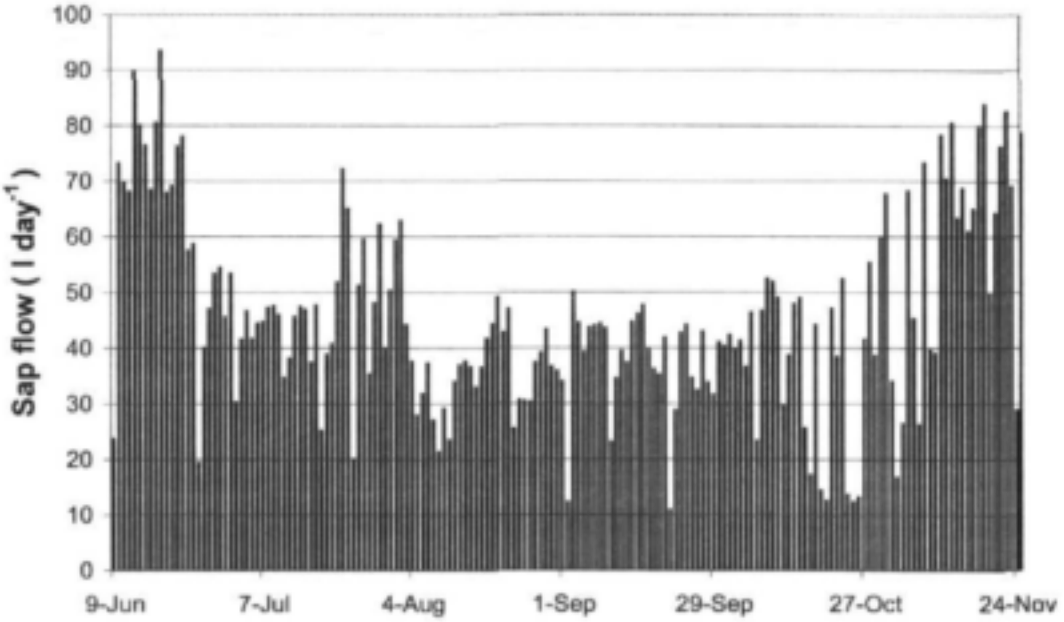

FIGURE 20: Daily sap flow recorded in the largest A. mearnsii *sample tree at the Seven Oaks site.*

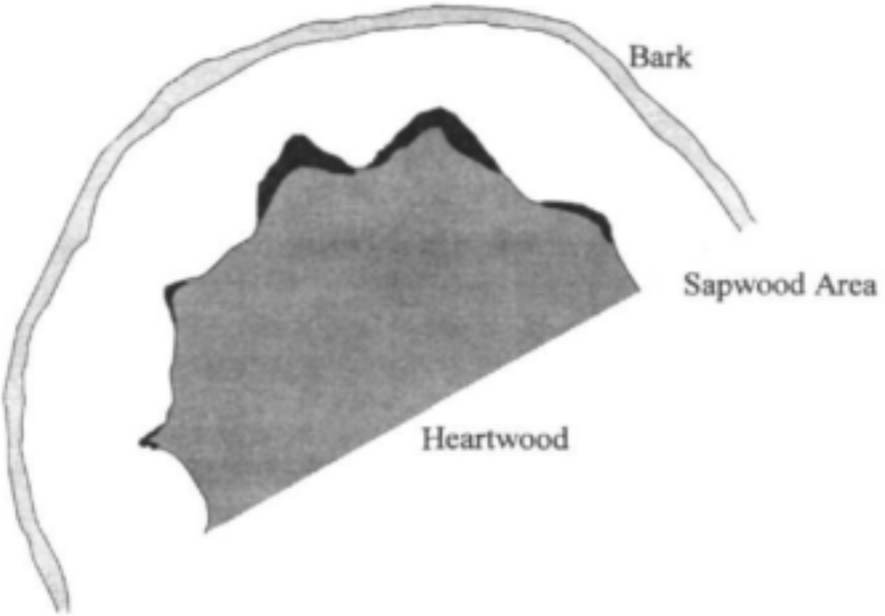

FIGURE 21: The pattern of resin exudation from the heartwood into the region of sapwood wounding caused by the implantation of the heat pulse probes.

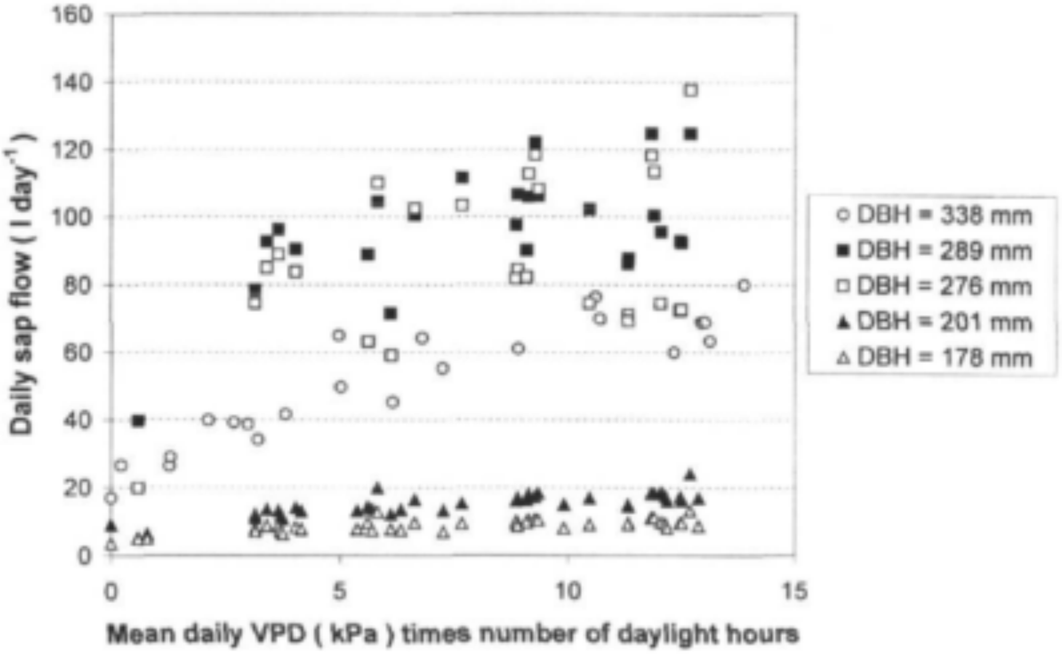

FIGURE 22: The relation between daily sap flow and the product of mean daily VPD and number of daylight hours, recorded for five sample trees at the Seven Oaks site.

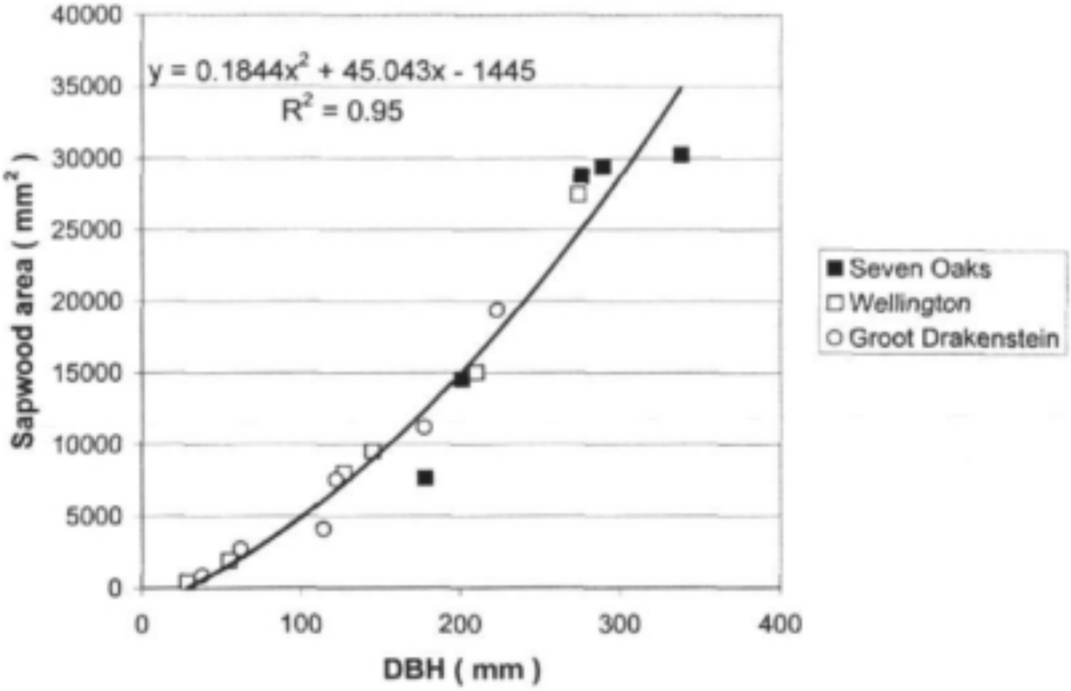

FIGURE 23: The relation between tree DBH and sapwood area recorded in the A. mearnsii *sample trees at Wellington, Groot Drakenstein and Seven Oaks.*

5.2.3 Comparison of annual water use by riparian A. mearnsii *and grassland at Gilboa*

In view of the complicated picture that emerged from the Seven Oaks study, we decided to use the model developed from the Western Cape sites to predict the water use of wattle at the Gilboa site. The Cape sites had the advantage of being self-established thickets, and were therefore more typical of the alien invasive tree problem than the plantation wattle at Seven Oaks. A full year's record of hourly temperature and relative humidity data were available from a Hobo sensor located within 2 km of the Gilboa site, and these data were used to calculate hourly, and then mean daily VPD. Daylength was calculated from the day of year and the site latitude using the formulae given by Jones (1983). The product of mean daily VPD and daylight hours was then used to predict wattle sap flow under Gilboa climatic conditions. Figure 24 illustrates the range of daily ET modelled in each month of the year.

We assumed the same size distribution of trees as was recorded at Wellington. This analysis led to an annual ET estimate of 1188 mm, to which a further 183 mm was added to represent the canopy interception loss. Again, in the absence of any experimental data, this component was estimated using a table of daily interception losses provided for this species by Schulze *et al.* (1995; Table 20.5.5, key 24). Total interception loss was calculated on the basis of these daily losses and the number of sample period rain days recorded at a gauge situated at the Gilboa forester's office. Where daily rainfall was less than the predicted daily interception loss, it was assumed that the interception loss equalled the daily rainfall. The estimated annual interception loss of 183 mm (17 % of the rainfall total of 1042 mm) was added to the sap flow total to yield an estimated annual ET of 1371 mm.

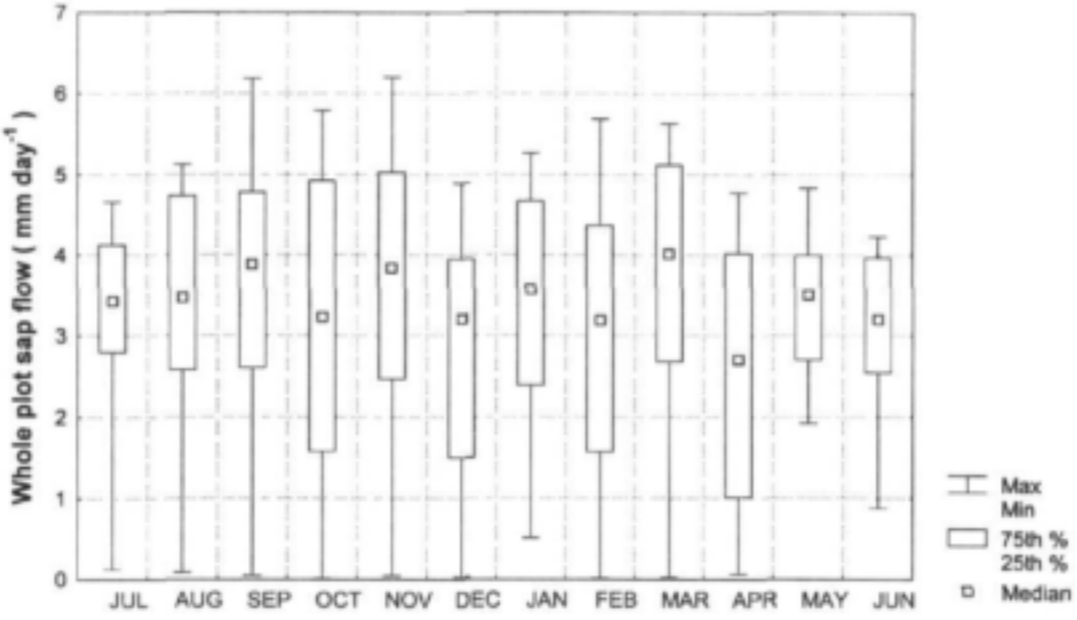

FIGURE 24: The median, upper and lower quartiles, and range of daily ET modelled for A. mearnsii *at the Gilboa site.*

6. DISCUSSION

In a list of research recommendations for improving our understanding of the impacts of alien invading plants, Versfeld *et al.* (1998) cited the need for improved measurement of water use by invading species, especially by *A. mearnsii*. This study has made a useful contribution in this direction, by providing comparative annual water use estimates between riparian wattle stands and indigenous plant communities in two different regions of the country, and by illustrating the major controls on plant water use, and how these may be modelled in other localities. Table 5 summarises the comparative data.

TABLE 5:. A summary of annual ET differences am ong the study sites.

Locality	***Vegetation***	***Annual water use (mm)***			
		Transpiration	***Rainfall interception***	***ET***	***Difference***
Jonkershoek	*A. mearnsii*	1304	171	1475	143
	Fynbos			1332	
Gilboa	*A. mearnsii*	1188	183	1371	535
	Grassland			836	

Comparison of riparian fynbos and wattle thicket at the Jonkershoek site predicts a net decline in annual ET of 143 mm if dense, mature wattle thicket growing in the upper Jonkershoek valley were to be removed and replaced in time by a well-developed riparian fynbos plant community. Likewise, a similar conversion of riparian wattle thicket to grassland at Gilboa would reduce annual ET by 535 mm. It is important to note that the calculated ET difference is significantly influenced by the estimated interception loss that is based on relative differences in LAI among different forest stands, and not on actual rainfall interception measurements (Schulze *et al.*, 1995). The estimated interception losses for stands of wattle need experimental verification.

This study has highlighted the need to consider the physiological characteristics of both the pre-clearing and post-clearing vegetation in order to predict the net change in ET. The large difference in annual ET between the Jonkershoek fynbos and Gilboa grassland well illustrates this point. This difference can be ascribed primarily to different patterns of green leaf area through the year. The Jonkershoek fynbos communities remained physiologically active throughout the year. High green leaf area ensured high rates of transpiration (Figure 4). By contrast, the grassland at Gilboa was dormant throughout the winter (Figure 19), and water use was below maximum in early and late summer due to changing green leaf area. These phenological differences are largely responsible for the relatively small annual ET difference between *A. mearnsii* and fynbos at Jonkershoek (compare Figures 4 and 14), and the much larger difference between *A. mearnsii* and grassland at Gilboa (compare Figures 19 and 24).

Rates of ET by *A. mearnsii* are comparable to closed-canopy plantation forests (Versfeld, 1994; Dye *et al.*, 1997). Canopies remain green throughout the year, and transpiration rates are regulated according to the ambient air humidity and daylength. Annual ET estimates for *A. mearnsii* at Jonkershoek and Gilboa differ by 104 mm. This is attributed largely to the different VPD regimes related to the difference in altitude.

This study has confirmed what has long been recognised by forest hydrologists, that ET from short vegetation is primarily controlled by solar radiation, whereas ET from forests is correlated more to the VPD of the ambient air. This is brought about by differences in the boundary layer resistance over canopies (Jarvis and Stewart, 1979; Jarvis *et al.*,1981). Our results demonstrate that relatively simple models based on the most limiting control on the ET of particular vegetation, may be used for predicting ET. This concept is expounded by Calder (1999) and holds great promise as a strategy for expanding our knowledge of ET from diverse vegetation types in South Africa.

A further useful outcome of this study is that daily sap flow in *A. mearnsii* may be modelled on the basis of DBH, and the product of VPD and number of daylight hours, when soil water availability and insect defoliation are not limiting transpiration rates. This is an eminently practical model that could be very useful in assessments of the influence of this species on catchment hydrology, especially where the trees are growing along wet riparian zones. However, the problem of predicting reduced sap flow rates under drying soil conditions was highlighted by the Groot Drakenstein study. In typically heterogeneous field conditions, it is quite impractical to physically describe the spatial pattern of soil water holding capacity, due to continuous variability in soil depth and stoniness in the soil/subsoil profile. The only practical prospect for spatially recording the intensity and duration of vegetation stress due to soil water deficits is from remote-sensing data. It is well established that trees under stress are associated with enhanced sensible heat, since less of the received solar radiation is converted into latent heat. The practicality of using remote sensing data to monitor stress development in forest canopies is currently under investigation in WRC project 1194 (determining plantation water use and growth from integrated remote sensing, water use models, geographic information systems (GIS) and field data).

7. CONCLUSIONS AND RECOMMENDATIONS

The principle implications of this study may be summarized as follows:

- Reduction in annual ET following removal of *A. mearnsii* from riparian zones is potentially large, but is highly variable, depending on the characteristics of the pre- and post-clearing plant communities, and climatic regime. The results of this research cannot be extrapolated to other sites without taking careful account of these factors.

- Assuming that soil water availability remains high throughout the year in riparian habitats, annual ET will be greatest in vegetation that maintains a high state of physiological activity and green leaf area through the year, and lowest where water use is curtailed by seasonal dormancy or any other cause of low green leaf area.

- The impact on catchment water yield of clearing *A. mearnsii* from riparian zones will vary in proportion to the area of riparian zone present in the catchment.

- Where *A. mearnsii* is present in non-riparian areas of a catchment, the potential for streamflow enhancement following clearing is greatly magnified. However, the hydrological effects of clearing these areas will depend on the annual ET characteristic of the pre- and post-clearing plant communities. The more constrained this is by soil water deficits, the less scope there is for large differences in annual ET between pre- and post-clearing vegetation.

- Clearing alien invasive trees in different parts of the country will lead to different catchment hydrological responses. Local assessments of such responses are required for prioritising clearing efforts and evaluating the cost-benefit of such actions. Simple predictive models are required to make such assessments.

- This study has demonstrated that annual water use of diverse plant communities may be adequately modelled on the basis of the factors most limiting ET rates. This is the basis of the "limits concept" propounded by Calder (1999). Models described in this report for predicting the water use of riparian *A. mearnsii*, grassland and fynbos are examples of such models.

- We recommend that a research programme be initiated to provide a simple modelling framework for assessing the annual water use of a wider range of vegetation types occurring in areas of the country invaded by alien invasive plants.

- Difficulties were experienced in applying the heat pulse velocity technique to *A. mearnsii*. These are described in order to assist researchers in future HPV studies involving this species. Project funds supported the development of an efficient HPV analysis programme that will greatly assist in any future HPV studies of alien invader trees.

- We recommend that research into the possibility of using remote sensing data to map plant physiological activity and water use over time should be supported.

8. DATA STORAGE

All relevant data files are copied onto CD disks, and lodged with the WRC and the senior author. An accompanying text file identifies the directory structure and describes the data files. Copies of the analysis programmes developed for analysing the Bowen ratio and heat pulse data are also included.

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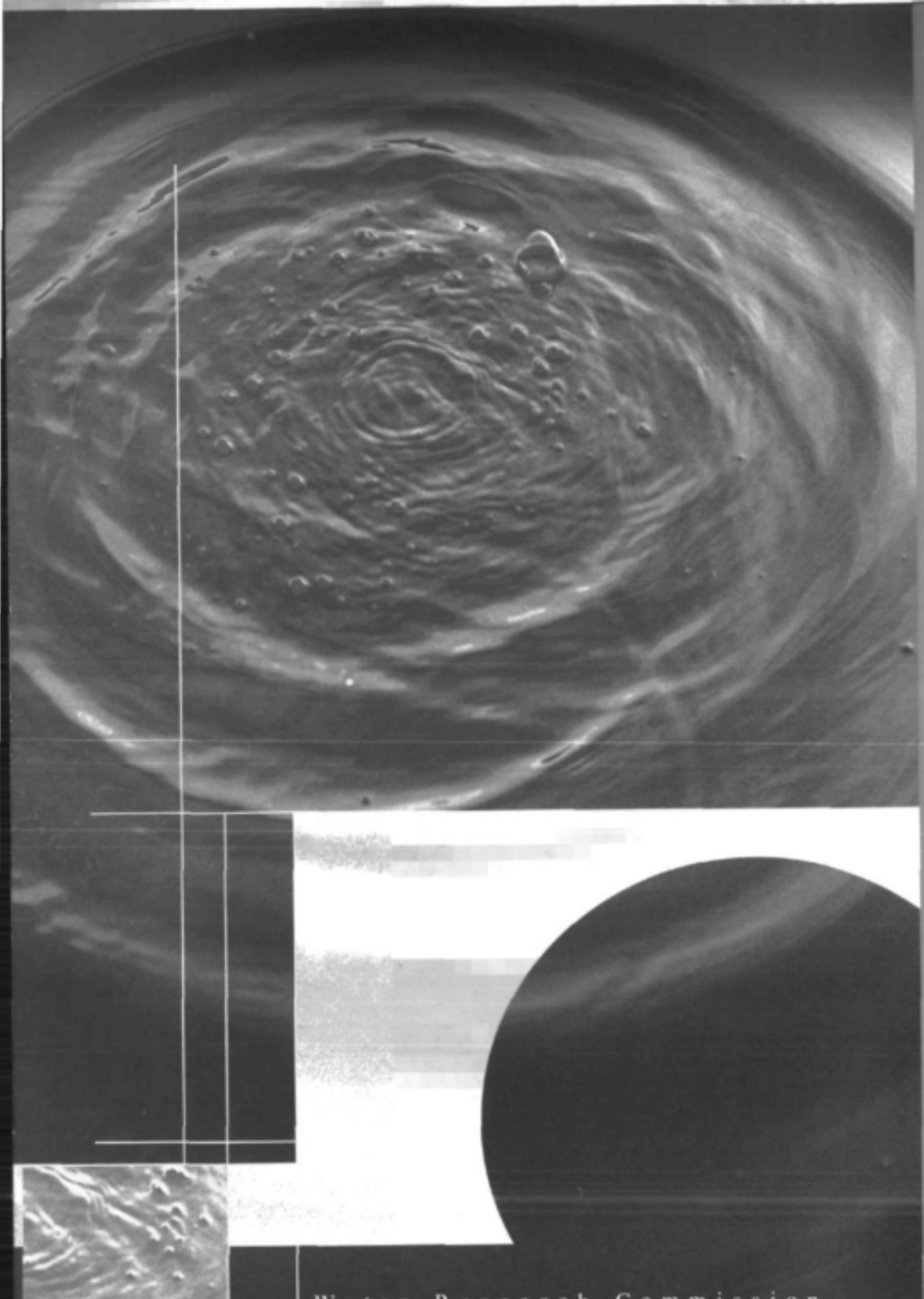

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