REHABILITATION OF ALIEN INVADED RIPARIAN ZONES AND CATCHMENTS USING INDIGENOUS TREES: AN ASSESSMENT OF INDIGENOUS TREE WATER-USE

Volume 1: Research Report

Report to the

WATER RESEARCH COMMISSION

and

DEPARTMENT OF ENVIRONMENTAL AFFAIRS

by

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WRC Report No. 2081/1/16

ISBN 978-1-4312-0828-9

August 2016

Obtainable from

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EXECUTIVE SUMMARY

REPORT STRUCTURE

This report is organized in two volumes:

Volume 1 (Research Report) outlines innovative approaches to the rehabilitation of invaded riparian forests and the impacts on their water-use for three case studies (Western Cape Afro-temperate forest, Eastern Mistbelt Forest and Maputaland Coastal Belt).

Volume 2 **(**Guidelines Report) provides recommendations and instructions on how to rehabilitate invaded riparian forests.

BACKGROUND

Agroforestry is receiving worldwide recognition as it has the potential to make an impact in many diverse areas such as poverty alleviation, global climate change, carbon sequestration, tree domestication and payments for environmental services (Hicks et al. 2014). While this is the case in most regions of the world, it is clear that South Africa has lagged behind in implementing agroforestry research. There is clearly a need to broaden agroforestry research beyond the traditional alley cropping approach. Innovative approaches recently used in South Africa include: (i) the management of regrowth after forest degradation to enable rural resource users to utilize resources while restoring the forest; and (ii) manipulation of plantation or invasive alien tree stands towards natural forest recovery with species that are also used by rural communities, i.e. combining forest rehabilitation actions with resource use needs satisfaction (Geldenhuys 1997, 2003, 2007; Geldenhuys & Delvaux 2007). Trees can be used for catchment rehabilitation and riparian zone management as well as to combat global climate change. In order to use trees for these purposes it is necessary to find alternatives to the use of fast growing exotic tree species which are high water-users. Much of the South African tree water-use research is based on forest hydrology and has focused on exotic tree species and their impacts on streamflow. In order to support the Government’s rural tree programmes, there is a need to expand current research to include the water-use of indigenous trees used in forest expansion, the rehabilitation of degraded lands and the restoration of riparian zones. One of the biggest problems with current rehabilitation programmes is that exotic species are used to restore the ecosystem services (e.g. water production, plant production and soil fertility). However, this ignores the importance of ecosystem structure and functioning (e.g. biodiversity). Research and policy support in South Africa is required to promote and scale-up indigenous tree planting and growing initiatives in degraded areas and riparian zones. The impact of expanding the use of indigenous trees to catchment hydrology is of critical importance in a water scarce country. It is therefore important to understand the plant water-use (transpirational changes) brought about by introducing indigenous trees into degraded landscapes and alien cleared riparian zones. A common practice to facilitate indigenous forest recovery after removal of alien tree is through selective thinning of the invader plant stand to stimulate the growth of natural forest seedlings (Cawe & Geldenhuys 2007; Geldenhuys & Bezuidenhout 2008; Geldenhuys & Delvaux 2007). An alternative is to plant relatively fast-growing indigenous forest pioneer and early regrowth species to promote establishment of late successional species. The question then is whether these indigenous species use less water than the fast-growing invader plant stands? There is a widespread belief in South Africa that indigenous tree species, in contrast to the exotic trees, are water efficient and should be planted more widely in land restoration programmes. This is based on observations that indigenous trees are generally slow growing, and that growth and water-use are broadly linked. However, tree water-use is technically difficult and expensive to measure, and so there is scant evidence of low water-use by indigenous trees.

This is even more so for pioneer tree species more suited to the rehabilitation of degraded lands and those found re-colonising riparian zones previously invaded with exotic trees (e.g. wattle). According to Clausnitzer et al. (2011), future riparian area conditions may not only include increasing temperatures and evaporative demands but also a higher frequency of extreme events. Stand water relations are crucial for valuing site conditions, and long term observations are necessary for a better understanding of inter- and intra-annual variability including responses to extremes or management effects (Clausnitzer et al., 2011).
For many field and modelling applications, accurate estimates of evapotranspiration (ET) are required, but are often lacking. Modelled estimates are often used without proper validation and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. Innovative approaches to forest restoration and rehabilitation of degraded land in South Africa include:

- the management of regrowth after forest degradation, to enable rural resource users to utilize resources, while restoring the forest; and
- the manipulation of plantation or invasive alien tree stands towards natural forest recovery with species that are also used by rural communities.

In order to use trees for these purposes it is necessary to find alternatives for the use of fast-growing exotic tree species, which are known to be high water-users. Although the ET of the riparian zone vegetation is a critical component of the overall catchment water balance, it is still poorly understood. Due to the availability of accurate techniques to quantify this large, and often poorly understood, component of the hydrological cycle, modelled estimates can be improved and therefore better understood, as can direct measurements. There is a need to expand current research and to include the water-use of indigenous trees used in forest expansion, the rehabilitation of degraded lands and the restoration of riparian zones.

SPECIFIC AIMS

1. To investigate the water-use (transpiration rates) of a selection of pioneer indigenous tree species suitable for forest expansion, rehabilitation programmes and riparian zone restoration following invasive alien clearing or manipulation.
2. To review available knowledge on the potential of indigenous trees for rehabilitation
3. Determine the potential impacts of alien tree removal on the re-establishment of indigenous tree species.
4. Incorporate the data into a modelling framework for temporal and spatial extrapolation of water-use predictions.
5. Provide guidelines and recommendations for the management of water-efficient indigenous tree species for use in land rehabilitation programmes.

METHODS

Study sites and species selection.

Various climatic regions were considered in order to investigate the water-use of species suitable for forest expansion and rehabilitation programmes throughout South Africa (Objective 1) and later, to incorporate the data into a modelling framework for water-use predictions (Objective 4). The presence of a Working for Water clearing programme in a location was essential to the selection of a site to meet Objective 3. With these requirements in mind, the following sites were selected: Western Cape Afro-temperate forest (Buffeljagsrivier), Eastern Mistbelt Forest (New Forest) and Maputaland Coastal Belt (Vasi pan).

The selection of priority species for this project was motivated by a combination of expert advice (workshops), gaps in past research, and a short-list of species selected by Gush et al. (2010) on the water-use and economic value of the biomass of indigenous trees under natural and plantation conditions (WRC Project K5/1876). The primary aim was to select species that occurred in the forest biome and over various climatic regions.

Based on this approach the alien species (e.g. *Acacia mearnsii* De Wild.) and the most important indigenous tree species (e.g. *Celtis africana* Burm.f. and *Vepris lanceolata* Lam. G.Don) were selected in the Western Cape. In the KwaZulu-Natal region important species were *Cetis africana* and *Sclerocroton intergerrimus* (Hochst.) J.Leonard. The selection of alien tree species was *Acacia mearnsii*, *Eucalyptus grandis* and *Solanum mauritianum*. In addition to plant water-use measurements, additional information on the size and age of both the alien and indigenous trees were collected in order to compare both within and between the different tree species. Measurements included height and diameter as well as soil moisture, rainfall, temperature and relative humidity in order to support the sap flow measurements.

Ecological studies.

To determine the ecological objectives, the study conducted intensive sampling of both natural forest and invasive alien plant stands at all three sites. At Buffeljagsrivier the study focused on mapping and measuring natural forest clusters within a black wattle stand. Stratified sampling was used to record the coordinates of each cluster as well as the shape, species composition and general site conditions. At New Forest and Vasi pan stratified and randomised sampling was conducted within indigenous and alien plant stands measuring both the species and size class of canopy and understory species. Statistical analysis was conducted on the data using ordination, importance values, stem class distributions and regressions. Aerial imagery was used to determine the forest change on the sites and landscape fire pattern. Allometric equations were calculated by field sampling, oven drying, calculating core density and then constructing biomass models by a transformed regression technique.

Hydrometeorological Studies.

The project conducted intensive measurements of individual tree water-use using heat energy balance techniques (HPV and Dynagage), weather variables, soil water dynamics as well as modelling the potential impact of the rehabilitation of invaded riparian zones using the SWAT and ACRU hydrological catchment models. The research focused on the priority individual indigenous tree species across the three distinct climatic zones (Western Cape Afro-temperate forest, Eastern Mistbelt Forest and Maputaland Coastal Belt).

RESULTS AND DISCUSSION

Ecological

The results of the ecological component of the study showed that natural forest species had the potential to regenerate (in previously forested areas) or colonise (in historically grassland or fynbos) within the confines of invasive alien plant stands. The results revealed two broad development processes (1) cluster development and (2) edge expansion of natural forest. Several hypotheses on forest development processes were tested which provided sound scientific rationale into the ecology of indigenous tree species establishing in IAP stands, particularly the development and expansion of clusters of native forest species, and the influence of distance to native seed sources.

Forest expansion process within alien plant stands

The study at Buffeljagsrivier focused on cluster development and it also provided some insight into forest edge expansion. This analysis showed that the successful establishment of natural forest species in clusters within the introduced invasive wattle occurred in different numbers and sizes according to distance from natural forest patches. Large clusters were most common closer to natural forest and smaller clusters were common further away from natural forest patches.

Importantly, the study found that clusters (which contained mature individual trees) were the catalysts for expansion and thus did not require the seed source from the initial forest patches to expand. This was interpreted as a type of edge expansion in itself. Insight into this process was supported by the analysis from the study at New Forest in Eastern Mistbelt forest, which showed that at intermediate and far distances from forest patches (i.e. between 200 and 600 m) pioneer forest species were likely to be recruited and at distances <40 m from native forest patches mature forest species were more abundant.

The influence of the alien plant stand structure on forest expansion

The New Forest study investigated how invasive plant stand structure might affect the establishment of the natural forest. The study showed that the IAP stands which were sampled were self-thinning, i.e. their density decreased with an increase in the age or mean stem diameter of the stand. This finding supported the theory outlined in the knowledge review of the project, which was that self-thinning and further manipulation of alien plant stands can facilitate the development of natural forest.

Many mature native forest specimens sampled at Buffeljagsrivier were >5 cm DBH and many areas had begun the forest catalytic expansion process. New Forest however, contained very few (<5%) trees >5 cm DBH, even though there were many young plants. This was thought to be because the forest development process at New Forest was in a much younger phase (initial cluster expansion) due to persisting disturbances (such as fire and/or timber harvesting) in the study area. In contrast at Vasi Pan (Northern Coastal Forest), forest development did not occur within alien plant stands, but was rather a consequence of the ecological conditions of a plantation environment, i.e. fire exclusion of a grassland environment. Similarities in the process of cluster expansion of grassland bush clumps and the catalytic expansion of clusters at Buffeljagsrivier and New Forest were thus noted at Vasi Pan.

Floristic composition of natural forest expansion

The differences in species composition between forest patches and alien plant stands conveyed information about the state of the development of the expanding forest. At Buffeljagsrivier and New Forest, the forest development process was relatively young. This was determined by the presence of expanding forest clusters within the alien plant stands. Most of the species within the clusters were pioneer shade tolerant forest species, while mature forest species were noted on the expanding edges of the forest patches.

The forest floristics at the three study sites in many ways represented the geographic location or the forest type of each forest and geographic area which contained different dominant forest species. However, there were some obvious dominant species in the process, for example, *Celtis africana* (White stinkwood) was present and common in all three sites. From a hydrological perspective understanding the water-use of such widespread species is important for choosing suitable species for rehabilitation programs.

The study showed that forest expansion processes were more or less similar (i.e. edge expansion and cluster development) throughout the three study sites. An in-depth analysis of forest development at Buffeljagsrivier and New Forest and a preliminary study conducted at Vasi Pan confirmed this. This showed the ability of the natural forest to initiate a catalytic reproductive process within areas of present or historical invader plant stands. The study revealed the dominant pioneer genera within each site, and where they are most likely to occur during the forest development process. This was critical from a water-use perspective as these data were synthesised with the hydrological data and incorporated into models of the water-use for riparian catchments. The conversion from invader plant stands into natural regrowth occurred naturally at the sites but findings showed that it also could be facilitated by manipulation to benefit the developing natural forest.

Hydro-meteorological Studies

Western Cape Afrotemperate Forest

Climate
At Buffeljagsrivier the long term MAP was 636 mm. The lowest rainfall year recorded was 1882 with 308 mm and the highest rainfall year was 1906 with 1045 mm. The 24 month study period between the 25th January 2012 and 12th December 2013 was characterised by higher than average rainfall (903 mm). For the

hydrological year from 1st October 2012 to the 1st October 2013, 902 mm of rainfall was recorded which is a higher than average year. The solar radiation was lowest in June (winter) and highest during January/December (summer). An average daily temperature of 22.1°C was recorded in the summer months. During these months, daily maximum temperatures reached an excess of 40°C. During the wet winter months, the temperatures averaged 12.1°C. The mean daily ET_o ranged from approximately 1 mm in the winter period to 4 mm during summer. The daily ET_o peaked at 7.5 mm, which is considered very high for grassland/fynbos cover.

Water-use

The indigenous trees in the wattle stand at Buffeljagsrivier showed significant differences in the daily sap flow rates varying from 15 to 32 $L.day^{-1}$ in summer (sap flow being directly proportional to tree size). In winter (June) this was reduced to only 5 $L.day^{-1}$ when less available energy was available to drive the transpiration process. The water-use in the *Acacia mearnsii* trees showed a peak in transpiration during the months of March 2012, September 2012 and February 2013. These periods corresponded to high average temperatures (21.45°C), and rainfall (76 mm in 2012) and high daily vapour pressure deficits (VPD) (average of 1.26 kPa). The average daily sap flow ranged from 15 L (Tree 6) to 35 L (Tree 4). The combined accumulated daily sap flow over the two year period for the three *Vepris lanceolata* and three *Acacia mearnsii* trees was 36 000 and 55 700 L respectively, clearly demonstrating the higher water-use of the exotic *Acacia* trees. From the above we concluded that, annually, the alien stand uses nearly six times more water per unit area than the indigenous stand.

Modelling

The differences in water-use between indigenous and invaded riparian zones were also reflected in the ACRU modelling where the streamflow reduction in the entire catchment was approximately 1 478 m^3 over the 50-year simulation period. Directly scaling up the actual tree water-use data showed similar findings with the impact of clearing the *Acacia mearnsii* showing clear water balance benefits.

Eastern mist-belt forest

Climate

The mean annual precipitation at New Forest was 941 mm with an average daily summer temperature of 18.4°C. Daily maximum temperatures reached in excess of 30°C. During the dry cold winter months, the temperatures averaged 11.7°C. The total rainfall during the study period was 1118 mm and wind speed fluctuated between 1 and 2 $m.s^{-1}$.

Water-use

Three of the trees studied (*Searsia pyroides* Burch. Moffett, *Maytenus peduncularis* Loes. and *Acacia mearnsii*) are evergreen species and showed little seasonal variation in their daily water-use patterns. The accumulated seasonal water-use was the least in the *Searsia* (~2100 L), moderate in the *Maytenus* (~7100 L) and high in the *Acacia* (~15900 L) trees. This again showed the more conservative water-use of indigenous when compared with exotic tree species.

Modelling

Modelled ET was consistently higher for the invaded riparian zone when compared with the pristine scenario by 1 to 2 mm daily. This resulted in an accumulated catchment difference of 10134 vs 9533 mm for the invaded and pristine areas respectively. The SWAT water balance showed that evaporation (598.6 mm) and transpiration (569.0 mm) were equally split after the 1301 mm of rainfall.

Maputaland coastal belt

Climate

Approximately 80% of the precipitation occurs in the summer months. The mean annual precipitation is between 750 and 800 mm. There is a distinct dry season from May to August. Average temperatures ranged from 11.5°C in the winter to 28.7°C in the summer. During these months, daily maximum temperatures reached an excess of 35°C. During the dry winter months, the temperatures averaged 18°C.

Water-use

The hourly sap flow measurements showed little difference in the heat energy balance between *Phoenix reclinata* Jacq. and *Pinus patula*. These results indicated that the *Phoenix* palm species is one of the highest water-users of the indigenous species.

Modelling
Vasi is a groundwater dominant system and therefore no attempt was made to use streamflow models to estimate the impact of different land-use scenarios. To be able to set up the *ACRU* Shallow Groundwater Routine for Catchment W70A, the inputs from the South African Quinary Database for the Quaternary W70A were used (Quinaries 5524-5526), including the driver rainfall with 50 years of daily historical climate data (1950 to 1999), as well as soil and vegetation information. The forest plantation size of 24 560 ha for the study catchment was extracted from the National Land Cover information (NLC 2000).

The monthly precipitation can be compared with the modelled recharge beyond the B horizon, which was calculated by the sum of the recharge out of the B horizon (*ACRU* Output SUR2) and the recharge out of the intermediate zone to groundwater (*ACRU* output SUR3). Results from a selected trial showed that recharge only takes place when there are high rainfall months. The simulated intermediate and groundwater zone recharge as well as utilisation by deep roots from the intermediate zone or groundwater (ATRAN3 + ATRAN4) were compared. The expected result was that the drainage into the intermediate zone and groundwater would be higher under shallow rooted than under deep rooted vegetation, and this is what was demonstrated by the results. The groundwater table levels under shallow roots and under deep roots of a forest plantation were simulated, as was the drawdown under deep roots. Both simulations showed a drawdown due to deep roots. Both simulations under shallow roots showed an initial drawdown and after that a slow but steady increase in water table level. This correlates with the increase in the driver rainfall. It is concluded by the modellers that plausible results were obtained with the ACRU shallow groundwater routine as the results are a starting point for future groundwater modelling.

CONCLUSIONS

There is a lack of information on riparian tree water-use for indigenous trees in South Africa. This study provided long term water-use for three different forest types, each at differing levels of rehabilitation. The techniques used were heat pulse velocity, stem steady state and thermal dissipation. A modelling component was used to upscale the data from individual trees to stands and catchment scales.

The results showed that indigenous trees in an established riparian stand in a Western Cape Afro-temperate forest can use high volumes of water throughout the year (little seasonal rainfall change in this region). The variability of water-use between species and tree size was large as this variable is largely dependent on location, tree condition and light dynamics. This further highlights the need for measurement replication. The comparison between individual trees indicated that the largest trees (*Celtis* and *Vepris*) used the most water. However, when extrapolated by stem density, the alien species (*Acacia mearnsii*) used significantly more water per unit area (up to five times more water in certain stand locations). The modelling results revealed that a significant amount of water can be conserved if alien invaded forest stands are rehabilitated.

Of particular importance, during the wetter season (May to August), the deciduous trees in the winter rainfall region were not using any water. This is in contrast to the deciduous species in the Eastern Mistbelt region and the Maputaland coastal belt that are dormant during the dry season when water is most scarce. In the Western Cape area, it is recommended that evergreen species be used for forest rehabilitation as they use less water than the deciduous trees during the drier months when water is needed the most.

The results for the Eastern Mistbelt forest, which had a highly disturbed/invaded stand, showed very low water-use volumes in comparison to the Western Cape site. The alien species used significantly more water than the indigenous species, which had approximately the same stem density in the measurement area. A key finding from this site was that the smaller trees (diameter 1-2.5 cm) in the understorey of pioneer species such as *Buddleja* (indigenous), *Solanum* and *Acacia* (introduced) used up to 4 L.day-1 individually. It is recommended that deciduous species in addition to low consumptive evergreen species be used for forest rehabilitation as they use very little water during the drier winter months when water is needed the most.

The results from the Maputaland Coastal belt revealed that the alien species (*Eucalyptus grandis* and *Pinus elliottii*) used significantly more water than the short forest that it invaded. A key recommendation for this site is that more detailed research be undertaken given the environmental, political, social and hydrological importance of the site.

Although modelling was not the primary focus of this study, unique input attributes for mixed riparian forests were derived for the ACRU and the SWAT models. This is an important step forward for future modelling (upscaling) as it allows users to accurately model these riparian systems that have constant access to water. The SWAT model is not commonly used in South Africa as the input parameters are not easily available nor are they easily transferable from one model to another. This model was run successfully using entirely site specific inputs and used to test various scenarios at each site. The model showed that it has the potential to provide a powerful tool for understanding the impact of various land-use scenarios.

The study investigated the influence of alien plant stand conditions (i.e. distance from seed source) and the development processes (i.e. cluster expansion) in which forest growth occurred. This challenged the perception that invasive plants nullify the capacity of native species to grow within IAP vegetation systems.

There were two distinct ways in which natural forest establishes within alien plant stands (1) Edge expansion and (2) Cluster development. Importantly, the study found that clusters (which contained mature individual trees) were self-regenerating and thus did not require the seed source from the initial forest patches to expand.

The New Forest study investigated how invasive plant stand structure might affect the establishment of the natural forest. The study showed that the IAP stands which were sampled were self-thinning, i.e. their density decreased with an increase in the age or mean stem diameter of the stand. This finding supported the theory outlined in the knowledge review of the project. Analysis of the results indicated that distance may have had a stronger influence on forest development than IAP stand structure.

The forest development process at New Forest was in a much younger phase (initial cluster expansion) due to persisting disturbances (such as fire and/or timber harvesting) in the study area. In contrast, at Vasi Pan (Northern Coastal Forest), forest expansion in grassland bush clumps was a consequence of the changed ecological conditions of a plantation environment through fire exclusion.

It is important to understand the genera of plant species within the forest, particularly with reference to the characteristics of the dominant pioneer species. Some species functioned as both pioneer and old growth forest species, e.g. *Celtis africana* and *Rapanea melanophloeos* (Cape Beach) which were recorded as dominant pioneer species and old growth forest species at New Forest and Buffeljagsrivier. Such species become established in large gaps or degraded forest and then persist into the canopy where they then nurse the regeneration and establishment of more shade-tolerant forest species This trend was also noted at Vasi Pan for example with *Hymenocardia ulmoides* (Redheart Tree). From a hydrological perspective understanding the water-use of such widespread species would be important for choosing suitable species for rehabilitation programs.

The study showed that the forest expansion processes (i.e. edge expansion and cluster development) were similar throughout the three study sites. The study revealed the dominant pioneer genera within each site, and where they are most likely to occur during the forest development process. This is critical from a water-use perspective as these data can be synthesised with the hydrological data and incorporated into models of the water-use for riparian catchments. The conversion from invader plant stands into natural regrowth forest is a process which can occur naturally but can also be facilitated by manipulation to benefit the developing natural forest. A practical guideline document was provided as part of this project to guide the natural resources managers on this process.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future research should focus on investigations into alternate monitoring methods such as remote sensing which could result in significant improvements into groundwater modelling which is closely linked to tree water use. Future ecological studies of this nature should also look at light and nutrient dynamics for forest rehabilitation. The impact of browsers and grazers on the impacts of seedling establishment and survival also needs further investigation. Furthermore, long term trials would be valuable to test many of the techniques explored in this study.

ACKNOWLEDGEMENTS

The research reported in this document forms part of a project funded and managed by the Water Research Commission of South Africa in the Key Strategic Area on Water Utilisation in Agriculture, with co-funding from the Department of Environmental Affairs in the Natural Resource Programme of Working for Water (WfW).

The project team would like to thank the reference group members who provided valuable information and guidance throughout the research period.

Dr GR Backeberg	*Water Research Commission (Chairman)*
Dr PJ Dye	*Wits University*
Dr JSB Scotcher	*ForestLore Consulting*
Prof JG Annandale	*University of Pretoria*
Dr RN Heath	*Forestry SA*
Mr DB Versfeld	*Dirk Versfeld CC*
Dr AJ Sanewe	*Water Research Commission*
Dr MB Gush	*CSIR*
Dr C Marais	*Department of Environmental Affairs*
Mr S McKean	*Ezemvelo KZN Wildlife*
Mr R Brudvig	*Department of Environmental Affairs*
Ms S J. van Rensburg	*SAEON GFW (Minutes)*
Mrs S Clulow	*Secretariat*

The following people provided valuable technical assistance to the experiments:
Alistair Clulow, Siphiwe Mfeka, Caren Jarmain, Terry Everson, Piet-Louis Grundling and Sihle Bukusini.

The following students provided assistance to the various field trips and experiments:
Matthew Becker and Hayden Jacobs.

Various land owners are acknowledged for allowing field work to be conducted on their property. We are very grateful for this and the assistance they provided during the monitoring period. The land owners are as follows:

- Brian and Janet Kilpen (Frog Mountain, Buffeljagsrivier)
- Alfie Messenger, (New Forest Farm, Fort Nottingham) Duncan Macfayden (Wakefield Farm), Laurence Stuart-Hill (Umgeni Poort Farm).
- Manzengwenya Plantation (DAFF, Vasi Pan)

Working for Water and specifically Mr Wessel Wentzel for the construction of security cages at Buffeljagsrivier. The South African Sugarcane Research Institute (SASRI) and specifically Alana Eksteen for temporary loan of two Dynamax systems.

The University of Pretoria Plant Production and Soil Science and the University of KwaZulu-Natal Centre for Water Resources Research is acknowledged for the use of facilities and equipment.

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Roman Symbols

cp	specific heat capacity of air at constant pressure (approximately 1040 J $kg^{-}1$ K^{-1})
D	deep drainage (mm)
E_s	soil evaporation (mm day^{-1})
ET	total evaporation (mm)
ETEC	total evaporation (mm) from eddy covariance measurements
ET_o	FAO-56 reference total evaporation (mm)
gc	canopy conductance (m s^{-1}) = (1.rs^{-1})
gc_{max}	maximum conductance (m s^{-1})
G	soil heat flux (W m^{-2})
H	sensible heat flux (W m^{-2})
LE	latent heat flux (W m^{-2})
P	precipitation (mm)
Q	streamflow (mm)
R	surface runoff (mm)
R_n	net irradiance (W m^{-2})
spha	stems per hectare
T	transpiration (mm or L)
T_a	temperature of the air (°C)
Tsonic	air temperature using sonic temperature (°C)
Vh	Heat Pulse Velocity (cm hr^{-1})
w	vertical wind velocity (m s^{-1})
W	contribution from water table upward (mm)

Abbreviations

AWS	Automatic weather station
CSIR	Council for Scientific and Industrial Research
DAFF/DOA	Department of Agriculture, Forestry and Fisheries
DWS/DWAF	Department of Water Affairs & Sanitation
FAO-56	Food and Agriculture Organisation, paper no. 56
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
LAI	Leaf Area Index
MAP	Mean Annual Precipitation
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
SWB	Soil Water Balance
TDR	Time Domain Reflectometry
VPD	Vapour Pressure Deficit
WUE	Water-use Efficiency

Terms

Core forest: Generally the oldest portion of a forest patch or specific forest. This may represent climax or mature areas in undisturbed forests or 'old' regrowth areas in younger developing forest.

Forest Cluster: one to several natural forest trees growing on a limited area within an alien plant stand or grassland. A requirement was that within the group there should be at least one reproductively mature tree present that would be able to attract dispersal agents. Three cluster size classes were defined: Small cluster, with one to three trees; Medium cluster with four to nine trees; and Large cluster with 10 and more trees.

Forest Patch: A small or large isolated area of mature or regrowth forest which can act as a seed source for forest expansion.

Invasive Alien Plants (IAPs): Species which do not occur naturally in an area (not indigenous), but which have been introduced and become invasive.

Naturalisation: Colonisation of alien or indigenous forest in areas in the landscape which historically did not contain forest, e.g. grassland areas.

Rehabilitation: Using some of the original species, plus, where necessary, introduced species, to reforest the site. In this case, there is no attempt to recreate the original ecosystem; rather the objective is to initiate the process that would return the forest to a stable and productive condition.

Regrowth Forest: A patch of regenerating natural forest which is not in a mature ecological condition where natural forest existed before. It may persist as a regrowth forest if located in a frequently disturbed area, i.e. river bed or on a successional pathway to mature forest, i.e. in a grassland area.

Self-perpetual cluster expansion: The ability of a new or young forest cluster to expand without the seed source from core or mature forest patches

Water Use Efficiency: Biomass produced per unit of water transpired.

1. INTRODUCTION

Agroforestry is receiving worldwide recognition as it has the potential to make an impact in many diverse areas such as poverty alleviation, global climate change, carbon sequestration, tree domestication and payments for environmental services (2nd World AF Congress, Nairobi, November 2009). However, South Africa has lagged behind in implementing agroforestry research, except for the WRC poverty alleviation programme focusing on the effect of traditional alley cropping (i.e. growing crops between rows of trees) to increase fodder production for small scale farmers. The need is to broaden agroforestry research to include innovative approaches towards combining forest rehabilitation actions with resource use needs satisfaction, by finding suitable alternatives to the use of fast growing introduced tree species which are high water-users.

There is also a need to expand current SA tree water-use research based on forest hydrology and the effects of introduced tree species on streamflow to include the water-use of indigenous trees used in forest expansion, and the rehabilitation of degraded lands and riparian zones. Current rehabilitation programmes using introduced species (e.g. vetiver grass) to restore ecosystem services (e.g. water and plant production and soil fertility) ignore the importance of ecosystem structure and functioning (e.g. biodiversity). Research and policy support in South Africa is required to promote and scale-up indigenous tree planting and growing initiatives in degraded areas and riparian zones. The impact of expanding the use of indigenous trees to catchment hydrology is of critical importance in a water scarce country. It is therefore important to understand the plant water-use (transpirational changes) brought about by introducing indigenous trees into degraded landscapes and alien cleared riparian zones.

For many field and modelling applications on the impact of rehabilitation on degraded forests, accurate estimates of evapotranspiration (ET) are required, but are often lacking. Modelled estimates are often used without proper validation and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. Innovative approaches to rehabilitation of degraded forest and degraded land in South Africa include:

- the management of regrowth after forest degradation, to enable rural resource users to utilize resources, while rehabilitation of the forest; and
- the manipulation of plantation or invasive alien tree stands towards natural forest recovery with species that are also used by rural communities.

1.1 Project Aims

The main aim of this project is to investigate the water use (transpiration rates) of a selection of pioneer indigenous tree species suitable for forest expansion, rehabilitation programmes and riparian zone restoration following invasive alien clearing or manipulation.
This study will focus on determining the water-use of potential indigenous, pioneer tree species suitable for rehabilitation programmes through the following objectives:

1. To investigate the water-use (transpiration rates) of a selection of pioneer indigenous tree species suitable for forest expansion and rehabilitation programmes, including riparian zones, following invasive alien clearing or manipulation;
2. To review available knowledge on the potential of indigenous trees for rehabilitation;

3. To determine the potential impacts of alien tree removal on the re-establishment of indigenous tree species;
4. To incorporate the data into a modelling framework for temporal and spatial extrapolation of water-use predictions;
5. To provide guidelines and recommendations for the management of water-efficient indigenous tree species for use in land rehabilitation programmes.

1.2 Experimental Approach

The experimental approach for this study was to:

- Build on existing tree water-use measurements in selected riparian forests based on information gathered from the ecological surveys;
- Improve modelling scenarios in order to assist in decision making; and
- Understand the broader ecology of riparian forests through seed dispersal and management dynamics.

1.3 Report Structure

This report is organized in two volumes:

Volume 1 (Research Report) outlines innovative approaches to the rehabilitation of invaded riparian forests and the impacts on their water-use for three case studies (Western Cape Afro-temperate forest, Eastern Mistbelt Forest and Maputaland Coastal Belt).

Volume 2 **(**Guidelines Report) provides recommendations and instructions on how to rehabilitate invaded riparian forests.

2. KNOWLEDGE REVIEW

Much of the South African tree water-use research is based on forest hydrology and has focused on introduced tree species and their impacts on streamflow. In order to support the Government's rural tree programmes, there is a need to expand current research to include the water-use of indigenous trees used in forest expansion, the rehabilitation of degraded lands and the restoration of riparian zones. One of the biggest problems with current rehabilitation programmes is that introduced species are used to restore the ecosystem services (e.g. water production plant production and soil fertility). However, this ignores the importance of ecosystem structure and functioning (e.g. biodiversity). Research and policy support in South Africa is required to promote and scale-up indigenous tree planting and growing initiatives in degraded areas and riparian zones. The impact of expanding the use of indigenous trees to catchment hydrology is of critical importance in a water scarce country. It is therefore important to understand the plant water-use (transpirational changes) brought about by introducing indigenous trees into degraded landscapes and alien cleared riparian zones. A common practice to facilitate indigenous forest recovery after removal of alien trees is through selective thinning of the invader plant stand to stimulate the growth of natural forest seedlings (Cawe & Geldenhuys 2007; Geldenhuys 1997, 2003, 2007, 2013; Geldenhuys & Bezuidenhout 2008, 2011; Geldenhuys & Delvaux 2007). An alternative is to plant relatively fast-growing indigenous forest pioneer and early regrowth species to promote establishment of late successional species. The question then is whether these indigenous species use less water than the fast-growing invader plant stands? There is a widespread belief in South Africa that indigenous tree species, in contrast to the introduced trees, are water efficient and should be planted more widely in land rehabilitation programmes. This is based on observations that indigenous trees are generally slow growing, and that growth and water-use are broadly linked. However, tree water-use is technically difficult and expensive to measure, and so there is scant evidence of low water-use by indigenous trees. This is even more so for pioneer tree species more suited to the rehabilitation of degraded lands and those found re-colonising riparian zones previously invaded with introduced tree species (e.g. wattle). According to Clausnitzer et al. (2011), future riparian area conditions may not only include increasing temperatures and evaporative demands but also a higher frequency of extreme events. Stand water relations are crucial for valuing site conditions, and long term observations are necessary for a better understanding of inter- and intra-annual variability including responses to extremes or management effects (Clausnitzer et al., 2011).

2.1 An Overview of Ecosystem Services

The natural capital of the natural forests has value to society through the direct and indirect goods/products, services and values they provide (Geldenhuys, 2004; Lawes et al., 2004; Seydack & Vermeulen 2004; Cawe & Geldenhuys, 2007). These include: Timber products such as boards and planks; Non-timber forest products such as fuel wood, poles, wood carving and household utensils; Non-wood forest products such as food and fruits, traditional medicines from different plant parts, fibres of various kinds for baskets, mats and construction, horticulture and hunting; and different values and services including ecotourism, hunting, crop agriculture, grazing/browsing by livestock and wildlife, maintenance of soil fertility, reduced soil erosion from catchments, and carbon sequestration and storage.

Trees and tree products play an important and often under-estimated role in the livelihoods of rural communities. The economic value of forests, riparian zone plant communities and of woodlands to rural communities often equates to a significant proportion of the income of rural households as well as indirect benefits through savings on purchasing products. These include, in order of importance:

1. Timber and poles for construction material for houses and home garden fences;
2. Fuel wood, the major source of energy for cooking, lighting and heating;
3. Bark for traditional medicine and making ropes for binding and weaving;
4. Other tree parts for medicinal products such as fruit, leaves and roots;
5. Wood for carving of utensils and crafts;
6. Tree fruits as an important dietary supplement;
7. Honey produced from flowers of different forest species,
8. Harvesting of bulb, herbs and climbers for traditional medicines from
9. Harvesting of insects, mushrooms and other edible plants.

Much of the literature on forests highlight the problem of forest degradation, loss of forest cover and associated biodiversity, threatening spread of invasive alien plants, climate/environmental change, etc. (FAO, 2005; Roberts, 2008). Such concerns have also been expressed on the well-being of the South African natural forests (Cooper, 1985; Mucina & Geldenhuys, 2006; CES 2008; Berliner, 2005). These negative perceptions are attributed to uncontrolled use of the timber, non-timber and non-wood forest resources, unsustainable slash-and-burn traditional agriculture, and uncontrolled fires.

Slash-and-burn traditional agriculture (also known as shifting cultivation or forest-agriculture) and associated practices have been seen as the major cause of deforestation and forest decline in the tropics (Brady, 1996; Brown, 2004; FAO, 2005), and also in coastal rural areas in the Eastern Cape (CES, 2008). However, in reality these traditional multiple resource use practices in rural areas integrate agriculture, forestry and nature conservation through which the farmers use and maintain forest biodiversity, and forest recovery (Feely, 1987; Brown, 2004; Mala, 2009). This is in sharp contrast to the conventional thinking of biodiversity and the segregation approach used at the forest-agriculture interface, i.e. separating forestry and agriculture as two separate units for management and research (spatially, administratively and conceptually) and setting aside of protected areas (Instone, 2003). As such, part of the diversity of the natural forest systems, away from natural disturbance-recovery cycles, is threatened. The question then arises as to how the natural forest systems should be managed to provide resource use needs and to maintain their biodiversity and the ecological processes that underlie that biodiversity. Sustainable resource use, control of invasive alien plants and maintenance of the ecological process and biodiversity of natural forests have to be managed in the context of the natural balances between disturbance and recovery.

South Africa has <0.5% cover by natural forests (Mucina & Geldenhuys, 2006; Berliner, 2009; different percentages are given by different sources). The climate determines the area where forests could potentially grow. In South Africa, natural forest can grow in areas with summer rainfall of >725 mm/annum, and winter and all-year rainfall of >525 mm/annum (Rutherford & Westfall, 1986). This means that potentially South Africa could have a forest cover of >7% if one considers the area enclosed by the 800 mm rainfall isohyets. Only a relatively small part of this difference between the potential forest cover based on climatic variables and the actual cover of <0.5% can be attributed to clearing of forest by people. Most of this difference has resulted from natural and anthropogenic fires in the landscape, driven mainly by the hot, dry berg winds. The fragmented natural forests persisted over millennia in wind/fire shadow areas, with grassland, shrublands and woodlands developing along the fire pathways, depending on the frequency of the fires (Geldenhuys, 1994). Many riparian zones are typical fire shadow areas below the level of the edge of the surrounding landscape (Geldenhuys & Bezuidenhout, 2008).

The use of fire in the management of the grasslands, shrublands and woodlands surrounding natural evergreen forests has changed for many reasons: Actions of people through resource use from forests; cultivation of crops (with forest clearing in some areas), fruit orchards and timber plantations, with or without directed fire control; livestock management (with burning for grazing), urban and settlement development; and development of infrastructure such as roads and power-lines. The changed fire regimes contributed to the dynamic interplay between grasslands, woodlands and forests, and the wide spread of invasive alien plants (IAPs). These activities contributed to forest loss and fragmentation in some areas but also forest expansion in other areas (Cooper, 1985; Geldenhuys and MacDevette, 1989; Geldenhuys, 1994, 2008; Geldenhuys & Venter 2002; Lawes et al*.,* 2006; De Klerk, 2007). For example, forest fragmentation is particularly evident through complete loss of many smaller forest patches (Kotze and Lawes, 2007), shrinkage of larger patches (Cooper and Swart, 1992), and transformation of the matrix vegetation between forest patches (Lawes et al*.,* 2004; Berliner et al*.,* 2009), with much of the grassy vegetation becoming invaded by both indigenous and/or introduced woody vegetation (Bond & Parr, 2010). Some of these changes contribute to expansion and wider spread of forest elements which eventually contribute to the development of new forest patches (for example Geldenhuys & Venter 2002 for the Limpopo Province forests; De Klerk 2007 for the Wild Coast forests). This changed environment causes changes in the physiognomy and species assemblages. This has been attributed to the carbon loading in the atmosphere associated with climate change (Bond, 2008), but much is directly related to changed land management practices.

Indigenous pioneer tree species such as *Acacia karroo* Hayne (De Klerk, 2007) and the invasive alien plants (Henderson, 2001; Holmes, et al., 2008) influence the dynamics between natural forest and the fire-adapted fynbos shrublands, wooded grassland (savanna) and woodlands as a result of changed fire regimes. They provide a major threat to the biodiversity of the fire-adapted fynbos shrublands, grasslands and woodlands because of their light requirements associated with disturbed environments (Holmes, et al. 2008). However, the natural forests in general benefit from the expansion of the invasive fast-growing, light-demanding alien plant species. The forest species are generally shade-tolerant and establish in the understorey of the planted and naturalizing stands of introduced species (Geldenhuys, 1996, 1997, 2008; 2011, 2013; Geldenhuys & Delvaux, 2007), and under stands of *Acacia karroo* (Von Maltitz et al., 1996; Richards Bay Minerals rehabilitation activities; Geldenhuys, et al., 2013).

The similarities in general function between native and introduced pioneer tree species provide a basis to develop a common concept for forest rehabilitation and recovery in the natural forest environment. The pioneer stands typically facilitate the recovery of disturbed sites, starting from mono-specific stands to species-diverse regrowth stands that eventually develop a species composition and stem size range similar to the surrounding mature forest (Geldenhuys, 1996a, 1997; Geldenhuys & Bezuidenhout, 2008; Geldenhuys & Delvaux, 2007; Parrotta et al., 1997,). The light-demanding alien species with invasive tendencies have one or more characteristics in common with the native pioneer species (Geldenhuys, 1986; Geldenhuys, et al. 1986):

- they are pioneer trees, shrubs and climbers in their natural environments;
- they have wind or animal-dispersed (birds, primates and bats) fruits or have long-living hard-coated seeds, and several develop long-living soil-stored seed banks;
- they rapidly colonize sites disturbed in terms of forest structure and cover;
- they are generally easily raised, and fast-growing in the open;
- they are intolerant of shade (cannot establish successfully under their own canopies or the closed forest canopy);
- they buffer the more variable and extreme conditions of regularly disturbed grassland, shrubland and agricultural fields and facilitate the establishment of more shade-tolerant forest species;

However, they have a competitive advantage outside of their natural environment because they do not have their natural enemies which control them in their native environments.

The success of the establishment of indigenous pioneer tree species in the understorey of stands of introduced or indigenous species (nurse stands), depends on the species of the nurse stand, the density and age of the nurse stand, or the distance into the nurse stand away from the natural forest seed source area and the dispersal of the indigenous tree species (Parrotta et al 1997 for global examples; Geldenhuys, 1997 for examples from the Limpopo Province forests). This is a typical succession process which can be managed to achieve specific resource use benefits (Geldenhuys, 2008, 2013; Geldenhuys & Bezuidenhout, 2008, 2011) and recovery of the forest (Van Wyk, et al. 1995). The alien black wattle (*Acacia mearnsii*) stands along the Buffeljagsrivier in the Western Cape (Geldenhuys & Bezuidenhout, 2006) and the extensive regrowth of the indigenous sweet thorn (*Acacia karroo*) along the Wild Coast of the Eastern Cape (Cawe & Geldenhuys, 2007; De Klerk, 2007; Geldenhuys, et al., 2013) provide good sites to study the spread of indigenous tree species into these pioneer nurse stands.

Many rural development projects promote the development of rural nurseries for growing of indigenous tree species to rehabilitate degraded natural forest. Besides providing a means of income generation, they provide resource-use needs and mitigate climate change through carbon sequestration. Many forest rehabilitation projects grow seedlings of a wide range of species in nurseries and transplant these on the rehabilitation site(s) (Knowles & Parrotta, 1995). However the ecological characteristics of the planted species are not considered in the selection process, for example, shade tolerant species of the mature forest are planted in very exposed sites, reducing their probability of successful establishment. There are also many constraints to successful forest rehabilitation through planting of nursery-raised plants. Nurseries, if not properly managed, are a source of spreading root-rot diseases into natural areas (Lübbe & Mostert, 1991). Nursery practices (e.g. watering) are expensive, particularly for poor rural societies. It is often not possible to find enough seeds of suitable selected species to grow in nurseries. The natural regeneration through pioneer tree species (indigenous and/or introduced species) is financially a better option because such species have a much better adaptation to establish under the disturbed conditions. Generally they have a fast growth rate and are able to cover the site and reduce erosion. They also contribute to restoring the nutrient cycling through litter and organic material, and facilitate the natural regeneration of the shade-tolerant forest species (Geldenhuys & Bezuidenhout, 2008, 2011). Clearing light-demanding invasive alien species in the natural forest environment followed by planting natural forest species is therefore unnecessary and not cost-effective.

Another option to promote indigenous forests is stand manipulation through selective thinning. This can be implemented to facilitate the typical succession process, to convert alien plant stands towards regrowth native forest, and to provide firewood, poles and timber for rural communities (Geldenhuys, et al., 1986, 2013; Geldenhuys & Bezuidenhout, 2008, 2011). This process has benefits over the conventional invasive alien clearing practice:

- it is a typical forest succession process which can be managed to achieve specific complementary objectives of forest protection and biodiversity recovery (Van Wyk et al. 1995);
- it is less expensive both in terms of clearing actions and establishing native tree species because nature does a large part of the job for free (birds and mammals carry many of the seeds into the recovering stand) (Geldenhuys, 1996b, 1997, 2008, 2013);
- stems removed during selective thinning (manipulative interference to speed up the process) could be used for laths, poles, firewood, timber, depending on the development stage of the nurse stand;
- the pioneer stands can be a source of seedlings of medicinal and food plants for planting in rural home gardens or rehabilitation actions without an expensive nursery (Geldenhuys & Delvaux 2007).

Training of resource users to facilitate the growth of natural regeneration could benefit many more people if the money used to maintain a nursery was allocated to capacity building. In current research programmes to convert alien tree stands to natural forest, no indigenous trees are planted. Instead, forest recovery is facilitated through selective thinning of the invader plant stand to stimulate the growth of natural forest seedlings, many of which are used for various products by rural communities (Cawe & Geldenhuys 2007; Geldenhuys & Delvaux 2007; Geldenhuys & Bezuidenhout 2008). Inter-planting could be considered but should be confined to species that will not easily become established, such as late-successional species, to overcome dispersal limitations (Martínez-Garza et al., 2005). If planting for forest rehabilitation is considered then areas within the fire pathway should be avoided unless costly fire protection actions could be implemented. Rehabilitation actions, with or without planting, should focus on areas near the natural forest margin which are clearly inside the 'fire-shadow' areas such as known cleared forest sites and within river/stream bank vegetation zones (Geldenhuys & Bezuidenhout, 2011; Geldenhuys, 2013).

There is a widespread belief in South Africa that indigenous tree species, in contrast to the introduced tree species, are water-efficient and should be planted more widely in land rehabilitation programmes. The question then is whether the relatively fast-growing indigenous forest pioneer and early regrowth species would use less water than the fast-growing invader plant stands? The general perception is that indigenous trees are generally slow growing, and that growth and water-use are broadly linked. A set of 16 long-term plots approximately 80 m x 80 m have been established in natural forest from the Cape Peninsula to the Soutpansberg to study the ingrowth, growth and mortality of forest tree species (Geldenhuys, 1998, 2000). All these plots are in mature forest that had not been disturbed through human activities for more than 50 years. Initial analyses (Geldenhuys & Golding, unpublished interim report) showed that many trees do have slow growth rates, but several species are fast-growing. No growth data is available for young regrowth stands, and counting annual growth rings may be needed to study the growth rate of such developing stands. A study in Miombo woodland has shown that young fast-growing trees in regrowth stands showed very clear growth rings, and could be used to assess the age of the trees and with the measurement of stem diameter, could provide growth rates (Syampungani, et al. 2010).

In the context of climate change mitigation, it is also important to consider how the conversion of stands of invasive alien species to regrowing natural forest would change the carbon sequestration potential from the mono-specific invader plant stands to regrowth stands of diverse natural forest species. Assessment of the carbon stocks and carbon sequestration potential require an inventory of the stand growing stock (stem density, tree biomass), the carbon stored in this biomass based on the specific gravity (wood density) of the stands, and the growth rate of the trees of different species (Chave et al. 2005; Geldenhuys & Berliner, 2010). The specific gravity or wood density of many indigenous tree species is higher than many of the invasive alien tree species (Kromhout, 1975). Tree biomass is calculated from the above-ground stem and branch volumes, and the underground roots. Equations have been developed to assess the above-ground tree biomass based on the stem diameter at breast height (DBH) (Chave et al. 2005), but it will be necessary to develop such equations for small-sized stems of the invader plant stands and the establishing natural forest species (Geldenhuys & Berliner 2010). This will require the measurement of DBH, stem length and tapering and tree crown depth (length) and diameter. The Geldenhuys & Berliner (2010) study used allometric data from other forest areas where the same species were present.

Maintenance of ecosystems in South Africa is of great importance in order to ensure the continuation of services produced under pristine or near pristine conditions. South Africa is generally a water scarce country with an uneven distribution of rainfall and runoff in space and time (Schulze, 2007). Therefore, a key policy response in South Africa has been to ensure that water allocations have an equitable foundation, in which the water needs of people and riparian ecosystems are of high priority and need to be protected (Scholes and Biggs, 2004). The term *ecosystem services* refers to the numerous processes and conditions associated with natural ecosystems that confer benefits to humanity (van Wilgen et al., 1996). The South Africa National Water Act (NWA, 1998) determines that South Africa's water resources be protected, used, developed, conserved, managed and controlled. This requires numerous factors to be considered, including ecosystem protection and the prevention of water resource degradation (Everson et al*.,* 2007), both of these being components of ecosystem services. A 4-year global assessment of the world's ecosystem services (Millennium Ecosystem Assessment, 2005) found that 60% of the services assessed were declining in condition due to a suite of anthropogenic drivers (such as habitat loss and alteration, water abstraction, overexploitation, and invasive alien species). The invasion of ecosystems by alien species has been identified as a large and growing threat to the delivery of ecosystem services (Drake et al., 1989). Payments for ecosystem services (PES) is a concept that could play an important role in achieving conservation goals and sustaining ecosystem health in sensitive areas of a catchment (Turpie et al., 2008). A PES system involves voluntary payments for certain ecosystem services (most commonly land uses that secure those services) that are conditional on service delivery (Wunder, 2005). This concept may be viable in sensitive riparian areas provided that conservation actions result in a marked improvement in the delivery of ecosystem services that can be traded (Turpie et al., 2008).

Ecosystem services can be grouped into those that meet basic human needs (supporting, regulating, and provisioning services) and those that enhance human well-being (cultural services). Supporting services underpin the basic life-support processes required to sustain all ecosystems, while regulating services control the flow of benefits and treatment of wastes, pests, and diseases (van Wilgen et al., 2008). Provisioning services provide products for human use, and cultural services enhance the quality of human life and human wellbeing (van Wilgen et al., 2008). The most appropriate approach to comparing alien and indigenous tree species is to assess how they impact on the different types of ecosystem goods and services, i.e. provisioning, regulating and cultural services.

A major shortcoming of past research is that it has not considered the overall ecosystem services provided by indigenous trees in their findings. Important questions raised in recent studies highlight that indigenous trees may be more appropriate than alien trees based on the issues highlighted in Table 2.1 (van Wilgen et al. 2008). The unavoidable negative impacts of alien plant invasion are spilling over into areas set aside for conservation and therefore water production (Richardson, 1997). In developing countries such as South Africa, where short-term economic growth and social delivery take precedence over conservation, placing a monetary value on the ecosystem services is the only solution to ensuring intervention (Alylward and Barbier, 1992). Understanding and quantifying ecosystem services provides a highly suitable and beneficial platform to compare the overall differences between indigenous and alien riparian vegetation. In particular, the water-use of these vegetation types can be related to numerous services introducing a more complex economical component to measurements which are otherwise ignored.

Table 2.1 A tabulated comparison of alien and indigenous tree species with respect to South African ecosystem services

Proposed Ecosystem Services	Alien Tree Species	Supported: (Y/N); References	Indigenous Tree Species	Supported: (Y/N); References
Provisioning Services	• Alien tree species can be used for garden and homestead fencing as well as construction. However, they negatively impact on the productive potential of land and therefore on food supply. • In riparian zones, invasive alien trees have a major negative impact on water provision (deep roots with a close water table). In addition they impact most on the environmental reserve flows. • Provide fuel wood but the mere fact that they are able to invade means that the demand for fuel wood is much less than the supply. • Alien trees alter the availability and quality of biochemical resources and provide 'ladder fuels' which carry fires to tree canopies (greater fire intensity induces water repellency and promotes erosion). • With regards to genetic resources it has a severe impact on biodiversity and in some circles is being seen as the 2nd biggest threat to biodiversity in South Africa. Although many individuals benefit from the activities and actions that lead to biodiversity loss and ecosystem change, the long-term costs borne by society of such changes is often higher.	• Y (van Wilgen et al., 2008) • Y (van Wilgen et al., 2008 ; Turpie et al., 2008) • Y (van Wilgen et al., 2008) • Y (Richardson & van Wilgen, 2004) • Y (van Wilgen et al., 2008 ; Millennium Ecosystem Assessment, 2005)	• Indigenous forests improve natural capital as well as providing building and craft materials, without reducing the productive potential of the land. • Use less water in comparison to alien tree species in riparian areas due to slow growth. Most species are slow growing and semi-deciduous and would therefore use less water in the dry season when low flow consistency is essential. • Provides high quality fuel wood and wood for furniture. However, supply is limited due to slow growth. Use of this high quality wood may provide an economically attractive alternative land-use option in areas where afforestation with exotic species is curtailed • Fire risk is lower in most indigenous species as their fuel properties do not promote fire. Therefore may have a positive impact on biochemical resources. • The biodiversity is enhanced with the presence of indigenous trees. This is supported by findings that Indigenous area biodiversity intactness can be reduced by approximately 80% under increasing levels of infestation.	• Y (van Wilgen et al., 2008) • Y (Limited: Everson et al., 2007) • Y (Gush & Dye, 2008) • Y (van Wilgen et al., 1990) • Y (Scholes & Biggs, 2005)
Regulating Services	• Single species alien stands are often more susceptible to disease "explosions" that could result in negative effects on production and loss of productive potential of the land. • Based on literature on water regulation, there are well known incidents of invasive alien plant stands in riparian zones that have significantly increased the extent and impacts of flood events. • With regards to water purification there are significant impacts on water quality. If sedimentation is included under water purification there are known examples of stands of invasives especially in riparian zones that have severe bank erosion impacts.	• Y (van Wilgen et al., 2008) • Y (van Wilgen et al., 2008) • Y (Richardson & van Wilgen, 2004 ; van Wilgen et al., 2008)	• Certain indigenous trees are highly susceptible to diseases and insects. This may, however, cause flaws in the hard wood and may reduce the value of the wood. • Water regulation can be improved as stormflow may be reduced and baseflow increased with the presence of indigenous species. This in turn reduces the potential for flood events and promotes water storage during dry periods. • Indigenous trees are known to improve the water purification processes within an ecosystem due to ideal litterfall dynamics and nutrient cycling..	• Y (Richardson, 1998) • Y (Schulze & Horan, 2007) • Y (Richardson & van Wilgen, 2004)
Cultural Services	• Alien trees have negative impacts on cultural services especially with reference to spiritual, ecotourism, aesthetic, inspirational and educational services. These species are known to erode natural capital, compromise ecosystem stability, and threaten economic productivity.	• Y (Richardson & van Wilgen, 2004, van Wilgen et al., 2008)	• Indigenous tree species provide traditional medicines and forest products which add to human well-being. Many forest products are used and marketed within urban communities.	• Y (Shackleton et al., 2007)

2.2 Indigenous Riparian Forests

Riparian areas were defined by the National Water Act (1998) as the physical structure and vegetation distinctly different from land of adjacent areas that are associated with a water course which is characterized by alluvial soils (inundated or flooded). Richardson et al. (2007) described riparian zones as the interface between terrestrial and aquatic ecosystems. Plants influence many properties of riparian ecosystems (Tabacchi et al., 2000). Through the process of evapotranspiration, riparian plants influence stream flow rates, groundwater levels, and local climates (Richardson et al., 2007). Vegetation along riverbanks filters surface and subsurface water moving across and through the soil to the river and therefore helps to maintain stream water quality by regulating the water temperature (through shading), bank stability and turbidity by controlling erosion and trapping debris. Riparian vegetation can access a wide range of water sources within the riparian zone which includes rainfall, soil water, stream water and groundwater (Grady et al., 2005). Rates of evapotranspiration and of groundwater-use vary widely between plant species depending on factors such as rooting depth, leaf area, and ability to regulate stomatal conductance (Scott et al., 2000; Dahm et al., 2002). Plants influence many properties of soils, such as salinity, organic matter, and C:N ratios, depending on their rate of litter production and on the chemical composition of the litter. There is a consensus among scientists that the vegetation in the riparian zone has a significant impact on the hydrology of a catchment due to the close proximity of riparian vegetation to the water table. The deep fertile soils with high soil moisture contents associated with riparian areas make them ideal for plant establishment and growth (Everson et al., 2007). Recently some attention has been given to selecting riparian plant species that pose little risk to the environment, but the ease and rapid benefits of alien species frequently override such considerations (Richardson, 1998).

2.2.1 Characteristics of pioneer tree species

Pioneer tree species are trees that initiate growth quickly within an ecosystem and allow for later successional species to establish. Pioneer tree species are usually susceptible to disturbances and therefore have a shorter growth cycle than most other species. *Trema*, *Albizia*, *Celtis* and *Vepris* are common pioneer species in riparian areas throughout South Africa. Common pioneer tree species, such as the ones discussed, may not necessarily be the first trees to grow following rehabilitation attempts.

2.2.2 Water-use of indigenous trees

There has been significant research on the comparative water-use of alien trees and the indigenous vegetation that it replaces in South Africa (Dye et al., 2001; Everson et al., 2007; Dye et al., 2008; Gush and Dye, 2008; Gush and Dye, 2009). According to Dye (2001), an important justification for alien vegetation removal programmes is the overall streamflow enhancement that follows removal or the replacement by indigenous plant communities that are largely herbaceous or shrub-dominated. However, most of the research does not focus on the water-use in riparian areas, nor does it extend to indigenous tree species. Due to data being scarce and indirect, interest has been placed on the water-use of indigenous trees where rehabilitation has occurred or can potentially occur. The slow growth rate of indigenous tree species suggests that these trees would use less water over time per unit area. This means that in theory, a comparison of an indigenous and an alien tree of the same age should indicate that less water is used by the indigenous tree as it would be smaller, have less established roots and a lower leaf area. Research to support and quantify these assumptions is limited as the extent of these changes is highly variable with location and vegetation type. In addition to this, few catchments where removal programmes are in operation have weirs to monitor the hydrological changes. Past experiments put forward that streamflow enhancement can occur immediately following riparian clearing; however, this research does not account for the water-use by indigenous plant communities that re-develops over time (Dye, 2001). Therefore, in order to support these assumptions it is imperative to characterise post-felling vegetation water-use and the related hydrological responses.

A study by Dye and Dye (2009), examined the water-use and water-use efficiency (WUE, i.e. biomass produced per unit of water transpired, termed productive green-water-use) of indigenous and introduced trees. When considering WUE in terms of the volumes of wood produced relative to the amount of water-used by the trees, the plantations of introduced tree species were consistently better. However, the overall water-use in indigenous trees was low, making them an attractive option in water-constrained catchments (Gush and Dye, 2009). If research supports this theory, it would promote the use of indigenous trees in riparian areas and add to the already attractive list of ecosystem services produced from this landuse scenario. Important results from ongoing research by Dye et al. (in press) are provided and discussed below. Before results for various locations can be compared, the climatic means should be considered. Ideally the measurements could be taken in the same area which would prevent errors occurring from above or below average conditions. The research was conducted on specific trees at Winterskloof (*Trema orientalis (L.) Blume*; above average rainfall), Karkloof (*Celtis africana, Podocarpus falcatus, and Ptaeroxylon obliquum* (Thumb.) Radlk. slightly below average rainfall) and Weenen (*Olea europaea* subsp. *africana* (Mill.) P.S.Green and *Berchemia zeyheri* (Sond.) Grubov; significantly below average rainfall). Based on the results of sap flow measurements, volumes for all of the indigenous species at various sites peaked during the wet summer months and declined during the cool, dry winter months (Gush and Dye, 2009). The variations in results were based on some of the trees being fully-deciduous, others semi-deciduous and the rest being evergreen species which are more conservative throughout the year but use more water in the dry periods (Gush and Dye, 2009).

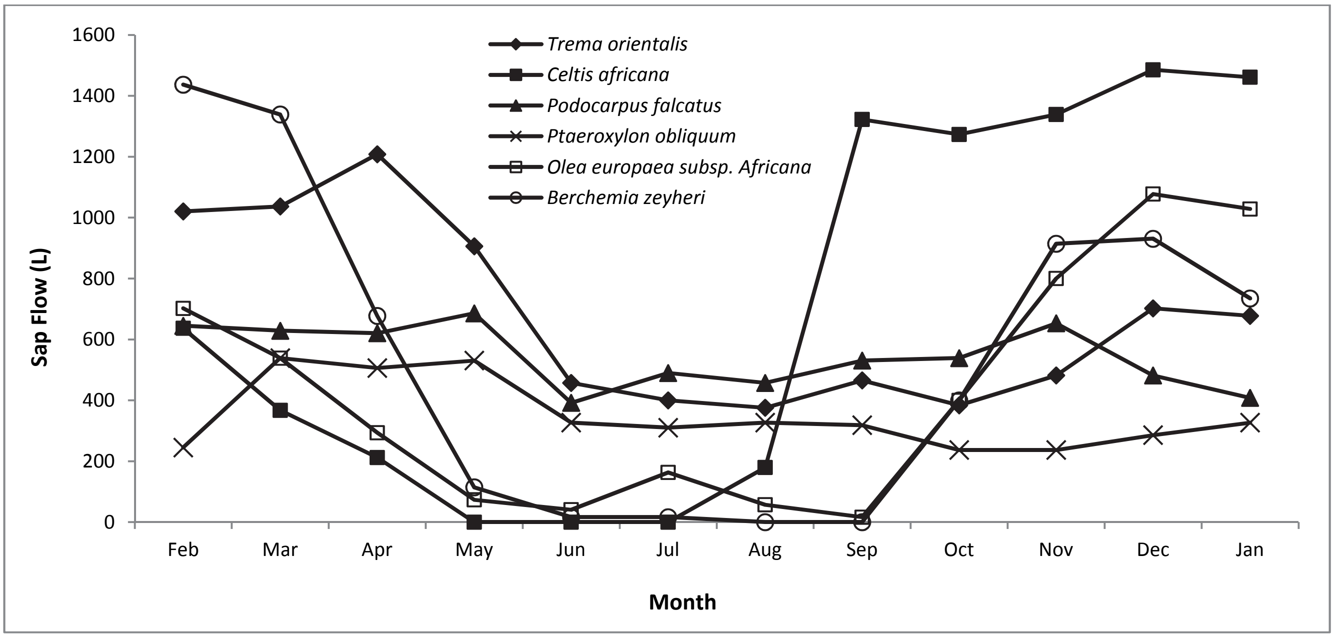


Figure 2.1 Monthly sap flow volumes of various South African indigenous tree species (Gush and Dye, 2009)

WUE could be a valuable indicator of ecosystem services. Figure 2.2 indicates the difference in the WUE between various alien tree species and indigenous species. The benefit of this quantification is that various species from various locations can be compared. Although the WUE for alien tree species was, on average, higher than the indigenous species, the annual cumulative sap flows were all less than 8.5 kL tree^{-1} yr^{-1} compared to 20 kL tree^{-1} yr^{-1} of alien trees (Gush and Dye, 2009). The significant difference in WUE can be explained by the extremely high stem mass increment to cumulative sap flow ratio present in exotic species. The research on indigenous trees was mostly conducted under wet conditions suggesting that the threshold water-use is significantly lower in indigenous trees and supports the assumption that these trees are better suited for diverse conditions or water constrained/sensitive areas such as the riparian zone (Gush and Dye, 2009).

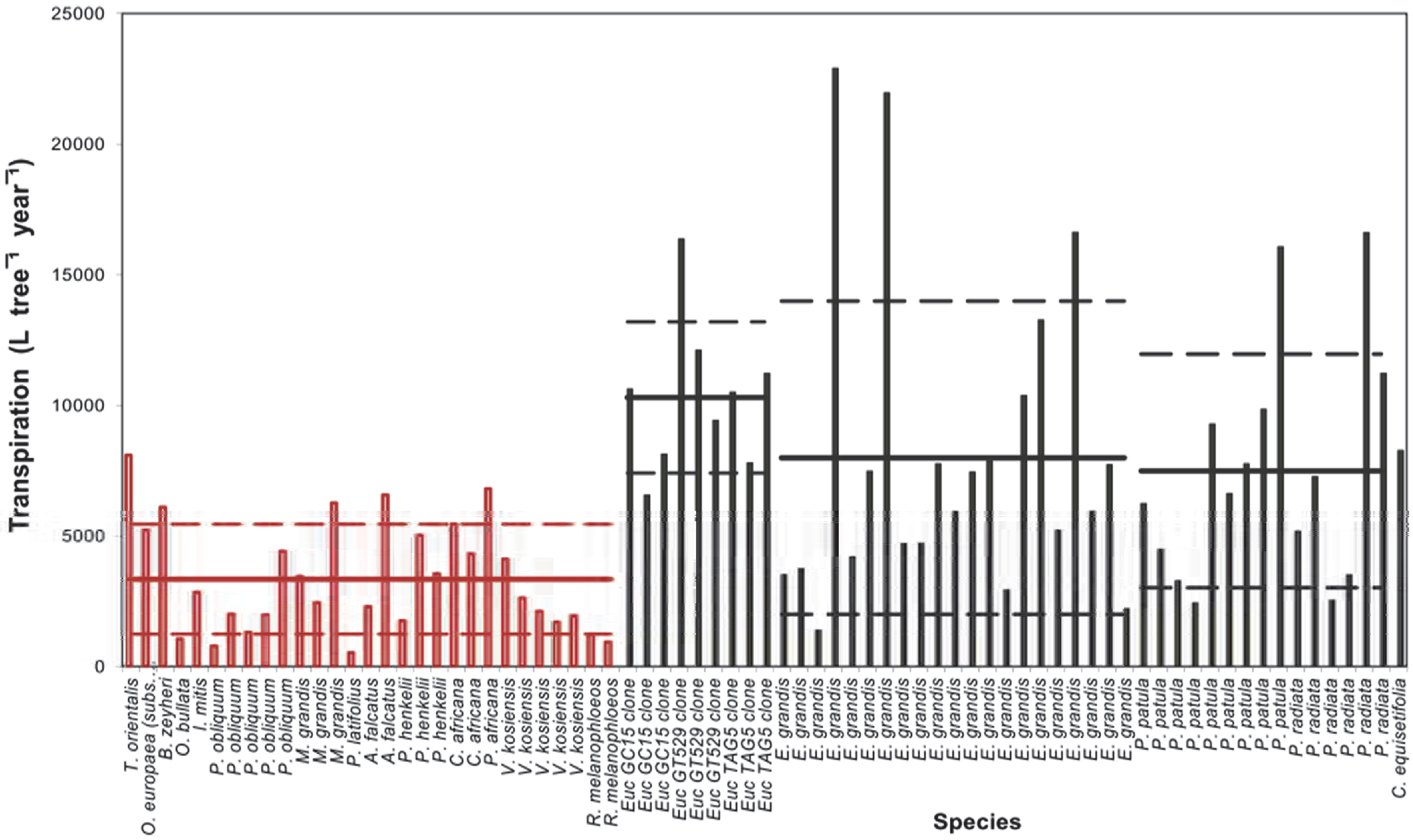


Figure 2.2 A comparison of 1 year sap flow (transpiration) between alien tree species (Olbrich et al., 1996; Dye et al., 2001) and indigenous tree species (Gush et al., 2015) measured in South Africa

Additional research at Kruger National Park and global studies (Zhang et al., 1999) estimated evapotranspiration (Et) for grasslands and various forest dominated catchments and showed distinct trends in catchment water yield (Gush and Dye, 2008). From Figure 2.3 it can be seen that there was a marked difference in global trends of evapotranspiration between grasslands, indigenous forests and alien forests. Key findings based on this research indicate that, generally, grasslands produce the least evapotranspiration followed by indigenous forests and then alien forests. It must also be noted that the difference between these trends increases as the mean annual precipitation (MAP) increases. According to Gush and Dye (2008), where rainfall is a limiting factor, all of the vegetation types evaporate most of the water that infiltrates the soil, resulting in small evaporation differences between vegetation types. Another important finding is that little information is available on the water use of indigenous forests in various climatic zones, and that none of the results are specific to riparian areas. Sap flow variations among the trees monitored in this study *(Combretum apiculatum* Sond., *Sclerocarya birrea* (A.Rich.) Hochst. and *Lannea schweinfurthii* Engl.) were mostly due to physiological differences (Gush and Dye, 2008). The results from this study further indicate that water-use is closely correlated to moisture availability, leaf area and vapour pressure deficits of the air (Gush and Dye, 2008).

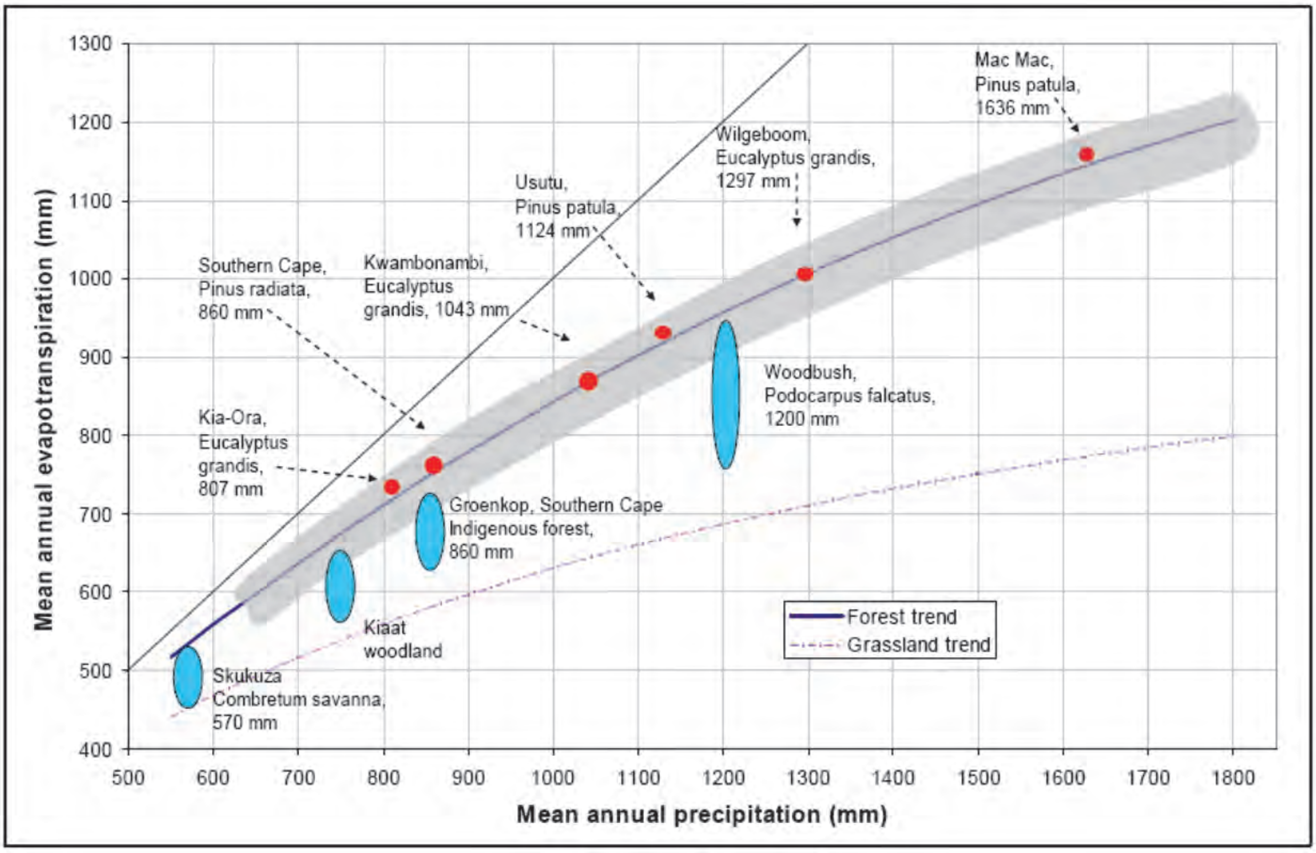


Figure 2.3 Relationship between mean annual precipitation and mean annual evapotranspiration for various vegetation types (Gush and Dye, 2008)

A report on the water-use of indigenous versus introduced species in southern Ethiopia (Fetene and Beck, 2004) highlighted that *Croton* (Indigenous) and *Eucalyptus* (Introduced) had the highest transpiration at the peak of the dry season. They transpired 4-5 times more than *Podocarpus* (Indigenous) and *Cupressus* (Introduced) trees of similar size. However, per unit leaf area, *Croton* had the highest with *Podocarpus* and *Cupressus* having the lowest daily transpiration rates (Fetene and Beck, 2004). These results show that differences between individual species are highly variable and generalisations about the impact of Introduced versus indigenous trees are risky.

In a study on indigenous riparian trees in the Kruger National Park, *Ficus sycomorus* trees were monitored continuously (*l* day^{-1}) over a two and a half year period (1993-1995) and the transpiration was compared to *Berchemia zeyheri*, *Diospyros mespiliformis* (Hochst. ex A. DC.), *Trichilia emetica* (Vahl.), and *Spirostachys africana* (Sond.) during four intensive water-use sampling surveys (Birkhead et al., 1996). The transpiration rates of the trees at the study site were found to be strongly correlated to modelling results and water budget components. This correlation indicated that the trees that were measured responded to the same environmental stimuli, and had ready access to a permanent water table (Birkhead et al., 1996). This further suggests that in the riparian habitat, the absolute transpiration rate depends more on tree size than the species concerned and that tree size could be used for extrapolating transpiration rates from one site to the entire river length (Birkhead et al., 1996). Integrated transpiration, bank storage, and river hydraulics modelling in the Kruger Park showed an average seasonal daily consumptive water-use by the riparian trees to be low at 1.6 mm day^{-1} and 2.8 mm day^{-1} during winter and summer, respectively (Birkhead et al., 1996). A key finding of the study was that the variability in transpiration corresponded approximately with that recorded in leaf area index (LAI) at the site (Figure 2.4).

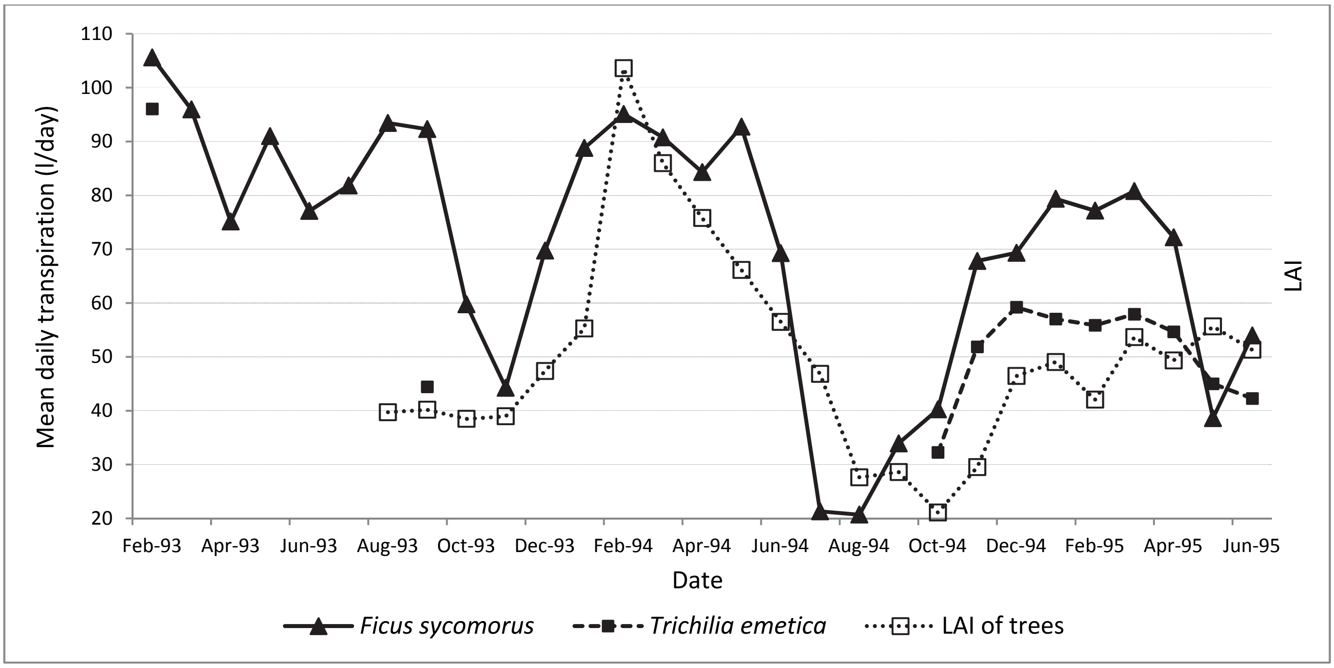


Figure 2.4 Variation in the monthly, mean daily transpiration rates recorded for *Ficus sycomorus* and *Trichilia emetica* trees, and the corresponding variation in LAI recorded in the riparian forest at Narina, Kruger National Park (Birkhead et al., 1996).

2.3 Invasive Alien Tree Species

Alien plant species can alter the composition and structure of the vegetation and those that replace indigenous vegetation over substantial areas are termed transformers and can change ecosystem functions (Richardson et al, 2007). The increased biomass of dense stands of invasive *Acacia mearnsii* or *Eucalyptus* species in riparian zones results in increased water-use by the vegetation (Le Maitre et al., 2002; Dye & Jarmain, 2004). Alien trees (commercial forestry) contribute significantly to the economy of South Africa. However, there are also significant costs associated with their widespread use in forestry (Richardson, 2008). Considerable attention has been placed on assessing the effects of plantations of alien trees species on the biodiversity of ecosystems (Armstrong and van Hensbergen, 1996; Spellerberg and Sawyer 1996) as well as water resources (Dye 1996) of afforested areas (Richardson, 2008). Such interest is causing major conflicts between foresters on the one hand and conservationists and hydrologists on the other (Richardson, 2008).

2.3.1 Characteristics of invasive alien tree species

According to Richardson (1998), species that frequently recruit seedlings in very large numbers and at distances of more than 100 m from the parent plants can be termed invaders. According to Le Maitre et al. (2000), alien plants have invaded an estimated 10.1 million ha of South Africa and Lesotho. There are numerous species of invasive alien trees that pose a major problem throughout South Africa (Versfeld et al., 1994). Many of these species form dense stands, maintain high leaf areas, and are particularly numerous in riparian zones. *Acacia mearnsii* which is characterised by high biomass and a large leaf area, is the most invasive species because of its tendency to spread rapidly along riparian zones. *Pinus* species on the other hand are characterized by a low seed mass, a short juvenile period and a short interval between large seed crops (Richardson, 1998) allowing the winged-seeds to be easily wind dispersed across wide areas.

The reason for the introduction of alien tree species has been summarized by Zobel et al. (1987) and Mather (1993):

- The wood of alien tree species is especially adaptable for a wide range of use and products;
- Alien trees are often preferred because they grow much faster than indigenous tree species;
- Indigenous species are more difficult to manage silviculturally than the aliens;
- Knowledge of the biology of indigenous species is often poor, including how to collect, store and germinate seed, how to produce seedlings in a nursery, and how to manage them in a forest. Consequently, foresters prefer to work with well-studied alien species;
- The availability of seed is a key to success in plantation forestry. Seeds of indigenous species are often hard to obtain, whereas seeds from genetically improved aliens are readily available;
- Alien tree species are better suited to planting in grasslands or shrublands (marginal forest lands) where most afforestation is required. Also, aliens are particularly successful in degraded forest lands; and
- It is frequently necessary to develop local forest industries to improve the balance of trade by reducing the need for imported wood products. Knowledge of markets and manufacturing technology currently favours the use of the wood of aliens such as pines or eucalypts.

A recent National Invasive Plant survey shows the very wide distribution of alien pants along the entire eastern seaboard of South Africa, which coincides with the higher rainfall regions (Working for Water, 2011).

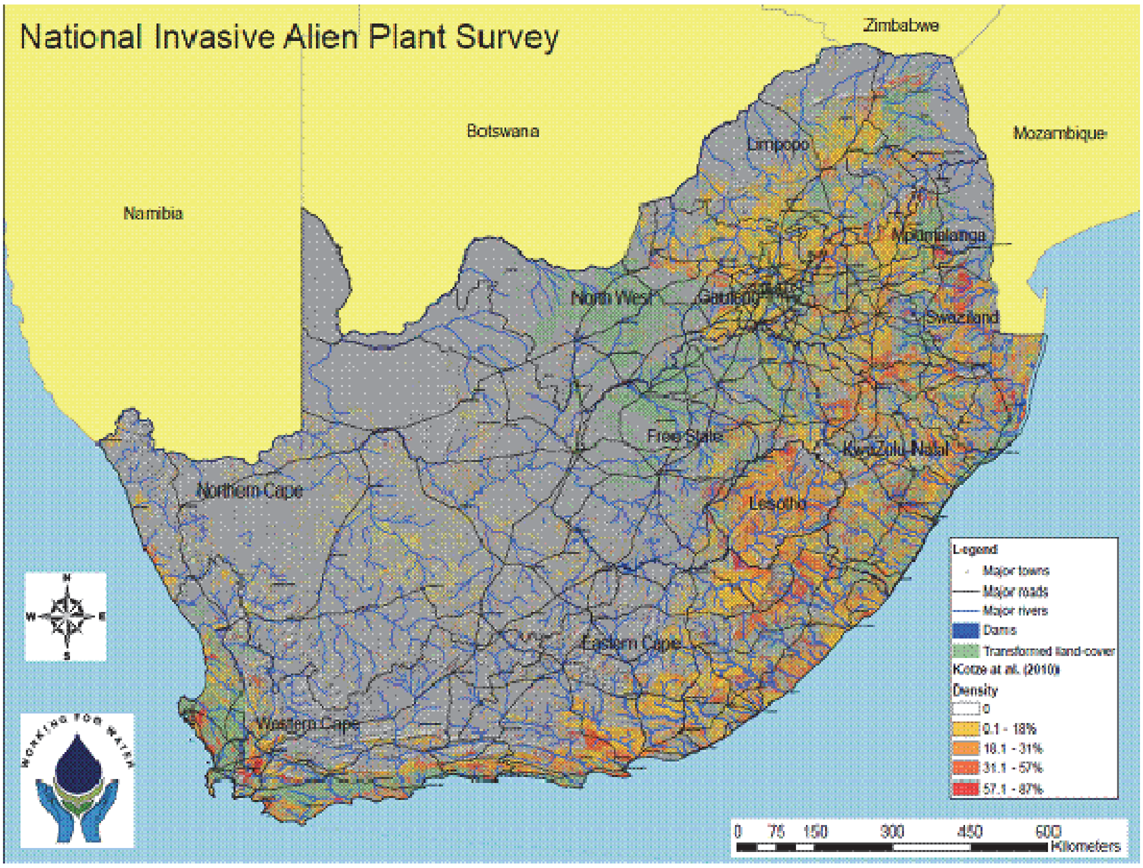


Figure 2.5 Density of alien plants in South Africa (Working for Water, 2011)

Indigenous species selected for rehabilitation programmes must grow well (also in plantations), establish on bare ground without shelter, produce desired products and be physiologically well adapted to take advantage of favourable growing periods in new environments.

2.3.2 Water-use of invasive alien tree species

Invasive alien plants are consumptive water-users, and may have reduced river flows in South Africa by about 6.7% according to broad-scale studies (Le Maitre et al., 2002). The total incremental water-use of invading alien plants is estimated at 3 300 million m^3 of water per year (Le Maitre et al., 2000), of which, most is associated with alien trees. Invasions of areas by alien vegetation typically show a sigmoid growth curve over time, involving an initial lag period, a period of rapid expansion and the final period when expansion slows as the available habitat becomes fully invaded (Richardson, 1998). The Conservation of Agricultural Resources Act (no. 43 of 1983) legislates against the spread of invasive alien plants. However, this has been poorly enforced which has led to growing concerns related to water resource management (Gillam and Haynes, 2001). According to Versfeld (1994), experiments have shown that afforestation by alien tree species significantly decreases streamflow where pre-afforestation vegetation was seasonally dormant mountain grassland or fynbos. Research on the water-use of alien tree species has evolved in recent years where Dye and Poulter (1995) noted a substantial increase in stream flow after clearing *Pinus patula* and *Acacia mearnsii* from riparian areas. Prinsloo and Scott (1999) also found that stream flow increased by 9, 10 and 12 m^3 ha^{-1} day^{-1} following riparian clearing. Based on the numerous studies in South Africa, it has become a recognised fact that the rate of alien tree water-use is believed to be relatively high and to result in substantial decreases in catchment water yields (Dye et al., 2008).

Most of the research done on the water-use of alien trees focuses on *Eucalyptus, Pinus* and *Acacia* and hence the following findings will focus mostly on these species. According to Dye and Jarmain (2004), these species commonly invade numerous forms of indigenous vegetation, and in contrast develop into dense, evergreen thickets, particularly along riparian zones. The natural vegetation that it replaces commonly exhibits pronounced seasonal dormancy brought about by soil dryness or frost (Dye and Jarmain, 2004). The potential for increased total evaporation, and therefore reduced catchment water yield, following invasion by these species is therefore great. Based on a combination of model and sap flow estimates, Dye and Jarmain (2004) documented that differences in evaporation following the invasion or removal or black wattle can be as high as 600 mm. It is also evident that alien vegetation has a high potential total evaporation suggesting that the more water available, the more water an alien tree will use as opposed to a lower threshold potential evident in natural vegetation.

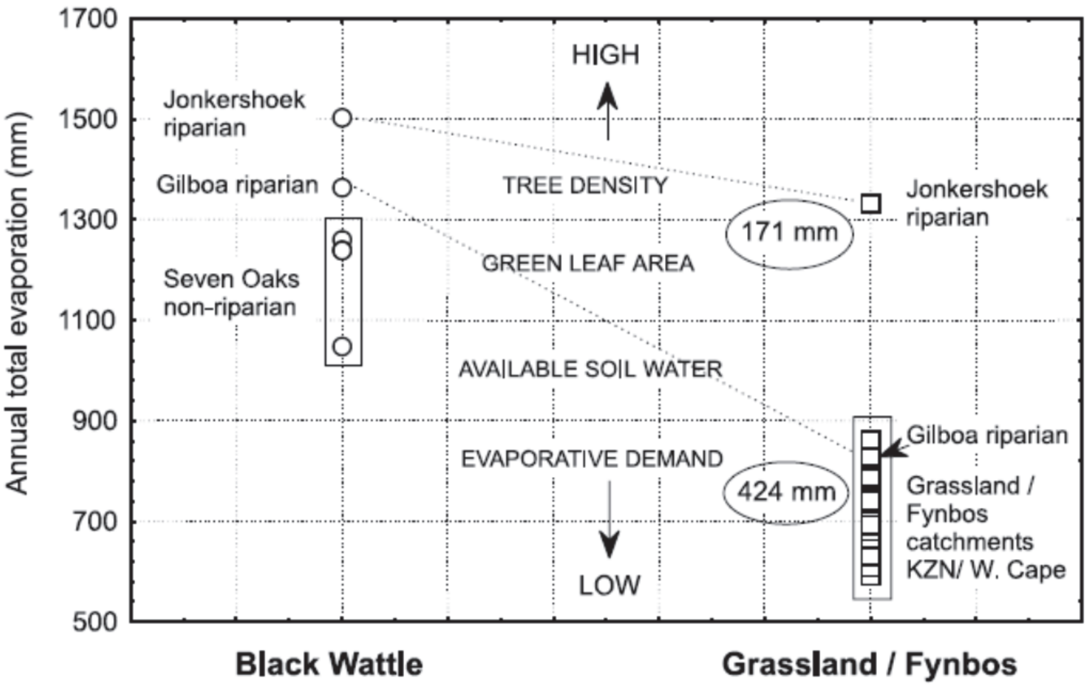
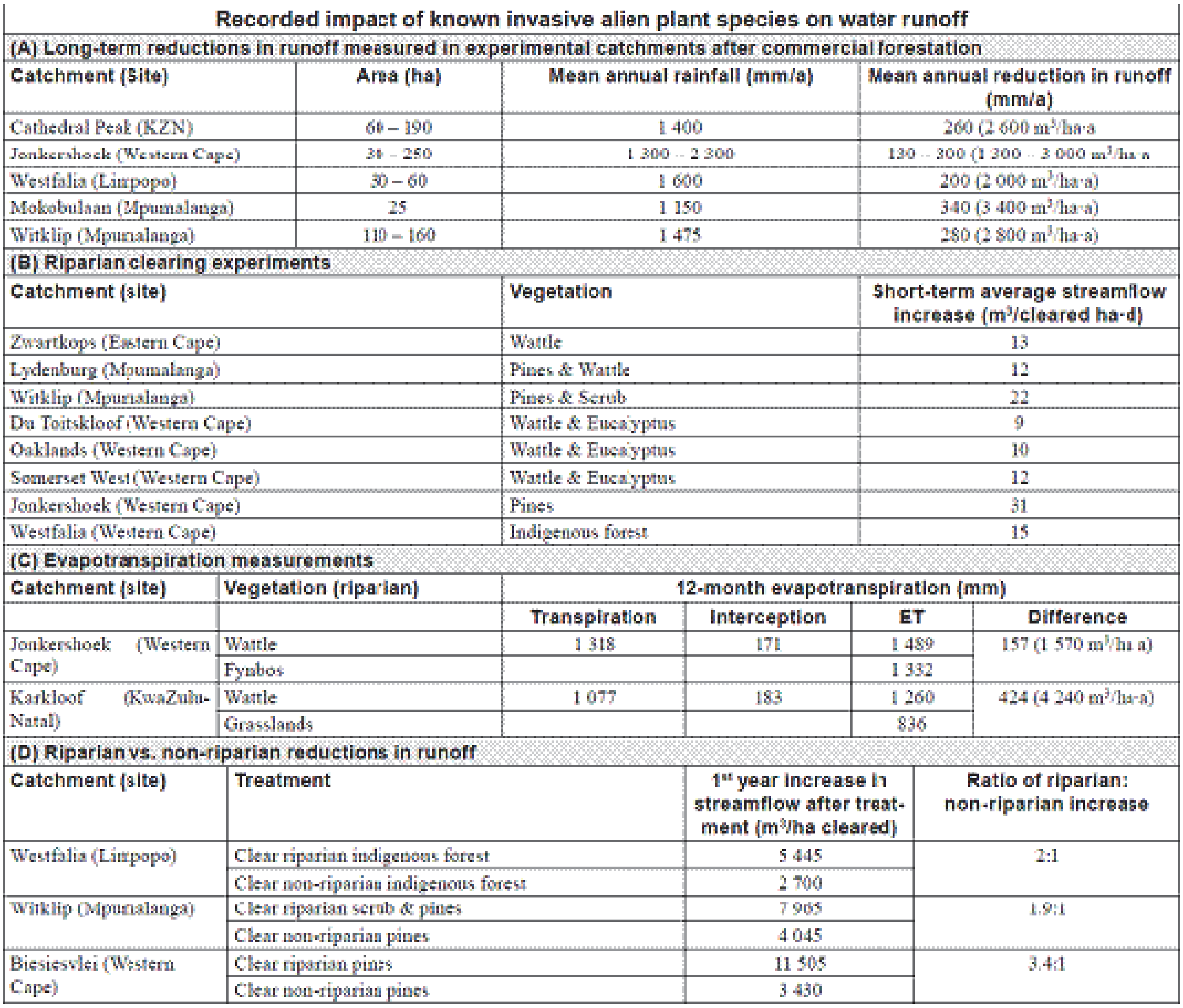


Figure 2.6 Annual total evaporation estimated for black wattle and grassland/Fynbos at various sites in KwaZulu-Natal and the Western Cape (Dye and Jarmain, 2004)

The results highlight some key findings relating to the impacts on water resources over various climatic regions. Over a long period of afforestation, the runoff was reduced by between 130 and 340 mm.yr^{-1} for all catchments studied. This equates to between 10 and 30% of the MAP. The short-term average streamflow increase after riparian clearing ranged from between 9-31 m^{3} ha^{-1} day^{-1} of cleared vegetation, where generally the largest increases were evident following clearing of pines. The evapotranspiration measurements indicated that wattle in the riparian areas of Jonkershoek used 157 mm yr^{-1} more water than the natural fynbos. Similarly, but to a greater extent, the wattle in the Karkloof used 424 mm yr^{-1} more water through transpiration than the natural grasslands. This suggests a significant increase in water-use in comparison to the natural vegetation. With regard to riparian vegetation, important findings indicate that in three catchments studied, the ratio of riparian to non-riparian increase in streamflow was always between 2 to 3.5 times higher, suggesting that riparian areas use more water per unit area and are highly sensitive to land use change. It is also important to note that there are no long term experiments for riparian clearing, nor are there extensive evapotranspiration measurements for these areas. Although alien plant control can be expensive, it has been shown that control programmes are cost-effective when compared with alternative water supply schemes (Le Maitre et al., 2000). The need for information on the water-use of both indigenous and introduced trees is therefore essential for water resource management decision making.

Table 2.2 Comparison of results between long term and short term impacts of alien plant species on water runoff (Görgens and van Wilgen, 2004)



Recorded impact of known invasive alien plant species on water runoff

(A) Long-term reductions in runoff measured in experimental catchments after commercial forestation

Catchment (Site)	Area (ha)	Mean annual rainfall (mm/a)	Mean annual reduction in runoff (mm/a)
Cathedral Peak (KZN)	60 – 190	1 400	260 (2 600 m^3/ha·a
Jonkershoek (Western Cape)	34 – 250	1 300 – 2 300	130 – 300 (1 300 – 3 000 m^3/ha·a
Westfalia (Limpopo)	30 – 60	1 600	200 (2 000 m^3/ha·a)
Mokobulaan (Mpumalanga)	25	1 150	340 (3 400 m^3/ha·a)
Witklip (Mpumalanga)	110 – 160	1 475	280 (2 800 m^3/ha·a)

(B) Riparian clearing experiments

Catchment (site)	Vegetation	Short-term average streamflow increase (m^3/cleared ha·d)
Zwartkops (Eastern Cape)	Wattle	13
Lydenburg (Mpumalanga)	Pines & Wattle	12
Witklip (Mpumalanga)	Pines & Scrub	22
Du Toitskloof (Western Cape)	Wattle & Eucalyptus	9
Oaklands (Western Cape)	Wattle & Eucalyptus	10
Somerset West (Western Cape)	Wattle & Eucalyptus	12
Jonkershoek (Western Cape)	Pines	31
Westfalia (Western Cape)	Indigenous forest	15

(C) Evapotranspiration measurements

Catchment (site)	Vegetation (riparian)	12-month evapotranspiration (mm)			
		Transpiration	Interception	ET	Difference
Jonkershoek (Western Cape)	Wattle	1 318	171	1 489	157 (1 570 m^3/ha·a)
	Fynbos			1 332	
Karkloof (KwaZulu-Natal)	Wattle	1 077	183	1 260	424 (4 240 m^3/ha·a)
	Grasslands			836	

(D) Riparian vs. non-riparian reductions in runoff

Catchment (site)	Treatment	1st year increase in streamflow after treatment (m^3/ha cleared)	Ratio of riparian: non-riparian increase
Westfalia (Limpopo)	Clear riparian indigenous forest	5 445	2:1
	Clear non-riparian indigenous forest	2 700	
Witklip (Mpumalanga)	Clear riparian scrub & pines	7 965	1.9:1
	Clear non-riparian pines	4 045	
Biesiesvlei (Western Cape)	Clear riparian pines	11 505	3.4:1
	Clear non-riparian pines	3 430	

2.4 Rehabilitation of Degraded Riparian Areas

At the outset of this discussion it is important to highlight the difference in the commonly used ecological terms rehabilitation and restoration ecology. Rehabilitation refers to the establishment of a plant community (which may or may not be similar to the original) on a degraded area with the aim of controlling soil and water loss (Xu et al., 2004). Ecological restoration can be defined as an "intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability" (SER, 2004). The practice of ecological restoration includes a wide scope of activities including: erosion control, reforestation, the use of genetically local native species, removal of non-native species and weeds, revegetation of disturbed areas, reintroduction of native species, as well as habitat and range improvement for targeted species. The process of ecological restoration is unique in land management, in that the goal is to restore the original or historic native ecosystem of a site, utilizing local native plant species, excluding Introduced plants, and to restore the ecosystem to a self-sustainable state, within a certain amount of time.

Restoration ecology has strongly emerged as an applied science for designing practical management options which ensure improvement in the quality of both the biological and human environment in an integrated perspective (Bradshaw, 1987). The implementation of environmentally friendly land-use packages for the rehabilitation of degraded lands in South Africa has direct relevance for improving several human associated problems such as food security and water quality. However, the vast diversity in ecology, culture and socio-economics in South Africa will require identification of area specific problems with implementation of specific land use interventions. Sustainable development requires a holistic vision suited to the socio-economic conditions of the affected communities. Establishment of a positive correlation between requirement, traditional knowledge, increasing population, science inputs, socio-economic setup and environmental conditions is required to ensure mitigation of many of the ecological problems faced by managers and communities. Participation and empowerment of the stakeholders is a major necessity for ensuring the success of such programmes (Baskota et al*.,* 2000). Aarde et al*.* (1996) pointed out that the evaluation of a rehabilitation program depends on firstly the trends of community development, and secondly on the temporal trends of community variables on rehabilitating stands.

A practical combination of social, mechanical and biological interventions together with nursery development, bio-composting, introduction of multipurpose tree/grass species and soil amendment techniques were some of the components that were instrumental in not just rehabilitating degraded lands, but also establishing a strong relationship between managers and communities (Ramakrishnan et al*.,* 1992). The benefits of rehabilitation can act as a rationale for conducting an in depth assessment as to whether the development of markets for ecosystem services is both appropriate and sufficient when dealing with the restoration of natural capital of degraded areas. It is generally found that the benefits of introducing improved management practices exceeds the costs in low to medium degraded quinaries, but not in heavily degraded quinaries (Blignaut et al*.,* 2010).

Environmental degradation and poverty in mountainous areas are ongoing threats to livelihoods and sustainable food production making environmental protection a particularly challenging task in mountainous regions (Rawat et al*.,* 2009, 2010; Saxena et al*.,* 2001). The exploitation of natural resources and anthropogenic land use modifications has given rise to multiple ecological complications in mountain regions. Decline in biological production, increasing land degradation, deforestation, and an overall decline in environmental quality are some of the basic problems that face mountain inhabitants in developing countries (Ramakrishnan et al*.,* 1992). In South Africa the communal areas in the montane grasslands of the Drakensberg are particularly susceptible to degradation as a result of overgrazing, high rainfall intensity, steep slopes and high population pressures (Carbutt and Edwards, 2006, Walters et al*.,* 2006, Blignaut et al*.,* 2010, Nel et al*.,* 2010). Soil erosion is a major threat to the sustainable use of land resources posing considerable challenges to development programmes. The requirement of food, fodder, fuel and shelter for the increasing population is rapidly changing the existing land use, and the production systems currently in use are accelerating the process of soil erosion which is already high due to geological and geomorphological forces (Everson et al*.,* 2007). To fulfil these requirements there is a need in development programmes to find suitable multipurpose indigenous species for use in rehabilitation programmes.

Rangelands occupy over 70% of the land surface of South Africa (1,219,000 km^2), making them the largest single land-use. Sixty-six percent is moderately to seriously degraded. Cattle grazing on rangelands are leading to degradation through nutrient leakage, soil compaction, competition, changes in micro-climate and lack of propagules (Larsson, 2003). Degraded vegetation, bush and shrub encroachment and erosion are generally visible symptoms of disturbed rangelands (Snyman, 2003). If the degradation is severe, succession may be arrested and the land remains bare even if the grazing ceases. Special interventions are therefore required to rehabilitate these bare areas including the planting of pioneer indigenous trees. The South African region has a spectacularly rich native flora with data on the distribution of individual taxa across a wide range of major habitats (deserts, semi-arid shrublands, Mediterranean type ecosystems, grasslands, savannas and evergreen forests) (Richardson et al*.,* 2005). However, there is a gap in the rehabilitation of degraded lands using indigenous plant species.

In certain rangeland areas of South Africa, the natural vegetation is degraded to such an extent that the application of management practices or even total withdrawal of grazing, will not have the desired recovery effect on cover and density (Hoffman and Ashwell, 2001). In these cases, more drastic rehabilitation measures must be applied to help the re-establishment of vegetation, so that the rangeland ecosystem can ensure sustainable animal production once again. These measures should strive towards increasing water infiltration into the soil and reducing soil erosion (Snyman, 1999b) by improving vegetation composition, cover and density.

Worldwide, riparian zones have been degraded due to a large scale invasion of alien species (Holmes et al*.,* 2008). In South Africa, most riparian zones are invaded to a greater or lesser extent: if all invasion densities are compressed to closed stands, this would be equivalent to 33% of closed-stand invasion across the total perennial and non-perennial riparian area (Cullis et al*.,* 2007), whereas, only 7% of closed stand riparian invasions has been cleared to date (Marais and Wannenburgh, 2008). The invasive alien species in riparian zones have reduced water yield, decreased biodiversity, and have reduced the productivity of the land (Dye and Jarmain, 2004, Anon, 2007). There is an urgent need to rehabilitate degraded riparian zones using indigenous riparian plants for enhancing ecological integrity particularly with respect to water resources. An understanding of the structural and functional feedback mechanisms in degraded areas can lead to a greater understanding of rehabilitation approaches (King and Hobbs 2006). Holmes et al. (2008) suggested that goals should be set according to the required functions of the riparian zone in the particular area; in other words to rehabilitate the riparian zones to fulfil appropriate ecosystem functions (e.g. bank stabilization, water filtration). Wherever possible, indigenous species should be used in the rehabilitation and invasive alien species removed. In order to rehabilitate indigenous tree communities, it is important that the gene pool of local species is used in order to prevent possible hybridization and loss of genetic integrity in ecosystems. Various ecological and economic factors, i.e. realistic targets, must be set to assist rehabilitation in practice (Hobbs, 2007).

Active rehabilitation of degraded riparian areas should be carried out to improve indigenous vegetation recovery potential at severely impacted sites and to suppress woody alien recruitment. However, it is important that any active plant re-introduction is coupled with regular alien follow up removals to secure the benefits into the future. The active rehabilitation is beneficial in facilitating ecosystem structure and function. Active rehabilitation of riparian tree and shrub components may be required in order to recover vegetation structure and composition within a reasonably short time frame and thus facilitate resistance to secondary alien species' invasions. A framework outlining these concepts is shown in Figure 2.7. Successful rehabilitation of study sites selected in this project will require adoption of this framework.

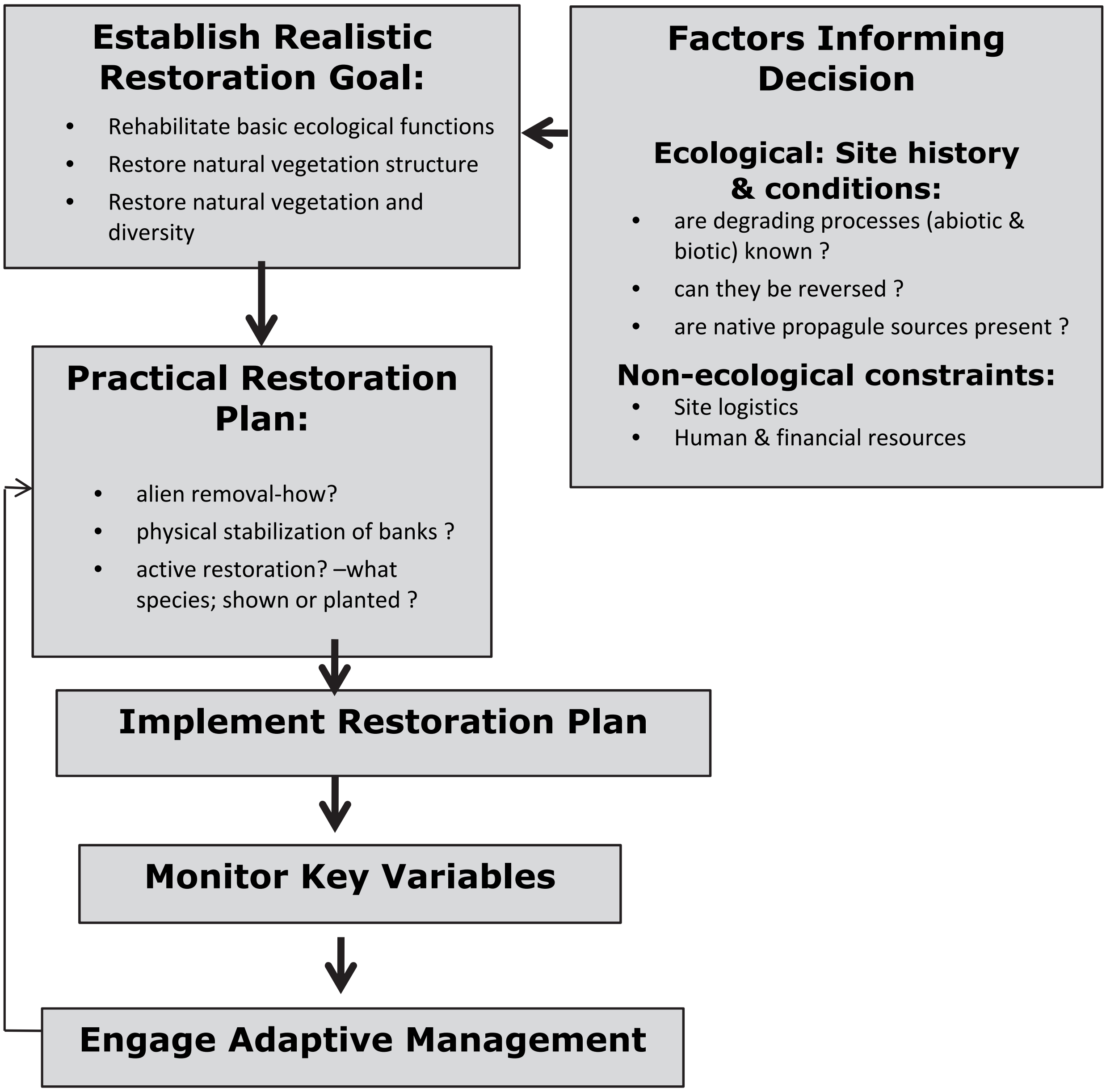


Figure 2.7 Conceptual framework for rehabilitation of riparian zones (Holmes et al. 2008)

2.5 Evaporation Measurement Techniques

In recent years the use of sap flow measurement techniques has increased as a result of on-going technological developments and the recognition that alternative approaches are often inapplicable (Hatton et al., 1995). In addition to this, sap flow measurements provide a specific estimate of transpiration *per se*, as opposed to total evaporation measurements (ET), therefore reducing additional measurements and analyses required to isolate the transpiration component (Hatton et al., 1995). Heat-based sap flow techniques are typically used at stem level and allow for whole-tree water-use measurements without influencing transpiration conditions (Schurr, 1998; Smith and Allen, 1996). Three commonly used sap flux density techniques are Heat Pulse Velocity (HPV), Thermal Dissipation (TD) and Heat Field Deformation (HFD). The HPV technique has been shown to provide accurate estimates of sap flow in both alien tree species such as *Acacia mearnsii*, and indigenous tree species such as *Podocarpus* *henkelii* (Smith et al., 1992; Dye et al., 2001; Everson et al, 2007; Dye et al., 2008). According to Hatton et al. (1995), the HPV method is a practical approach to estimating the water-use of individual trees and heat pulse techniques are often the only reasonable alternative for measuring forest and woodland transpiration in the complex heterogeneous terrain that is often found in riparian areas. A typical HPV installation on a *Eucalyptus grandis* at New Forest is provided in Figure 2.8.

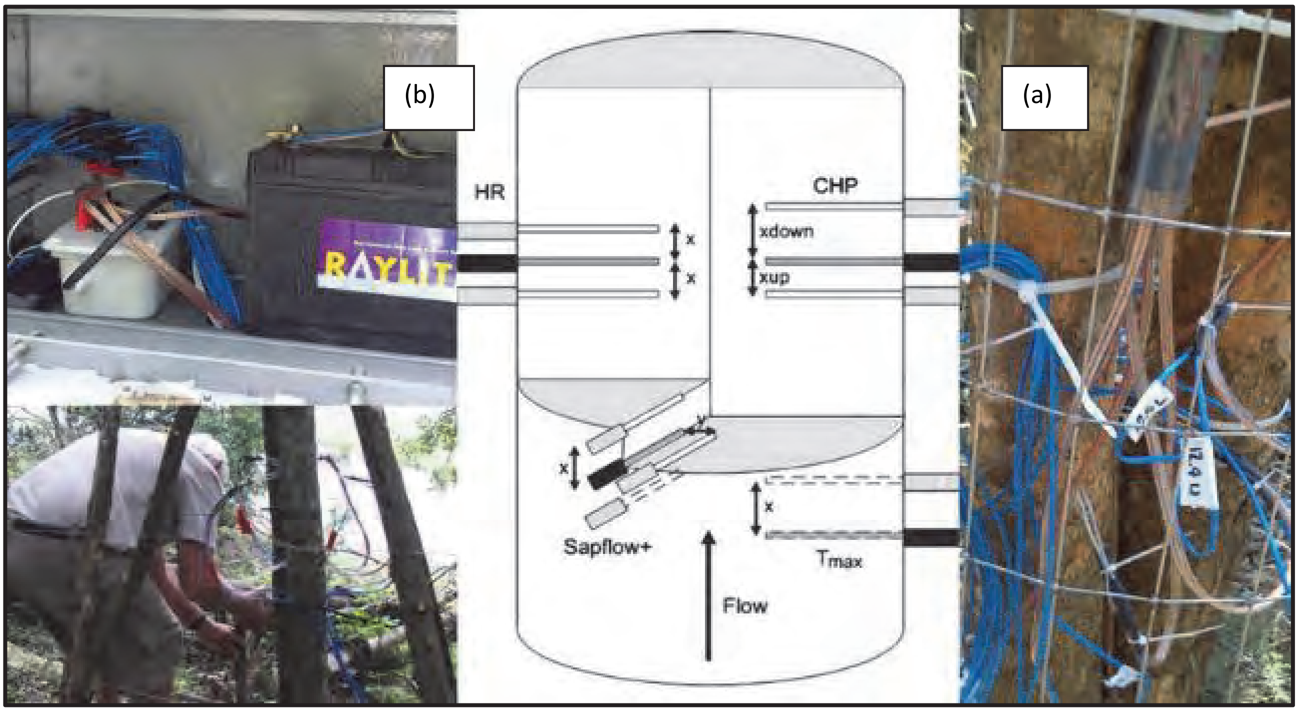


Figure 2.8 HPV equipment installed on a *Eucalyptus grandis* (a) at Buffeljagsrivier and New Forest with four heaters and thermocouple pairs (a), as well as a CR1000 datalogger, an AM16/32 multiplexer and a relay control module (b)

According to Hatton et al. (1995), a major concern of the HPV method is the up-scaling of sapflow estimates from a sample of individual stems (usually measured in litres) to an area basis (usually measured in mm). Without this up-scaling, the measurements may only be compared to other direct *in situ* measurements and cannot be used for broader hydrological interpretations. Up-scaling measurements taken in a plantation of uniform spacing and size is relatively easy and considered to be accurate. According to Wilson et al. (2000), difficulty may occur when attempting to extrapolate sapflow measurements from individual stems to a spatial scale comparable to a catchment, due to the large species diversity. The *a priori* determination of the area occupied by a tree in open woodlands or forests, which are particularly non-uniform in riparian areas, is problematic (Hatton et al., 1995). Ideally, all the trees in a given area should be measured and then up-scaled. However, due to the high cost and user effort required for this approach, it is not considered feasible.

According to Schwärzel et al. (2007), the temporal and spatial scales of transpiration studies are usually extended by modelling. Hatton et al. (1995) proposed that an appropriate alternative is to scale the measurements of tree water-use by a scalar of the tree characteristics, where the distribution of this scalar is known for the entire stand. Up-scaling methods have evolved significantly in the past, where Ladefoged (1963) considered a scalar relating crown size and area occupied by each tree to sapflow. Čermák and Kuæera (1987) used allometric relationships, based on tree basal area, while Werk et al. (1988) used leaf area estimates. The best relationship, as documented by Thorburn et al. (1993), was between the sap flux density and sapwood area and has since been used by Granier et al. (1990) and Dunn and Connor (1993). This indicates that more appropriate parameterisations of forest stands are required, to represent variation in site conditions and structural parameters including stand age, stand height, tree density, forest composition and the long-term range of flux rates (Cienciala et al., 1999).

Evapotranspiration is an important process across a wide range of disciplines, including ecology, hydrology and meteorology (Wilson et al., 2000). Based on this multidisciplinary focus, numerous methodologies have been developed to measure evapotranspiration, or components of evapotranspiration (transpiration, soil evaporation and interception), over a range of spatial scales from individual plants and entire watersheds (Wilson et al., 2000). The selection of specific methods to obtain the required results is largely dependent on the location of the research to be done, the physical characteristics of the vegetation and the time and funds available to implement such research. Common methods used to measure or estimate vegetation water-use are direct sap flow measurements, micrometeorological methods, various modelling approaches and remote sensing. Each method has advantages and disadvantages which depend largely on the site characteristics and requirements. Micrometeorological methods can provide estimates of flux on an areal basis which allows for direct comparisons with other hydrological components over a site or stand (Hatton et al., 1995). *In situ* measurements of tree water-use (i.e. sap flow) enable the role of transpiration in trees to be quantified (Hatton et al., 1995). Modelling can provide estimates of vegetation water-use where measurements are not possible or available. However, the accuracy of modelling depends largely on the quality of the input data used and on studies to validate the simulated results.

Numerous techniques can be used to estimate water vapour exchange rates between the surface and atmosphere, but these techniques often vary in that each technique is only representative within a particular spatial and temporal scale, and either interpolation or extrapolation is necessary to infer evaporation rates outside these scales (Wilson et al., 2000). Secondly, the techniques may also differ in whether they measure evapotranspiration or just one or several of its components (e.g. in energy balance techniques the sensible and soil heat fluxes are used to determine the latent heat flux (evaporation). In addition, each of the techniques introduces a unique set of assumptions, technical difficulties, measurement errors and biases (Wilson et al., 2000).

A summary to some of the evaporation measurement techniques has been provided in Table 2.3.

Table 2.3 Summary of a selection of techniques used in the measurement or estimation of sensible heat (H) and/or latent heat flux density (LE) using the surface energy balance (after Savage et al., 2004)

Method	Measurement area, distance or height	Averaging period	Theoretical basis/comment	Comment
Reference evaporation*	Point measurement (2 m above short grass) of solar irradiance, air temperature, wind speed, water vapour pressure	Hourly/daily	Penman-Monteith method for reference evaporation estimation (FAO 56), and use of a crop factor (Allen et al., 2006) for short grass (0.1 m tall) and tall crops (0.5 m tall)	Only reference evaporation and estimated crop evaporation calculated
Heat pulse/sap flow (Stem Heat Balance (SSS))*	In situ measurement (<200 mm)	Sub-hourly/hourly	Dynamax collars allow for the measurement of radial and vertical temperature gradients $C_{st}\frac{dT_{st}}{dt} = P - Q_r - Q_v - Q_f$ (C_{st} is the heat capacity, P is the heat with losses through conduction radially (Q_r), vertically (Q_v) and by convection (Q_f).	Transpiration measurements only. Can be up-scaled to stand transpiration. Woody or herbaceous measurements
Heat pulse/sap flow (Heat Ratio Method)*	In situ measurement (<200 mm)	Sub-hourly/hourly	Rate of movement of stem heat pulse, stem energy balance with continuous heat applied	Transpiration measurements only. Can be up-scaled to stand transpiration
Eddy Covariance (EC) (1 sensor)	Sonic path length of 100 to 150 mm	20 to 60 min	$H = \rho_a C_P \overline{w'T'}$ (ρ_a is the air density and w' and T' are fluctuations in vertical wind speed and air temperature)	By definition, $LE + H = R_n - G$

*Techniques used in this study

2.5.1 Sap flux density

2.5.1.1 Stem Steady State (SSS)

The SSS technique estimates sap flow by solving a heat balance for a segment of stem that is supplied with a known amount of heat (Grime and Sinclair, 1999). The amount of heat conducted in the sapwood (Q_f) is calculated as the difference between the amount of heat released into the system and the sum of the conductive heat loses (Grime and Sinclair, 1999). The heat capacity of the xylem sap is assumed to be that of water. This method uses insulated collars which have direct contact with a smooth stem surface (Grime and Sinclair, 1999). Heat is applied to the entire circumference of the stem which is encircled by the heater (Baker and van Bavel, 1987). A foam insulation and weather shield surrounds the stem and extends above and below the heater in order to sufficiently minimize extraneous thermal gradients that may influence the heated section of stem (Smith and Allen, 1996). The conduction of heat vertically upwards and downwards is calculated by measuring voltages which correspond to the temperature difference between two points above and below the heater (Savage et al., 2000). The radial heat is calculated by measuring the temperature difference of the insulated layer surrounding the heater (Savage et al., 2000). Finally the voltage applied to the heater is measured. These measurements allow the energy flux ($j.s^{-1}$) to be calculated (Savage et al., 2000). Appendix 3 provides a greater detail of the theory behind the SSS technique. An overview of this system is provided in Figure 2.9.

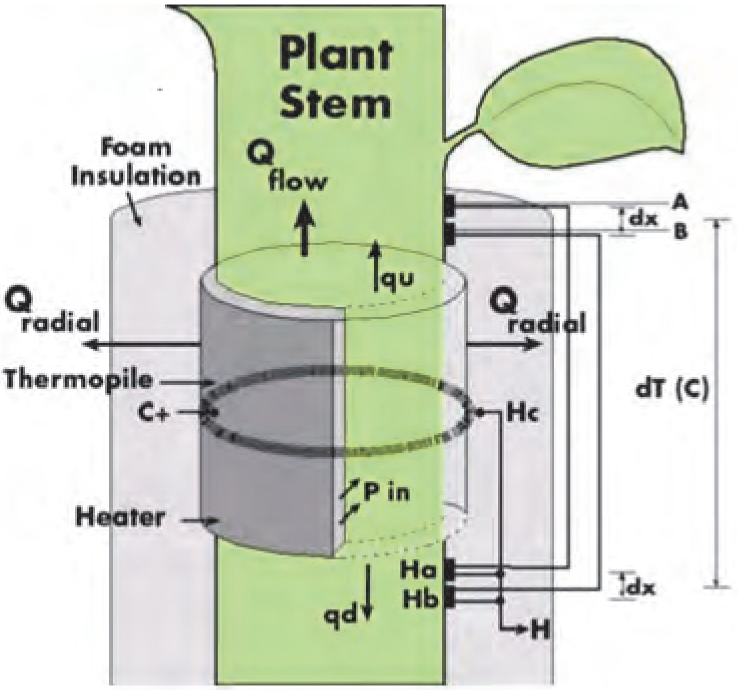


Figure 2.9 Representation of the Stem Steady State Energy Balance technique (van Bavel, 2005). The energy fluxes have been defined in Appendix 3

Little research has been done using the SHB method in South Africa. Advantages of this technique include its applicability to both woody and herbaceous plants, its ease of installation, its use on multi-stemmed plants and its representation of the symmetrical sap wood area. Disadvantages include the high power requirement of the equipment and the limitation of collar sizes for larger tree species. Practical considerations (after Smith and Allen, 1996; Savage et al., 2000) are:

- Gauges should be installed on straight section of stem (stem/bark should be manually smoothed);

- An electrical insulating compound should be applied to the stem prior to installation and an electrical check should be undertaken on the gauges;
- A conical collar should be should be installed above and below the collar to prevent water from entering the heated system and to prevent damage to the sensor; and
- The voltage across the heater should be adjusted according to the size of the gauge and the sap flow rates. This is usually tested in the laboratory and may prevent overheating of the stem.

The correct evaluation of K_{sh} (thermal conductivity of the sheath) must be undertaken when the sap flow is zero (using wooden dials).

2.5.2 Eddy Covariance (EC)

In recent years the eddy covariance (EC) method has become a valuable tool for evaluating the fluxes of carbon dioxide between terrestrial ecosystems and the atmosphere over a period of time (Baldocchi, 2003). According to Dye et al. (2008), the EC system is based on the very high frequency measurements (10 Hz) of water vapour and CO_2 above vegetation canopies. Such frequent measurements describe gas concentrations in eddies of air that are particularly important drivers of gas exchange above aerodynamically rough vegetation (Dye et al., 2008a). According to Savage and Everson (1997), this technique is beneficial for determining sensible (F_h) and latent (L_vF_w) heat flux densities, because the measurement is absolute. The data obtained from this technique can be checked, by confirming that the net irradiance (I_{net} measured separately with a net radiometer) satisfies the equation $I_{net} = L_vF_w + F_h + F_s$, where F_s is the soil heat flux density. The technique is especially valuable in studies where information on both the water and carbon fluxes are significant indicators of water-use efficiency. These may be compared to similar data obtained over vegetation in other countries. According to Baldocchi (2003), there are four factors which make this measurement technique popular. The first is that it is a scale-appropriate method, as it can provide canopy scale measurements. Secondly, this technique provides a direct measure of net carbon dioxide exchange across the canopy-atmosphere interface (Baldocchi, 2003). The third and fourth factors are that the area sampled by this technique can range from a hundred meters, to several kilometres (Schmid, 1994) and that this technique can measure across a range of time scales.

Eddy covariance measurements above the canopy provide estimates of evapotranspiration at the high temporal resolution necessary to examine processes, but also at much greater spatial scales than sapflow (Wilson et al., 2000). Simultaneous measurements of sensible heat flux and other trace gas fluxes, such as carbon dioxide, are also feasible. These advantages, *inter alia*, allow for this technique to probe vital links between hydrological and other biogeochemical processes. In addition, simultaneous heat flux and energy balance estimates are used as independent checks on the validity of the measurements (Baldocchi et al., 1988).

One major weakness of the eddy covariance technique is that the size and shape of the representative region contributing to the measured flux, is not fixed in time (Horst, 1992). Eddy covariance measurements are sometimes difficult to interpret during weakly turbulent periods, usually at night (Paw U et al., 2000 and Baldocchi, 2003). The technique also cannot directly account for advection in areas of significant heterogeneous or complex terrain, limiting its applicability in some locations.

2.6 Total Evaporation Modelling

2.6.1 Background Information

There is a need for suitable hydrological models to assist in predicting the impacts of land and water management alternatives, such as rehabilitation programmes (Everson et al., 2007). Riparian areas constitute an important and variable land-use within a catchment, which means that models used to simulate these areas need to be spatially explicit (Everson et al., 2007). Modelling riparian areas can be useful for catchment scale quantifications of water-use. Modelling can be difficult, if little information is available on the physiological and functional components of riparian areas, which are largely heterogeneous. Hydrological modelling allows users to mimic the plant-water cycle in a manner which is accurate, depending on the information used, and which can be implemented according to required scales, costs and time constraints.

Current modelling studies often rely upon coarse, empirical estimates of riparian vegetation total evaporation (ET), to validate their modelling calibrations (Scott et al., 2008). In particular, the transpiration component of the riparian water balance can be modelled, using such empirical approaches, as they have been previously used successfully for trees growing under non-limiting water conditions (Birkhead et al., 1997). Usually, detailed data in riparian areas is difficult to collect. This problem was overcome in a study in the Kruger National Park (KNP), by using a simple regression modelling approach, rather than a process-based approach, which requires data such as stomatal conductance or aerodynamic roughness of the canopy (Birkhead et al., 1997). Models used in water-use modelling need to find a balance between simplicity and reliability, while at the same time they need to have an appropriate regional scale for the research being conducted (Le Maitre et al., 2000). A biomass model was developed and used by Le Maitre et al. (2000), that predicts incremental water-use by determining the additional water-used by alien tree species, compared to the indigenous vegetation it has replaced, rather than the total water-use.

The basic requirements of models are that they:

- extrapolate data to a wide range of invader and indigenous tree species and over a wide range of rainfall areas;
- model links between leaf area, biomass, growth and productivity; and
- predict ET at a high resolution (i.e. daily or sub-daily).

Several water balance models, that apply flexible growth routines, are available. However, the inputs required by these models could potentially limit their applications for complex, species-diverse vegetation types (Jarmain et al., 2004). The 3-PG forest growth model is based on absorbed photosynthetically-active radiation, where relationships are required by the model, that ensure the allocation of new growth to foliage and the stem, proceeds in a balanced fashion as the trees grow (Dye, 2001). The WAVES (Water, Vegetation, Energy, Solute) model has been used extensively throughout the world (Zhang et al., 1999) and more recently in South Africa (Dye et al., 2008b), to model vegetation water-use. The model is well suited for simulations of hydrological and ecological responses, to changes in land management and climatic variation (Dye et al., 2008b). It can be used on a wide range of plant functional types as it accounts for a wide range of factors limiting plant growth and water-use (Dye et al., 2008b). WAVES is a process-based model, which enables it to keep track of the site water balance (accounting for daily rainfall, interception, overland flow, soil water distribution and plant water uptake) and can therefore predict the availability of soil water on any given day (Dye et al., 2008a). The WAVES model has been applied and validated over nine vegetation types in South Africa ranging from, *inter alia*, grasslands, indigenous forest species, invasive alien tree species and wetland species. The modelled results showed a strong correlation to the measured ET values, where realistic seasonal patterns and whole-year cumulative ET were observed for most vegetation types (Dye et al., 2008b). Figure 2.10 shows the accuracy of the modelled transpiration over a year period.

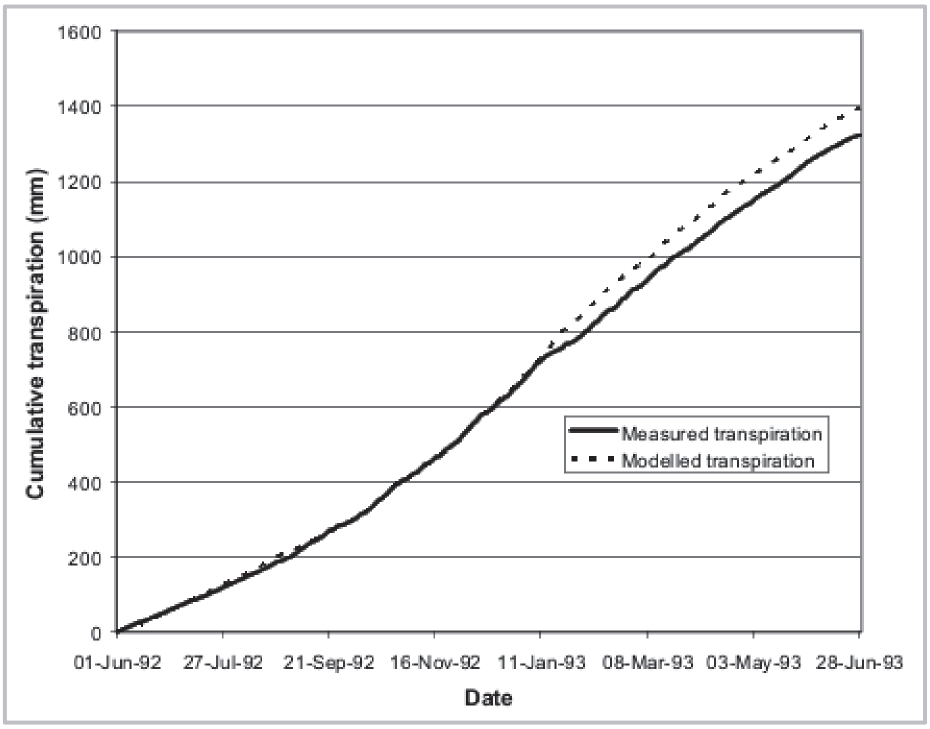


Figure 2.10 Simulated daily accumulated transpiration against measured accumulated transpiration at a Eucalyptus grandis canopy in the Sabie area (Dye et al., 2008b)

The *SWAT* (Soil and Water Assessment Tool) is a conceptual, continuous time model developed in the early 1990s, to assist in water resource management, in order to assess the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins (Arnold, 2005). Forest growth, which is a more recent addition to the *SWAT* model, allows for a plant growth component. This model, which is continuously updated, has an improved weather generator, as well as the ability to read in daily solar radiation, relative humidity, wind speed and potential ET (Arnold, 2005). It is physically-based, uses readily available inputs and is computationally efficient to operate on large catchments over extended time periods (Everson et al., 2007). The *SWAT* model has an extension to Arcview, which has increased the versatility of the model, and this spatial component makes it attractive to modelling evaporation components.

One method of streamflow reduction estimation is to use the land-use sensitive Agricultural Catchments Research Unit (*ACRU*) rainfall-runoff catchment model (Smithers and Schulze, 2004). *ACRU* is a physical-conceptual model that operates at a daily time step and is capable of simulating hydrological processes realistically under varying climatic, land-use and hydrological regimes (Schulze, 1995). The *ACRU* model has been developed and shown to be sensitive to land cover, land-use and land management changes and has been used frequently in assessing this impact on runoff (Schulze et al., 1995). Evaporation is a key hydrological process, when considering the water-use of alien vegetation in riparian areas. Evaporative demand on the plant is dependent on the atmospheric demand, as well as the structure and stage of the plant's growth, and is limited by water availability (Gillham and Haynes, 2001). ACRU estimates atmospheric demand, using a reference potential evaporation derived from monthly totals of daily A-pan equivalent. Crop coefficient data are required as one of the main indicators of the hydrological impact of removing alien vegetation. The *ACRU* model has been used extensively in catchments throughout South Africa. The uMgeni Catchment is one such example. Data for this catchment was visually assessed and the vegetation within the riparian zones was classified and captured into a geographical information system (GIS). A hydrological investigation using the *ACRU* model, was used to determine the amount of surplus water that would be obtained in the uMgeni Catchment if the alien vegetation occurring in the riparian zones were to be cleared and returned to natural vegetation (Gillham and Haynes, 2001). According to Gillham and Haynes (2001), the scenarios of land-use in riparian areas of the uMgeni catchment that were considered in the model were:

- the impact of the current level of infestation of the riparian zones with alien vegetation;
- the impact of cleared and rehabilitated riparian zones; and
- the impact of delaying the riparian zone clearing, resulting in denser infestation.

The findings from this research indicated that the present-day riparian zone vegetation impacted negatively on the water resources of the Catchment. Furthermore, hypothetically, if these zones are not rehabilitated and the densification of alien vegetation is allowed to occur at an assumed rate, then these impacts will increase significantly (Gillham and Haynes, 2001). According to Jarmain et al. (2004), the *ACRU* model has further been employed widely, to establish compensatory forestry approaches to clearing invasive alien vegetation from riparian zones (Jewitt et al., 2002), as well as to establish approaches to modelling streamflow reductions, resulting from commercial afforestation (Gush et al., 2002).

A groundwater component was identified as a necessity for the flat area at the Vasi Pan site. In addition, little or no surface water is present in the catchment and water flow is predominantly through sub-surface movement. As such, the *ACRU* Shallow Groundwater Routine for the W70A Quinary Catchment was set up. The purpose was to be able to model impacts of forest plantations with deep roots versus natural vegetation with shallower roots on the groundwater responses. The routine was last used about 20 years ago, and had since not been in use and was disconnected from the remainder of the ACRU code, which had undergone computational and other updates.

When last used about 20 years ago, the routine was used to assess the effects of afforestation on groundwater resources, and a paper on the results was published (Kienzle and Schulze, 1992). The shallow groundwater routine has not been used in the past two decades and considerable institutional memory on its functioning was lost. The routine is described in the standard *ACRU* literature (Schulze, 1995; Smithers and Schulze, 1995) and the description will not be repeated here.

Several challenges were encountered during this project. While various updates had been made to the *ACRU* model since 1995, this routine was disconnected and not updated. For this current project, some computational adjustments were made, so that the routine could be run again, however, with certain limitations, which will be discussed later. A unit error was found in the *ACRU* literature, but that error was not in the original code. It was found that the instructions on the detailed setup and running in the *ACRU* literature were insufficient for new users and this report aims to improve this. Furthermore, sensitivity studies were undertaken to establish the influence of various input variables on relevant outputs.

2.6.2 Model selection

Arguably one of the most important components of a scientific simulation model is that it should be as easy as possible to understand in light of the assumptions and mechanisms represented in the simulator, so that critical evaluations can be made of the predictions (Thornley, 1998). Models in the public domain are promoted differently, and explained differently, resulting in model comparisons being more difficult than initially expected. Because numerous models developed for a variety of uses are available, a predicament exists as to which model or sub-model is best suited for the intended use. Some models are designed and developed for specific purposes, while others are more general and integrated in their applicability (Schulze, 2007). Model complexity is a major determinant as to which model is selected, as the input data available, time constraints and budget will also influence model selection. The level of detail on processes, on spatial disaggregation and temporal disaggregation should also be considered in models (Schulze et al., 1995).

Comparisons of simple and complex models provide insights on the model structure in order to make a suitable model selection. According to Schulze et al. (1995), models of differing complexity range from simple formulae to complex physiologically-based models. The advantage of simple models is that simple and readily obtainable inputs are required in order to provide estimations (Schulze et al., 1995). Simple models cannot expect to provide a detailed estimation, but may be accurate in terms of general large scale modelling. Simple models should not be used for extrapolation of estimates under different conditions from the ones under which these models were developed, nor for risk analysis (Schulze et al., 1995). More complex models can provide accurate estimates of hydrological components in comparison to simple models, provided that quality information is readily available and time and money are not limited. “The development of complex models from the processes of analysis, assembly of data, model construction and validation, take up costly resources in the form of skilled man hours and computer time” (Schulze et al., 1995, AT19-3). The *ACRU*, *SWAT* and *MAESTRA* model have been selected for this study due to the availability of data and the timeframes required for the project. Due to time constraints the WAVES model was not selected.

2.6.2.1 The ACRU agro-hydrological model

The *ACRU* agro-hydrological model has been chosen as a foundation for a potential hydrological model because it has been intensively and extensively used and verified in South Africa and utilises a sound set of databases available in the country. “The *ACRU* model has been developed and shown to be sensitive to land cover, land use and land management changes and has been used frequently in assessing this impact on runoff” (Schulze et al*.,* 1995. AT2-10). *ACRU* is a physical-conceptual model, physical in that processes are represented explicitly with initial and boundary conditions and conceptual in that it conceives of a system where important couplings and processes are idealised (Figure 2.11; Schulze et al*.,* 1995, AT2-2). The *ACRU* model operates on a daily time step, therefore making optimal use of available climatic information, and making the model suitable in terms of flow regimes and sediment yield, which are highly correlated with individual rainfall events (Schulze et al*.,* 1995).

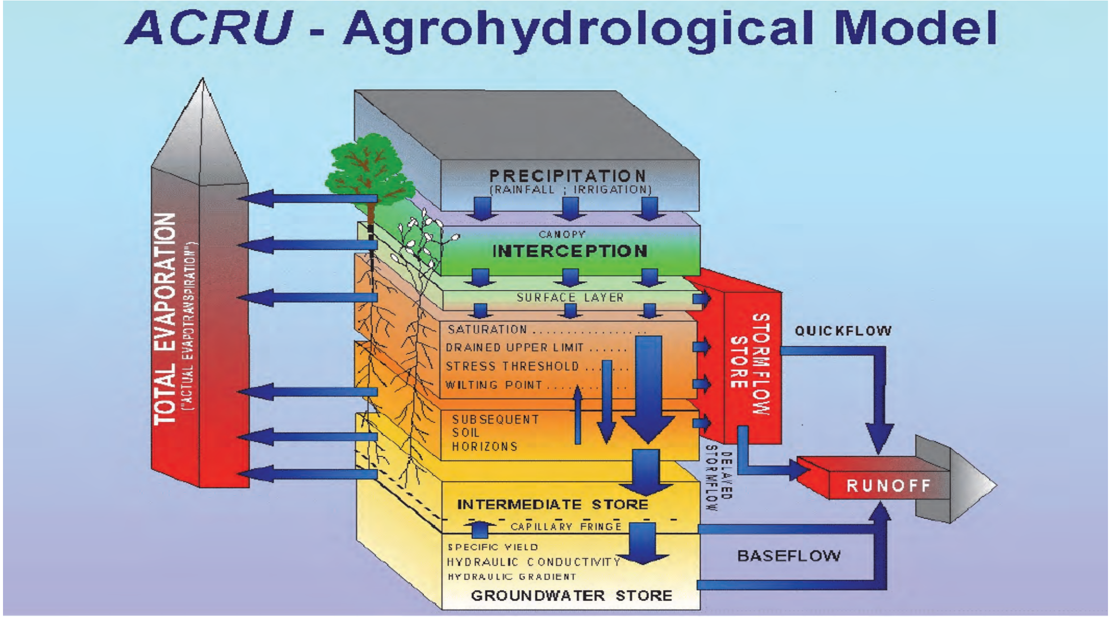


Figure 2.11 Structure of the *ACRU* agro-hydrological modelling system (Schulze et al., 1995).

An important concept of *ACRU* in terms of land use modelling is that it can operate as a distributed model, thereby accounting for spatial variability in rainfall, land uses and soils and thus providing accuracy in the location of hydrological responses within the catchment (Schulze et al., 1995). This model is suited to scenario testing as it is relatively easy to modify hydrological vegetation attributes that are input into the model. Furthermore, the total evaporation output can be separated into soil evaporation (ASOEV) and transpiration (ATRAN 1 + ATRAN 2) which can then be compared to transpiration measurements. The *ACRU* dynamic file input has potential for this and similar studies where known environmental or management changes are present. This component allows the user to modify the monthly inputs of each year to include burning, felling, plant mortality, etc. *ACRU* specific information on the soils, vegetation, climate and management are available for each of the selected sites.

2.6.2.2 The Soil Water Assessment Tool (ARCSWAT)

SWAT requires soils data, land use/management information, and elevation data to drive flows and direct sub-basin routing (Arnold, 2005). While these data may be spatially explicit, *SWAT* lumps the parameters into hydrologic response units (HRU), effectively ignoring the underlying spatial distribution. Traditionally, HRUs are defined by the coincidence of soil type (Hydrologic Soil Group, USDA, 1972) and land use. Simulations require meteorological input data including precipitation, temperature, and solar radiation. This model was chosen to provide large scale estimates of the effect of clearing on the hydrological cycle and to provide a comparison to the *ACRU* model. This will minimise any bias that may be present with the model selection.

2.6.2.3 The MAESPA model (updated from the MAESTRA model)

The *MAESPA* model became of interest to the authors during the last reference group meeting and after correspondence with the water-use experts. This model was selected as a tool to up-scale the transpiration data at the sites. This model can be used to interpret and integrate experimental results (Duursma and Redlyn, 2012). The *MAESPA* model was developed as an individual tree-based model (Duursma and Redlyn, 2012). The model includes a hydraulically-based model of stomatal conductance, root water uptake routines, drainage, infiltration, runoff and canopy interception, as well as detailed radiation interception and leaf physiology routines (Duursma and Redlyn, 2012). The model can be applied both to individual plants of varying size and shape, as well as stands of trees.

3. METHODS

Throughout the course of the project, annual reference group meetings were held to promote discussions on potential sites and/or species of interest to this project and to initiate the implementation of monitoring equipment at the most appropriate sites. The suggestions and ideas were referred back to the project objectives to ensure that they were realistic and achievable. The information gained from these meetings assisted in creating a database of species and a list of sites that could meet the requirements of the project objectives and develop criteria for the experimental design of this project. Further guidance and expertise were utilised by the group as the project progressed.

3.1 Motivation of Site and Species Selection

There were a number of requirements for the site selection. Various climatic regions were needed in order to investigate the water-use of species suitable for forest expansion and rehabilitation programmes throughout South Africa (Objective 1) and later, to incorporate this data into a modelling framework for water-use predictions (Objective 4). A further requirement for the selection of a suitable site was that the trees of interest (both indigenous and alien) were in close proximity to each other in order to enable wiring to the equipment and access to the power source. Security is also an important factor and was therefore considered in the site determination. The presence of a Working for Water or similar alien clearing programme in a location was essential to the selection of a site to meet Objective 3. With these requirements in mind, the following sites were suggested by the members present (Table 3.1):

Table 3.1 List of preferred sites and their characteristics

Location	MAP(mm)/Rainfall Region	Biome/Bioregion	Alien clearing programme? (Y/N)	Secure (Y/N)
Berg River (B)	600-800/Winter rainfall	Western Cape Afrotemperate Forest	Y (Working For Water)	Y
Buffeljagsrivier (Bu)	800-1000/Winter rainfall	Western Cape Afrotemperate Forest	Y (Working For Water)	Y
New Forest (F)	800-1000/Summer rainfall	Eastern Mistbelt Forest	Y (Working For Water)	Y
Vernon Crooks (V)	1000-1200/Summer rainfall	Eastern Scarp Forest	Y (Working For Water)	Y
Hluhluwe (H)	600-800/Summer rainfall	Eastern Scarp Forest	Y (Working For Water/EKZNW)	Y
Vasi Pan (VP)	800-1000/Summer rainfall	KwaZulu-Natal Coastal Forest	Y (Mondi clearing teams)	Y

Very few indigenous riparian forests have been mapped or are too small to be shown at a national scale. The focus was therefore on the sites falling under indigenous forest types (Figure 3.1). The discussions among the participants highlighted the need for a combination of climatically different forest regions where alien clearing projects existed. There was consensus that the Western Cape Afrotemperate Forest (Buffeljagsrivier), Eastern Scarp Forest (Vernon Crooks) and Eastern Mistbelt Forest (New Forest) would be ideal sites as they were uncommonly secure areas that had both pristine indigenous forests and alien trees in close proximity.

The Working for Water alien clearing projects occurring throughout South Africa and coinciding with indigenous forests are distributed mainly along the eastern escarpment and coast of KwaZulu-Natal and the Western Cape (Figure 3.2). The Expanded Public Works Programme of the South African Government is aimed at promoting the sustainable management of natural resources through the control and management of invasive alien plants while enhancing socio-economic empowerment in South Africa (Marais and Wannenburgh, 2008). Most of the alien clearing projects are within protected areas as there is a greater interest in conservation and a need for improved ecosystem service delivery. Approximately 7% of riparian invasions have been cleared in South Africa, resulting in significant flow yield increases (Marais and Wannenburgh, 2008). The increased estimated flow yield of 34.4 million m^3 is about 42% of the yield of the new Berg River Scheme in the Western Cape (81 million m^3).

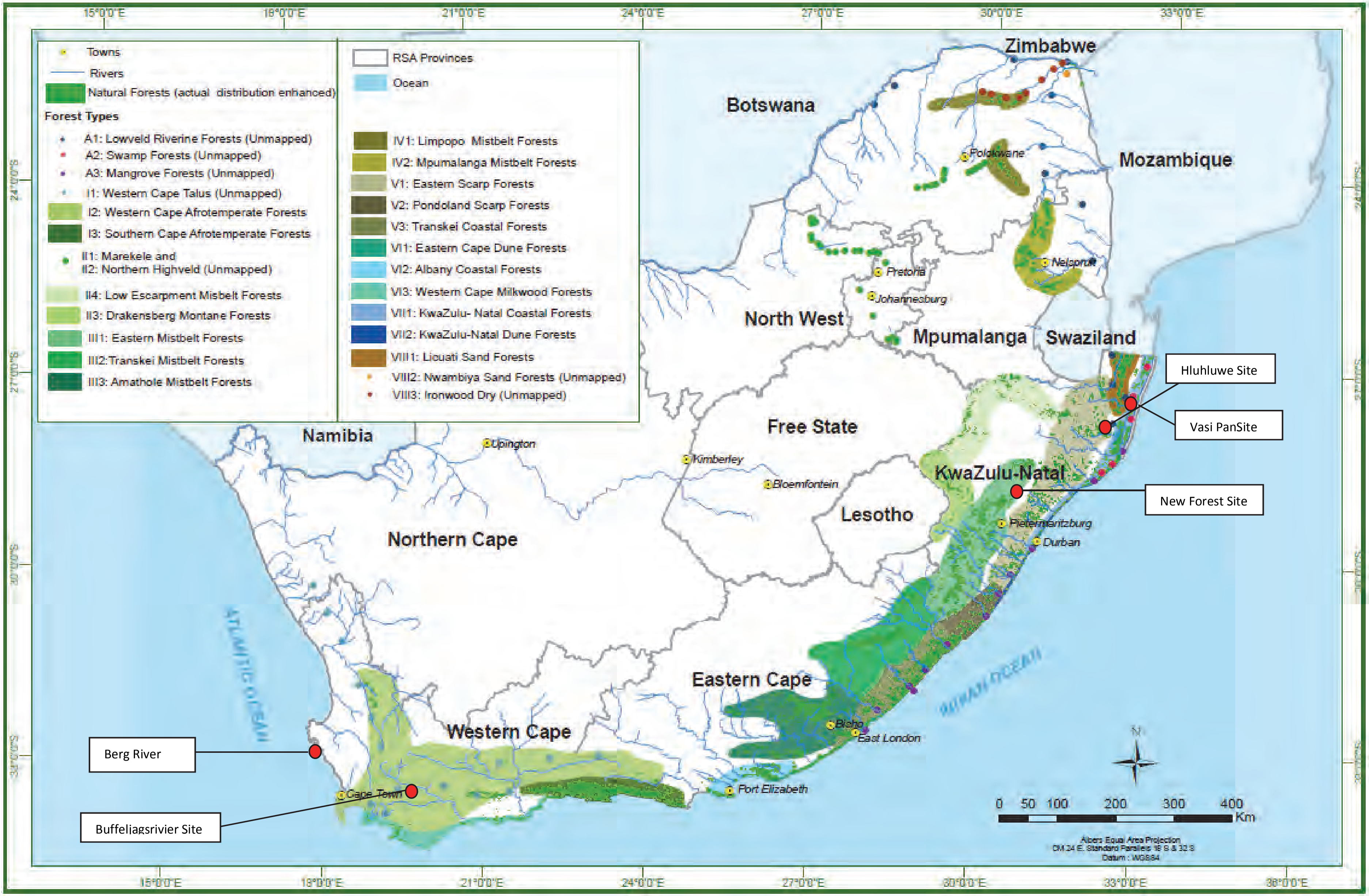
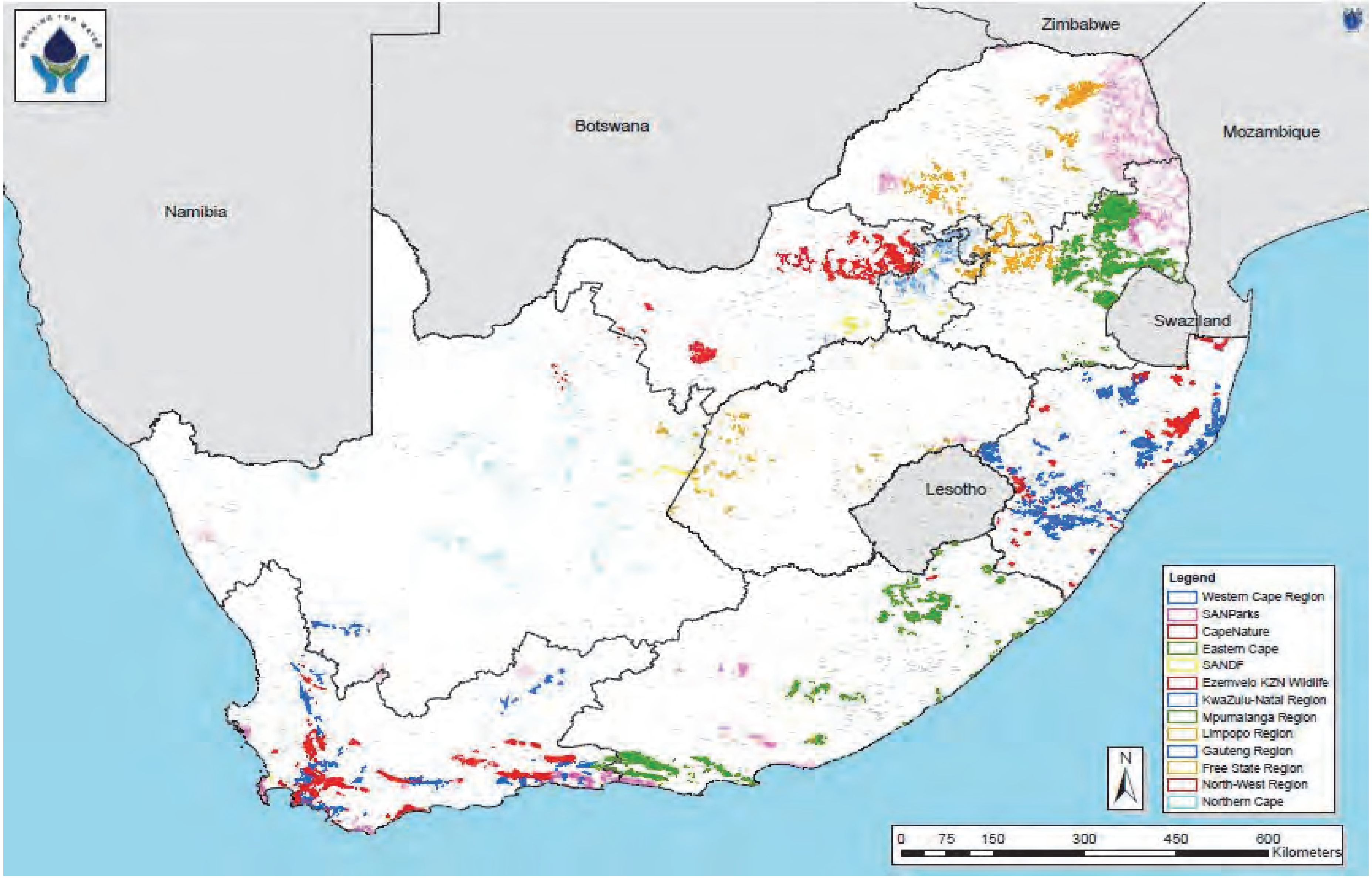


Figure 3.1 Locations of indigenous forest types throughout South Africa (Geldenhuys, 2010) showing the position of the final selected sites


Zimbabwe
Botswana
Mozambique
Namibia
Swaziland
Lesotho
Legend
Western Cape Region
SANParks
CapeNature
Eastern Cape
SANDF
Ezemvelo KZN Wildlife
KwaZulu-Natal Region
Mpumalanga Region
Limpopo Region
Gauteng Region
Free State Region
North-West Region
Northern Cape
N
0
75
150
300
450
600
Kilometers

The selection of priority species for this project were motivated by a combination of expert advice, gaps in past research, species plots undertaken by Ezemvelo KZN Wildlife and a short-list of species selected by Gush et al. (2010) on the water-use and economic value of the biomass of indigenous trees under natural and plantation conditions (Gush *et al.*, 2015). The primary aims were to select species that occur in the forest biome and over various climatic regions. As the focus was on riparian areas, growth rate and therefore pioneer order needed to be considered in the species selection. In addition, as sites where Working for Water has cleared alien trees was a requirement (Objective 1 and 3), the choice of species and sites were somewhat limited. The selection of indigenous pioneer tree species would be dependent on the representativeness and size of trees available at a site. The water-use of numerous species would also need to be measured in order to meet the requirements for Objective 1. From an extensive list of potential indigenous tree species, the following (Table 3.2, Scott-Shaw, 2012 – Personal Communication) were selected as important and valuable species.

Table 3.2 List of important indigenous riparian tree species in South Africa

Location	Species	Description	Growth Stage (primary/secondary)
H/VP	*Acacia schweinfurthii*		Secondary/Climax
V/H/ VP	*Albizia adianthifolia*	High general use value	Primary
All	*Apodytes dimidiata*	High general use value	All
H/ VP	*Breonadia salicina*	Protected, very high wood value	Secondary/Climax
V/H/ VP	*Bridelia micrantha*	Fast growing, high general use	Primary/Secondary
V/H/ VP	*Cassipourea gummiflua*	Slower growing	Secondary
All	*Celtis africana*	Common, high general use value	Primary/Secondary/Climax
H/ VP	*Celtis durandii*	Slower growing but reaches 25 m	Secondary/Climax
V/H/ VP	*Chaetachme aristata*	Common but slow growing	Secondary/Climax
All	*Chionanthus peglerae*	Large tree, high general use value	Climax
V/H/ VP	*Combretum*	High general use value	Primary/Secondary
V/H/ VP /S	*Combretum kraussii*	Fast growing tree	Secondary/Climax
All	*Croton sylvaticus*	Very high general use value	Primary/Secondary
V/H/ VP	*Cryptocarya latifolia*	Medium sized evergreen	Climax
B/Bu	*Cunonia capensis*	Fast growing tree	All
All	*Dais cotinifolia*	Fast growing tree	Primary/Secondary
V/H/ VP	*Dalbergia melanoxylon*	Very high wood value	Secondary/Climax
All	*Ekebergia capensis*	Fast growing, high general use	All
V/H/ VP	*Englerophytum natalense*	Coastal, very high general use value	Primary/Secondary
H/ VP	*Ficus capreifolia*	Horizontally spread fruit tree	Primary/Secondary
V/H/ VP /S	*Ficus natalensis*	Fast growing evergreen	Primary/Secondary
H/ VP	*Ficus sycamorus*	Large semi-deciduous	All
All	*Halleria lucida*	Fast growing, high general use	Primary/Secondary
B/Bu/V/H/	*Harpephyllum caffrum*	Fast growing, high general use	Secondary/Climax
All	*Ilex mitis*	Very fast, very high general use	Secondary/Climax
V/H/ VP	*Macaranga capensis*	Frequently occurring medium tree	All
V/H/ VP	*Manilkara discolor*		Climax
V	*Millettia grandis*	Good pioneer, very high wood value	All
All	*Olea capensis macrocarpa*	High general use value	Climax
B/Bu	*Olinia ventosa*	Very high wood value	Secondary/Climax
All	*Pittosporum viridiflorum*	Fast growing tree	Secondary
B/Bu	*Platylophus trifoliatus*	High general use	Primary/Secondary
Bu	*Podocarpus elongatis*	Naturally occurring in Swellendam	Secondary
V/H/ VP	*Protorhus longifolia*	Fast growing, high general use	Secondary
B/Bu	*Prunus africana*	High wood value, high general use	Secondary/Primary
B/Bu/V/S	*Rapanea melanophloeos*	Fast growing, high general use	Primary/Secondary
V/ VP	*Schefflera umbellifera*	Fast growing tree	Secondary/Climax
H/ VP	*Schotia brachypetala*	Medium deciduous tree	Secondary/Climax

Location	Species	Description	Growth Stage (primary/secondary)
All	*Scolopia zeyheri*	Small tree, little economic use	Climax
Carletonville	*Sersia pendulina*	High general use value	All
All	*Sideroxylon inerme*	High general use value	Climax
V/H/ VP	*Strychnos gerrardii*	Large fruit bearing	Climax
V/H/ VP	*Syzygium cordatum*	High general use value	All
V/H/ VP	*Teclea gerarrdii*	Small evergreen, little use	Climax
All	*Trema orientalis*	Common pioneer, fast growing tree	Primary/Secondary
H/ VP	*Trichilia emetica*	Medium evergreen, good wood	Secondary/Climax
All	*Vepris lanceolata*	Fast growing, high general use	Secondary/Primary
B/Bu	*Virgilia divaricata*	Fast growing pioneer	Secondary
B/Bu	*Virgilia oroboides*	Fast growing pioneer	Secondary

Based on past work by Dr Geldenhuys in the Western Cape site, the selection of indigenous species was limited to those occurring within the clearing projects so that measurements could be undertaken on both the alien species (e.g. *Acacia mearnsii*) and indigenous species (e.g. *Celtis africana* and *Vepris lanceolata*) by the same equipment and therefore under the same conditions. There was more freedom in the KwaZulu-Natal sites as the alien trees were scattered throughout the riparian areas and there was a greater choice of indigenous tree species to measure. The selection of alien tree species was therefore site dependent and included *Acacia mearnsii* and *Eucalyptus* spp. It was also noted that when measurements were undertaken, the size and age of both the alien and indigenous trees were considered in order to compare the water-use measurements accurately. Growth (height and diameter) measurements were taken, as well as soil moisture, rainfall, temperature and relative humidity in order to support the sap flow measurements.

3.2 Ecological Monitoring Techniques

3.2.1 Forest Sampling at Buffeljagsrivier

There were four specific objectives of the study:

1. To map and assess the patterns in the distribution, size and species composition of forest clusters within the Black wattle stand
2. To determine the relationships in species composition between natural forest clusters and neighbouring forest patches as potential seed sources for developing forest clusters
3. To determine the nature of the spread of indigenous forest species from developing forest clusters into the surrounding Black wattle stand
4. To use fenced enclosed plots to assess the effect of browsing by cattle and wildlife on the establishment success of natural forest seedlings

3.2.1.1 Zonation, mapping and selection of study sample

Zonation of the study area

The Black wattle stand was divided into three zones in relation to the proximity to the indigenous forest patches: Proximal zone, Intermediate zone and Distant zone, using natural boundaries (Figure 3.3).

- The proximal zone

The zone starts at the western limit of the largest moist forest patch, with no physical boundary between the two areas. It also has patches of riparian forest, some to the north and some to the south of the Black wattle stand. It is the most accessible one and regularly visited by both humans and domestic animals such as cattle. The cattle caused considerable browsing of the establishing seedlings of the natural forest species.

- The intermediate zone

The Intermediate zone, middle section of the Black wattle stand, is also subject to regular human and cattle movements. This zone has two parts; the eastern part is most easily accessed by cattle with associated heavy browsing, and it was cleared of the Black wattle before 2004. A strip was also cleared during 2006 in the conventional WfW practice to compare with the new approach of selected removal of Black wattle around establishing forest clusters (Geldenhuys and Bezuidenhout, 2008). The western part of this zone has more difficult access for cattle with possible less heavy browsing.

- The distant zone

This zone forms the largest part of the Black wattle stand with a generally low accessibility to cattle, but is relatively far from the potential seed sources. The general view of this part of the stand is relatively dense stocking of smaller Black wattle with many dead big old trees (probably natural forest species and Black wattle or other introduced species). This area has many signs of past human activities such as vestiges of houses, empty containers, and shallow drainage channels.

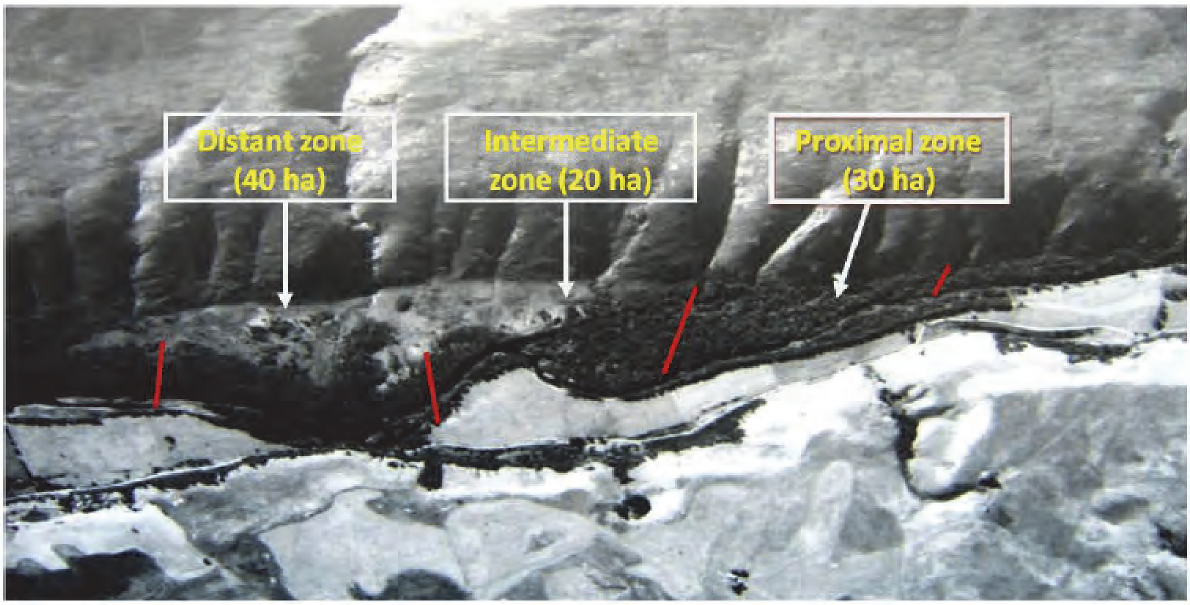


Figure 3.3 The three zones with approximate area of the Black wattle stand in relation to the proximity of the natural forest patches (Google image January 2011).

Mapping of forest clusters

A forest cluster for this study was defined as one to several natural forest trees growing on a limited area within the Black wattle stand. A requirement was that within the group there should be at least one reproductively mature tree present that would be able to attract dispersal agents. Three cluster size classes were defined: Small cluster, with one to three trees; Medium cluster with four to nine trees; and Large cluster with 10 and more trees.

The total Black wattle stand of 90 ha was traversed along parallel 20 m wide transect belts between the river and the foot of the mountain. The location coordinates of each existing cluster were recorded with a

GPS. In the case of larger clusters, the GPS coordinates of the largest tree in the cluster were marked and recorded, with the species name.

A sample of forest clusters was selected by stratified sampling as described by Kindt and Coe (2005) to assess the shapes and the species composition of the forest clusters. The hypothesis that species composition would differ with the distance to seed sources and with the succession development stage of the stand guided the selection. The accessibility of the forest cluster was set as an additional condition for selection. When a random number presented an inaccessible forest cluster, it was replaced by the nearest accessible one. Initially 63 forest clusters were randomly selected, using tables of thousand digit random numbers, and proportional to the total number of small, medium and large clusters within the identified Proximal, Intermediate and Distant zones. After sampling, the large clusters surrounded by Riparian forest north appeared to be more like forest patches and were then excluded from this selection.

The following general information was recorded for each of the 59 selected forest clusters: forest cluster number; GPS coordinates; site slope (level, gentle, steep or very steep); canopy closure (1 = ≤ 25%; 2 = 51-75%, 4 = ≤ 75+%); and main growth forms of the ground cover (grass, herbs, climbers, ferns, and/or tree regeneration). In addition, information on the species composition of the trees within the forest cluster was recorded: All stems ≥5 cm DBH (stem diameter at 1.3 m breast height above ground level) by species and DBH; Count of stems <5 cm DBH per species as regeneration, by three categories (seedlings = stems <50 cm height; saplings = stems ≥50 cm height and <1 cm DBH; poles = stems 1.0-4.9 cm DBH). For multi-stem trees, each stem was measured and recorded separately but the tree number was the same for each stem of the tree (to indicate that they belong to the same tree). Unknown species were recorded as such but material was collected for later identification.

Selection of study sample and data collection from transects

Natural forest patches of different size, canopy characteristics and site conditions in close proximity to the Black wattle stand were selected: Moist forest (three patches); Dry forest (three patches); Riparian forest south of the wattle stand (Riparian forest south) (four patches); and Riparian forest north of the Black wattle stand (Riparian forest north) (five patches). The species composition and structure of these patches were compared with the seven selected large forest clusters.

Randomly located line transects were sampled in the forest patches to cover a topographical gradient and general composition and structure of a patch or cluster. Rectangular plots (10 m x 20 m) were systematically sampled along the line transect, with the long axis of the plot perpendicular to the direction of the transect line.

The following data were recorded on each main (10 m x 20 m) plot: All stems ≥ 5 cm DBH, tree number, species and DBH. In the case of multiple stems of a tree, each stem was recorded with the same number to indicate that they belonged to the same tree. In a 5 m x 10 m sub-plot centred within the main plot, all stems <5 cm DBH were recorded by stem counts per species. The following was recorded at the centre of each plot: canopy closure (1 = <30% closed, 2 = 31-50%, 3 = 51-75%, 4 = >75% closed); altitude; aspect (N, NE, E, SE, S, SW, W, NW); slope (1 = gentle, 2 = steep and 3 = very steep). Ground cover was described by dominant growth forms, such as grass, trees, regeneration, ferns or others.

3.2.1.2 Sampling forest expansion around clusters

Seven forest clusters (six large, one medium) were systematically selected from the three black wattle stand zones to assess the possible expansion of the forest clusters and the influence of distance from seed sources. Large and medium clusters were preferred since they contain several mature indigenous trees of different species, which would assure visit by different dispersal agents. Finally, criteria for selection of specific large and medium clusters were accessibility and the ability to accommodate the plot design.
The pattern of regeneration found in the immediate surroundings (expansion) of a selected forest cluster was investigated only within 18 m distance away from the boundary of the forest cluster. Fruit/seed characteristics and dispersal system were the considered factors for the expansion.

The borders and centre of each selected forest cluster were marked. Forest cluster borders were determined by simple projection of crown limits of indigenous trees on the boundary of the cluster, onto the ground. The cluster centre was the centre of the main axis of the forest cluster. From that cluster centre, eight line directions were considered (N, NE, E, SE, S, SW, W, NW). Four lines were then randomly selected. Three directions were used when the position did not allow four, because of natural obstacles such as river, ravine, etc. Along each selected line, two to three 10 m x 5 m rectangular plots (expansion plots) were sampled every 6 m from the cluster border. Two plots were used in the case of an obstacle or to avoid interference when another existing but non-selected cluster was in close proximity. All stems ≥ 5 cm DBH within the cluster area were recorded by species and DBH. Stems <5 cm DBH were recorded as part of regeneration within the cluster, by species and stem counts. On the 50 m^2 expansion plots, regeneration was recorded by species and stem counts and the number of mature Black wattle stems was recorded. Unknown plants were collected for later identification.

Two species lists were generated to assess the contribution of seed characteristics and the influence of dispersal mechanisms. The first list contained species from sampled plots in dry forest, moist forest and riparian forest. The second list contained species from the selected 59 forest clusters. Information on fruit/seed characteristics and dispersal mechanism of each species was obtained from the literature (Geldenhuys, 1996b) and supported by field observations.

3.2.1.3 Data analysis

Clusters analysis

A geo-referenced aerial photograph of the study site was obtained from the National Geo-spatial Information Institute (NGI) to map the recorded forest clusters. The aerial photograph was opened in Arc-map and the GPS points collected in the field were superimposed on the image. Then the map was created and patterns were highlighted. The Excel file containing measurements of different forest clusters, was loaded in Arc-map to draw the forest cluster shapes by interpolation of the points. Stems of natural forest species were differentiated from stems of invasive species, and the biggest stems were highlighted, using different colours and generating a legend. The surface areas of forest clusters were calculated using area menu in Arc-map.

The mean number of clusters per ha per zone (the zones varied in total surface area) were calculated and described in relation to the location of natural forest patches in order to investigate the patterns of forest cluster size distribution within the Black wattle stand. Analyses of Variance (ANOVA) were performed on the mean cluster size per zone, to test the hypothesis that more stems will be found close to the potential seed sources and that number of Black wattle stems will decrease with the cluster size. A Bonferroni comparison test was applied to the forest cluster size distribution to reinforce the ANOVA results. Mean species density per zone was calculated and histograms were generated to explain the species composition and distribution per cluster size and per stand zone. These data were used to check if the expected sequences of species establishment in relation to the succession stage as described in the literature were verified in this study.

Floristic analysis

A hierarchical cluster analysis (Dufrêne and Legendre, 1997; Kindt and Coe, 2005) was performed in Biodiversity R to differentiate forest clusters according to their resemblance in species composition. It consists of grouping together plots with high similarities based on their Bray and Curtis (1957) distance matrix. In that way two matrices were constructed; the first, a species matrix with species density (number of stems) as response variable and species identity and plots as factors. The second matrix was an environmental matrix (two-way table) which has in the first column the plot codes for the sampled forest clusters and forest patches, followed by columns for the three selected environmental factors: slope, aspect and canopy closure. Cell values were the values for each as recorded on site (see previous section). Results were given in a hierarchical dendogram placing plots gradually into distinctive community groups according to their average similarities in species composition. A Mantel test (Mantel, 1967) was performed to establish the correlation between the two matrices, i.e. to check the accuracy of the selected ecological distance measures. If the calculated Cophenetic-distance was high, it meant that the representation in the diagram was more accurate. In order to explain any possible pattern through the clustering results, a follow-up ordination analysis was conducted using the environmental factors slope, aspect, and canopy closure. Canonical Correspondence Analysis (CCA) (Ter Braak, 1986) was used to relate the species and environmental variables with the identified communities. Communities were then described through the Importance Value (IV) of different species to explain the relationship between the forest patches and forest clusters. The IV of each species with stems ≥5 cm DBH in each species group was calculated as follows:

IV = (RF + RD + RBA)/3, where

- RF = Relative frequency, calculated from the number of plots in a species group in which the species was present, and expressed as a percentage of all plots sampled in the species group;
- RD = Relative density, calculated from the number of stems of a species in a species group and expressed as a percentage of all stems of all species in the species group;
- RBA = Relative basal area, calculated from the total basal area (horizontal surface area of a stem at 1.3 m above ground level) of a species in a species group and expressed as a percentage of total basal area of all stems of all species in the species group.

Histograms of stem diameter distributions of selected important species were analysed to evaluate the population dynamics of those species in the different stand conditions.

3.2.1.4 Enclosure experiments in wattle stand

Eight square plots of 20 m x 20 m each were established in four sets within the wattle stand (*Acacia mearnsii*) at Buffeljagsrivier (Figure 3.4). In each set one plot was fenced to exclude cattle from eating the establishing forest seedlings and the fencing was done through the Bellville office of Working for Water (Figure 3.5). The other plot remained unfenced as a control. Each plot was subdivided into 5 m x 5 m subplots with the intention to implement four treatments on the ground cover as a means to facilitate the establishment of indigenous tree seedlings. The four exclosure plots (Plot 1, 2 3 & 4) are shown along the path running from the forest at the one station for measurement of sap flow (WStat 1) to beyond the other two sap flow measurement stations (WStat 2 and 3). The unfenced plots are located close to each fenced plot as a paired sample.

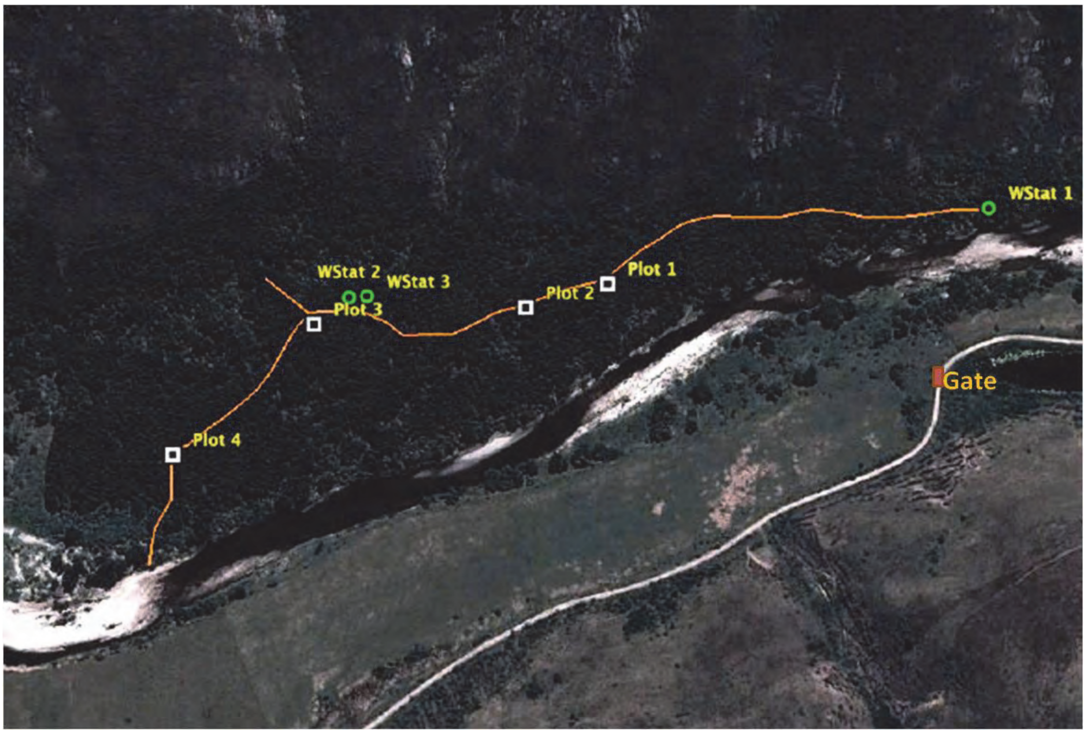
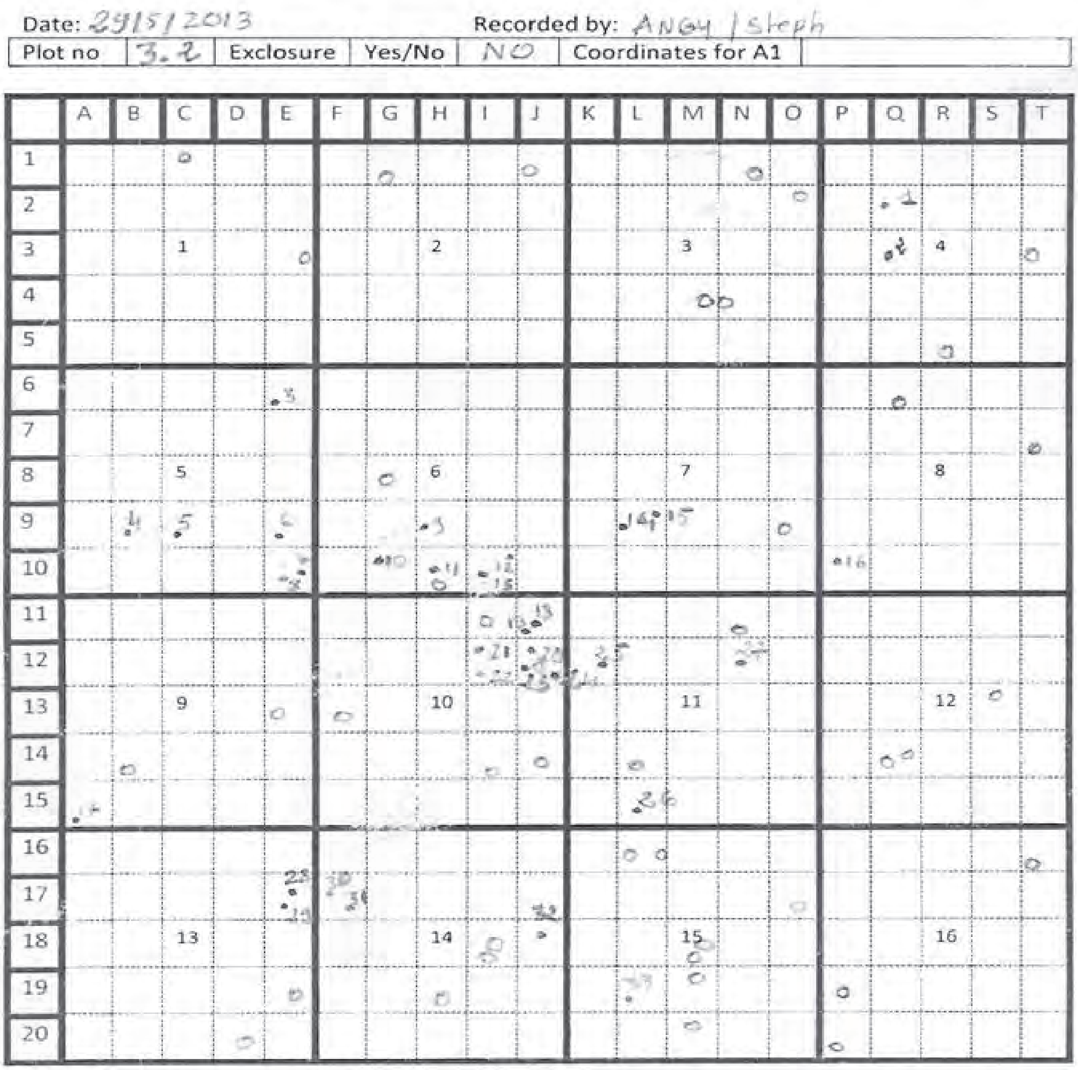


Figure 3.4 Location of the four exclosure plots (Plots 1 to 4) in the Buffeljagsrivier Study Site along the footpath in the vicinity of the three measurement stations of sap flow (WStat 1 to 3). At each plot, the indicated demarcated plot was fenced. Adjacent to this fenced plot, a second unfenced plot was demarcated.

Figure 3.5 The fenced enclosure plot 1 in the wattle stand.

In each subplot, the following variables were measured for each tree ≥5 cm stem diameter at 1.3 m above ground level (DBH): species, DBH, and its approximate position within the plot, marked with an open circle on a map of the plot (Figure 3.6). Each woody plant of <5 cm DBH in the understory was tagged (Figure 3.7), numbered consecutively and its position in the plot was indicated by a point with a plant number on the map of the plot. The species, height (mm), degree of browsing, the regeneration and overhead tree stand were recorded into an Excel spreadsheet.



Date: 29/5/2013

Recorded by: ANGY / Steph

Plot no	3.2	Exclosure	Yes/No	NO	Coordinates for A1	

Figure 3.6 A map of each selected plot (in this case plot 3.2), subdivided into 16 subplots of 5 m x 5 m each) to indicate the approximate position of each regenerating seedling (dot with number) and tree ≥5 cm DBH (open circle). Note the micro clusters of seedlings.

Figure 3.7 Tagged seedlings of *Celtis africana* in fenced plot 1.

3.2.2 Objectives and Ecological Methodology at New Forest

There were three specific objectives for the study

1. Assess the floristic relationship between mature forest and the regeneration of natural forest species in IAP stands at New Forest.
2. To assess the influence of distance from natural forest as a seed source area on the regeneration of native forest species in IAP stands at New Forest
3. To assess regeneration success of native forest species in relation to the IAP stand structural dynamics at New Forest (this would include the self-thinning process of pioneer IAP stands).

3.2.2.1 Forest Sampling

Four general forest stand-types were identified during initial site visits: mature forest, various mixtures of regrowth forest (this is a mixture of IAP and pioneer native species), abandoned plantation forest and riparian invasion forest (Table 3.3). Sampling was conducted during the summer months and included indigenous and alien woody and herbaceous species. This component of the study used only indigenous species in the analyses. The sampling localities of these stand types (Figure 3.8 Map of sampling sites and forest stand types at New Forest) were based upon their location in the landscape in relation to each other, proximity to natural forest and dominant canopy cover. Natural forest and abandoned plantation plots were chosen at known intervals along random transects. Regrowth plots and riparian invasion plots were chosen randomly within stratified parameters based on stand age and canopy dominance. In total 53 plots of 400 m^2 in size were sampled across the four targeted stand types, including two *Solanum mauritianum* dominated stands (Table 3.3).

Circular plots of 400 m^2 (11.3 m radius) were used to sample canopy species of trees with stems ≥5 cm DBH. Sub-plots of 100 m^2 (5.65 m radius) were used to record regeneration data around the same mid-point as for the main plot. The following categories were sampled for regeneration (stems counts by species): i) Established tree and shrub seedlings = diameter <1 cm; ii) Saplings = diameter 1-5 cm. Structural variables such as upper and lower canopy cover were recorded using Braun-blanquet cover abundance values. Canopy height and slope where recorded using a hypsometer.

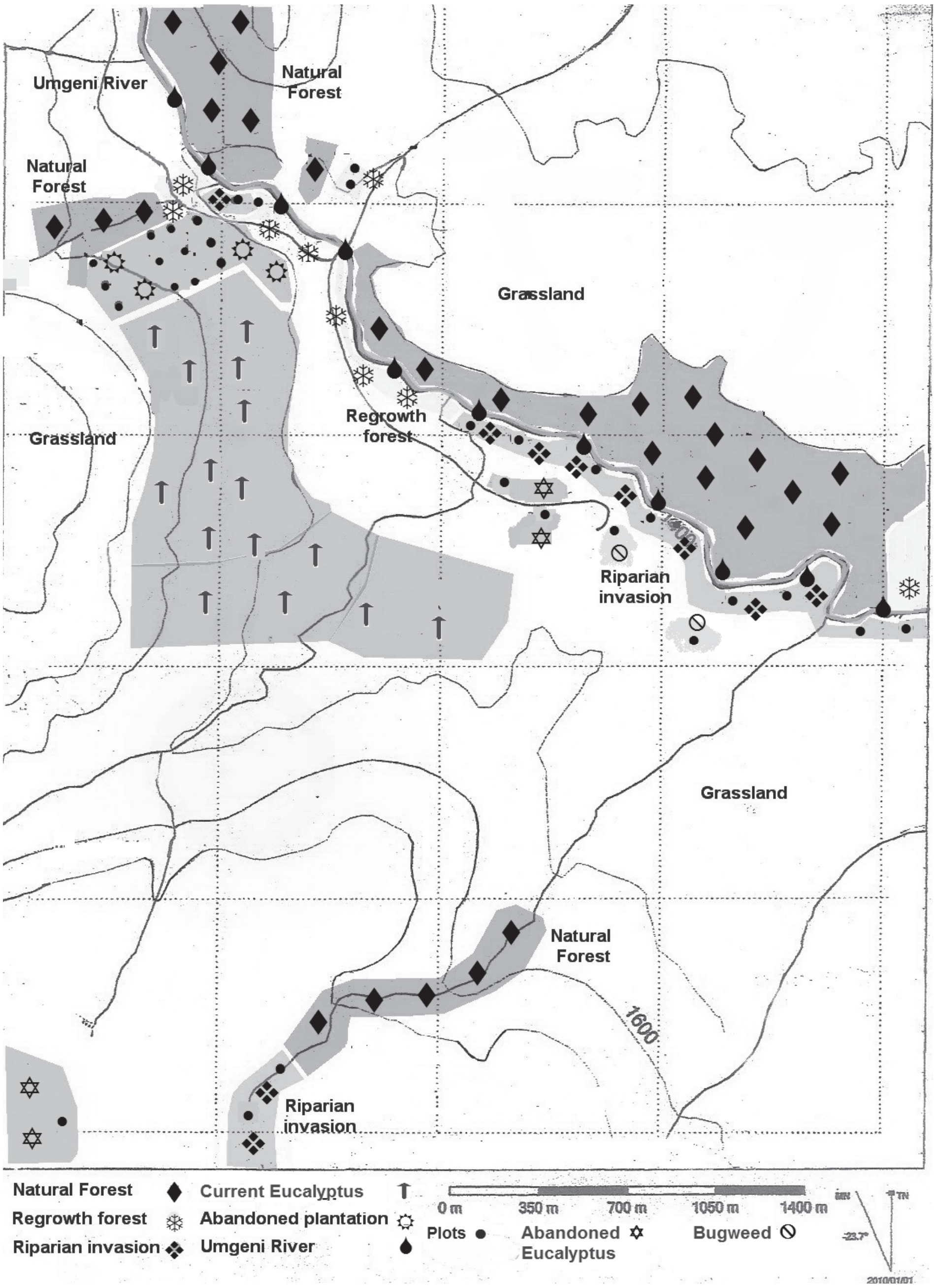


Figure 3.8 Map of sampling sites and forest stand types at New Forest.

Table 3.3 Sampling methodology of general forest stand-types

Forest Type	Description	Sample strategy	Total plots
Natural Forest	Undisturbed middle slope and valley bottom forest	Transects along centre contour in the forest were chosen and plots based at 60 m intervals were sampled.	15
Mixed regrowth forest	Older low canopy regrowth forest and developing forest ecotone areas or highly disturbed riparian sites. Common species *Leucosidea sericea* (native pioneer) and *Acacia mearnsii* (IAP).	Areas divided into strata on the basis of stand age and species dominance. Plots were then chosen using randomly generated coordinates.	10
Abandoned plantation	Mixtures of *Acacia mearnsii, Eucalyptus* spp. and/or *Pinus patula*	Transects within an abandoned forestry plantation located on a grid and separated by 60 m intervals.	12
Riparian invasion	*Acacia mearnsii* invasion on Umgeni river bank	Areas divided into strata on the basis of stand age and species dominance on the Umgeni river. Plots were then chosen using randomly generated coordinates.	10
Solanum mauritianum	*Solanum mauritianum* dominant stands in riparian forest areas	Areas divided into strata on the basis of stand age and species dominance. Plots were then chosen using randomly generated coordinates.	2
***Eucalyptus* spp.**	*Eucalyptus* hybrid dominant stands afforested in historical grassland areas	Areas divided into strata on the basis of stand age and species dominance. Plots were then chosen using randomly generated coordinates.	4

3.2.2.2 Data Analysis

Data capture

All data were captured in Microsoft Excel and converted into matrices containing data on species type and their quantity using the pivot table function. An approach adopted by Lawes et al. (2007) using Non-metric Multidimensional Scaling (NMDS) was used to differentiate between canopy and understory communities. This was conducted on the data using the Community Analysis Package (CAP) by Pisces software (Seaby and Henderson, 2007). NMDS produces an ordination of plots in *n*-dimensional space. Floristics were characterised by species composition and density, and communities were then defined by clustering similar plots in ordination space (Seaby and Henderson, 2007).

Variables defined in the study

(1) Regeneration was defined as **density** (no. of stems per seedling or saplings per plot converted into stems ha^{-1}) and **species richness** (no. of species per plot) (Powers et al., 1997).

(2) **Distance to seed source** was calculated as the most direct distance from the edge of mature or old regrowth forest to the centre point of the sampling plot using the 'measure line' tool in Quantum GIS 1.8.0.
(3) Tree canopy data was calculated as **density** (this is the amount of native or alien tree stems >5 cm DBH within 1 ha^{-1}) and **mean stem diameter** (this is the mean stem diameter of all trees in each plot).

Importance Values

Importance Values (IVs) of species in each community were calculated to determine the dominant species in each floristic community. It is a species ranking systems based on frequency, density and dominance of a certain tree species within a given community. Trees ≥15 cm DBH were referred to as canopy trees and deemed dominant if IV was >40 or otherwise indicated. Trees between 5-15 cm DBH were referred to as sub-canopy trees and considered dominant if IV was >20 or otherwise indicated. Regeneration communities were stems sampled ≤5 cm DBH and considered dominant if IVs were ≥20.

IVs in the canopy and sub-canopy at New Forest were calculated using the equation IV = (RF+RD+RBA)/3, though in the combined Eastern Mistbelt data set and in the regeneration communities IVs were calculated as (RF+RD)/2.
RF = Relative Frequency, i.e. the percentage of plots in a community in which the species was present
RD = Relative Density, i.e. stem density of a species in a community and expressed as a percentage of all stems of all species in a community
RBA = Relative basal area, i.e. basal area (horizontal surface area of a stem at 1.3 m above ground level) of a species in a community and expressed as a percentage of total basal area of all species in the community.

Indicator species

Indicator species were calculated in the regeneration communities with the goal to characterise a set of species which indicated a specific regeneration type. Indicator species (IndVal) were species that indicate information about the specific characteristics of habitats. A good indicator species is a species that is both abundant in a specific type of habitat (termed specificity) and predominately found in that type of habitat (termed fidelity). The equation for IndVal is: IndValij = Specificityij * Fidelityij * 100 (Dufrêne and Legendre, 1997), where specificity is the degree to which a species is found only in a given group of site and fidelity is the degree to which a species is an indicator to the conditions in a group of sites. IndVal analysis was calculated in the labdsv library in package (R Core Team, 2013).

Woody seedling and sapling data from sampling was converted into a species matrix with stem density values represented as stems per ha^{-1} for each plot and species richness as number of species per plot. Data collected in the field were entered into Microsoft Excel and matrices constructed using pivot tables. Species with a single occurrence within the data set (singletons) were removed and the data were square root transformed when species were widely distributed.

Ordination

Canonical Correspondence Analysis (CCA) was run in CANOCO (Lepš and Šmilauer, 2005) to test the hypothesis that distance from seed source had an effect on native species distribution pattern. CCA is a multivariate constrained ordination method used to clarify the relationship between biological assemblages of species and environmental variables. The result is a plot that shows the relationship between species samples and environmental variables which is a tool used to justify ecological interpretation of vegetation systems (Seaby and Henderson, 2007).

Regression analysis

Linear and non-linear regression analysis was conducted in GenStat (Street and Hempstead, 2011) to test the relationships between measured variables within the data.

3.2.3 Objectives and Methodology at Vasi Pan

The aim of the ecological component of the vegetation study at Vasi Pan was to ascertain development history of the forest area adjacent to Vasi Pan. This entailed three objectives:

1) Analyse historical and current aerial imagery of the area.
2) Investigate edge expansion or cluster effects of the development process of the forest
3) Determine the dominant pioneer tree species and development process of the regrowth forest at Vasi

Information from this component of the study provided insight into the key ecological processes which were studied in detail at Buffeljagsrivier and New Forest. The research looked to answer two basic ecological questions.

1) How have land-use practices influenced the development of forest on the site?
2) Was there evidence of cluster development and/or forest edge expansion within the forested area at Vasi?

3.2.3.1 Forest Sampling

From preliminary investigation and aerial photography analysis, it was noted that there were no historical mature forest areas, but two clearly distinct vegetation systems were present in the study site: Forest regrowth and woodland (i.e. bush encroached grassland). The sampling design is shown in Figure 3.9. The forest regrowth areas were sampled by laying out plots along perpendicular transects through the forest. Where possible transects were chosen to bisect older appearing portions of forest and their associated forest edge areas. Woodland areas were sampled by following a transect along the western border of the forest. It was thought that this approach would record different aged forest and woodland communities and provide data to differentiate forest establishment along a successional path from woodland to forest. Transects were set at either 200, 300 or 400 m apart depending on stratification and plots were located at distances of either 100, 150 or 200 m apart (depending on the width of the forest). The goal was to record at least four plots per transect. Plots within the interior of the forest were circular 400 m^2 plots, and forest edge plots were 40x10 m rectangular plots. Within the main plot the following was recorded: stem diameter of all stems ≥5 cm DBH by species, height of the canopy and slope. A subplot of 100 m^2 was measured and the understory was recorded. This included counting and naming all stems within the cohort of 1-3 cm DBH and 3-5 cm DBH. Notes on medicinal plant usage and condition of the canopy were also recorded.

3.2.3.2 Data Analysis

Ordination

All data were captured in Microsoft Excel and converted into matrices containing data on species and their number of stems using the pivot table function. An approach adopted by Lawes et al. (2007) using Non-metric Multidimensional Scaling (NMDS) was used to differentiate the canopy and understory communities. This was conducted on the data by using the Community Analysis Package (CAP) by Pisces software (Seaby and Henderson, 2007). NMDS produces an ordination of plots in *n*-dimensional space. Floristics were characterised by species composition and density, communities are then defined by clustering similar plots in ordination space (Seaby and Henderson, 2007)

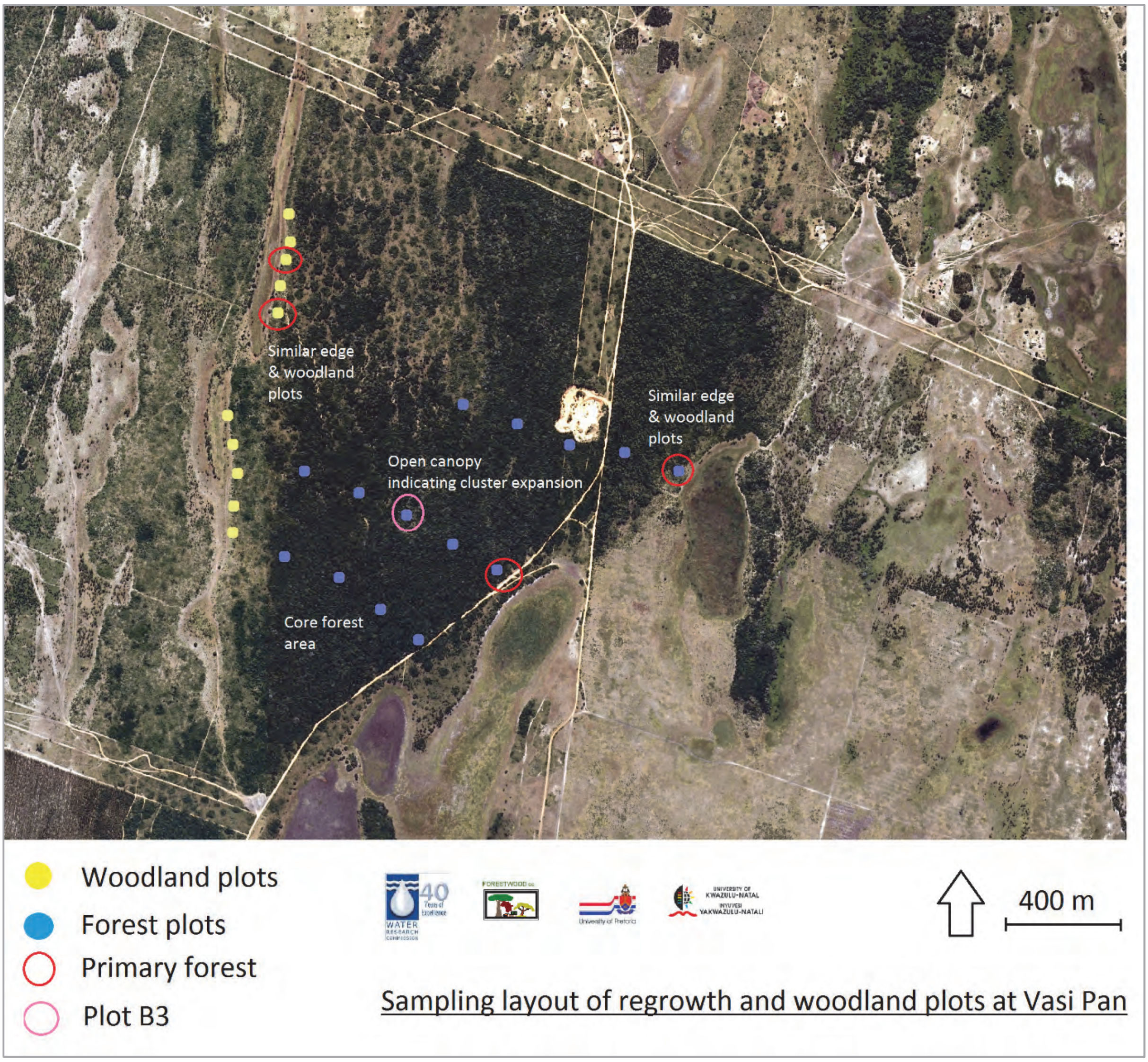


Figure 3.9 Sampling layout of regrowth and woodland plots at Vasi Pan

Importance Values

Importance Values (IVs) of species in each community were calculated to determine the dominant species in each floristic community. It is a species ranking systems based on frequency, density and dominance of a certain tree species within a given community. Trees ≥5 cm DBH are referred to as canopy trees and deemed dominant based on IV.

IVs in the canopy and sub-canopy were calculated using the equation IV = (RF+RD+RBA)/3.
RF = Relative Frequency, i.e. the percentage of plots in a community in which the species was present
RD = Relative Density, i.e. stem density of a species in a community and expressed as a percentage of all stems of all species in a community
RBA = Relative basal area, i.e. basal area (horizontal surface area of a stem at 1.3 m above ground level) of a species in a community and expressed as a percentage of total basal area of all species in the community

Historical aerial imagery from 1942, 1959, 1990 and 2009 was compared to determine the change in effects of land-use on vegetation cover of the site and broader areas around Vasi Pan.

3.3 Biomass Modelling

3.3.1 Objective of the study

To determine the allometric equations for *Celtis africana* (White stinkwood), *Rapanea melanophloeos* (L.) Mez (Cape Beech) and *Vepris lanceolata* (White ironwood) for estimating tree volume and biomass of indigenous forest at Buffeljagsrivier.

3.3.2 Biomass sampling procedure in the field

Thirty (30) canopy trees were sampled within forest clusters in the wattle area (10 trees each of *Celtis africana*, *Vepris lanceolata*, and *Rapanea melanophloeos*). They were the commonly occurring natural forest species that were dominant in the riparian zone and in forest clusters in the proximate, intermediate and distant wattle stands. Tree selection followed a stratified random sampling procedure, within the following stem diameter classes: 5-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm diameter at breast height (dbh). Trees on slopes with atypical form, deformed or dying trees were avoided. Total height, diameter at breast height, and crown width were measured and recorded for each tree. A climbing approach was used for non-destructive measuring stem and branch variables of standing trees, as described by Vann et al. (1998). Stem diameter was measured every two meters along the stem. Two stem core samples were collected per individual tree with a 5 mm Pressler type borer to get an estimate of the stem wood density. One core was taken at 1.30 m above ground level, and another one was collected by the tree climber at the crown base height. The diameter of each first order branch was measured at its insertion point at the stem. Only three branch samples were cut per tree to limit damage to the tree. These were selected, one at the bottom of the tree crown, one in the middle and one at the top of the tree crown. The sample branches were cut and packed in plastic bags. All samples (wood and foliage) taken in field were packed up in a box, and labelled and taken to the laboratory for further analysis.

3.3.3 Oven drying procedure of biomass samples in the laboratory

Branch samples were separated in the different components (wood, foliage and fruits) in the laboratory. Wood, foliage and fruits were placed into paper bags, for drying. The samples were placed into the oven at 60 °C until equilibrium weight was reached (Phiri, 2013).

3.3.4 Determination of core density from CT scanner

Wood density of the sampled trees was determined on the core samples from each tree, taken at breast height and at the crown base height, using a V|tome|x L-240 CT scanner (Computer tomograph) from General Electric.

Through image analysis, the average grey values (from the two core samples) were determined, and then the data from the average grey values were converted to the density. Based on a calibration function two plastic rods of known density were scanned with every batch of five core samples to account for individual fluctuations in the relation between grey value and density.

3.3.5 Data analysis

Data analysis was partly done with Microsoft Excel scatter plots to identify outliers, which were rechecked for mistakes in data handling and were excluded from further analysis if no conclusive rectification was found. The data from biomass of wood, leaves and branches of *Celtis africana, Vepris lanceolata* and *Rapanea melanophloeos* was ln transformed to cater for heteroscedastic variance with increasing biomass. The R statistical software was used to build biomass models with a transformed regression (R Core Team, 2013). The linear regression model Ln (BM) = a +b ln (DBH) was used: Biomass (BM) was the dependent variable, a was the intercept and b was the slope (both were estimated in the regression), and DBH was the independent variable. Allometric models were developed for all three natural tree species. The biomass estimation at sample level dealt with regression equations of tree components (leaves. branch wood, and stem wood).

3.4 Hydro-Meteorological Techniques

3.4.1 Meteorological Station

A meteorological station was established on the 25th of January 2012 at Buffeljagsrivier, on 19th of September 2012 at New Forest farm and on the 20th of November 2014 at Vasi Pan. All stations were erected in nearby grasslands (cf. Figure 4.3 and 3.10). A flat and uniform short grassland area was selected to meet the requirement for FAO 56 reference evaporation calculation. The measurements at these stations included air temperature, relative humidity, wind speed and direction, net radiation and rainfall. A modem was connected to the stations to allow for remote access to the data. The new modems used allowed for real-time data to be streamed to the internet and accessed by logging on to the Logger Net website. Figure 3.10 (c) shows the meteorological station with a tipping bucket rain gauge at 1.2 m from the ground surface, a wind anemometer and vane (wind sentry), a pyranometer and a radiation shield with a temperature and relative humidity sensor all at 2.0 m. A 10 W solar panel was installed to maintain the charge of the battery. The system was run using a Campbell Scientific CR200x datalogger. The stations at New Forest and Buffeljagsrivier are shown in Figure 3.10 (a) and (b) respectively.

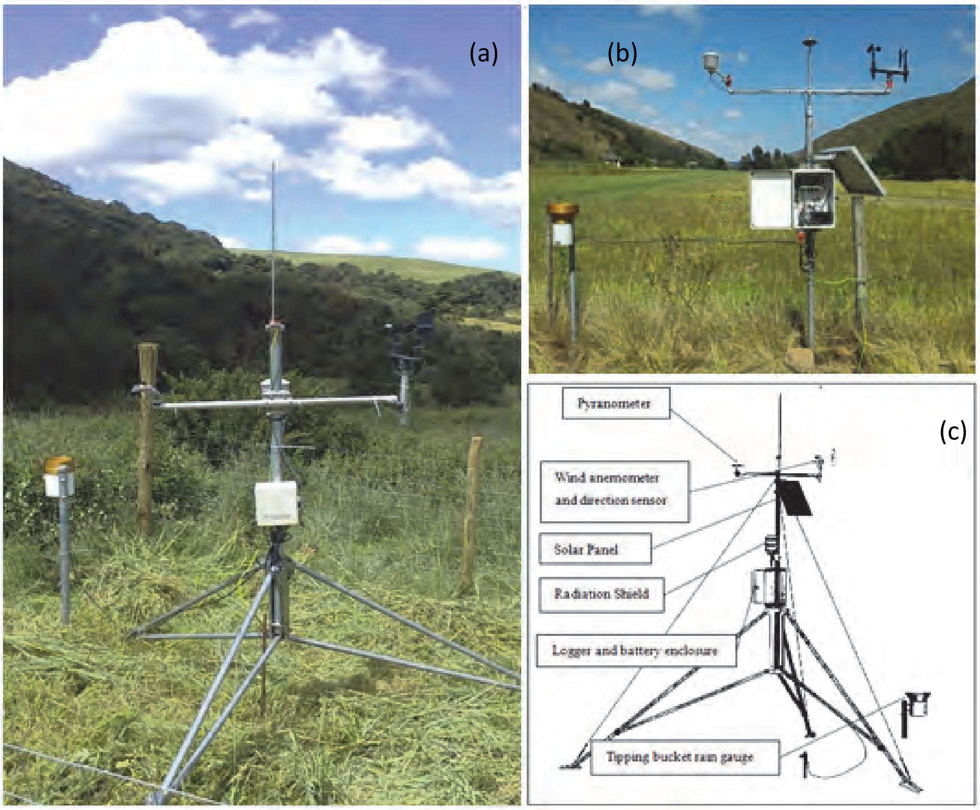


Figure 3.10 Campbell Automatic Weather Station mounted on CM10 tripod

3.4.2 Historical Rainfall

The SAWS rainfall station shapefile was projected on to the GIS layer of Buffeljagsrivier. Any rainfall station was considered if it was within a 15 km radius of the study site. Information on the five stations within this range has been provided in Table 3.4. The records were obtained using the daily rainfall extraction utility (Kunz, 2004). From this selection, stations were considered if they had at least 30 years of recorded rainfall (related to the reliability by the amount of patched data) and an altitude of between 80 m and 160 m. On observation of the data from stations closest to the site, it was evident that most of the records had been patched and that between 1920 and 1950 the records were questionable. Due to the inconsistency of the data, known periods of reliable data were used from various stations and were synthesized into a new corrected rainfall record. The most consistent rainfall record has been run by the Swellendam municipality. This data formed the majority of the synthesized record. The water bailiff at Buffeljags dam was contacted and has since provided rainfall and evaporation data.

Table 3.4 Details of the rainfall stations considered for the synthesis of a rainfall record at Buffeljagsrivier

Name	SAWS No.	Years	Reliable	Observed MAP (mm)	Altitude (m)	Distance from Study Site (km)
Swellendam (MUN)	0008782 W	114	94.2	719	160	13.4
Suurbrak (COL)	0009241 W	99	13.0	648	123	5.8
van Reenens Crest	0009365 W	121	54.5	545	326	16.1
Zuurbrak	0025270 W	119	23.6	750	143	7.1
Buffeljagsrivier (SKL)	0009031 P	121	18.4	571	81	7.4

A detailed historical rainfall analysis was done on the New Forest site. The SAWS rainfall station shapefile was projected on to the GIS layer of New Forest farm. Information on the seven stations within range of the site has been provided in Table 3.5. From this selection, stations were considered if they had at least 30 years of recorded rainfall (related to the reliability by the amount of patched data) and an altitude of between 1200 m and 1800 m. On observation of the data from stations closest to the site, it was evident that most of the records had been patched and that between 1900 and 1940 the records were questionable. Due to the inconsistency of the data, known periods of reliable data were used from various stations and were synthesized into a new corrected rainfall record. The data was used mostly from stations 0238636 W and 0239002 W as they had the most consistent records.

Table 3.5 Details of the rainfall stations considered for the synthesis of a rainfall record at New Forest farm

Name	SAWS No.	Years	Reliable	Observed MAP (mm)	Altitude (m)	Distance from Study Site (km)
Ivanhoe	0238662 A	107	16.5	850	1749	6.4
The Grange	0238543 A	106	37.0	775	1710	10.3
Impendle (POL)	0238636 W	112	58.5	947	1554	13.9
Blesbok Ridge	0268806 A	112	13.6	841	1464	9.1
Dargle (BOS)	0239002 W	106	39.0	900	1222	14.6
Fort Nottingham	0268715 W	94	8.1	978	1474	8.0
Aberdeen Angus Stud	0268683 A	91	5.2	942	1478	10.1

3.4.3 Tree water-use measurement techniques

3.4.3.1 Heat Ratio Method (HRM)

A Heat Pulse Velocity (HPV) system using the heat ratio algorithm (Burgess, 2001) was set up to monitor long-term sapflow at Buffeljagsrivier, New Forest farm and Vasi Pan. At Buffeljagsrivier, three *Acacia mearnsii* species representing three different size classes were selected for water-use measurements in the lower reach *A. mearnsii* dominated zone (termed the wattle site). In the same area three *Vepris lanceolata* species were also selected and monitored using a second AM 16/32 multiplexer connected to the CR1000 datalogger. In addition, in the upper reach indigenous forest (termed the indigenous site), two *Vepris lanceolata* species were selected to allow for replication of the species measured in the alien stand and to provide insight into water-use differences as a result of competition with the fast growing *A. mearnsii* trees compared with the natural indigenous forest situation. One *Rothmannia capensis* (Thunb.) tree was also selected as it was abundant in the indigenous stand. Two *Celtis africana* trees have been monitored since March 2013.

An assessment of the bark and sapwood depth was made on the selected tree species of a similar size using an increment borer. This assessment allowed for an estimation to be made on how deep the HPV probes should be inserted. These preliminary depths were to scope the activity in the tree sapwood. The heaters in each tree were inserted 4.2 cm into the tree to allow for possible changes. A CR1000 logger was installed at the wattle site with two AM 16/32 multiplexers. This allowed for hourly readings of sap flow in six trees (cf. Table 3.5 and Table 3.6 and Table 3.7). A second CR1000 logger was installed at the upper reach indigenous site with one multiplexer for continued hourly monitoring of the three selected trees (Figure 3.11). All the equipment was installed into security boxes specially manufactured for the batteries, loggers, multiplexers and an HPV relay control module to reduce the risk of theft. Further information on the background and the wiring of the HPV system has been provided in Appendices 1 and 2.

Figure 3.11 HPV system installation at the lower reach wattle stand for *V. lanceolata* trees 1, 2 and 3

Table 3.6 Species physiology, HPV probe and CS615 insertion depths at Buffeljagsrivier

Site	Tree No. and Species	Height (m)	Diameter (cm)	Circumference (cm)	HPV Probe Depths (cm)	CS 615 Depth (cm)
Wattle Site	1. *Vepris lanceolata*	14.6	17.4	54.5	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	Probe 1: 10 Probe 2: 30 Probe 3: 50
	2. *Vepris lanceolata*	12.6	16.6	52.1	Probe 1: 0.5 Probe 2: 0.9 Probe 3: 1.5 Probe 4: 2.0	
	3. *Vepris lanceolata*	11.3	20.2	63.3	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
	4. *Acacia mearnsii*	14.9	16.7	52.5	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
	5. *Acacia mearnsii*	15.1	19.4	61.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
	6. *Acacia mearnsii*	11.2	12.1	38.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
Indigenous Site	7. *Vepris lanceolata*	10.4	13.4	42.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	Probe 1: 10 Probe 2: 20 Probe 3: 30
	8. *Vepris lanceolata*	11.5	19.9	39.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
	9. *Rothmannia capensis*	9.4	12.5	62.4	Probe 1: 0.3 Probe 2: 0.8 Probe 3: 1.3 Probe 4: 1.8	
Celtis Site	*10. Celtis africana*	15.4	42.2	132.5	Probe 1: 0.5 Probe 2: 1.5 Probe 3: 2.0 Probe 4: 2.5	
	11. Celtis africana	10.1	31.9	100.3	Probe 1: 0.5 Probe 2: 1.5 Probe 3: 2.0 Probe 4: 2.5	

The New Forest site was selected as an intensive study site and water-use measurements of numerous trees were set up. A list of these trees and their details can be seen in Table 3.67. Tree anatomy and physiology measurements have been, and will continue to be (if the project is to continue for long term research), taken for all the trees in order to monitor their growth, conducting area and to assist in the installation process. The measurements on *Acacia mearnsii*, *Celtis Africana*, *Solanum mauritianum* and *Leucosidea sericea* (Eckl. & Zeyh.) were replicated to reduce the intra-specific sampling variability between trees and provide a range of tree diameters.

Due to equipment limitations on the small trunk size of *Solanum mauritanum*, dynamax collars were selected to measure this species. The diversity in the species measured at this site assisted in the improvement of modelling the riparian areas within this region. *Solanum mauritianum* has not been monitored for plant water-use in South Africa and this is important as it is a very common invader throughout the country as an understory tree, where it grows quickly and in very dense stands. This species can also be a canopy tree in some of the smaller forests.

The HPV systems that were installed on some of the other trees at New Forest farm are shown in Figures 3.12 to 3.15. Heaters were inserted into each tree and powered through a relay control module. CR1000 data loggers were installed at two of the sites, with two AM 16/32 multiplexers connected to each logger. This allowed for hourly readings of sapflow in 12 trees. A *Buddleja salviifolia* (Figure 3.16) was selected for measurement with the dynagage Dynamax collars.

Figure 3.12 HPV system installation of tree 1 (*Searsia pyroides*), 2 (*Maytenus peduncularis*) and 3 (*Leucosidea sericea*) at New Forest farm

Figure 3.13 System installation of tree 6 (*Kiggelaria africana*) at New Forest farm

Figure 3.14 HPV system installation of trees 8, 9 and 10 (*Acacia mearnsii*) at New Forest farm

Figure 3.15 HPV system installation of trees 10, 11 and 12 (*Eucalyptus grandis* and *Acacia mearnsii*) at New Forest farm

Figure 3.16 Selected species for Dynamax collars (*Buddleja salviifolia*)

Table 3.7 Species physiology, HPV probe and CS616 insertion depths at New Forest

Site	Tree No. and Species	Height (m)	Diameter (cm)	Circumference (cm)	HPV Probe Depths (cm)	CS 616 Depth (m)
1.	1. *Searsia pyroides*	4.1	9.8	30.8	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	Probe 1:0.1 Probe 2:0.3 Probe 3:0.5
	2. *Gymnosporia buxifolia*	5.8	11.4	35.8	Probe 1: 0.5 Probe 2: 0.9 Probe 3: 1.5 Probe 4: 2.0	
	3. *Gymnosporia buxifolia*	5.9	12.1	38.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
2.	4. *Celtis africana*	7.2	10.2	32.0	Probe 1: 0.5 Probe 2: 1.5 Probe 3: 2.5	
	5. *Kiggelaria africana*	5.1	5.0	15.7	Probe 1: 1.0 Probe 2: 2.0 Probe 3: 3.0	
	6. *Leucosidea sericea*	4.3	21.2	66.6	Probe 1: 0.5 Probe 2: 1.5 Probe 3: 2.5	
3.	7. *Acacia mearnsii*	9.4	13.1	41.2	Probe 1: 0.5 Probe 2: 1.5 Probe 3: 2.5 Probe 4: 3.5	Probe 1:0.1 Probe 2:0.2 Probe 3:0.5
	8. *Acacia mearnsii*	9.8	16.6	52.2	Probe 1: 1.0 Probe 2: 2.0 Probe 3: 3.0 Probe 4: 4.0	
	9. *Acacia mearnsii*	9.2	15.6	49.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	
4.	10. *Eucalyptus grandis*	12.4	16.5	51.8	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	
	11. *Eucalyptus grandis*	9.3	9.6	30.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
	12. *Acacia mearnsii*	6.6	10.5	33.0	Probe 1: 1.0 Probe 2: 2.0 Probe 3: 3.0 Probe 4 : 4.0	

The Vasi Pan site was selected to monitor long-term sapflow in both the indigenous and alien forest canopy trees. A list of these trees and their details can be seen in Table 3.78. Tree anatomy and physiology measurements were taken for all the trees in order to monitor their growth, conducting area and to assist in the installation process. The measurements on *Pinus patula*, *Eucalyptus grandis*, and *Shirakiopsis ellipticum* were replicated to reduce the intra-specific sampling variablity between trees and provide a range of tree diameters (size classes).

Due to the fact that *Phoenix reclinata* has scattered vascular bundles in the stem (monocotyledon), dynamax collars were selected to measure this species. The water-use of palm species have not been monitored before and these measurements are important as it is very common throughout the north coast of KZN, where it grows quickly and in fairly dense stands.

The HPV systems that were installed on some of the other trees at Vasi are shown in Figure 3.17 to 3.19. Heaters were inserted into each tree and powered through a relay control module. CR1000 data loggers were installed at two of the sites, with one AM 16/32 multiplexer connected to a logger. This allowed for hourly readings of sapflow in 9 trees.

Figure 3.17 HPV system installation of tree 1 (*Shirakiopsis ellipticum*), 2 (*Albizia adianthifolia*) and 3 (*Shirakiopsis ellipticum*) at Vasi North

Figure 3.18 System installation of trees 4, 5 and 6 (*Pinus patula*) at Vasi North

Figure 3.19 HPV system installation of trees 7, 8 and 9 (*Eucalyptus grandis*) at Vasi North

Table 3.8 Species physiology, HPV probe and CS616 insertion depths at Vasi Pan

Site	Tree No. and Species	Height (m)	Diameter (cm)	Circumference (cm)	HPV Probe Depths (cm)	CS 616 Depth (m)
1.	1. *Shirakiopsis ellipticum*	4.7	9.8	30.8	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8
	2. *Albizia adianthifolia*	5.1	11.4	35.8	Probe 1: 0.5 Probe 2: 0.9 Probe 3: 1.5 Probe 4: 2.0	
	3. *Shirakiopsis ellipticum*	4.6	12.1	38.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	
2.	4. *Pinus patula*	5.9	10.2	43.5	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 3: 2.5	
	5. *Pinus patula*	5.7	5.0	51.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 3: 2.5	
	6. *Pinus patula*	6.0	21.2	40.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 3: 2.5	
3.	7. *Eucalyptus grandis*	8.1	13.1	41.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8
	8. *Eucalyptus grandis*	8.2	16.6	52.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	
	9. *Eucalyptus grandis*	8.2	15.6	49.0	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	
4.	10. *Phoenix reclinata*	2.1	N/A	N/A	N/A	
	11. *Phoenix reclinata*	2.3	N/A	N/A	N/A	

3.4.3.2 Stem Steady State Heat Balance (SSS)

Two Dynamax Flow 32-K systems (Dynamax, Houston, TX, USA) were obtained for Buffeljagsrivier and New Forest. Each of these systems was powered by a 12V 100Ah battery, which was regulated by an amp (Figure 3.20b). Each system was composed of a CR1000 data logger and an AM16/32B multiplexer (Figure 3.20a). A voltage control unit regulated the voltage output depending on the number of collars and the size of the collars. The gauge's insulating sheath (referred to as a 'collar' in this report) contained a system of thermocouples that measured temperature gradients associated with conductive heat losses vertically (up and down the stem), and radially through the sheath (Allen and Grime, 1994). This enabled the mass flow rate of the water in the stem to be calculated.

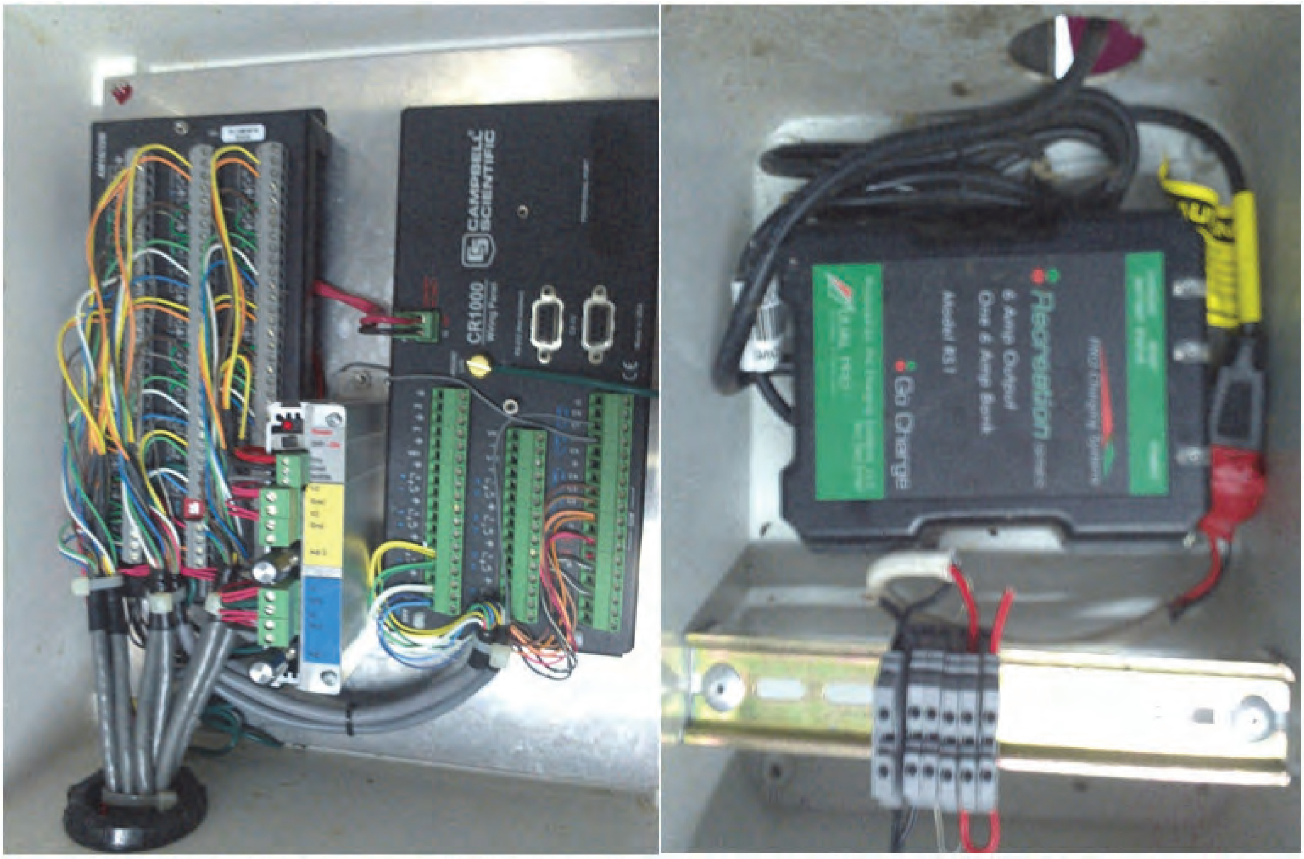


Figure 3.20 An overview of the wiring of the Dynamax system with a CR1000 data logger and AM16/32B multiplexer (a) as well as a recreation amp (b)

Two trial measurements were undertaken in a greenhouse on the UKZN Science and Agriculture campus. The water-use of *Leucosidea sericea* and *Buddleja salviifolia* were measured using Dynamax collars. This was done in order to check the equipment before it was installed at the site.

Figure 3.21 Dynamax system installation of *Solanum mauritianum* (a) and *Buddleja salviifolia* (b) at New Forest farm

An overview of the various species that had Dynamax systems installed is shown in Table 3.9. Figure 3.21a shows the five *Solanum mauritianum* stems and Figure 3.21b shows the one multi-stemmed *Buddleja salviifolia* installed with Dynamax collars. Two Dynamax Flow 32-K systems (Dynamax, Houston, TX, USA) were installed at Vasi Pan. New flexible collars were installed on palm fronds at the site.

The data output from the Dynamax systems was in g.hr^{-1} (using the specific heat of water). The conversion to L.day^{-1} is as follows:

1. Convert to latent heat flux: L_vF (W.m^{-2}) : $\frac{x \times 1000}{3600}$

2. Convert λET ($W.m^{-2}$) to ET ($mm.day^{-1}$) where λ = 2454000 $J.kg^{-1}$: $\frac{x}{245400} \times (60 \times 60)$
3. 1 $kg.m^{-2}$ of water is equal to 1 mm
4. Therefore sapflow is in $mm.hr^{-1}$ × area of the stem provides $L.hr^{-1}$
5. Summed for the day provides $L.day^{-1}$

Table 3.9 Species physiology and Dynamax collar installation at New Forest

<table>
<tr><th>Site</th><th>Tree No. and Species</th><th>Height (m)</th><th colspan="6">Diameter (mm)</th><th colspan="6">Circumference (mm)</th><th>Collar Size (mm)</th></tr>
<tr><td rowspan="8">5.</td><td>1. *Solanum mauritianum*</td><td>2.4</td><td colspan="6">25.0</td><td colspan="6">78.5</td><td>25</td></tr>
<tr><td>2. *Solanum mauritianum*</td><td>1.2</td><td colspan="6">10.0</td><td colspan="6">31.4</td><td>10</td></tr>
<tr><td>3. *Solanum mauritianum*</td><td>1.8</td><td colspan="6">17.0</td><td colspan="6">53.4</td><td>19</td></tr>
<tr><td>4. *Solanum mauritianum*</td><td>2.0</td><td colspan="6">19.1</td><td colspan="6">60.0</td><td>19</td></tr>
<tr><td>5. *Solanum mauritianum*</td><td>2.5</td><td colspan="6">26.7</td><td colspan="6">84.0</td><td>25</td></tr>
<tr><td>6. *Solanum mauritianum*</td><td>2.2</td><td colspan="6">25.0</td><td colspan="6">78.5</td><td>25</td></tr>
<tr><td>7. *Solanum mauritianum*</td><td>2.1</td><td colspan="6">22.6</td><td colspan="6">71.0</td><td>19</td></tr>
<tr><td>8. *Solanum mauritianum*</td><td>0.9</td><td colspan="6">10.0</td><td colspan="6">31.4</td><td>10</td></tr>
<tr><td rowspan="3">6.</td><td>9. *Buddleja salviifolia*</td><td>3.2</td><td>26</td><td>27</td><td>24</td><td>24</td><td>26</td><td>31</td><td>81</td><td>84</td><td>76</td><td>77</td><td>82</td><td>98</td><td>15-25</td></tr>
<tr><td>10. *Acacia mearnsii*</td><td>3.5</td><td colspan="6">25.6</td><td colspan="6">80.4</td><td>25</td></tr>
<tr><td>11. *Acacia mearnsii*</td><td>4.8</td><td colspan="6">23.9</td><td colspan="6">75.1</td><td>25</td></tr>
</table>

3.4.3.3 Data Patching

Data patching is an important component in data analysis, as it allows for the construction of a complete data set by means of extrapolation and interpolation and provides information on the nature of a relationship between two or more sets of data. When working with high frequency data such as hourly sap flow, it is common to have periods of no data or 'noisy' data. Poor data may be a result of, *inter alia*, broken equipment, animal and weather disturbance and power shortages. Data from the weather station (recorded at the same frequency) can be used to patch this data as the sap flow is directly related to the available energy and therefore atmospheric conditions. Unreliable data was identified when noisy periods (extreme spikes, negative values, NAN – not a number or constant zeros) were flagged in the output data files.

The reference evapotranspiration (ET_0), which is derived using the Penman-Monteith equation, provided the best correlation with hourly sap flow at Buffeljagsrivier and New Forest. An example of the relationship between sapflow and ET_0 for an *Acacia mearnsii* at Buffeljagsrivier has been provided in Figure 3.22a. If data from individual probes were missing, data from the next probe (within the same tree) were used to patch the missing data. However, if data from an entire tree were missing, the hourly ET_0 was used to patch the missing values. A relationship was derived using good quality observed data over a time period before and after the missing data. This was done in order to preserve the seasonal variability in water-use existing in most species (deciduous or evergreen). The same patching process was applied to data from New Forest farm.

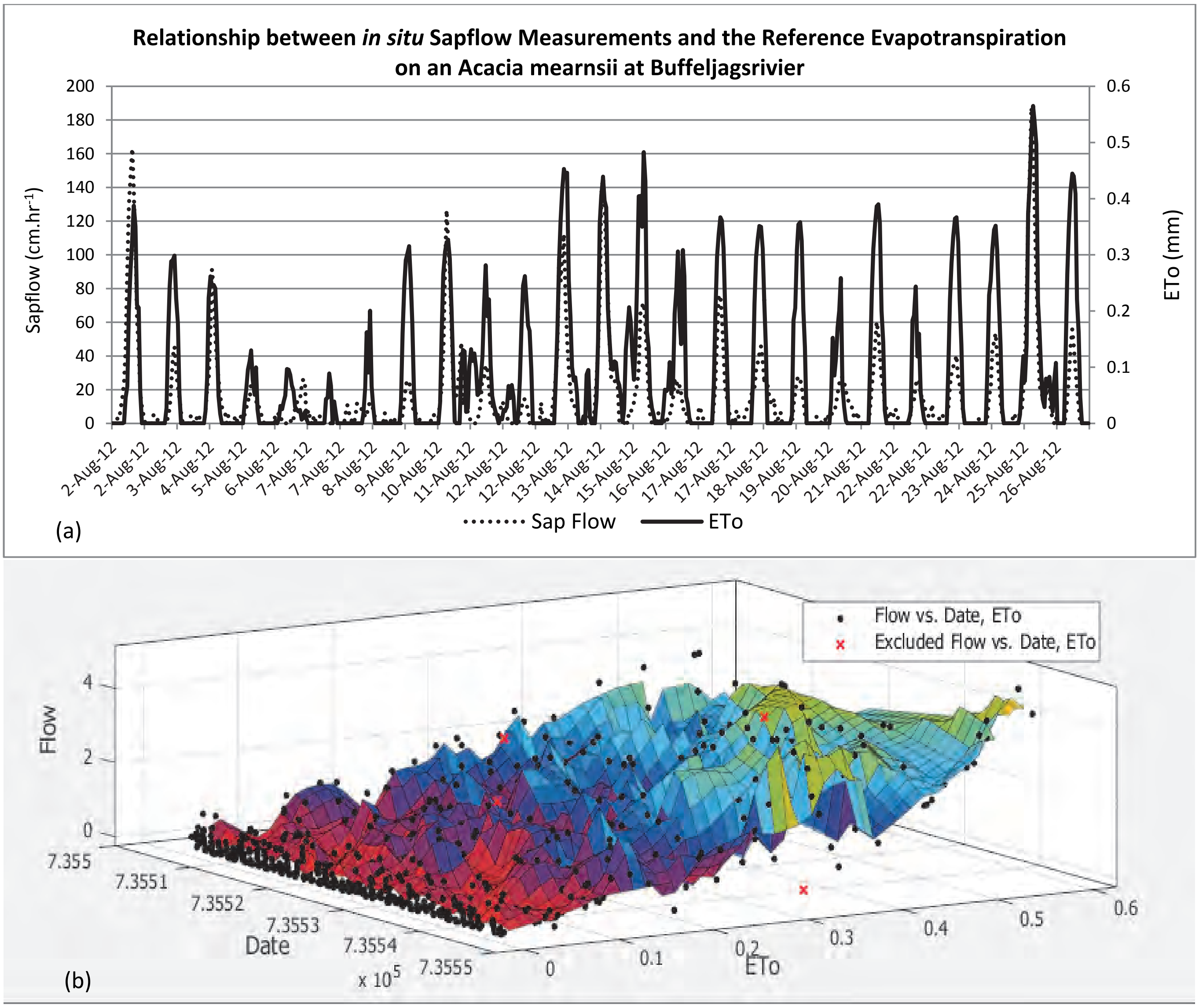


Figure 3.22 Time series analysis of sap flow and ET_0 data for a *Celtis africana* at Buffeljagsrivier (a) and interpolant analysis on the data (b)

The data were analysed for outliers that may negatively influence the relationship (Figure 3.22b). An interpolant mesh was placed on the data so that the outliers could be highlighted. In addition, this regression was viewed on an active 3D plane so that daily regressions could be observed. The sum of squares due to error (SSE), the R-squared (how successfully the fit explains the variation in the data), the residual degrees of freedom (DFE, number of response values minus the number of fitted coefficients estimated from the response values) and the root mean squared error (RMSE, standard deviation of the data's randomness) were considered in the model fit (Table 3.10).

Table 3.10 Comparison of curve fitting techniques used on the sapflow and reference evapotranspiration data at Buffeljagsrivier

Fit Type	SSE	R-squared	DFE	Adj R-squared	RMSE	Model *Coefficients with 95% confidence bounds
Gaussian	229	0.74	971	0.74	0.48	$f(x) = 3.119 \times e^{\left(\frac{x-0.5511^2}{0.3353}\right)}$
Custom	223	0.75	971	0.75	0.48	$f(x) = -566 \times e^{(-0.01008 \times x)} + 566.1$
Exponential	283	068	972	0.68	0.54	$f(x) = 0.3555 \times e^{(4.503 \times x)}$
Fourier	221.8	0.75	970.0	0.76	0.47	$f(x) = 2.407 - 2.272\cos(x \times 2.057) + 2.137\sin(x \times 2.057)$
Polynomial 1st	223.5	0.75	972.0	0.75	0.48	$f(x) = 5.704 \times x + 0.1119$
Polynomial 3rd	221.8	0.75	970.0	0.75	0.47	$f(x) = -4.228x^3 + 5.09x^2 + 4.371x + 0.1348$

From observation of the fitting techniques, it was determined that the 3rd order polynomial provided the best fit as it had a high R-squared value as well as a low SSE. A unique model was derived for each tree where patching was needed. Figure 3.23 and Figure 3.24 show the strong relationship between sap flow and total evaporation and the resultant patched data.

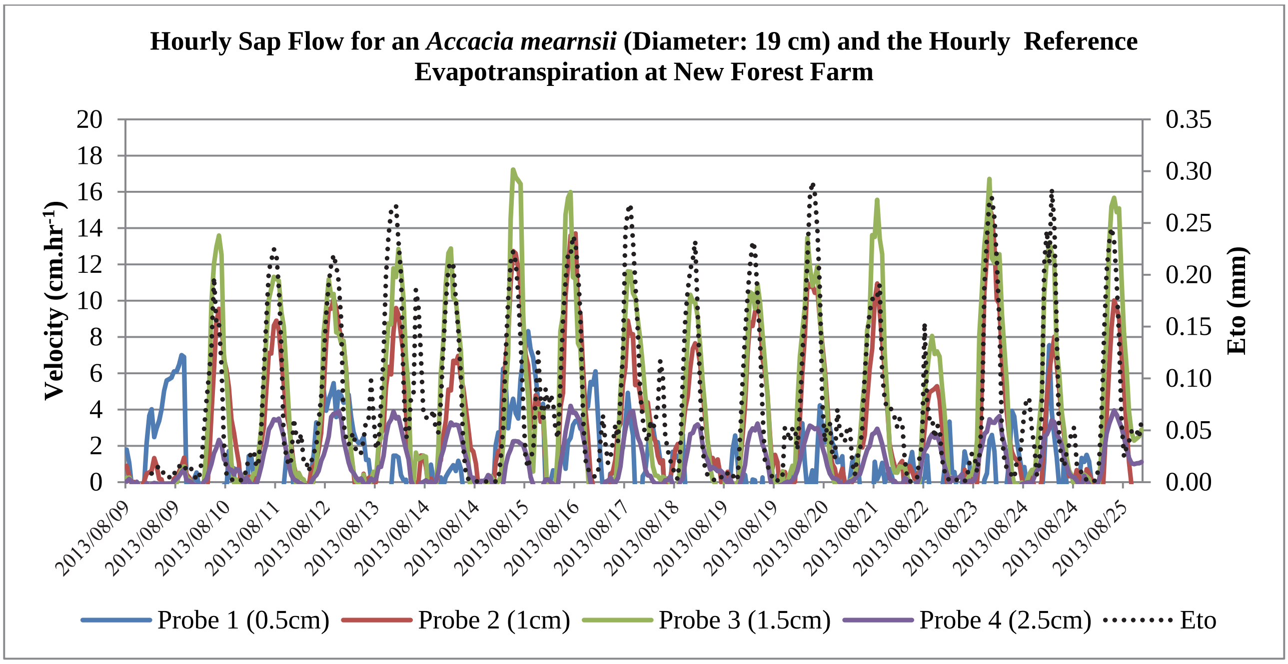


Figure 3.23 Comparison between heat pulse velocity and reference total evaporation at New Forest

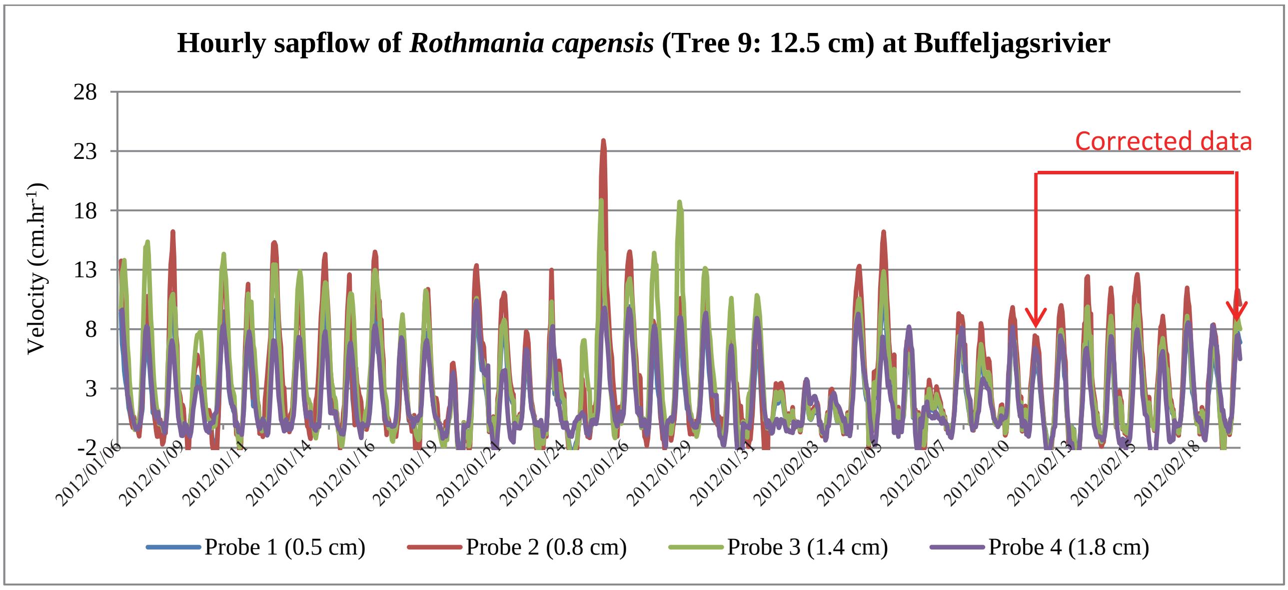


Figure 3.24 An example of some of the patched data used for Tree 9 at Buffeljagsrivier

3.4.3.4 Data Validation

A validation study was undertaken to test the accuracy of the Heat Ratio HPV method against other internationally used and accepted techniques. The Dynamax Stem Steady State technique, the Thermal Dissipation technique and the Heat Ratio technique were installed on the same tree. Two replications were done on similar sized trees. Two window periods of three days each were measured. Each tree had the following:

- 1 × 100 mm Dynamax Collar
- 2 × double thermocoupled Thermal Dissipation Probes
- 4 × modified HPV Heat Ratio pairs

The data validation study indicated that the three techniques recorded very similar values of sap flow. In addition, the diurnal trend was captured accurately by all the techniques. The TDP probe gave a slightly lower reading than the SSS and HPV readings. This may be due to the limitation of insertion depths as the probes have a set spacing between the thermocouples in each paired probe.

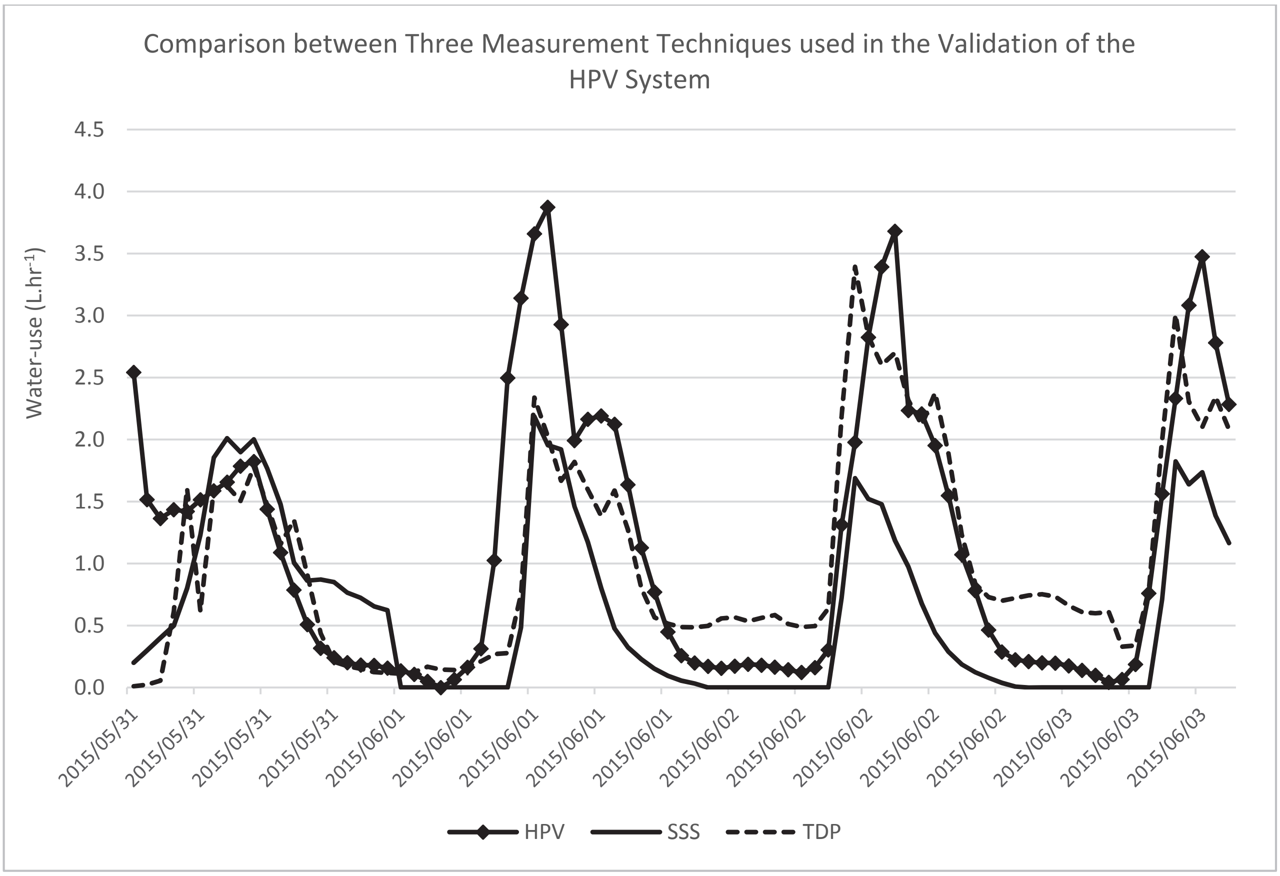


Figure 3.25 HRM, SSS and TDP validation results

3.4.4 Soil water profile measurements

Soil water content probes were installed at Buffeljagsrivier and New Forest. At each site pits were dug for the installation of soil water content probes for soil water profile measurements. In each profile three Campbell Sci. CS 615 probes were installed horizontally at various depths depending on the soil profile depth (cf. Table 3.6, Table 3.7 and Table 3.8). The CS 616 probes were connected to spare channels on the CR1000 datalogger. With high frequency volumetric water content measurements, the response of trees to rainfall events, or stressed conditions, were monitored and supported the interpretation of the HPV measurements. Figure 3.26 shows the soil pits dug at the New Forest KwaZulu-Natal site.

Figure 3.26 Soil profiles at site 1 (a) and 3 (b), with CS 616 probes installed at New Forest

Boreholes were installed at Buffeljagsrivier to monitor the water table depth in relation to the tree rooting depths (Figure 3.27). Solinst sensors (Per Levelogger Edge LT) were temporarily placed in each of the boreholes in order to measure sub-daily water table levels. After the installation of the first borehole in the lower wattle stand, the water table depth was measured at 6.7 m. However, this level changed rapidly once the water had settled. Water quality measurements were taken from borehole samples during each site visit. In addition, measurements were taken in the river along the upper indigenous and the lower wattle stand. The aim of these measurements were to identify any significant differences in water quality indicators between the two stands.

A YSI water quality sensor was used to measure the following variables:

- Temperature
- pH
- Salinity
- Atmospheric pressure
- Dissolved oxygen
- Conductivity/specific conductivity
- Total Dissolved Solids (TDS)

Figure 3.27 Borehole piping for installation at Buffeljagsrivier

Soil water content probes were installed at Vasi Pan. At each site pits were dug for the installation of soil water content probes for soil water profile measurements. In each profile three Campbell Sci. CS 615 probes were installed horizontally at various depths depending on the soil profile depth (Table 3.8).

The soil at both sites consisted of a deep uniform sandy profile (>10 m). A unique peat swamp was present in the nearby Vasi Pan. The water table depth was approximately 0.15 m in the pan during the site visit. The litter layer was observed to be highly variable throughout the fringe area, due to patches of dense alien clusters in the indigenous stand. Remnants of old pine trees were seen throughout this area. The CS 616 probes were connected to spare channels on the CR1000 datalogger. With high frequency volumetric water content measurements, the response of trees to rainfall events, or stressed conditions, was monitored and supported the interpretation of the HPV measurements. Figure 3.28 shows the soil pits dug at the Vasi sites.

Figure 3.28 Soil profiles at site 1 and 2, with CS 616 probes installed at the Vasi Pan site

3.4.5 Up-scaling tree water-use measurements

The Buffeljagsrivier site was ideal for up-scaling tree-level transpiration measurements to stand and catchment level transpiration as detailed vegetation surveys had been completed which assisted in the up-scaling process. Different up-scaling techniques were undertaken in this study to:

1. validate results;
2. investigate the most appropriate up-scaling techniques; and
3. assist in the modelling component of this study, where the model inputs for highly sensitive riparian areas could be incorporated.

The methodology that was developed was based on recent up-scaling studies and applicability to the sites monitored in this study (Ford et al., 2007; Miller et al., 2007):

- Medoid (representative of the population) trees were selected for sap flow measurement
  - most commonly occurring indigenous species (canopy and understorey)
  - most commonly occurring alien species (three species have been selected)
  - a range of size classes for each species
- A species density analysis was undertaken (species and diameter (>50 mm) in multiple 400 m^2 plots). This was linked to the vegetation survey.
- Heat pulse velocity was measured at various depths in each tree to represent the entire conducting sapwood.
- Velocity was then converted to whole tree water-use (Q_{tree}) using various tree/wood properties (explained in Section 4.5).
- A relationship was derived between Q_{tree} and each representative size class and species class identified in the density measurements. This allowed for the estimation of the stand water flux (Q_{stand}).
- The Q_{stand} was divided by the plot area (400 m^2) so that the values could be compared to Eddy covariance measurements (where available) and the remotely sensed data.

An intensive stand height measurement survey was done at Buffeljagsrivier, in collaboration with the vegetation survey. These results assisted in the extrapolation of insertion depth measurements to single-tree water-use measurements. Tree crown size estimates were used to estimate the stand transpiration. In addition, knowledge of the anatomy and physiology of the tree was used to explain variations in the transpiration measurements. At both sites, a statistical analysis (paired T-Test) was undertaken on the density plots (400 m^2) and remotely sensed images of daily evaporation and LAI (developed in the SEBS model) to further validate measurements.

3.4.5.1 Sapwood depth

At the start of this study, tree diameters at breast height (Table 3.6) were measured at each site for all the selected tree species using a pair of callipers and a tape measure. Subsequently, dendrometers were installed on the selected trees (Figure 3.29). The dendrometers consist of a collar of stainless sheet metal wrapped around the tree fed through a ‘tool’ of metal which allows the collar to move freely. Springs were installed on the collar in order to place tension on the collar. After installation a notch was made on the collar with the starting diameter and date. As the tree grows the collar feeds through the tool and the springs expand. The growth was simply measured from the starting notch.

Figure 3.29 Dendrometer collar installed on an *Acacia mearnsii* at New Forest farm

Core samples were taken from nearby trees of the same species for sap wood depth information. Figure 3.30 indicates the distinct difference between the heartwood and sap wood depths for an *Acacia mearnsii* (a), a *Celtis Africana* (b) and a *Leucosidea sericea* (c) tree, and the lack of differentiation between these two regions in the *Celtis* and *Leucosidea* sample. It is clear from the samples that there was little to no differentiation between the sapwood and the heartwood in the indigenous tree samples. A more detailed microscopic analysis was therefore carried out to determine the exact depth of the sapwood. Microscopic analysis was done on *Acacia mearnsii* and *Solanum mauritianum*. An interesting finding from sampling over 30 different wattles trees at the sites was that the ratio of sapwood to heartwood was not consistent between different sizes/ages. Younger or smaller trees had greater sapwood depths in proportion to the heartwood than older or larger trees. Allometric relationships between the sapwood: heartwood ratio versus tree diameter were investigated for up-scaling from individual to whole canopy tree water-use. Numerous tree heights were also measured with a Haglöf vertex laser VL 402 hypsometer.

Figure 3.30 Core samples from an *Acacia mearnsii* tree (a), a *Celtis africana* (b) and a *Leucosidea sericea* (c)

3.4.5.2 Wood density and moisture content measurements

Wood density measurements of the sapwood are important in determining the nature of the wood. Wood density and moisture measurements were used in the calculation of sap flux density for each probe which was then summed to calculate the daily water-use in L.day^{-1}. The density was calculated based on the oven-dry mass and the green volume, which was determined by its water displacement (Malan, 2005).

Multiple samples from each tree were extracted and the wet mass measurement taken. Some of the samples were then oven dried and used to calculate the under bark moisture content. The other samples were then immersed in water for 30 minutes. These samples were used to measure the weight of the displaced water in a water filled container. A needle was then used to obtain this measurement without touching the sides of the container. The measured weight of the displaced water is equal to the volume of the wet sample. These samples were then oven dried to constant mass at 105 °C for 24 hours and the measurements were used to calculate the basic wood density.

3.4.5.3 Tree crown measurements

Estimations of the tree crown area or canopy area are important when up-scaling the single tree water-use to an aerial value, assuming little to no understorey transpiration. Crown area can be highly useful when comparing water interactions between indigenous and alien species. A tree with a large canopy may use more water than a smaller canopy tree, but the smaller canopy tree may use more water per unit area.

The outline of the canopy was marked at ground level, using a hypsometer at 90º from the ground. An irregular shaped canopy required more measurement points. An average of the diameters was calculated if the canopy was symmetrical. Overlapping canopies were considered in the measurement of the canopy area. For asymmetrical canopies, a rope was used to outline the canopy and calculate the circular circumference. Measurements of the canopy depth and structure were not needed, as the actual transpiration could be directly compared to the area shaded by the canopy. Monthly Leaf Area Index (LAI) measurements were related to the canopy structure, as well as the tree transpiration. The Li-COR 2000 plant canopy analyser was used to calculate the monthly LAI over the measurement period. This was undertaken at set points under each canopy area on a monthly interval.

3.4.5.4 Remote Sensing

Remote sensing data were obtained for the Buffeljagsrivier and New Forest sites. These data were analysed using the SEBS model (WRC K) and were used in the validation of the stand evapotranspiration. The data from New Forest (Figure 3.31) has been provided here as an example. This shows an ET of approximately 3 mm on the 17/05/2013 and 4 mm on the 14/03/2013 over the alien stand.

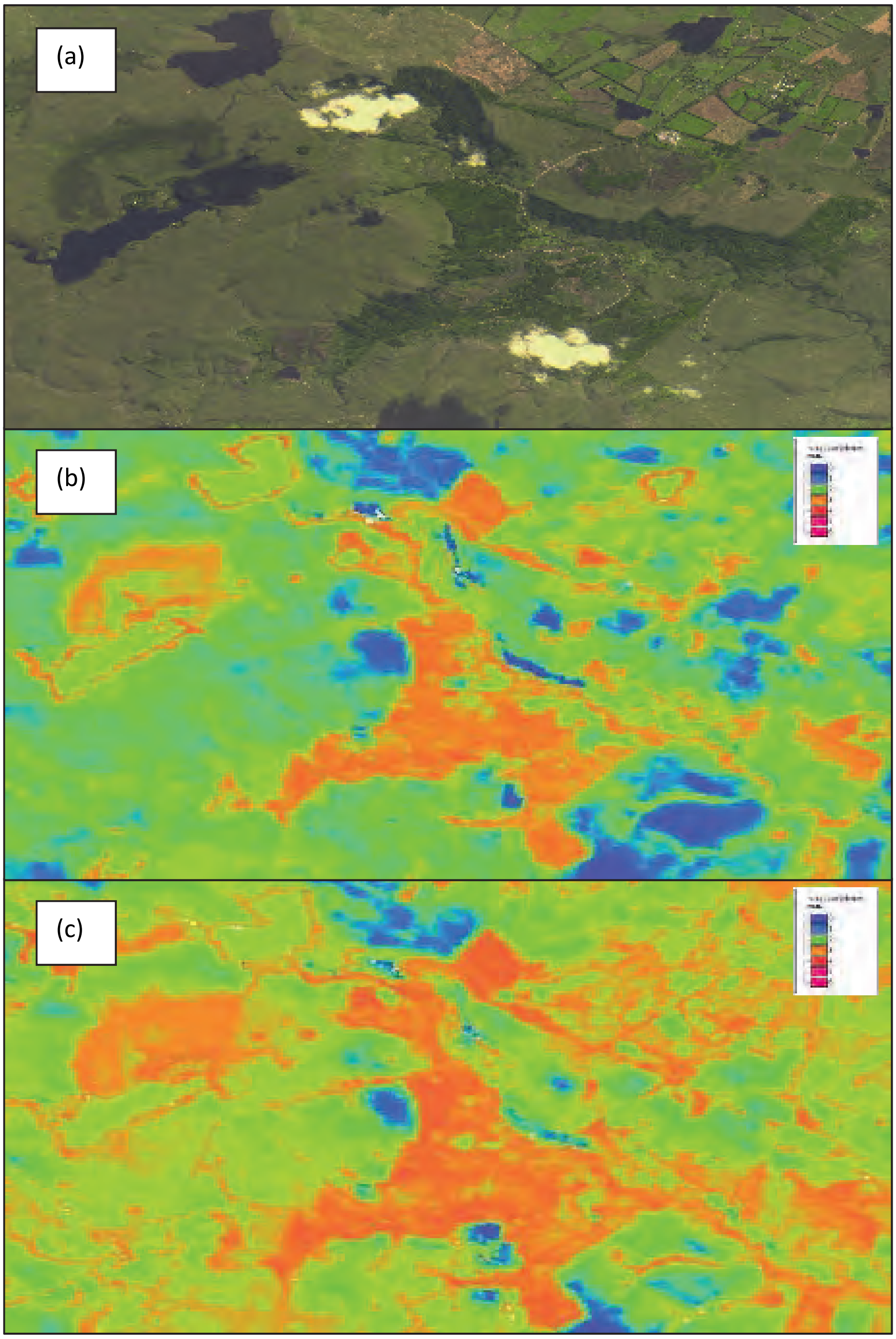


Figure 3.31 Remote sensing data at New Forest farm (a) with evapotranspiration data for the 17th May (b) and the 14th March 2013 (c)

3.5 Modelling Framework

Three scenarios were tested for this study. These scenarios, which are specifically related to the riparian forest areas, are as follows:

- Baseline Scenario (Current state)
- Pristine Forest Scenario
- Invaded Forest Scenario (Degraded)

As no surface water was present for the Vasi Pan site, a groundwater modelling approach was adopted. This modelling component focused mostly on Buffeljagsrivier and New Forest given the longer periods of observed data.

3.5.1 ACRU Agro-hydrological Model Input

The input values for the *ACRU* model form the basis for this agro-hydrological modelling approach, as the output from the model can only be as accurate as the input data used in the model. Table 3.11 and Figure 3.32 and Figure 3.33 outline the important input variables for this modelling approach. The sub-sections that follow further describe the input data that were used with the *ACRU* model for simulations at Buffeljagsrivier and New Forest in order to construct a water balance of the catchment.

Table 3.11 Definitions of key *ACRU* model variables relative to this study (Smithers and Schulze, 2004)

Variable	Definition	Unit
CAY	Average monthly crop coefficients, K_{cm}, for the pervious land cover of a catchment/sub-catchment. It represents the proportion of water "consumed" by a plant under conditions of maximum evaporation in relation to that evaporated by an A-pan in a given period.	Dimensionless
VEGINT	Maximum canopy interception losses on a rainday, dependent on above-ground biomass.	mm.rainday^{-1}
ROOTA	The fraction of active roots in the critical topsoil horizon.	Dimensionless
COIAM	Monthly coefficient of initial abstraction and an index of infiltrability, used to estimate the rainfall abstracted by interception, surface storage and infiltration before stormflow commences.	Dimensionless
PCSUCO	Percentage surface cover, i.e. the degree to which the soil surface is typically covered by litter and which influences the soil water evaporation from the topsoil and the magnitude of sediments lost.	%
COVER	Experimentally derived above-ground biomass factor which influences sediment yield.	Dimensionless
COLON	Percentage of roots which colonize the subsoil horizon, and hence affect root water extraction from that horizon.	%
PANCOR	Switch to invoke the application of evaporation correction factors	Switch (yes or no)
CORPAN	Monthly adjustment factors applied to evaporation pan data to correct for pan screening and other systematic errors	Dimensionless
DEPAHO	Thickness of the topsoil of the soil profile	m
DEPBHO	Thickness of the subsoil of the soil profile	m

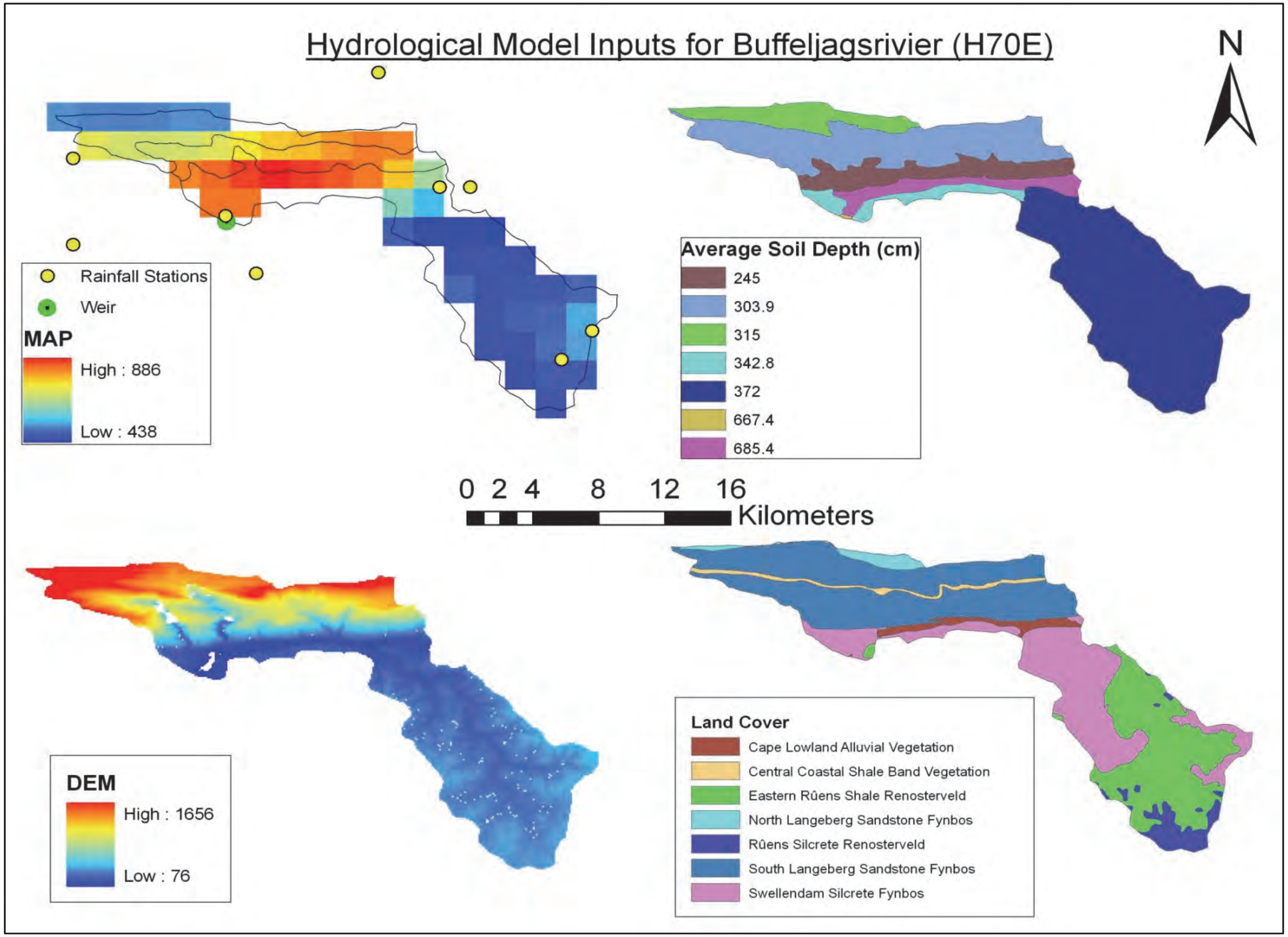


Figure 3.32 Hydrological model inputs for Quaternary Catchment H70E

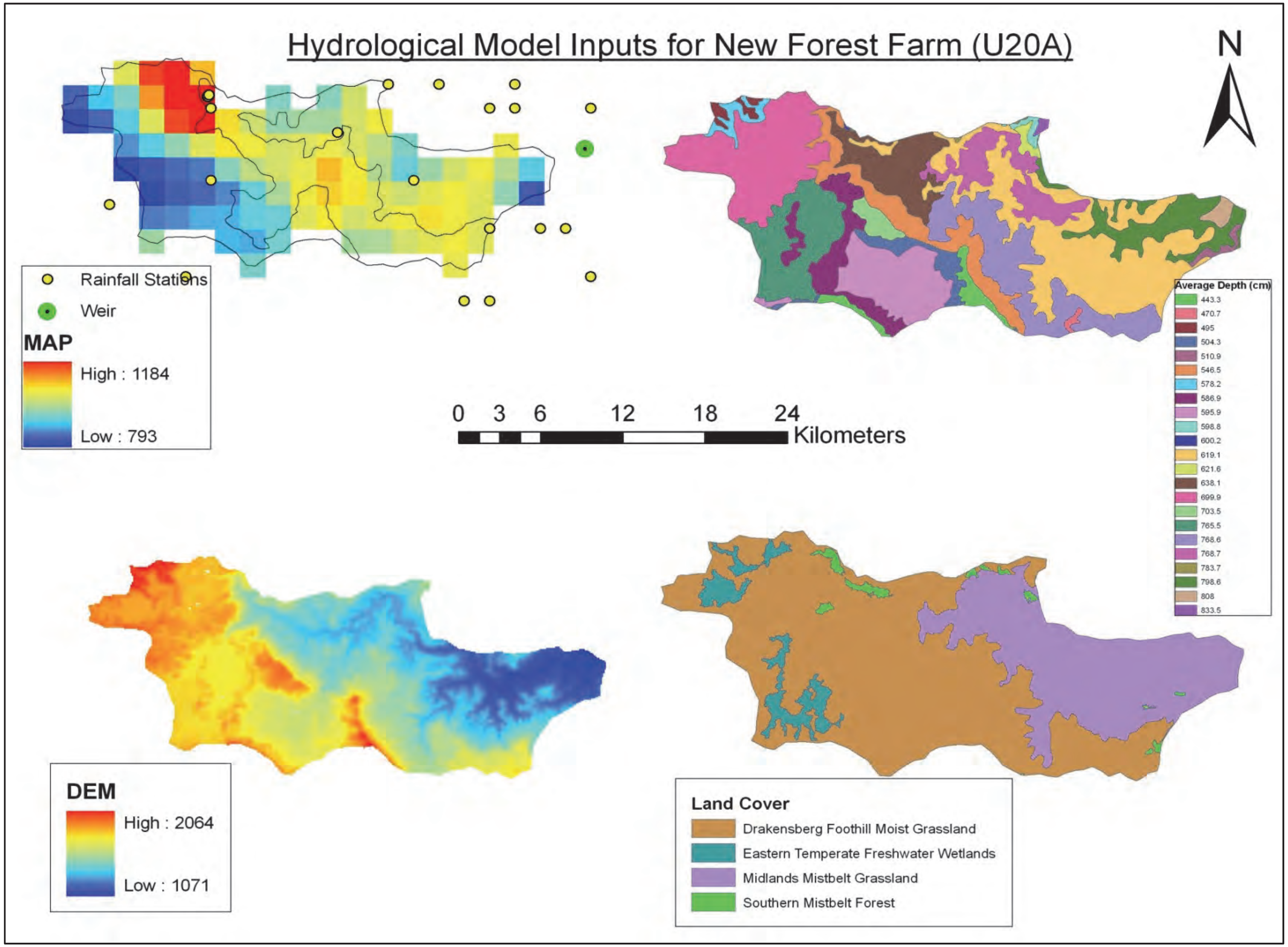


Figure 3.33 Hydrological model inputs for Quaternary Catchment U20A

3.5.2 Climate data

Rainfall is a fundamental driving force and pulsed input behind most hydrological processes (Schulze et al., 2004). Agro-hydrological models therefore require an accurate estimate of rainfall in order to mimic the different components of the hydrological cycle with a greater accuracy. Rainfall records should exclude any bias resulting from short record lengths, and a minimum of 30 years' record should be used, with the record length also considering the climate variability of an area, where arid regions will require a longer record length than wetter areas (Schulze et al., 2004). The rainfall stations at Buffeljagsrivier had good quality rainfall records due to their importance for the Buffeljags dam. However, New Forest had a segregated rainfall record which was patched by nearby reliable stations.

- A search was undertaken to identify nearby rainfall stations with long rainfall records of good quality. This was achieved by using a Geographical Information System (GIS).
- A station close to the study sites was only considered if it had a similar altitude, similar MAP, as well as a high reliability of data.
- The data were then collected from such stations using the Rainfall Extraction Utility developed by Kunz (2004).
- The daily evaporation and temperature data were obtained from the BEEH's Quinary Catchment Database (Schulze et al., 2010).
- The reference potential evaporation used was the Penman-Monteith (PM) equivalent crop evaporation, which needs a correction factor as the PM under-estimates reference potential evaporation compared to the A-pan, to which crop coefficients were linked (Schulze, 1995).
- CORPAN, which is the switch to specify if an adjustment of evaporation values is to be used, was turned on and the PANCOR (correction factor value) from PM to A-pan equivalent was determined from FAO 56 (Allen et al., 2000), with values shown in Table 3.12.

Table 3.12 Monthly adjustment factors applied to Penman-Monteith evaporation values to obtain equivalents of A-pan data (CORPAN) at New Forest

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.24	1.23	1.23	1.23	1.24	1.24	1.24	1.25	1.27	1.26	1.26	1.25

3.5.3 Baseline land cover

Land cover may be defined as groups of major vegetation types, and for the purpose of this study, groups containing certain hydrological attributes (Schulze and Horan, 2007). Acocks' Veld Types (1988) was chosen as the baseline land cover for this study because Acocks' classification is based on dominant indicator species at a local, regional and national scale, making it easily manageable for modelling, and being based on the allocation of natural vegetation types from human induced influences (Schulze, 2004). The Acocks' Veld Types have become the *de facto* baseline land cover for hydrological impact studies over South Africa (Gush et al., 2002; Schulze, 2004). EVTR was set to 2 (i.e. soil water evaporation and plant transpiration were calculated separately), which facilitated the percentage surface cover (PCSUCO) to be included in the calculation. The values of PCSUCO were deduced from site observations.

3.5.4 Current land-use

The current land-use features were identified for both sites (examples provided for New Forest farm). Groups of soils and vegetation were selected to form a hydrological response Unit (HRU) for each class within the sub-catchment. The area of each HRU was calculated for the *ACRU* model input (Figure 3.34). These HRUs were then conceptually routed in the model depending on their layout within the sub-catchment (Figure 3.35). Each of these HRUs was defined in the model by their hydrological attributes/variables which were input into the model (Table 3.13).

Table 3.13 Monthly hydrological attributes of vegetation inputs for the *ACRU* model

Description	Cropno	Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
FOREST PLANTATIONS EUCALYPTUS	5081203	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
FOREST PLANTATIONS EUCALYPTUS	5081203	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
FOREST PLANTATIONS EUCALYPTUS	5081203	CONST	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
FOREST PLANTATIONS EUCALYPTUS	5081203	COVER	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
FOREST PLANTATIONS EUCALYPTUS	5081203	ROOTA	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
FOREST PLANTATIONS EUCALYPTUS	5081203	VEGINT	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
FOREST PLANTATIONS PINE	5082203	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
FOREST PLANTATIONS PINE	5082203	COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
FOREST PLANTATIONS PINE	5082203	CONST	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
FOREST PLANTATIONS PINE	5082203	COVER	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
FOREST PLANTATIONS PINE	5082203	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
FOREST PLANTATIONS PINE	5082203	VEGINT	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
FOREST PLANTATIONS WATTLE	5083203	CAY	0.9	0.9	0.9	0.88	0.85	0.86	0.89	0.9	0.92	0.92	0.9	0.9
FOREST PLANTATIONS WATTLE	5083203	COIAM	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.25
FOREST PLANTATIONS WATTLE	5083203	CONST	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
FOREST PLANTATIONS WATTLE	5083203	COVER	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
FOREST PLANTATIONS WATTLE	5083203	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
FOREST PLANTATIONS WATTLE	5083203	VEGINT	2	2	2	2	1.9	1.85	1.85	1.85	1.9	1.95	2	2
INDIGENOUS RIPARIAN FOREST	2080101	CAY	0.9	0.9	0.9	0.85	0.8	0.75	0.75	0.8	0.85	0.9	0.9	0.9
INDIGENOUS RIPARIAN FOREST	2080101	COIAM	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.25
INDIGENOUS RIPARIAN FOREST	2080101	CONST	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
INDIGENOUS RIPARIAN FOREST	2080101	COVER	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
INDIGENOUS RIPARIAN FOREST	2080101	ROOTA	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
INDIGENOUS RIPARIAN FOREST	2080101	VEGINT	3	3	3	2.5	2.5	2	2	2.5	2.5	3	3	3

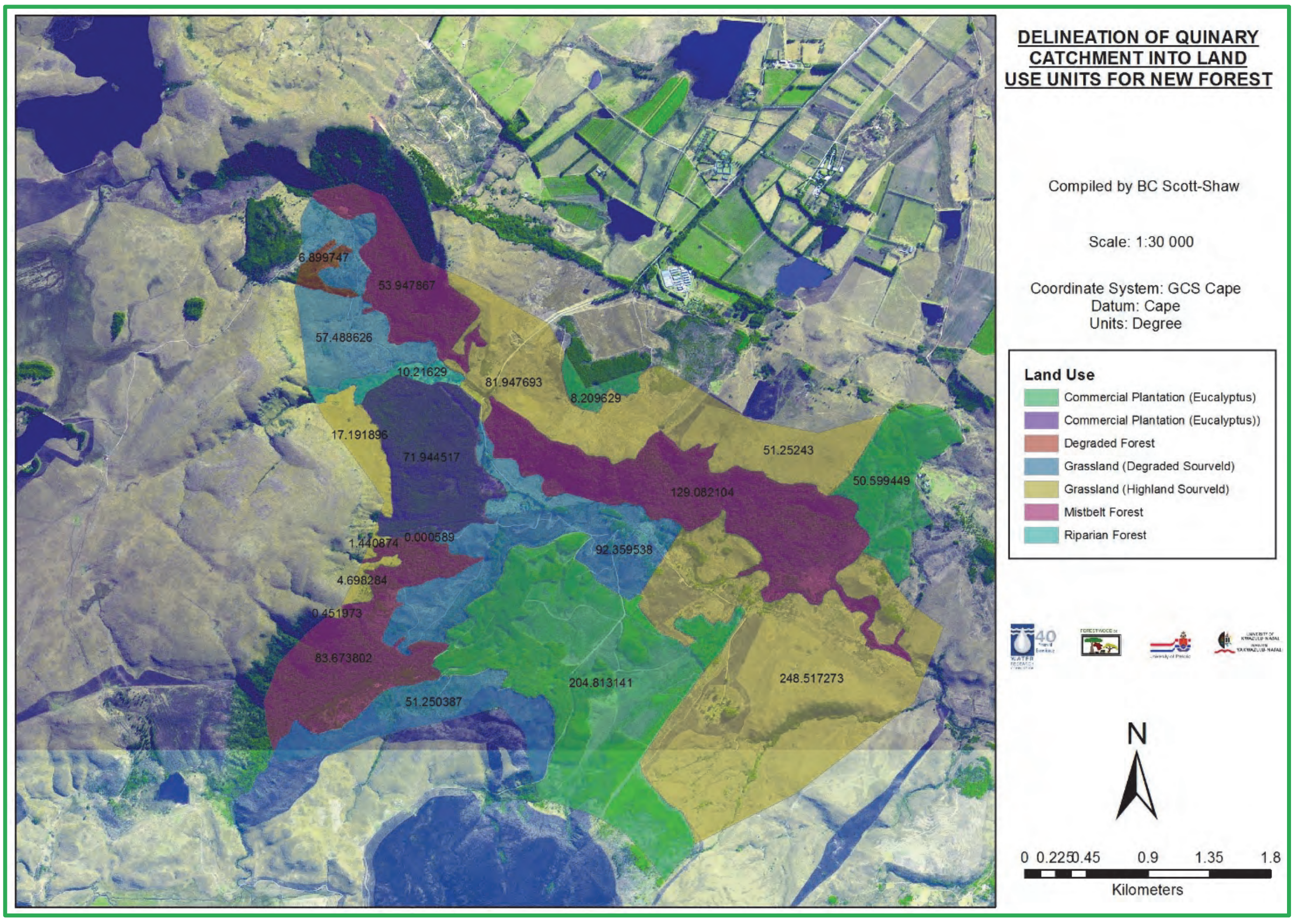


Figure 3.34 An example of the vegetation HRUs identified around New Forest farm

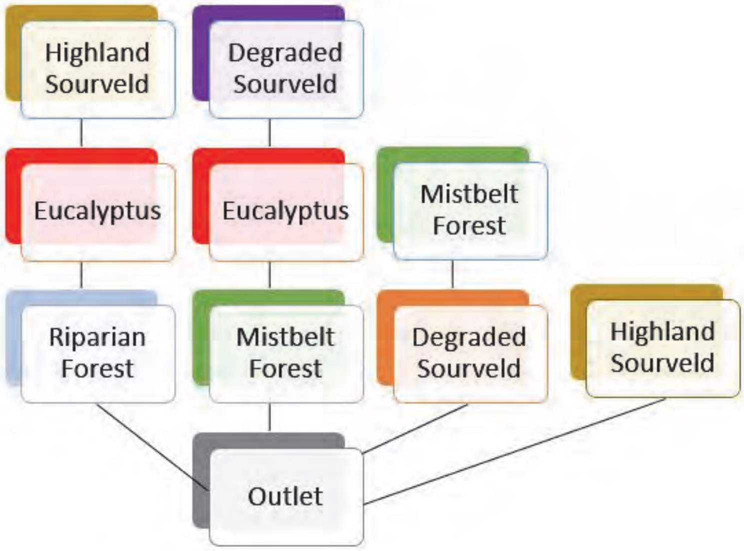


Figure 3.35 Conceptual flow routing for the New Forest vegetation HRUs in the *ACRU* model

3.5.5 Soils data

The soils at Buffeljagsrivier consisted of structureless sandy soils, a result of previous alluvial deposition. The wattle site had a thin litter layer consisting mostly of broken branches and bark. The indigenous site has a thicker litter layer with a large amount of organic matter from the various tree species and understorey vegetation. The soils at New Forest consisted of a deep orthic A-horizon (~0.2-0.3 m), underlain by a yellow-brown apedal B-horizon (~0.3-0.8 m). This is indicative of a well formed clovelly soil, where the depth of the A-horizon is determined by the amount of alluvial deposits from the slopes. Basaltic boulders were observed at about 0.6 m below the surface of site 2. Due to basaltic boulders in the riparian areas, the soils at New Forest were very shallow consisting of an orthic A-horizon and a sandy-clay-loam apedal B-horizon of approximately 1 m. The soils on the higher slopes were identified as having Mispah profiles (Orthic A underlain by ecca shale).

- Soil samples were taken for the riparian areas of both locations, with the soil thickness being measured and the texture estimated.
- The permanent wilting point (WP in $m.m^{-1}$) was derived from the Quinary Catchment Database (QnCDB).
- The soil water content at the drained upper limit (FC in $m.m^{-1}$) was again derived from the QnCDB.
- The soil water content at saturation (PO) and the bulk density was determined in the lab using samples from each site.
- The fraction of saturated soil water to be redistributed from the topsoil horizon to the subsoil horizon (ABRESP) when the topsoil horizon is above its drained upper limit was set to 0.27 of the saturated component per day, with the fraction of water redistributed to the groundwater store from the subsoil horizon (BFRESP) also set to 0.27 of the saturated component per day, with the information derived again from the QnCDB.

3.5.6 Management practices and unpredictable dynamics

The management practices present (although limited) at each site were considered during this study and were incorporated into the modelling process. The Dynamic Input File for *ACRU* was identified as a suitable modelling option. This approach allows the inputs to *ACRU* to be changed per month within each year. For example, this is ideal for scenarios where biennial or triennial burns are implemented, if clear-felling is applied to the plantations every 15 years and if alien clearing and follow up practices are implemented at set time frames. For unpredictable events, such as the fire that occurred at New Forest, this technique could not be used for extrapolation but was used for validation studies. The project team noticed that after the fire at New Forest, the transpiration increased significantly (likely due to opening the forest stand). The dynamic file input was used in this instance to improve the accuracy of the validation by including this event using the Dynamic Input file.

To be able to set up the *ACRU* Shallow Groundwater Routine for the W70A Catchment, various trials with the *ACRU* model were run. For most model runs, the inputs from the South African Quinary Catchments Database for the Quinary W70A were used, including the driver rainfall with 50 years of daily historical climate data (1950 to 1999). A sensitivity study was carried out together with an analysis of rainfall data to show the influence of selected input variables.

3.5.7 The Soil Water Assessment Tool (ARCSWAT)

Catchment information has been collated for the Buffeljagsrivier and New Forest sites using the *ArcSWAT* model. This model is highly dependent on the resolution of the input data, in particular the Digital Elevation Model (DEM). A large amount of manipulation is required for modelling outside of the United States. The DEM is used to configure the catchment by dividing it into a sub-basin or sub-catchment. The automatic watershed delineation tool allows for the creation and selection of outlet nodes and the determination of sub-catchment properties and river reach attributes. Subsequently, the sub-catchments were divided into HRUs which were derived from the land use and soil information. The methods followed for the baseline (current state scenario) were as follows (steps also provided in Figure 3.36):

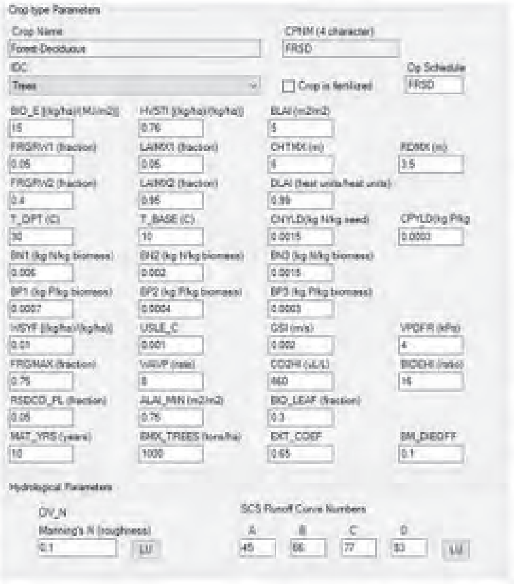
- The 30 m DEM was used (WGS 1984 UTM Zone 36S at New Forest) to delineate the watershed;
- An HRU analysis was undertaken using:
    - Land Use data – a combination of existing databases and user defined boundaries. This data was reclassified using a look up table to be recognizable by the *SWAT* model;
    - Soils data were extracted from existing databases containing hydrological soil attributes. The *ArcSWAT* database (.mbd) was modified to allow for user defined soils to be accepted by the model. These soils were again reclassified using a look up table to match the unique identification codes in the modified database;
    - Slope classes were reclassified into five classes using the DEM;
    - HRUs were subsequently created, each with unique attributes (492 HRUs for Buffeljagsrivier and 1188 HRUs for New Forest).
- Weather Data Definitions were modified to allow for user defined data to be included. A table was created for each rainfall station including the Station ID, location and altitude. This was edited into the *SWAT2012*.mbd. Individual text files containing daily rainfall, temperature, solar radiation, relative humidity and wind speed were created that could be linked to the modified database;
- The Land Use Update (.LUP) model was used to add land-use components for the various scenarios. Soils and Land-use attributes were checked and/or modified according to the scenarios as per the tables below;

Soil Component Parameters

SNAM: AF1-1016
NLAYERS: 2
HYDGRP: C
SOL_ZMX (mm): 1000
ANION_EXCL (fraction): 0.5
SOL_CRK (m3/m3): 0.5
TEXTURE: SANDY_CLAY_LOAM

Soil Layer Parameters

Soil Layer: 1
SOL_Z (mm): 300
SOL_BD (g/ cm3): 1.4
SOL_AWC (mm/mm): 0.08
SOL_CBN (% wt.): 1.1
SOL_K (mm/hr): 11.29
CLAY (% wt.): 25
SILT (% wt.): 18
SAND (% wt.): 57
ROCK (% wt.): 0
SOL_ALB (fraction): 0.0587
USLE_K: 0.2385
SOL_EC (dS/m): 0
SOL_CAL (%): 0
SOL_PH: 0



Crop type Parameters

Crop Name: Forest-Deciduous
CPNM (4 character): FRSD
IDC: Trees
☐ Crop is fertilized
Op Schedule: FRSD
BIO_E ((kg/ha)/(MJ/m2)): 15
HVSTI ((kg/ha)/(kg/ha)): 0.76
BLAI (m2/m2): 5
FRGRW1 (fraction): 0.05
LAIMX1 (fraction): 0.05
CHTMX (m): 6
RDMX (m): 3.5
FRGRW2 (fraction): 0.4
LAIMX2 (fraction): 0.95
DLAI (heat units/heat units): 0.99
T_OPT (C): 30
T_BASE (C): 10
CNYLD(kg N/kg seed): 0.0015
CPYLD(kg P/kg: 0.0003
BN1 (kg N/kg biomass): 0.006
BN2 (kg N/kg biomass): 0.002
BN3 (kg N/kg biomass): 0.0015
BP1 (kg P/kg biomass): 0.0007
BP2 (kg P/kg biomass): 0.0004
BP3 (kg P/kg biomass): 0.0003
WSYF ((kg/ha)/(kg/ha)): 0.01
USLE_C: 0.001
GSI (m/s): 0.002
VPDFR (kPa): 4
FRGMAX (fraction): 0.75
WAVP (rate): 8
CO2HI (uL/L): 660
BIOEHI (ratio): 16
RSDCO_PL (fraction): 0.05
ALAI_MIN (m2/m2): 0.75
BIO_LEAF (fraction): 0.3
MAT_YRS (years): 10
BMX_TREES (tons/ha): 1000
EXT_COEF: 0.65
BM_DIEOFF: 0.1

Hydrological Parameters

OV_N Manning's N (roughness): 0.1
SCS Runoff Curve Numbers: A 45, B 66, C 77, D 83

- The *ArcSWAT* model was run at a daily time step with a warm up period of three years;
- Observed streamflow and transpiration were used to validate the model.

The important input variables have been summarised in Table 3.14.

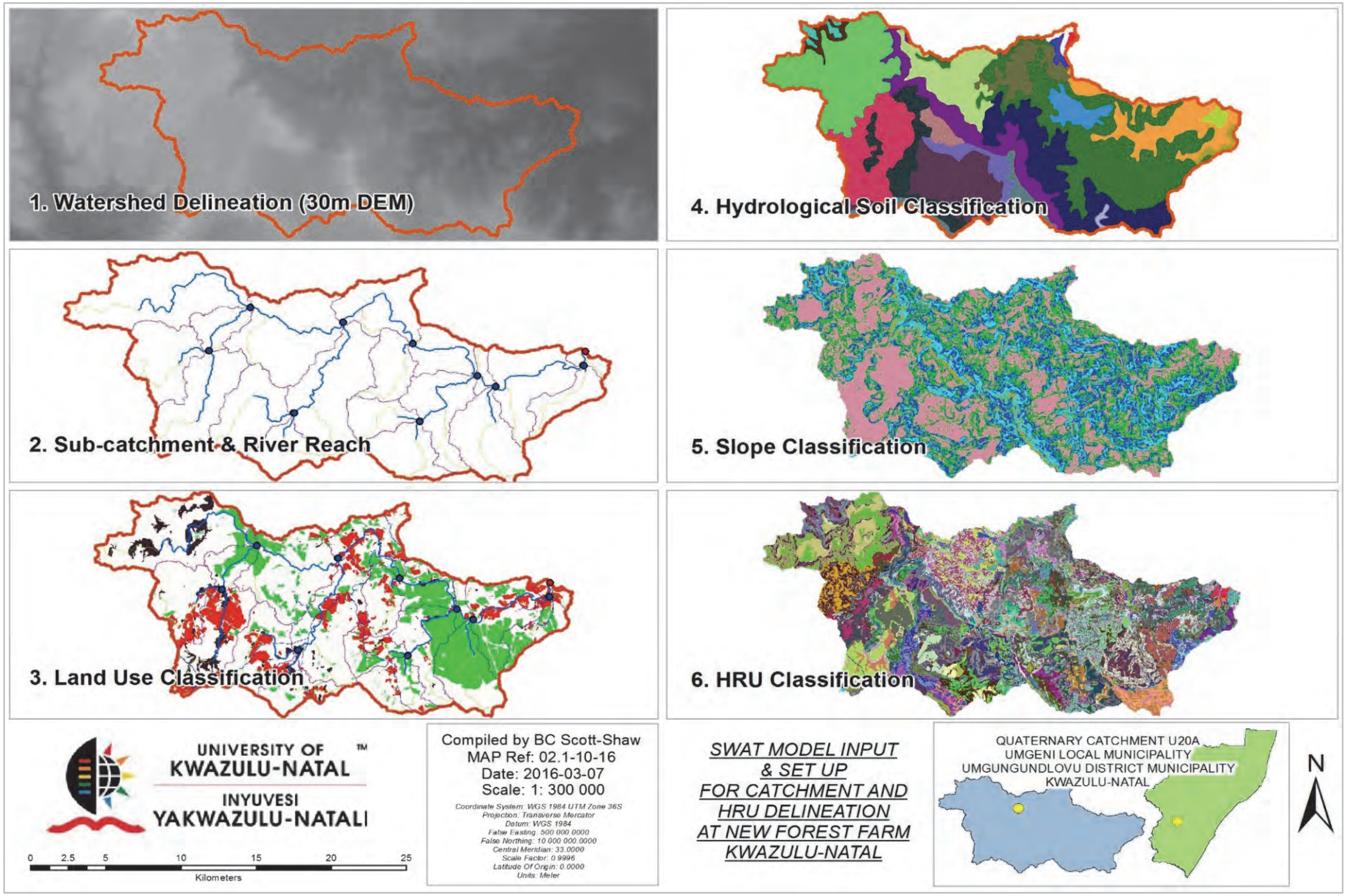


Figure 3.36 Watershed delineation and Model Set-up for Quaternary Catchment U20A using *SWAT*

Table 3.14 Summary of key *SWAT* input variables (after Arnold et al.**, 2012)**

File name	Description
File.cio	*Watershed file that names catchment levels for output parameters*
.fig	*Watershed configuration file*
.pcp	*Precipitation input file (up to 300 stations)*
.tmp	*Temperature file with daily minimum and maximum temperatures*
Crop.dat	*Land cover/plant growth database file containing plant growth parameters*
.hru	*HRU level parameters*
.sol	*Soil input file*

As the *SWAT* model contains numerous databases for United States conditions, users wanting to use the model outside of the United States need to modify the database and input their own soils, land use and weather data. The modified land-use data for a South African context has been provided in Table 3.15.

Table 3.15 Summary of modified land-use attributes used for the *SWAT* model

Land-use Cover/Plant Growth Database							
Cover	**BLAI (m2/m2)**	**LAIMX1 (frac)**	**CHTMX (m)**	**T_BASE (C)**	**RDMX (m)**	**T_OPT (C)**	**GSI (m/s)**
Eucalyptus	5	0.15	24	7	5	30	0.012
Pine	5	0.05	20	0	5	30	0.01
Mixed Riparian Forest	4	0.15	16	3	4	30	0.004

4. WESTERN CAPE AFROTEMPERATE FOREST

The Western Cape Afrotemperate forest site (referred to as Buffeljagsrivier) was the' pilot' site for this study as it was one of a very few sites in the country where rehabilitation techniques had already been applied. In addition, the site contained important species that had been identified during the stakeholder's site selection workshop. Important ecological and hydrological findings for this site are outlined in this chapter.

4.1 Study Site

Although a riparian forest, the study site has been named the Western Cape Afrotemperate Forest site as it falls under one of the various forest types that have been considered within the forest biome. Based on feedback from the site and species selection workshop and a previous site visit, it was decided that the focus would be on both the alien and the indigenous stands. In addition, it was decided that Heat Pulse Velocity (HPV) systems, soil water profile measurements and a meteorological station would be the most suitable techniques to meet the aims of the project. The terrain of the site was characterized by a narrow riparian zone with poor fetch limiting the use of energy balance techniques (e.g. eddy covariance) at this site. The HPV technique was also better suited for single tree transpiration measurements which were the focus of this project.

The upper region of this research site was dominated by indigenous riparian forest (Figure 4.1a) and the lower region by alien wattle stands (Figure 4.1b). An overview of the layout of the study site in relation to the Buffeljags dam is shown in Figure 4.3.

Figure 4.1 The upper indigenous forest stand (a) and the lower wattle stand (b)

The Buffeljagsrivier flows southwards along the Langeberg Wes mountain range into the Buffeljags dam. Approximately 11 km downstream of the dam and just south of the Bontebok National Park, the river merges with the Breede River. This peat-stained tributary of the Breede originates where the Grootvadersbos River and the Tradou River merge. The Buffeljagsrivier study area is at latitude 34°00'15"S and longitude 20°33'58"E approximately 95-110 m above mean sea level. The research area is within Quaternary Catchment (QC) H70E and within Quinary Catchment (QnC) 7384 (Figure 4.2). The research area falls under the Western Cape Afrotemperate forest type which is characteristic of very small forest patches occurring along boulder screes consisting of streams, gorges and mountain slopes (Geldenhuys, 2010). The Langeberg Mountains consist of Table Mountain Sandstone/quartzite (north of the Buffeljagsrivier) with a ridge of shales to the south of the river. The climate is typical of the Southern Cape with hot summers and cold winters. However, the rainfall is fairly evenly spread throughout the year. Swellendam normally receives about 600 mm of rain per year with the highest monthly rainfall occurring in August. The daily maximum temperatures range from 17.1 °C in July to 27.5 °C in January. The mean daily minimum temperature is 15°C in February and 5°C in July. The stand height ranges from 3 to 15 m with little diversity of fauna and flora. The surrounding vegetation is mountainous fynbos and renosterveld.

Historically *Acacia mearnsii* trees were planted for small scale uses (firewood and building material) on the nearby farms. Working for Water cleared most of the alien trees which have since grown back over the last 15 years. Currently the invasion extends approximately one kilometre along the river. Ongoing research by Geldenhuys (2010-present) involves thinning the current alien stand to allow for indigenous patches to expand. This approach, which manipulates the alien species to act as pioneers for the indigenous species, could be a more practical alternative to complete clearfelling as it is economical, fast (compared to potential alien regrowth) and does not leave the soil open to erosion. The indigenous stand along the river had various species such as *Celtis africana*, *Vepris lanceolata*, *Prunus africana* (Hook.f.) Kalkman and *Podocarpus falcatus* (Thunb.) R.Br. ex Mirb**.**

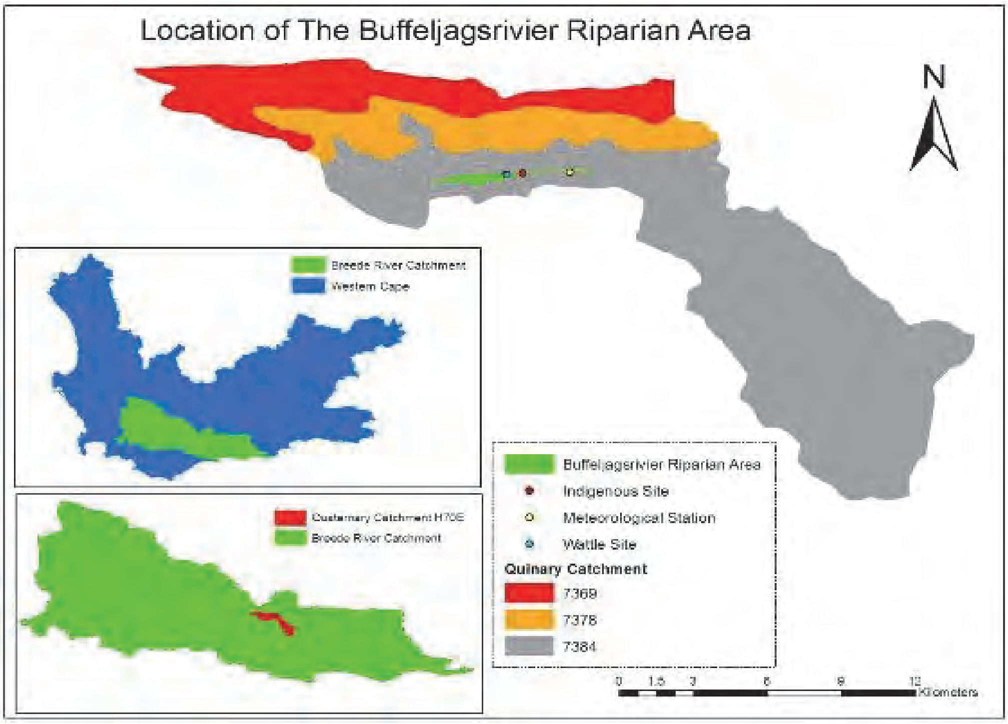


Figure 4.2 Buffeljagsrivier Forest Study Site, showing the indigenous site, wattle site and meteorological station in relation to the Western Cape and the Breede River Catchment

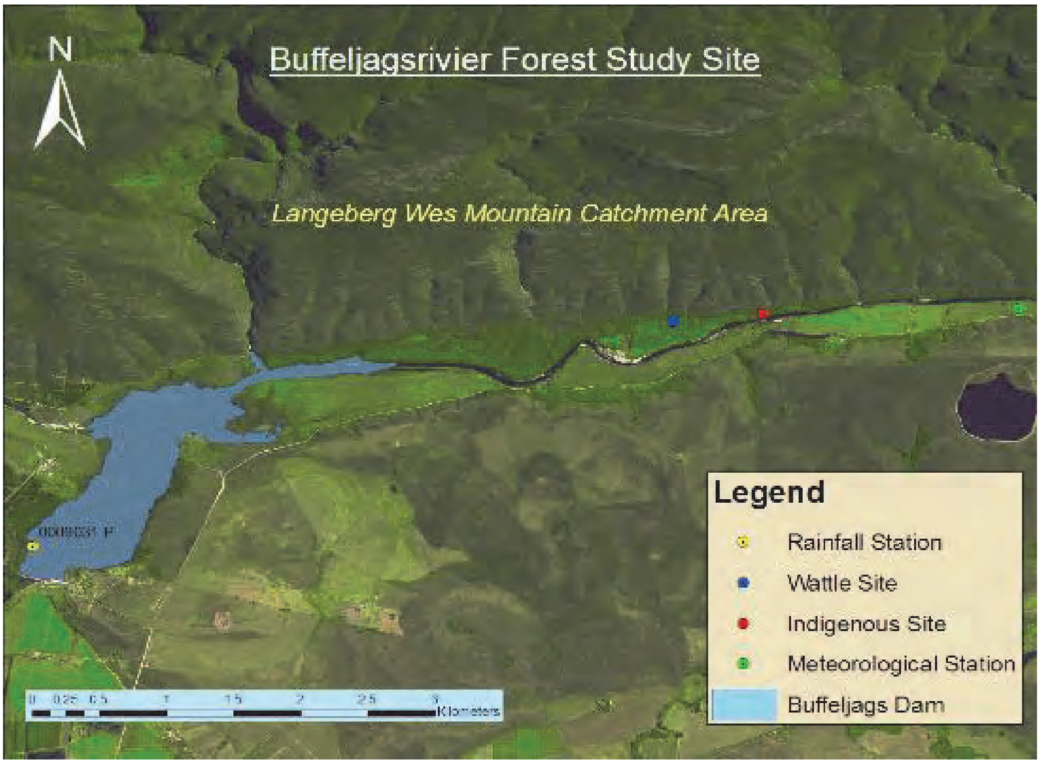


Figure 4.3 Location of the research areas within the Buffeljagsrivier riparian area

Figure 4.4 *Rothmannia capensis* bark and leaves (a) and *Celtis africana* bark and leaves (b)

4.2 Ecological Findings

4.2.1 Spatial characteristics of natural forest clusters

4.2.1.1 Distribution of natural forest clusters within the Black wattle stand

A total of 329 forest clusters were recorded and they were distributed across the total Black wattle stand (Figure 4.5). The majority of large clusters (59.2%; 0.53 ha) occurred in the Proximal zone and the majority of small clusters (53.0%; 3.52 ha) in the Distant zone. Medium-sized clusters were present in similar proportions in the Proximal (44.4%; 0.53 ha) and Intermediate zones (33.3%; 0.6 ha). The number of forest clusters differed significantly across the size classes and zones. A P-value = 0.009 was calculated in the one-way ANOVA.

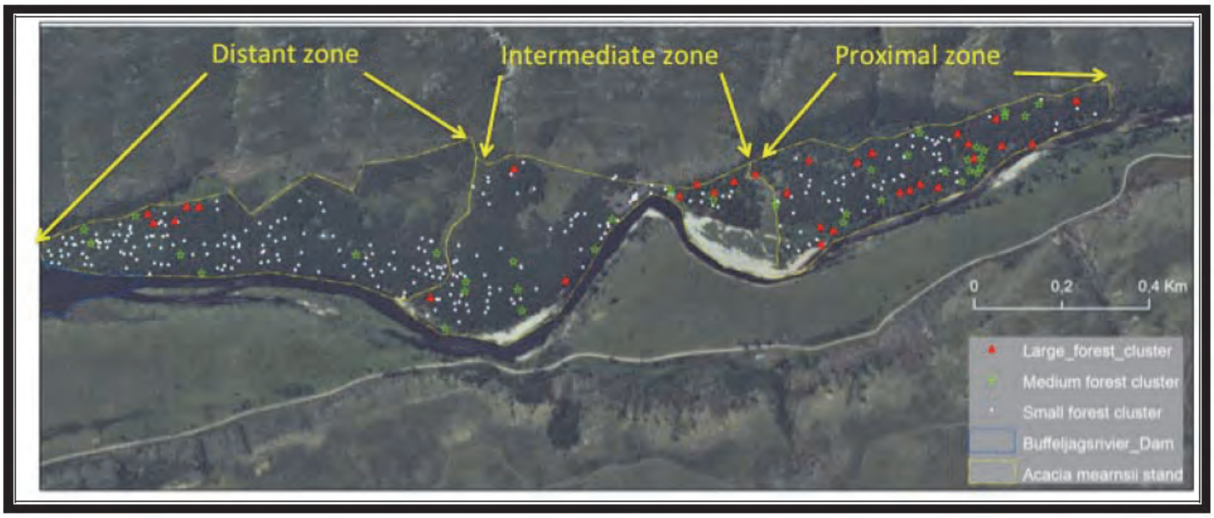


Figure 4.5 Map of the distribution of small, medium and large forest clusters in the Proximal.Intermediate and Distant zones within the Black wattle stand at Buffeljagsrivier.

The Bonferroni test showed that forest cluster distribution differed significantly between Small and Large clusters between the Proximal and Distant zones, and between the Proximal and Intermediate zone, whereas distributions of Medium and Large clusters were quite similar (Table 4.1).

Table 4.1 Bonferroni test results; the stand zones differ in cluster size distribution at Buffeljagsrivier.

Means with the same letter are not significantly different

Bonfer Grouping	Mean	N	Size
A	2.9120	3	small
B	0.3933	3	medium
B	0.3183	3	large

4.2.1.2 Species composition of forest clusters per zone and per size

The distribution of 28 species recorded in the 59 selected forest clusters varied per stand zone and cluster size (Table 4.2) and included 78.6% trees and 21.4% shrubs.

Table 4.2 Summary table of the total number of clusters by size category sampled in the different zones, and the selected clusters for more detailed study

Black wattle stand zone	Zone Area (ha)	All clusters	All mapped clusters						Clusters selected for study		
			Cluster size								
			Small		Medium		Large		Small	Medium	Large
			n	n/ha	n	n/ha	n	n/ha	n	n	n
Proximal zone	30	94	62	2.07	16	0.53	16	0.53	11	5	5
Intermediate zone	20	81	63	3.15	12	0.60	6	0.30	11	4	2
Distant zone	40	154	141	3.52	8	0.05	5	0.13	17	2	2
Total	90	329	266		36		27		39	11	9

The 28 species belonged to 20 families. The majority of species were represented in the larger size classes, as well as in the regeneration, with few exceptions. The two main invasive alien species were Black wattle and Bugweed (*Solanum mauritianum),* and both were light-demanding. A third invasive alien species was present (*Melia azedarach* (L.)) but only as mature trees. The six most commonly found species in the forest clusters were *Canthium inerme* (L.F.) Kuntze*, Celtis africana, Diospyros glabra* (L.)*, Gymnosporia buxifolia* (L.), *Rapanea melanophloeos* and *Vepris lanceolata*.

Although species composition differed across the stand zones and between the three forest cluster size classes, there was no distinct pattern in terms of tree or shrub distribution. Species were scattered throughout the three zones for all the size classes. However, some species were dominant in one zone and completely absent in other zones. For example, *C. africana*, dominant in the Proximal zone, was almost absent in the Distant zone, and *V. lanceolata*, with good representation in the Proximal and Intermediate zones, became rare in the Distant zone. *Rapanea melanophloeos* occurred in all three zones, but was dominant in the Distant zone. Most of the species recorded within the three zones were found in the small clusters and large clusters.

4.2.1.3 Discussion

Evidence of establishment of natural forest species under the Black wattle stand

The general perception around invasive tree species is that wherever they occur there is no chance of establishment of indigenous tree species. However, within the 90 ha stand of the invasive alien Wattle, a total of 329 natural forest clusters were recorded. From these forest clusters, 81% consisted of one to three trees, 11% of four to nine trees and 8% of more than ten trees. The forest clusters contained 22 tree (78.6%) and six shrub (21.4%) species. This is evidence for the successful establishment of natural forest species within this Black wattle stand, contrary to the general perception. The shade caused by canopy closure of the Black wattle stand prevented the regeneration and replacement of this light demanding invasive alien species under its own canopy. The Black wattle stand therefore facilitated germination and establishment of more shade-tolerant natural forest species and contributed to forest succession (Geldenhuys, 1997; Lugo, 1997; Parrotta et al., 1997).

More large forest clusters closer to natural forest patches.

The unequal distribution of forest clusters across the Black wattle stand suggested a directional process in the establishment of natural forest clusters within the Black wattle stand. The nearest (Proximal) zone to the natural forest patches had the highest number of large natural forest clusters (16), followed by the Intermediate zone (6) and Distant zone (5). However, the Distant zone had the highest number (141) of small, newly establishing forest clusters. In terms of the forest succession process, the understanding is that most of the trees first established near to potential seed sources, formed clusters and as they expanded, they facilitated the progressive establishment of new small forest clusters to the distant zone, via the intermediate zone. The existence of adjacent natural forest patches appeared to be a necessity for such succession to take place. The majority of such case studies highlighted this requirement (Geldenhuys, 1986, 1997, 2004; Loumeto and Huttel, 1997; Lugo, 1997; Parrotta et al., 1997). However, the presence of forest species at points far away from the seed source areas may relate to the characteristics of the dispersal agents. For example, some species such as *Ocotea bullata* (Burch.) Baill., *Apodytes dimidiata* E.Mey. ex Arn. and *Olinia ventosa* (L.) Cuford. were present in the Distant zone but were absent from the Proximal and/or Intermediate zones which may be related to dispersal by baboons.

Traditional forest rehabilitation practices tend to rely on nurseries for seedlings to be established on the site to be rehabilitated. However, the associated costs are always a limiting factor to the success of such management actions (Geldenhuys, 2013). The role of adjacent remnant forests as potential seed sources in forest succession and recovery has been confirmed in this study and perhaps should be considered as a better approach to forest rehabilitation where natural forest patches exist nearby.

Species distribution in relation to forest succession

The sample of 59 clusters represented 18% of the identified forest clusters within the stand. In total, 1329 indigenous stems were recorded, with 678 stems in the Proximal zone alone (51.01%). The recorded stems belonged to 20 species of 18 families. This is an indication of diverse regeneration. There was no clear pattern relating to the sequence of establishment of the species in the forest succession process. Based on Lugo (1997) the expected pattern is that woody shrub species would be associated with Small clusters in the Distant zone or the early successional stage and that more mature forest canopy species would be associated with the large clusters in the Proximal zone or advanced successional stage.

However, most of the common species of the stand were well represented in the Proximal zone which would suggest that this zone is in an advanced successional stage (Table 4.2).

Some species were dominant in one particular zone but completely absent from another zone. For example, *C. africana* was abundant in the Proximal zone but almost absent from the Distant zone. *Rapanea melanophloeos* was the most represented canopy tree species in the three zones. This indicated that certain conditions would favour some species and limit others. This is a fundamental principle that allows succession of plant species diversity in forests (Geldenhuys, 1986, 1997, 2004; Loumeto and Huttel, 1997; Lugo, 1997; Parrotta et al., 1997). It is important to understand such useful information in forest rehabilitation interventions, such as what species need to be used in what kind of conditions when planting is necessary (Van Daalen, 1981). The rare species are useful indicators when trying to understand the interactions between type of forest and the dynamics at a regional scale. *Olinia bullata* and *O. ventosa* were recorded once in the Distant zone and not at all in the Proximal zone. Such information may not relate to the site conditions but to the mode of seed dispersal (in this case most likely by baboons), and shows the importance of understanding the type of interactions that may prevail between the rehabilitation area (the Black wattle stand) and the adjacent natural forest patches.

4.2.1.4 Conclusion and Recommendations

The analysis of the 329 natural forest clusters which were identified and mapped at the Buffeljagsrivier forest site indicated that natural forest species were able to regenerate and establish within an extensive stand of vigorously invasive Black wattle. Natural forest species first established in the zone close to the potential seed sources (the nearby forest patches). The nursing of the natural forest species promoted their development. These findings are expected to change the common negative perception of invasive species stands in the forest environment and to persuade policy makers of the need to review the current approach of total clearing of invasive species stands to control invasive species. The approach of total clearing of invasive stands would stop and restart the on-going succession process. Careful interventions with selective thinning while preserving the closed canopy would enable most of these 329 clusters to grow into natural forest canopy species and gradually replace the Black wattle stand. Eventually this approach of selective manipulation of the invader plant stand to facilitate the succession process, rather than clearing the invader plant stand, should be extended to other natural forests in South Africa.

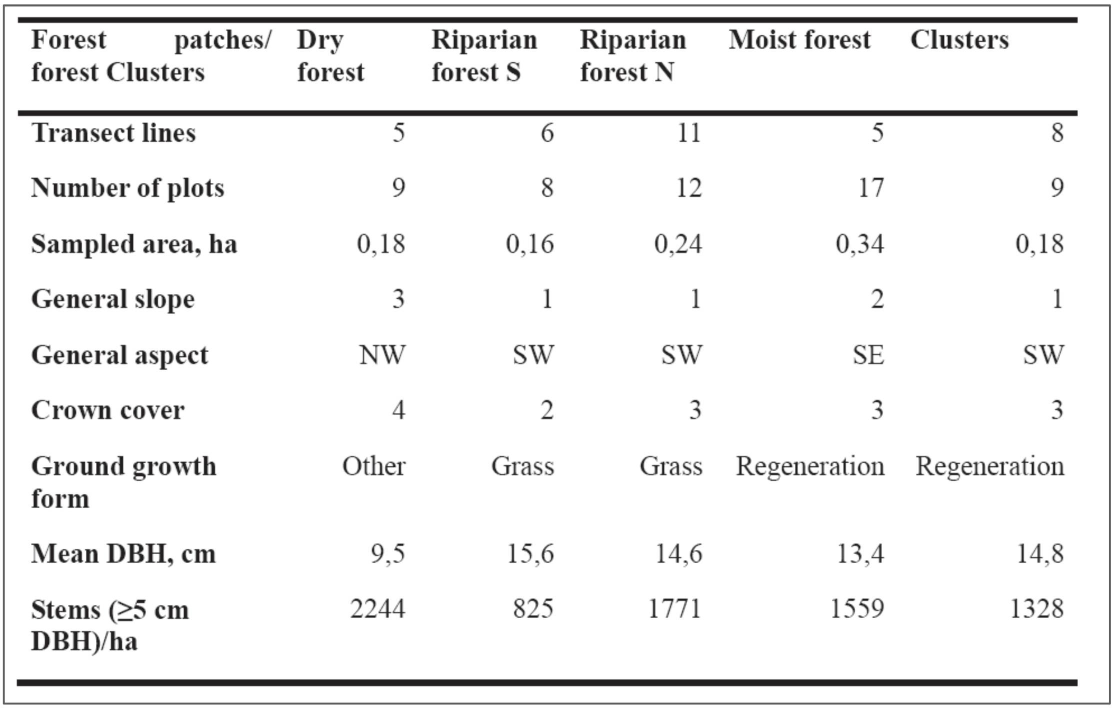
The existence of neighbouring forest patches appeared to have an accelerating impact on the process. Results of the presented study indicated that natural forest species would start to colonise the stand from zones close to the remnant adjacent forests, and their density would also be high in the same zones. Results from this study provide a baseline for potential further studies on the relationship between the establishing clusters and the adjacent patches of natural forest in order to better understand the ecology of seed sources and the related dispersal systems.

4.2.2 Floristic characteristics of natural forest clusters

4.2.2.1 General characteristics of forest clusters and forest patches

A broad comparison of the forest patch types and the sampled clusters showed that the clusters related more to the Riparian forest South and North in terms of similar very gentle south-westerly slope and mean stem diameter (Table 4.3). Forest tree regeneration was lacking within the Riparian forest patches, but was the dominant ground cover within the Moist and Dry forest patches and Forest clusters. Dry forest had steep north-westerly slopes (warm), a high crown cover (>75% closed), the highest stem diameter per ha but with small trees. Moist forest had relatively steep south-easterly slopes (cool), with the mean stem diameter (13.6 cm DBH) between that of Dry forest and the Riparian forest North and South and the forest clusters. Crown cover was similarly relatively closed in Moist forest, Riparian forest North and forest clusters (51-75% closed). Riparian forest South had relatively sparse crown cover (31-50% closed).

Table 4.3 Characteristics of the forest patches in relation to the forest clusters



Forest patches/ forest Clusters	Dry forest	Riparian forest S	Riparian forest N	Moist forest	Clusters
Transect lines	5	6	11	5	8
Number of plots	9	8	12	17	9
Sampled area, ha	0,18	0,16	0,24	0,34	0,18
General slope	3	1	1	2	1
General aspect	NW	SW	SW	SE	SW
Crown cover	4	2	3	3	3
Ground growth form	Other	Grass	Grass	Regeneration	Regeneration
Mean DBH, cm	9,5	15,6	14,6	13,4	14,8
Stems (≥5 cm DBH)/ha	2244	825	1771	1559	1328

4.2.2.2 Relationship between forest clusters and forest patches

<u>Classification</u>

The hierarchical clustering method of Legendre and Legendre (1998) and Kindt and Coe (2005) was used to group plots according to their similarities in number of stems per species recorded within each plot independently of the forest type (Figure 4.6). A matrix of the calculated Bray-Curtis ecological distances (minimum value of 0.17, mean value of 0.79 and one as a maximum value for absolute dissimilarity in species composition) showed connectivity and sufficient dissimilarities between plots to generate classification categories. This was supported by the Mantel cophenetic distance statistic (calculated with

100 permutations) of r = 68.3% with a p-value of 0.0099, indicating that classification was a good representation of ecological differences between plots (reliability increased with a higher Mantel statistic).

Three main groups were formed at a Mantel value of 0.8, named G1, G2 and G3, representing the three main types of forest (Moist forest, Riparian forest and Dry forest). The main groups were subdivided into 10 subgroups at Mantel value of 0.7, described as community groups G1a, G1b and G1c within Moist forest, G2a, G2b, G2c, G2d and G2e within Riparian forest, and G3a and G3b within Dry forest (Figure 4.6). However, Riparian forest north (G2a, G2d and G2e) and Riparian forest south (G2b and G2c) were classified in separate subgroups.

Plots from the forest clusters were distributed in four community subgroups within the Riparian forest (G2): four in G2a, three in G2b, and one each in G2d and G2e. Moist forest (G1) and Dry forest (G3) did not share any group with the forest clusters. Two plots of Riparian forest north shared subgroups within Moist forest (G1a and G1c) and two plots of Riparian forest south were found in the Dry forest subgroup (G3b) (Figure 4.6).

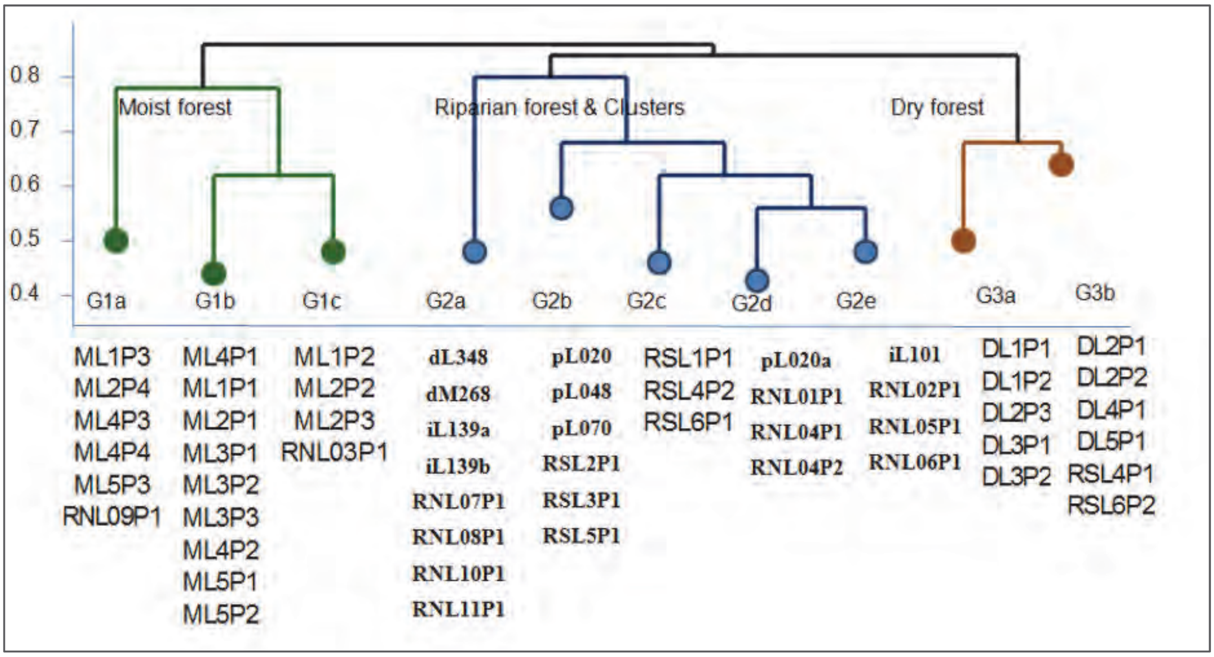


Figure 4.6 **Classification of plots of different sites into groups and subgroups (plant communities) according to the similarities in species composition. Note: All the forest clusters were grouped within the G2.**

The Canonical Correspondence Analysis (CCA), applied to the same sampled matrix and related to the three factors aspect, slope and canopy closure, reinforced the grouping obtained by the classification analysis. The ordination plot highlighted specific patterns (Figure 4.7): The Riparian and Cluster forest community (G2) was associated with a SW aspect and flat areas; the Dry forest community (G3) was associated with a NW aspect and steeper slope; the Moist forest community (G1) was associated with a SE aspect and canopy closure. The ordination plot also showed the association between the main communities and certain species in ordination space (Figure 4.7).

Apodytes dimidiata was important within G1 in the moist forest patches, *Gymnosporia buxifolia* was more important within G3 in the dry forest patches, *Celtis africana*, within G2 in the forest clusters, and *Vepris* *lanceolata* within G2 in the riparian patches, together with *Ilex mitis* (L.) Radlk which was scattered in G2 although it is normally associated with moist forest. *Canthium inerme* and *Rapanea melanophloeos* were recorded in all the forest patches. This was supported by the ordination diagram where the two species were not site specific; they are displayed close to the origin of the axis (Figure 4.7).

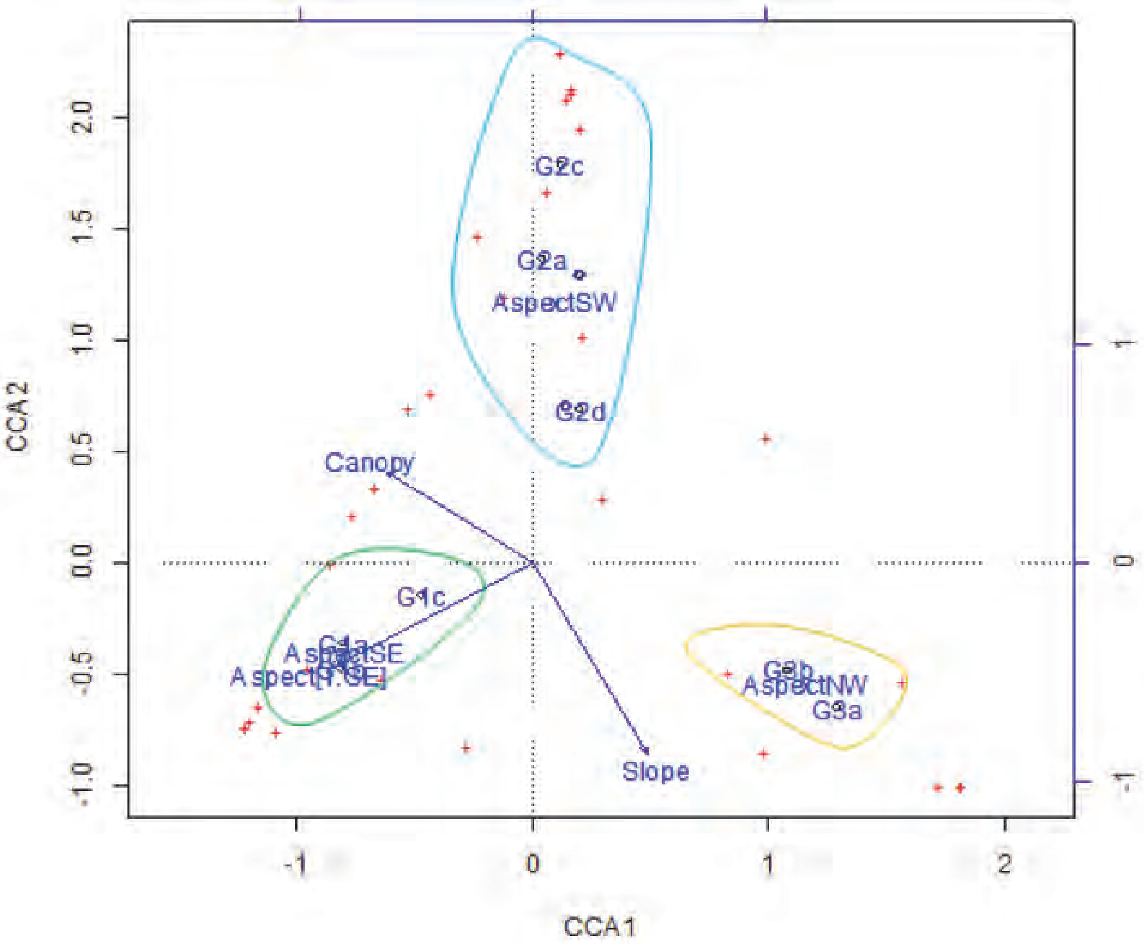


Figure 4.7 Ordination diagram showing how forest types (G1, G2 and G3) and G3b) are associated with the environmental vectors (aspect, slope, canopy).

4.2.2.3 Community species composition in relation to the forest clusters

Species importance value (IVs)

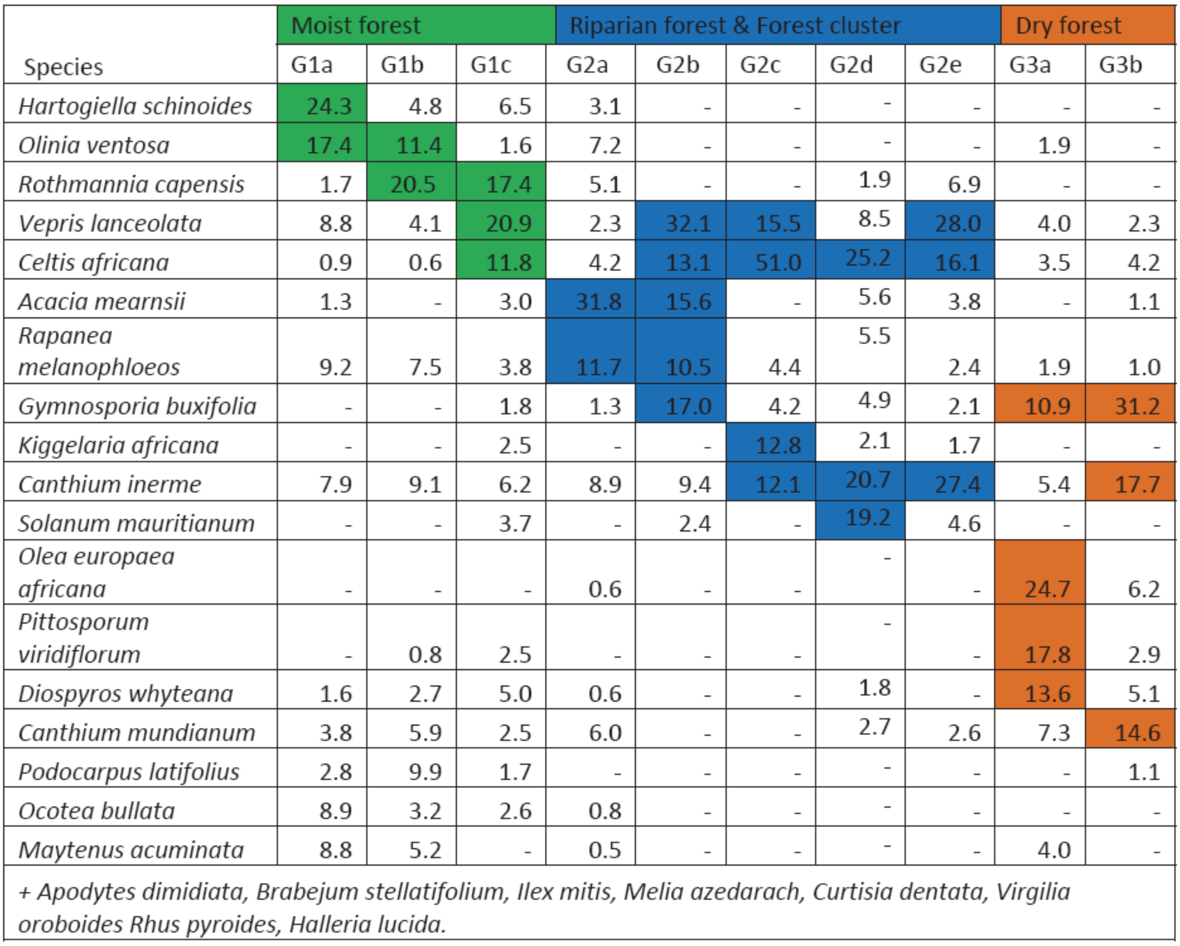
Communities differed significantly from one another according to the species importance values (Table 4.4).

- Moist forest (G1) was dominated by *Hartogiella schinoides* (IV 24.3) and *Olinia ventosa* (IV 17.4) in subgroup G1a, *Rothmannia capensis* (IV 20.5) and *O. ventosa* (IV 11.4) in subgroup G1b, and *Vepris lanceolata* (20.9)*, R. capensis* (17.4) and *Celtis africana* (11.8) in subgroup G1c.
- Riparian forest and forest clusters (G2) were dominated by Black wattle (IV 31.8) and *Rapanea melanophloeos* (IV 11.7) in subgroup G2a (this subgroup is in several comparisons of species relatively similar to Moist forest), *V. lanceolata* (IV 32.1), *Gymnosporia buxifolia* (IV 17.0), black wattle (IV 15.6), *C. africana* (IV 13.1) and *R. melanophloeos* (IV 10.5) in subgroup G2b, *C. africana* (IV 51.0), *V. lanceolata* (IV 32.1), *Kiggelaria africana* (IV 12.8) and *Canthium inerme* (IV 12.1) in

subgroup G2c, *C. africana* (IV 25.2), *C. inerme* (IV 20.7) and *Solanum mauritianum* (IV 19.2) in subgroup G2d, and *V. lanceolata* (IV 28.0), *C. inerme* (IV 27.4) and *C. africana* (IV 16.1) in subgroup G2e. In this Group 2 the main species in most subgroups are *C. africana*, *V. lanceolata* and *C. inerme*.

- Dry forest (G3) was dominated by *Olea europaea africana* (IV 24.7), *Pittosporum viridiflorum* (Sims) (IV 17.8), *Diospyros whyteana* (IV 13.6) and *G. buxifolia* (IV 10.9) in subgroup G3a and by *G. buxifolia* (IV 31.2), *C. inerme* (IV 17.1) and *Canthium mundianum* (Cham & Schlechfd) (IV 14.6) in subgroup G3b.
- The two invasive species, Black wattle and Bugweed, were more prominent within Riparian forest and forest clusters, but were dominant in only one subgroup each, respectively G2a (IV 31.8) and G2d (IV 19.2). Both have a low to zero presence in Moist and Dry forest. The considerable number of empty cells within Table 4.4 indicates a number of species which only occur in some subgroups. For example, *Podocarpus latifolius, Ocotea bullata, H. schinoides and R. capensis* are mostly absent from the Riparian forest and forest clusters, and also from Dry forest. *P. viridiflorum* and *O. africana* are mostly absent from the Riparian forest and forest clusters, and from Moist forest.

Table 4.4 Species importance values (IVs) over different sub-groups (forest communities) at Buffeljagsrivier.



Species	Moist forest			Riparian forest & Forest cluster					Dry forest	
	G1a	G1b	G1c	G2a	G2b	G2c	G2d	G2e	G3a	G3b
Hartogiella schinoides	24.3	4.8	6.5	3.1	-	-	-	-	-	-
Olinia ventosa	17.4	11.4	1.6	7.2	-	-	-	-	1.9	-
Rothmannia capensis	1.7	20.5	17.4	5.1	-	-	1.9	6.9	-	-
Vepris lanceolata	8.8	4.1	20.9	2.3	32.1	15.5	8.5	28.0	4.0	2.3
Celtis africana	0.9	0.6	11.8	4.2	13.1	51.0	25.2	16.1	3.5	4.2
Acacia mearnsii	1.3	-	3.0	31.8	15.6	-	5.6	3.8	-	1.1
Rapanea melanophloeos	9.2	7.5	3.8	11.7	10.5	4.4	5.5	2.4	1.9	1.0
Gymnosporia buxifolia	-	-	1.8	1.3	17.0	4.2	4.9	2.1	10.9	31.2
Kiggelaria africana	-	-	2.5	-	-	12.8	2.1	1.7	-	-
Canthium inerme	7.9	9.1	6.2	8.9	9.4	12.1	20.7	27.4	5.4	17.7
Solanum mauritianum	-	-	3.7	-	2.4	-	19.2	4.6	-	-
Olea europaea africana	-	-	-	0.6	-	-	-	-	24.7	6.2
Pittosporum viridiflorum	-	0.8	2.5	-	-	-	-	-	17.8	2.9
Diospyros whyteana	1.6	2.7	5.0	0.6	-	-	1.8	-	13.6	5.1
Canthium mundianum	3.8	5.9	2.5	6.0	-	-	2.7	2.6	7.3	14.6
Podocarpus latifolius	2.8	9.9	1.7	-	-	-	-	-	-	1.1
Ocotea bullata	8.9	3.2	2.6	0.8	-	-	-	-	-	-
Maytenus acuminata	8.8	5.2	-	0.5	-	-	-	-	4.0	-
+ Apodytes dimidiata, Brabejum stellatifolium, Ilex mitis, Melia azedarach, Curtisia dentata, Virgilia oroboides Rhus pyroides, Halleria lucida.										

Stem diameter distribution

In general, small trees (5-20 cm DBH) dominated the stem diameter distributions for all the important species over all communities, but the actual peaks varied between species and communities. Many species such as *P. latifolius* in Moist forest and *O. africana* in Dry forest showed the inverse-J shaped stem diameter distribution with many small stems and fewer larger stems. No clear inverse-J stem distribution was noted in Riparian forest except for *R. capensis* and *C. mundianum*. Some species showed the opposite distribution pattern such as *O. ventosa* in Moist forest and Riparian forest. Some species show a typical bell-shaped curve with high numbers in the intermediate sizes and fewer stems in the smaller and larger sizes such as *C. africana* in Riparian forest.

The common more widespread natural forest canopy species such as *C. africana*, *R. melanophloeos, V. lanceolata* and *C. inerme* occurred more prominently within Riparian forest and forest clusters than in the Moist and Dry forest patches. However, the two Dry forest species that were also present in some clusters, *O. africana* and *G. buxifolia*, had strong regenerating populations in the Dry forest. Moist forest canopy species were found to be regenerating in moist forest but not riparian forest or forest clusters. However a species such as *Apodytes dimidiata* which was not regenerating in Moist forest was prolific in the regeneration cohort in Riparian forest.

The two common invasive alien species, Black wattle and Bugweed*,* showed different diameter class distributions in different parts of the Riparian forests and forest clusters. Black wattle was prominent in Riparian forest and some clusters related to Group2a, but had a low presence in the other parts of Riparian forest and related forest clusters. It showed a more advanced development of the population with a decline in stems <10 cm DBH (a typical bell-shaped curve of a light-demanding species). Bugweed was absent from the G2a community and more prominent in the other Riparian forests and associated forest clusters (G2b-e), but it was a smaller-sized tree. The two invasive species were almost absent from Moist and Dry forest patches (G1 and G3).

4.2.2.4 Discussion

Forest clusters and forest patches

Natural forest patches adjacent to the Black wattle stand were expected to influence the forest succession process through the natural forest clusters establishing within the Black wattle stand. The assumption was that seeds from these adjacent forest patches would influence the establishing clusters within the Black wattle stand. A number of forest species such as *C. inerme, C. africana, G. buxifolia, R. melanophloeos* and *V. lanceolata* were found to be common across the forest patches and forest clusters. The species are well known to generally occur widely through different forest types (Geldenhuys and Macdevette, 1989; Mucina and Rutherford, 2006). Although their widespread distribution did not indicate specific relationships between each of the forest patches and the establishing forest clusters, there were differences in their stem number, importance values and stem diameter distribution for each type of forest patch sampled. That variability allowed some comparisons between the three generated distinct forest communities: G1, G2 and G3.

Moist forest patch and forest cluster species

Geographically moist forest patches occurred directly next to the black wattle stand in which natural forest clusters were establishing. The expectation was that some characteristics would be common between the two compartments. However, results from investigations revealed numerous differences between the two compartments. From general characteristics, Moist forest patches generally grew on steep South-Easterly slopes, whereas the forest clusters grew on sites with a gentle South-Westerly slope. Even the species composition between the Moist forest (G1) and forest clusters (G2, as part of Riparian forest) was significantly different. Analyses of species importance values and stem diameter distributions showed that canopy and sub-canopy tree species of the Moist forest patches that had large stem diameters also had good regeneration within those patches, but some were almost absent from the sampled forest clusters in the black wattle stand but present within the Riparian/forest cluster community (G2a*)*. The three sub-canopy species, *H. schinoides*, *R. capensis* and *M. acuminata*, showed some presence in the Riparian forest G2a with associated forest clusters.

These results suggest that it is unlikely that the moist forest patches are the principal seed sources of the establishing forest clusters. Because of the presence of three Moist forest canopy species and some sub-canopy species in the forest clusters, Moist forest cannot be excluded as influencing the colonisation of the wattle stand. However, the close proximity of the two components is not enough to ensure seed movement of more species from the moist forest into the establishing forest clusters. It was therefore necessary to have a closer look at other factors such as seed characteristics and dispersal systems.

Dry Forest patches and forest clusters

Dry forest (G3) was clearly different from the establishing forest Clusters (G2, as part of Riparian forest) in terms of classification based on species similarities, IVs and ordination analyses. The two sites shared very few species, and most of the species related to the dry forest were almost absent from the forest clusters. However, *G. buxifolia* was present in many parts of the Black wattle stand but as small plants <5 cm DBH, while *C. mundianum* was present in the Riparian forest G2a, and to a lesser degree also *O. africana*, a typical dry forest species (Aerts et al., 2007). Species of Dry forest were related to steep North-Westerly slopes, whereas forest clusters occurred on gentle slope or flat areas. The distance and the river as a physical obstacle between the two sites may limit seed movement and explain the species dissimilarities. However, possible interactions between these two sites cannot be excluded, even though statistically such interactions were negligible. The examples mentioned above of some of the Dry forest species suggest that the seeds of some Dry forest species were dispersed and established in the black wattle stand, but were still at an early stage of colonization.

Riparian forest patches potential principal seed source of establishing forest clusters

Forest clusters were more similar to Riparian forest patches in terms of species composition. They were displayed in the same community, G2. The interpretation is that the established species found in those forest clusters would have their seed sources from the two Riparian forests. From their spatial position, Riparian forest south occurred along the southern side of the Black wattle stand and Riparian forest north at the foot of the mountain slope. These sites shared the longest borders with the Black wattle stand, which gave them the advantage of interconnection compared to Moist forest patches and notably Dry forest patches. Distance from the source has always been an important factor influencing the seedling establishment. However, species from both the Moist forest and the Dry forest patches also contributed to forest cluster development. Seed characteristics of species may therefore also be a determinant factor in forest cluster development (Hooper et al., 2005; Geldenhuys, 2013).

One could expect that most large-size stems of species recorded within the forest clusters would be found in the parent site, i.e. Riparian forest north and south patches. A comparison of the average stem DBH of common species between Riparian forest patches and forest clusters showed no significant differences between these three zones. This indicates that common species in the three sites had similar sizes. This suggests that most of the large indigenous trees in the clusters in the Black wattle stand have existed before the recent disturbance of the site, and may have contributed to the rapid expansion of the larger clusters. Remnant trees are known to accelerate forest succession (Keeton and Franklin, 2005).

Introduced Black wattle not susceptible to establish in closed canopy forests

The two main invasive species present in the study area, Black wattle and Bugweed, were almost absent from the moist and dry forest patches. This is in agreement with results from many previous studies in South Africa (Geldenhuys, 1986, 2013; MacDonald et al., 1986; Geldenhuys and Bezuidenhout, 2008; Corrigan et al., 2010). These two species, like all the light demanding invasive species, are unable to establish under closed canopies such as those occurring in the moist or dry forest patches. The germination and establishment of seeds of these species require light. That is why the well-developed Black wattle stand of 90 ha at Buffeljagsrivier was most likely caused by clearing of possible forest patches which increased light in this area some time ago. The smaller stems in the area are more likely suppressed stems of the same age as the larger trees. The results confirm the view that in the absence of disturbance, Black wattle is not a threat in the forest environment.

Environmental factors

The plots of the Riparian forest patches and of the forest clusters had similar relatively flat to gentle aspects and may moderate the temperature conditions between more southern or more northern aspects. The plots possibly also have similar light and radiation conditions (opposite end of slope arrow in Figure 4.7). Adequate light is known to stimulate the seeds of certain species to germinate (Bazzaz, 1979). The similar site conditions may explain the similarities in species composition of the three sites. Aspect however, only explains 49% of the variance of species composition of the sample. Some other factors that were not subjected to measurement may contribute better to the observed patterns.

4.2.2.5 Conclusion

Every type of forest patch contributes to a greater or lesser degree to the development of forest clusters within the Black wattle stand. The results indicated that the Riparian forest was the primary seed source of the establishing forest clusters. The developing forest clusters related more to the Riparian forest in terms of slope (similar very gentle south-westerly slopes) and mean stem diameter. Remnant forest species in many large forest clusters contributed to the local seed sources. The presence of Moist and Dry forest species in some forest clusters indicated that these forest types were contributing to seed sources for the developing forest clusters within the black wattle stand.

The study has used a comparative approach to underline the relationship between forest patches and forest clusters. For this reason similar plots had to be used in both forest patches and forest clusters. Only large clusters were able to accommodate a 10 m x 20 m rectangular plot, which automatically excluded the medium and small clusters from the sample. However, an important number of forest species were observed in excluded clusters indicating that they were more characteristic of the Moist and Dry forest patches. The interpretation of this observation is that if small and medium clusters had been included in the analysis, the contribution of Moist and Dry forest patches might have indicated a more distinct relationship to the forest clusters. The expectation is that seed characteristics and dispersal systems would constitute the main explanatory factors for the actual natural forest species distribution in the wattle stand. Further studies are needed to explore this observation.

4.2.3 Expansion of natural forest clusters within an *Acacia mearnsii* stand at Buffeljagsrivier

4.2.3.1 Cluster expansion and seed sources

Similarities in composition of natural forest species between clusters and surrounding regeneration, based on Bray-Curtis ecological distance, differed between clusters. Cluster pL048 presented the highest similarity with its surrounding regeneration (0.07 Bray-Curtis distance matrix value) followed by pL070, and iL101 both with 0.38 Bray-Curtis distance matrix (Table 4.5).

Table 4.5 Matrix of ecological distance between species composition of the clusters and their surrounding regeneration (R). A value close to 1 means a high dissimilarity and close to zero means high similarity.p=Proximal zone, L=large cluster, i=Intermediate zone, d= Distant zone, M=medium cluster.

Species composition within forest cluster

Species regeneration around forest cluster	pL020	pL048	pL070	iL101	iL139	dM268	dL348
(R)pL020	**0.45**						
(R)pL048		**0.07**					
(R)pL070			**0.38**				
(R)iL101				**0.38**			
(R)iL139					**0.64**		
(R)dM268						**0.60**	
(R)dL348							**0.50**

The Mantel test gave a non-significant p-value (0.26) demonstrating the similarities between clusters and their respective surrounding regeneration. Most dominant species in the surrounding regeneration had an adult tree within the clusters (*Celtis africana* for forest clusters pL020, pL048 and pL070, *Rapanea melanophloeos* for dM268 and dM348, *Vepris lanceolata* for iL101 and *Maytenus acuminata* for iL139). Dominant species in some forest clusters were not dominant in the regeneration, such as in pL020 dominated by *Gymnosporia buxifolia* with surrounding regeneration dominated by *Celtis Africana* and the iL139 cluster which was dominated by *Canthium inerme* while its surrounding regeneration was dominated by *Maytenus acuminata*. Some of the dominant species in the clusters were even absent from the regeneration, while the existence of several different species were recorded in the regeneration outside the forest cluster. For example, *Olinia ventosa* (L.) Cuford. was the dominant species in dL348 but was completely absent in the regeneration zone. Species such as *Halleria lucida, Brabejum stellatifolium* (L.), and *Olea europaea africana* were only recorded in the regeneration zone.

4.2.3.2 Influence of distance from seed sources

Looking at distance class levels (6 m; 12 m; 18 m), analysis of patterns showed three visible scenarios (Figure 4.8). The first scenario exhibited decreasing regeneration with increasing distance (pL020, pL048, pL070). The second scenario showed greater regeneration occurring with increasing distance, with relative decrease in the intermediate distance (iL139, dM268). The third scenario showed no pattern; all distance classes had the same amount of regeneration (dL348).

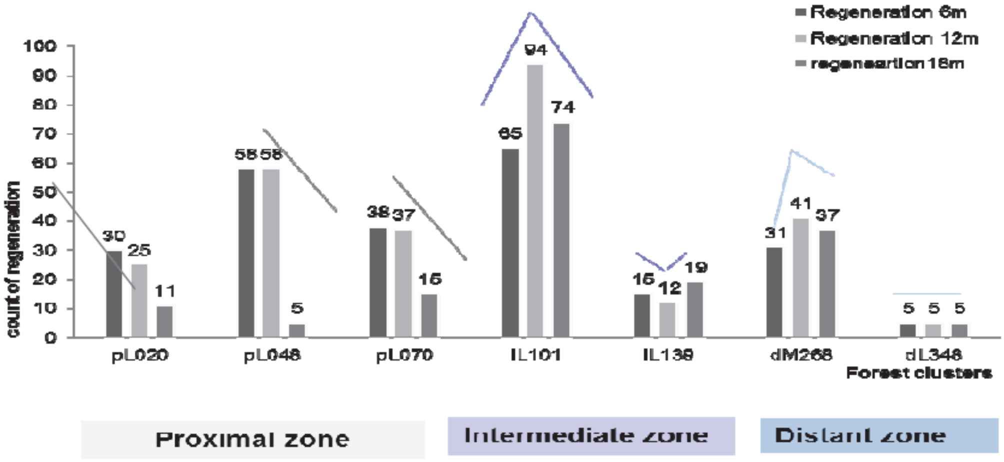


Figure 4.8 Species regeneration count per distance class around the seven selected clusters sampled within the wattle stand at Buffeljagsrivier.

Species composition at the same distance class showed that *C. africana* presented its highest regeneration at the intermediate distance (12 m). This was verified in all the forest clusters where the species was present apart from forest cluster pL020 where regeneration increased with increasing distance. The same results were found with *G. buxifolia*, in the forest cluster pL048 where the regeneration was higher in the first distance classes (6 m). There was no noticeable pattern with other species.

4.2.3.3 Contribution of fruit-seed characteristics and dispersal mechanism on the cluster expansion into the Black wattle stand.

The two species lists combined included 40 species, including the two main invasive species (Black wattle and bugweed). The species presented a wide range of fruit and seed characteristics that are important for understanding the movement of tree and shrub species between the forest patches and the Black wattle stand, and within the Black wattle stand away from the establishing forest clusters (Table 4.6). In summary, species with fleshy and large fruit dominated the list of 40 species (34 or 85%), followed by dry and large fruit (3 or 7.5%), with two species with fleshy and small fruit (2 or 5%) and one species with dry and small fruit (1 or 2.5%). Species with soft and small seeds dominated the sample with 22 species (55%), followed by 12 species with soft and large seeds (32.5%); four species with hard and large seeds (10%), and one of hard and small seed (2.5%)

Table 4.6 Characteristics of the fruit and seed and potential dispersal mode of species recorded within the forest patches and forest clusters in the Buffeljagsrivier.

	Presence in clusters & patches2	Fruit type3	Seed type4	Dispersal agents5	General notes
Acacia mearnsii	C-M-D-Rs-Rn	Pod, d,L	H,L		
Apodytes dimidiata	C-M-D	Nut, f,L	S,L	B/M	
Brabejum stellatifolium	C-M-Rn	Nut, f,L	S,L	Wa+/M	Stream water
Buddleja saligna	Rs-C-	Capsule, d,S	S,S	Wi+	windy
Canthium inerme	C-M-D-Rs-Rn	Drupe, f,L	S,L	B+/M+	Rameron pigeon
Canthium mundianum	C-M-Rn-D	Drupe, f,L	S,S	B+/	Rameron pigeon
Cassine peraqua	C-D-	Drupe f,L	S,L	B	
Carissa bispinosa	D-	Berry, f,L	S,S	B	
Celtis africana	C-M-D-Rs-Rn	Drupe, f,L	S,L	B+	Rameron pigeon
Cussonia spicata	D-	Berry, f,S	S,L	B	
Curtisia dentata	Rn-	Drupe, f,L	H,S	B/M	
Diospyros glabra	C-Rn-	Berry, f,L	H, L	B/M	Chacme baboon
Diospyros whyteana	C-M-D-	Berry, f,L	H,L	B+/M+	Chacme baboon
Eucalyptus sp	D-	Capsule, d,L	S,S		
Grewia occidentalis	D-	Drupe, f,L	S,S	B+	Birds
Gymnosporia buxifolia	C-M-D-Rs-Rn	Capsule, f,L	S,f,L	B+	Birds
Halleria lucida	C-	Berry, f,L	S,S	B+	Birds
Hartogiella schinoides	M-Rn	Berry, f,L	S,S	B+	Rameron pigeon
Ilex mitis	Rn-C-	Berry, f,L	S,S	B+	Birds
Kiggelaria africana	Rn-C-	Capsule, f,L	S,f,S	B+	Birds
Lantana camara	C-	Drupe, FL	SS	B	
Maytenus acuminata	C-D-M	Capsule, f,L	S,f,S	B+	Birds
Melia azedarach	C-Rn	Drupe, f,L	S,L		
Metrosideros angustifolia	C-	Capsule, f,S	SS		
Ocotea bullata	C-M	Berry, f,L	S,L	B+	Bushbuck Rameron pigeon
Olea europaea africana	C-D	Drupe, f,L	S,S	B+	Birds
Olinia ventosa	C-M-Rn	Drupe, f,L	H,L	B+/M+	Chacma baboon
Pittosporum viridiflorum	C-D-M	Capsule, f,L	S,f,S	B+/M+	Birds/ baboon
Podocarpus latifolius	M-	Nut, f,L	S,L	B+/M+	Chacma baboon
Pterocelastrus tricuspidatus	Rn	Capsule, f,L	S,f,L	B+/M?	Birds
Rapanea melanophloeos	C-M-Rs-Rn	Berry, f,L	S,L	B+/M+	Rameron pigeon
Rhoicisus tomentosa	C-M-D-Rs-Rn	Berry, f,L	S,L	M+	Chacma baboon
Rothmannia capensis	M-Rn-C-	Berry, f,L	S,S	B+/M+	Chacma baboon
Searsia (Rhus) pyroides	C-	Drupe, f,L	S,S?	B+/M+	Chacma baboon
Searsia (Rhus) tomentosa	C-	Drupe, f,L	S,S?	B+	Birds
Scolopia mundii	M-C-	Berry, f,L	S,S	B+	Birds
Scutia myrtina	C-	Berry, f,L	S,S	B+	Birds

	Presence in clusters & patches2	Fruit type3	Seed type4	Dispersal agents5	General notes
Solanum mauritianum	C-Rs-Rn	Berry, f,L	S,S	B+	Birds
Vepris lanceolata	C-M-Rs-Rn	Berry/cap, f,L	S,S	B+/M+	Rameron pigeon
Virgilia oroboides	M-C-	Pod, d,L	H,L	M/Wa+	stream water

1 = * introduced species; 2 = C for Cluster, D for Dry forest, M for Moist forest, Rs for Riparian forest South, Rn for Riparian forest North; 3 = f for fleshy, d for dry; L for large (> 5 mm diameter), S for small (< 5 mm diameter); 4 = H for hard, S for soft; f for fleshy attachment; L for large(> 5 mm), S for small (< 5 mm); 5 = B for birds, M for mammal, Wa for water, Wi for Wind; + for observed on site (Adapted from Geldenhuys, 1996a).

Table 4.7 Summary of the fruit and seed characteristics of species within the sample

Seeds Characteristics	Fruit Characteristics				
	Fleshy-Large	Fleshy-Small	Dry-Large	Dry-Small	Total
Soft-Small	19	1	1	1	22
Soft-Large	12	1	0	0	13
Hard-Small	1	0	0	0	1
Hard-Large	2	0	2	0	4
Total	34	2	3	1	40

Four distinct species groups can be extracted from the species listed in Table 4.6 in relation to their presence/absence in the forests patches and forest clusters (Table 4.8) and their fruit and seed characteristics.

Most of the recorded species are bird and/or mammal dispersed (Geldenhuys and Macdevette, 1989; Geldenhuys, 1996b; Coates Palgrave, 2002; Mucina and Rutherford, 2006); Exceptions are *Buddleja saligna* with very small seeds mostly dispersed by wind; *Virgilia oroboides* could use a ballistic mechanism and wind-dispersal could be from the shake of the branches that would release the seed from the open pods. Both mentioned species are also known to be dispersed by water.

A non-exhaustive list of birds and mammals that could potentially play a role in seed dispersal within the area was obtained from the literature and field observation (underlined names) This included birds such as Rameron pigeon (*Columba arquatrix*), Sombre bulbul (*Andropadus importunes*), Cape thrush (*Monticola rupestris*) Red-wing starling (*Onychognathus morio*), and Cape White-eye (*Zosterops pallidus*), and mammals such as Chacma baboon (*Papio ursinus*), Vervet monkey (*Cercopithecus pygerythrus*), Cape porcupine (*Hystricomorph hystricidae*), Bush pig (*Potamochoerus larvatus*) and Bushbuck (*Tragelaphus scriptus*). The list is merely indicative and should be verified with more detailed observation.

Table 4.8 Summary of species distribution groups in terms of their fruit-seed characteristics

Group 1: Common in forest patches / Present in the clusters. 8 species: *Canthium inerme, Canthium mundianum, Celtis africana, Gymnosporia buxifolia, Maytenus accuminata, Rapanea melanophloeos Rhoicisus tomentosa and Vepris lanceolata*
Fruit type: Drupe 37.5%, Capsule 25%, Berry 37.5%; Fruit texture: Fleshy 100%; Fruit size: Large 100%
Seed texture/size: Soft -Large 62.5%, Soft-Small 37.5%
Group 2: Specific to forest patches / present in forest clusters. 16 species: **Acacia mearnsii; Apodytes dimidiata, Brabejum stellatifolium, Buddleja saligna, Diospyros glabra, Diospyros whyteana, Ilex mitis, Kiggelaria africana, Melia azedarach*, Ocotea bullata, Olea eur. africana, Olinia ventosa, Rothmannia capensis, Solanum mauritianum*, Scolopia mundii, Virgilia oroboides*
Fruit type: Drupe 18.8%, Capsule 12.5%, Berry 43.7%, Pod 12.5%, Nut 12.5%; Fruit texture/size: Fleshy Large 81.3%, Dry-Large 12.5%; Dry-Small 6.2%
Seed texture/size: Soft- Small 43.8%, Soft-Large 31.2%, Hard-Large 25%
Group 3: Present in forest patches / absent in clusters. 10 species: *Cassine peragua, Cussonia spicata, Curtisia dentata, Eucalyptus sp*, Grewia occidentalis, Hartogiella schinoides, Pittosporum viridiflorum, Podocarpus latifolius, Pterocelastrus tricuspidatus, Scutia myrtina*
Fruit type: Drupe 30%, Capsule 30%, Berry 40%; Fruit texture/size: Fleshy-Large 80%, Fleshy-Small 10%; Dry-Large 10%
Seed texture/size: Soft-Small 50%, Hard-Small 10%; Soft-Large 40%,
Group 4: Absent in forest patches / present in forest clusters. 6 species: *Halleria lucida, Lantana camara*, Metrosideros angustifolia, Searsia angustifolia, Searsia pyroides, Searsia tomentosa.*
Fruit type: Drupe 16.7%, Capsule 16.7%; Berry 66.6%; Fruit texture/size: Fleshy- Large 100%
Seed texture/size: Soft-Small 83.3%; Soft-Large 16.7%

4.2.3.4 Discussion

Clusters: main seed sources of cluster expansion at relative short distance from seed sources.

In general, regeneration around the clusters showed similarities with species composition of the forest clusters. These results confirm what was expected, i.e. that (1) forest clusters would expand toward the rest of the Black wattle stand, and (2) they would constitute the main seed sources for their expansion. They are in line with reports in the literature about forest recovery through succession in which shade tolerant indigenous forest tree and shrub species establish in clusters under the closed canopy of early successional pioneer stands of light-demanding species, which will then favour regeneration of more late successional species (Clements, 1936; Geldenhuys, 1996c, 2010; Hooper et al., 2005).

Different patterns were observed in terms of the distance of expansion of regeneration from the clusters, and they could be explained in terms of mature species present within the forest clusters. The first scenario showed a decrease in regeneration with increasing distance from the cluster. This scenario related mainly to clusters dominated by species such as *Celtis africana, Gymnosporia buxifolia*, *Rapanea melanophloeos* and *Vepris lanceolata.* It was more visible in the Proximal zone of the stand where most of the large and well established clusters contained many remnant indigenous trees. Following the nucleation succession model of Yarranton and Morrison (1974) remnant trees are said to play an accelerative role in the succession process (Finegan, 1984; Guevara et al., 1986; Keeton and Franklin, 2005). This scenario suggests a relatively low dispersal activity since not many seeds were moved far from the clusters. The second scenario showed increasing regeneration with increasing distance from the cluster. This scenario related to clusters in the Intermediate and Distant zone. The observed pattern seemed to be influenced by species such as *Canthium inerme* and *Maytenus acuminata*. The third scenario showed no distinct pattern and was observed around cluster dl348 in the Distant zone. It is characterised by a lack of regeneration of the dominant species of the clusters (*Ocotea bullata* and *Olinia ventosa)* which could be explained by the early stage of the succession in the Distant zone with a high density of the black wattle stand and very low light infiltration. The tendency of increasing dissimilarities in regeneration as clusters approached the Distant zone, suggests that their expansion in the faraway zone depended on external contributions. The expansion varied strongly with species, indicating the importance of developing a better understanding of the behaviour of individual species in terms of their fruit or seed characteristics and the related dispersal mode.

Fruit-Seed characteristics as determinant factors for establishing forest clusters within the stand

Even though the sites were composed of different forest types (Riparian, Dry and Moist forest patches), the majority of species were described as widespread species and could be recorded in all three forest types. The assessment of fruit-seed characteristics of those species, summarized in Table 4.8, showed that most species that were common to the forest patches and to the forest clusters had large fleshy fruit but 37.5% had soft small seeds that in general, confer them the ability to easily colonize new areas (Geldenhuys, 1996b)

Only a few species with hard seeds were counted within the second group of Table 4.8. The two species with dry pods with dry hard seeds were *A. mearnsii* and *V. oroboides*. Both are known as light-demanding pioneer species. *Virgilia oroboides* was recorded just once in moist forest and once in the Distant zone of the Black wattle stand. The two other species with hard seeds were *Olinia vintosa* and *Diospyros glabra* but both have fleshy fruit and had a low presence within the Black wattle stand. Their presence in the clusters may be due to them being eaten by baboons and spread through dropped faeces (Table 4.7).

The reason why the third group of species was absent from the forest clusters is not clear. Most of those species (*Cassine peragua, Cussonia spicata, Curtisia dentata, Grewia occidentalis, Hartogiella schinoides, Podocarpus latifolius and Scutia myrtina*) have large fleshy fruits and 50% had soft small seeds. The large fruits may be too large to be dispersed by the smaller birds, but they can be eaten by the Rameron pigeon, some other intermediate-sized birds and by baboons. *Cussonia spicata* has relatively small fleshy drupes and could be dispersed by a variety of birds (Geldenhuys, 1996b). *Pittosporum viridiflorum* capsules open to expose the small orange seeds and are often dispersed by a variety of birds, but in the study area their source may be too distant for dispersal into the Black wattle stand. For more distant dispersal the frugivorous birds need to swallow the whole fruit or at least the seeds from very large fleshy fruits (Geldenhuys, 1996b). Sometimes when mammals such as the baboon and bush pig eat the fruit they may destroy the seed (such as of *Podocarpus latifolius* as shown by Geldenhuys, 1993b), but often some seeds escape destruction (Geldenhuys, 1996b). Several of the species in this group are associated with the Dry forest patches (Table 4.7), with most likely very limited exchanges of seeds taking place between these patches and the forest clusters. Dry forest patches occur south of the river at some distance from the river, with much human activity in the transition zone between the Dry forest patches and the Black wattle stand across the river. Physical obstructions and human activities have been listed among obstacles or limitations of seed dispersal (Hardwick et al., 1997).

The fourth group of species (only recorded in the forest clusters) generally has large fleshy fruits with mainly small soft seeds. *Halleria lucida* is present in low numbers in the moist forest but was not recorded within the sampled plots. *Searsia angustifolia* (L.)*, S. pyroides* and *S. tomentosa* (L.) F.A Barkley were more related to the drier forest margins and are dispersed by a variety of small birds and baboons. *Metrosideros angustifolia* (L.) J.E.Sm. grows along stream banks, often within the Fynbos biome. This is a light-demanding species with many-seeded small dry capsules which may be dispersed by wind and water. *Lantana camara* (L) is an invasive introduced species and has escaped from gardens through dispersal by a variety of birds. Most of the species within the group are known to be woody shrubs and early pioneer species during forest succession (Geldenhuys, 1993a).

Dispersal agents: Contributing factors for establishing forest clusters within the stand

Frugivorous animals disperse up to 90% of tropical tree species and between 30% and 50% of tree species in temperate zones (Howe and Smallwood, 1982). Large frugivorous mammals are also expected to disperse a wider range of fruit and seed sizes than smaller frugivors (Wilson and Downs, 2012).

The results of this study showed a dominance of trees with large fleshy fruit and small soft seeds suggesting that there are sufficient species that can potentially colonise the Black wattle stand. It is therefore comprehensible that birds and mammals constitute the major dispersal agents for this site. The fleshy part of the fruit or seed of most fruits is large enough to attract birds and mammals. It is generally said that in Africa, frugivorous birds play a more important role in forest seed dispersal than mammals and other mechanisms (Medellin and Gaona, 1999; Otsamo, 2000; Wilson and Downs, 2012). In the Buffeljagsriver area there were several bird species that could contribute to the dispersal of forest species. More detailed observations on the role of the Rameron pigeon and baboons is needed to understand their contribution to the dispersal process in the establishment and development of forest clusters within the wattle stand. The irregular flowering and fruiting phenology of many species may also play a role in their less active colonisation within the Black wattle stand (Geldenhuys, 1996a).

4.2.3.5 Conclusion

Forest clusters in the stand play a major role as a seed source of the surrounding regeneration. They were found to be main seed sources for the expansion of well-established forest clusters in the study area. In general, quantity of regeneration decreased with distance from forest clusters. Most of the species recorded in the forest clusters were found with seedlings in the surrounding area, with the exception of *Ocotea bullata* and *Olinia ventosa*. Both species generally produce small numbers of fruit and their relatively large fruit limit their dispersal over longer distances, except by agents such as the Rameron pigeon and baboons (Geldenhuys, 1996b).

Compiling the list of woody plant species from the area, with their associated fruit and seed characteristics based on literature, field observations together with information on the faunal diversity of the area as potential seed dispersal agents (Coates Palgrave, 2002; Mucina and Rutherford, 2006) proved to be useful for the interpretation of the observed patterns in forest cluster development within the black wattle stand. Species with large, fleshy fruits with small soft seeds dispersed by birds and mammals dominated the species distribution through the Black wattle stand. However, some species with similar fruit-seed characteristics with good regeneration in the forest patches where they are present, such as *Hartogiella schinoides*, *Podocarpus latifolius* and *Pittosporum viridiflorum,* were absent in the forest clusters. The reasons of this absence are speculative, and may be outside the possible limitations of dispersal. Very few exchanges were observed between dry forest patches and forest clusters. The distances and existence of natural obstacles could explain this low interaction. Some isolated species were found within the newly establishing clusters in the zones distant from large clusters and neighbouring forest patches. Their seed sources were not clear. Further studies with a focus on first establishing and isolating species are needed to provide a more conclusive interpretation on their absence from forest clusters.

4.2.4 Enclosure experiments in wattle stands

4.2.4.1 Wattle stands in selected plots

The selected stands were dominated by *Acacia mearnsii* but a small cluster of indigenous tree species was present in plot 2.1 with single stems of indigenous species present in plots 2.2 and 4.1 (Table 4.9). These plants were treated as part of the nurse stand.

Table 4.9 The stem density and mean stem diameter (DBH, cm) of the tree stands in the selected fenced and unfenced plots in the Wattle stand, Buffeljagsrivier.

Species	Variable	Plot (*n*.1 plots fenced; *n*.2 plots unfenced)								Species mean
		1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2	
Acacia mearnsii	Stems/ha	1775	2025	1100	1475	1350	1050	3075	1525	1671.9
	DBH, cm	11.4	9.7	12.1	12.4	11.7	12.0	9.5	10.8	10.9
Canthium inerme	Stems/ha	-	-	-	25	-	-	-	-	3.1
	DBH, cm	-	-	-	3.6	-	-	-	-	3.6
Gymnosporia buxifolia	Stems/ha	-	-	125	-	-	-	-	-	15.6
	DBH, cm	-	-	7.1	-	-	-	-	-	7.1
Halleria lucida	Stems/ha	-	-	25	-	-	-	-	-	3.1
	DBH, cm	-	-	14.0	-	-	-	-	-	14.0
Solanum mauritianum	Stems/ha	-	-	50	-	-	-	25	-	9.4
	DBH, cm	-	-	4.8	-	-	-	7.5	-	5.7
Plot	Stems/ha	1775	2025	1300	1500	1350	1050	3100	1525	1705.1
	DBH, cm	11.4	9.7	11.4	12.2	11.7	12.0	9.5	10.8	10.8

Twelve species (two invasive and 10 indigenous) were recorded in the eight demarcated plots (Table 4.10). The mean density and height of the two introduced species suggest that they may be stunted individuals that may be part of the original invasive plant stand. The three main species in the selected plots were *Celtis africana, Gymnosporia buxifolia* and *Vepris lanceolata*. The mean density and height of the marked seedlings in the selected fenced and unfenced plots were used as a basis to follow the development of the natural forest species under the wattle stands. The seedlings in the demarcated plots were re-measured at regular intervals, i.e. every 6 months during the first year and thereafter once a year for five years.

Table 4.10 Mean density and height of forest regeneration under wattle in the selected plots

Species	Variable	Plot (*n*.1 plots fenced; *n*.2 plots unfenced)								Species mean
		1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2	
Acacia mearnsii	Stems/ha	-	-	-	75	25	25	-	25	18.8
	Height cm	-	-	-	167.8	186.5	226.0	-	30	157.7
Solanum mauritianum	Stems/ha	50	100	125	50	-	25	-	150	62.5
	Height cm	30.5	17.8	57.9	185.0	-	69.0	-	59.3	60.8
Celtis africana	Stems/ha	875	125	450	100	100	450	300	600	375.0
	Height cm	42.5	36.9	39.6	31.1	35.8	46.7	34.5	26.3	37.8
Gymnosporia buxifolia	Stems/ha	350	125	1700	75	25	-	275	125	334.4
	Height cm	22.1	14.6	97.1	28.3	10.5	-	24.2	87.0	72.7
Vepris lanceolata	Stems/ha	50	25	25	25	25	325	25	50	68.8
	Height cm	16.0	10.0	32.0	9.0	30.0	59.3	25.5	23.0	43.5
Canthium inerme	Stems/ha	-	-	-	150	-	-	-	-	18.8
	Height cm	-	-	-	177.8	-	-	-	-	177.8
Olea europaea africana	Stems/ha	-	25	-	25	-	-	75	-	15.6
	Height cm	-	47.0	-	57.0	-	-	36.4	-	42.6
Scutia myrtina	Stems/ha	-	-	75	-	-	-	25	-	12.5
	Height cm	-	-	37.7	-	-	-	281.0	-	98.5
Canthium mundianum	Stems/ha	-	25	-	-	-	-	-	-	3.1
	Height cm	-	32.0	-	-	-	-	-	-	32.0
Rhus species	Stems/ha	25	-	-	-	-	-	-	-	3.1
	Height cm	285	-	-	-	-	-	-	-	28.5
Halleria lucida	Stems/ha	-	-	-	-	-	-	25	-	3.1
	Height cm	-	-	-	-	-	-	15.5	-	15.5
Grewia occidentalis	Stems/ha	-	-	-	-	-	-	25	-	3.1
	Height cm	-	-	-	-	-	-	13.5	-	13.5
Plot	Stems/ha	1350	425	2375	500	175	825	750	950	918.8
	Mean height	35.5	24.6	81.5	110.8	52.9	57.8	37.5	39.4	58.5

4.2.5 Biomass equations for selected indigenous trees

4.2.5.1 Estimation of biomass equation at the sample level for *Celtis africana*

Different models were formulated for biomass prediction (Figure 4.9). However the transformed linear models were selected for the best fit. The relationship of Model 2.1 was observed when the logarithmically transformed (ln) stem (indicated as branch diameter) was plotted against logarithmically transformed dry mass of the stem (indicated as dry mass branch, branch wood and foliage). Results from linear regression within branch row showed that all models were significant ($p < 0.05$). Furthermore, the slope associated with the stem diameter was highly significant ($p < 0.001$) and directly proportional to the stem biomass. Model 2.2 was the best fit, and model 2.3 had the lowest R^2. An Allometric function of tree components is presented in Table 4.11.

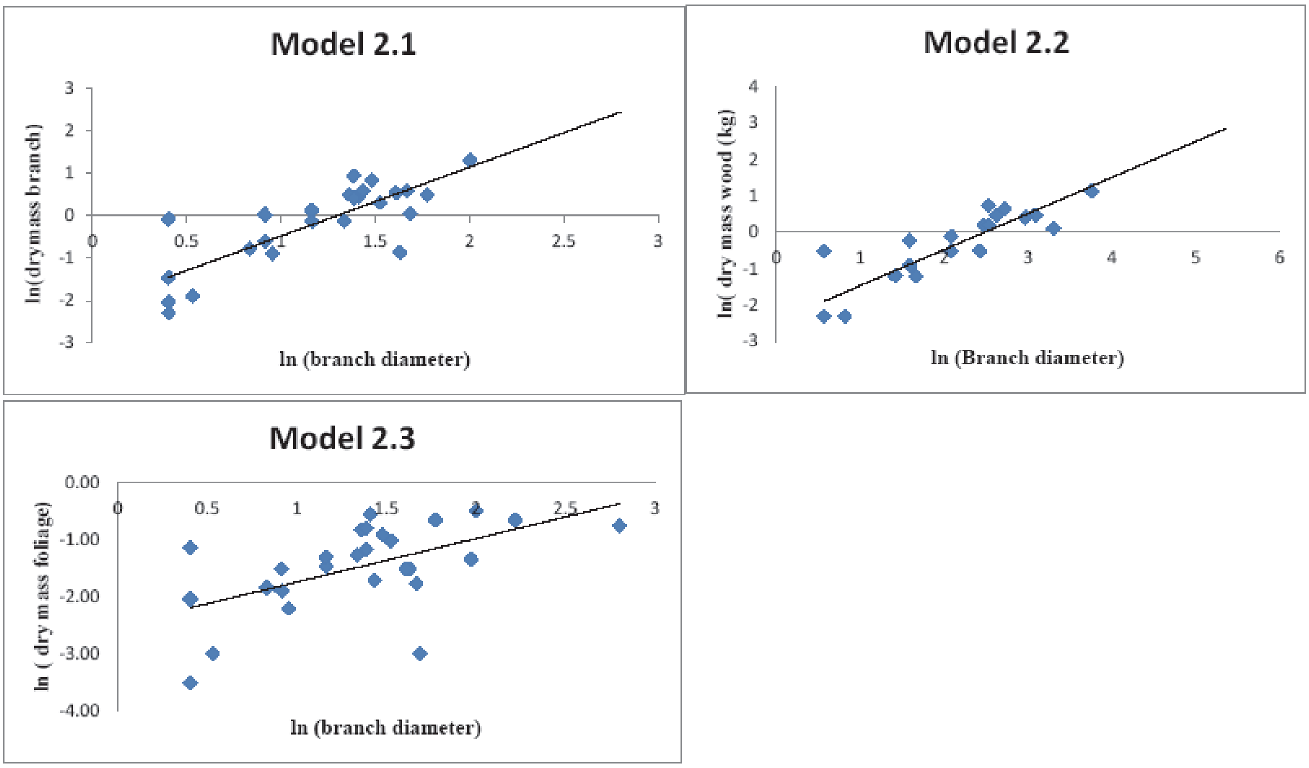


Figure 4.9 Relationship between log transformation of branch diameter (In branch diameter) and log transformation of dry mass branch, wood and foliage for *Celtis africana*.

4.2.5.2 Estimation of biomass equation at the sample level *Rapanea melanophloeos*

Nine models were used to predict the biomass of this species, however models 2.4, 2.5 and 2.6 presented the best fit, representing the relationship between logarithm transformed stem (indicated as branch diameter) with dry mass of the stem components (indicated as dry mass branch, branch wood and foliage) (Figure 4.10). The results showed that all models were significant $p < 0.05$, though the model of leaf biomass (Model 2.6) was the best model with the highest R^2 value (R^2=0.801).

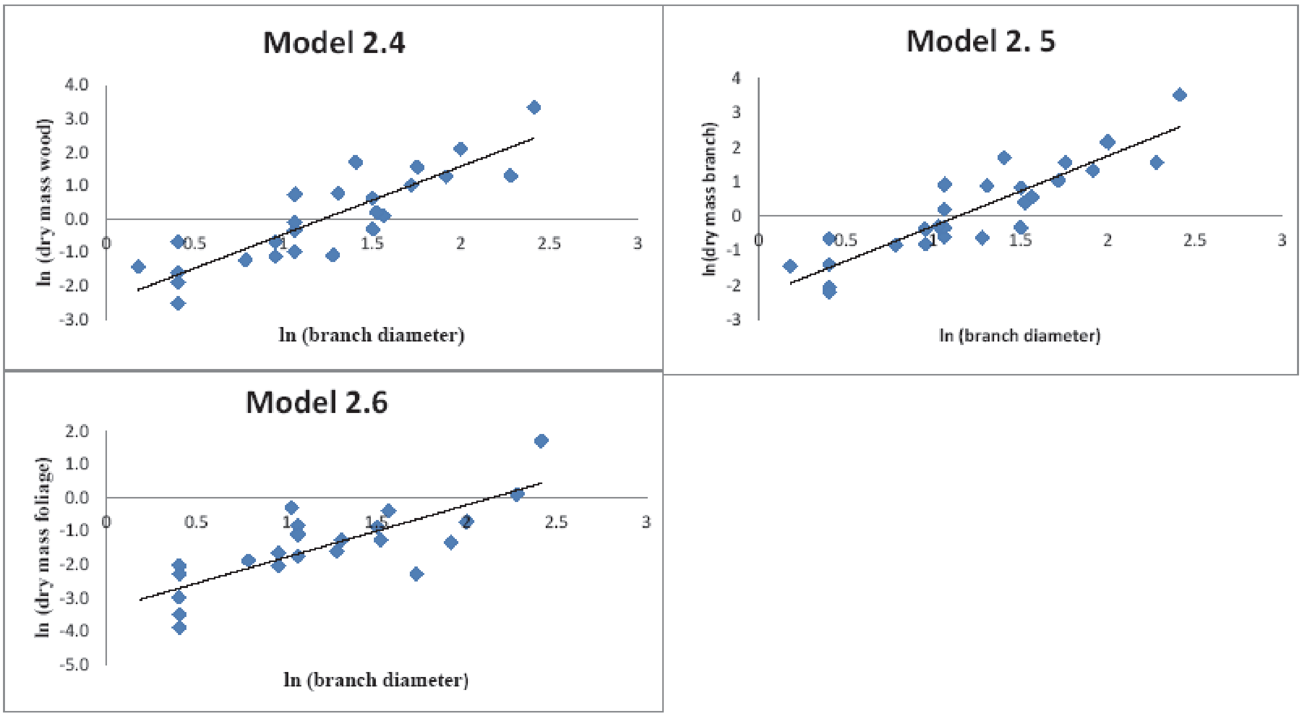


Figure 4.10 Relationship between logarithm transformed stem (indicated as branch) diameter and dry mass of stem (indicated as branch), branchwood wood and foliage of *Rapanea melanophloeos.*

4.2.5.3 Estimation of biomass equation at the sample level *Vepris lanceolata*

Biomass prediction Models 2.7, 2.8, and 2.9 were tested for fit, with logarithm (ln) transformed stem (indicated as dry mass foliage, wood and foliage). The results showed that the linear regression of Models 2.7, 2.8, and 2.9 were all good fits (Figure 4.11).

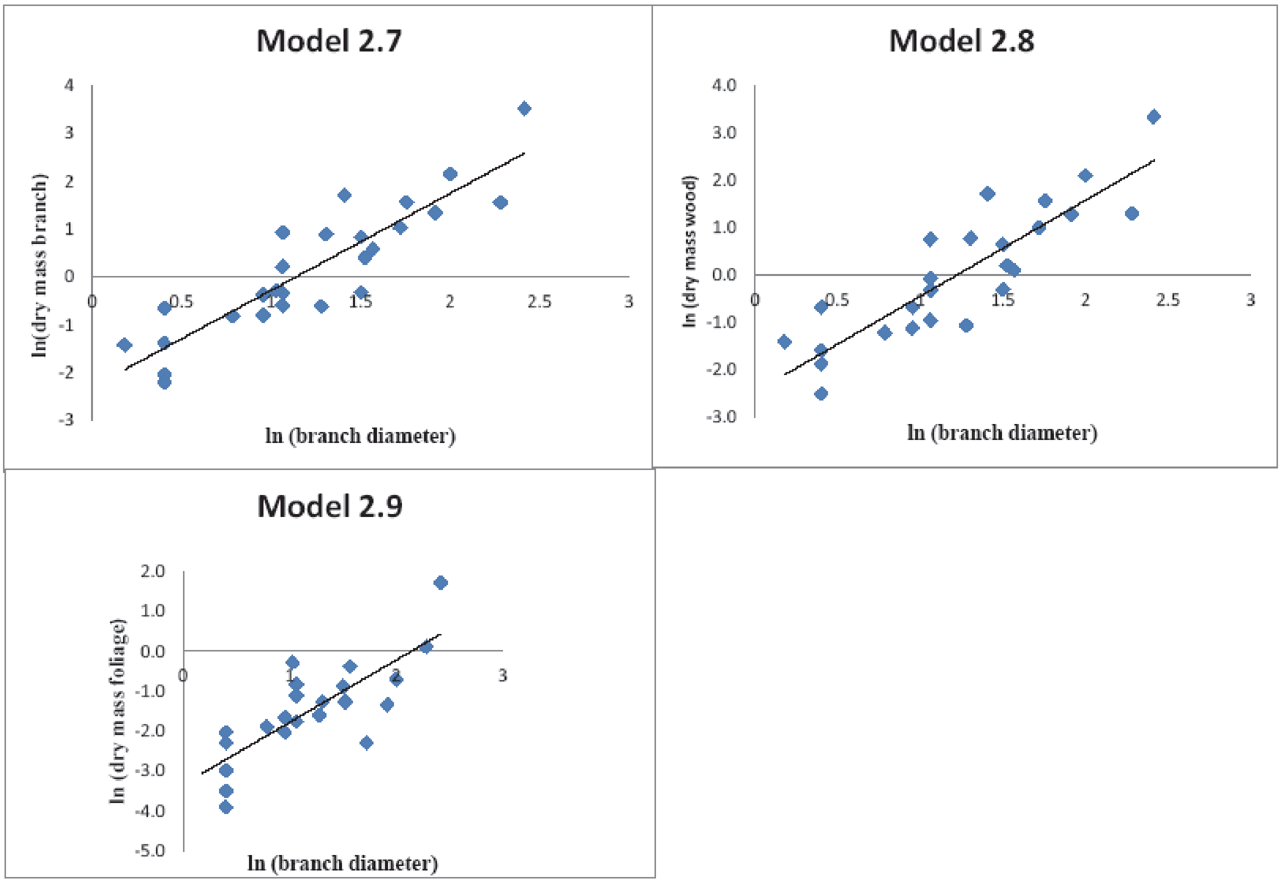


Figure 4.11 Relationship between logarithms transformed of branch diameter (ln branch diameter) and log transformation of branch with dry mass branch of *Vepris lanceolata.*

Table 4.11 Allometric function of tree components

Species	Stem (indicated as Branch)	Branchwood	Foliage
	Allometric equations		
Celtis africana	ln BMbranch = -2.0968 + 1.6223*ln (D)	ln wood = -2.6929 + 1.9745 * ln (D)	lnfoliage == -2.6669 + 0.7106 *ln (D)
Vepris lanceolata	lnBMbranch = -2.302 + 2.0266* ln (D)	ln wood =- 2.4893 + 2.0331 * ln (D)	ln foliage =- 3.3506 + 1.5624 * ln (D)
Rapanea melanophloeos	ln BMbranch = -3.1308 + 2.374 *ln (D)	ln wood =- 3.3593 + 2.4188)* ln (D)	ln foliage = - 4.3633 + 2.1101 * ln (D)

4.2.5.4 Estimation of tree biomass equation at the tree level for *Celtis africana*

Results from the transformed linear regression showed that stem (indicated as branch diameter) explained 91% of the variation in total biomass and the model was significant ($P < 0.05$) (Figure 4.12).

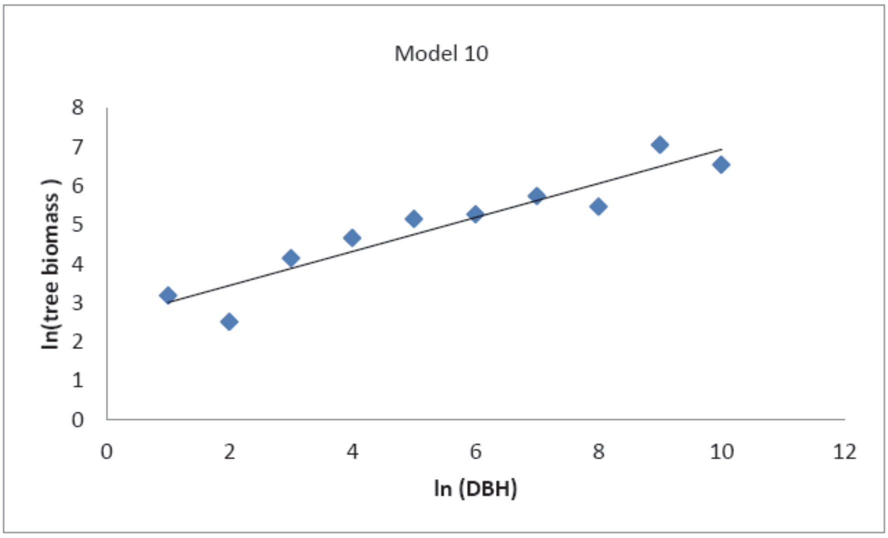


Figure 4.12 Relationship between dbh and logarithm transformed of total tree biomass of *Celtis africana*

4.2.5.5 Estimation of biomass equation at the tree level for *Vepris lanceolata*

Results from the transformed linear regression showed that stem (indicated as branch diameter) explained 94% of the variation in total biomass, and the model was significant (P < 0.05) (Figure 4.13).

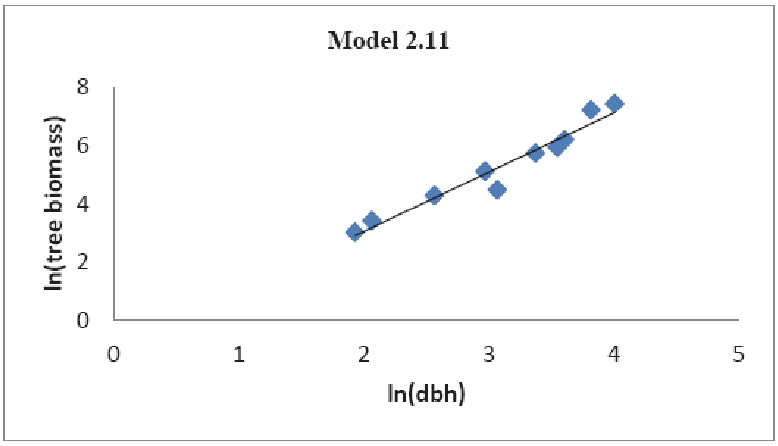


Figure 4.13 Relationship between ln dhb and logarithm transformed (Figure 4.13) total tree biomass of *Vepris lanceolata* Model 2.11

4.2.5.6 Estimation of biomass equation at the tree level for *Rapanea melanophloeos*

Results from the transformed linear regression showed that stem (indicated as branch diameter) explained 86% of the variation in total biomass, and the model was significant (P < 0.05) (Figure 4.14).

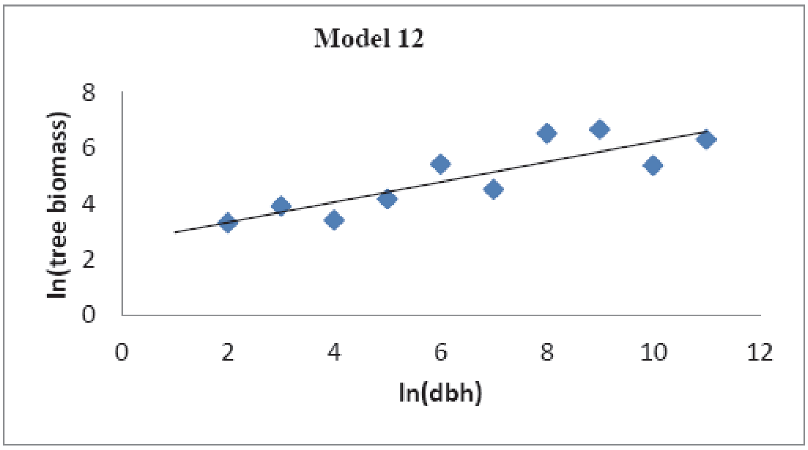


Figure 4.14 Relationship between dbh and logarithm transformed of total biomass of *Rapanea melanophloeos.*

4.2.5.7 Discussion

The specific study objective was to develop allometric equations for three natural forest species. In previous studies two different models were developed, with diameter at breast height (1.3 m), and height, as variable predictors (Brown, 1997). Since the trees from this study were obtained from a confined area with similar conditions, height did not add additional predictive value to the model. This was also observed by Van Laar & Geldenhuys (1975) for indigenous forest species in the Southern Cape, and Phiri (2013) for Eucalypts. The present study showed that the different models developed to estimate above ground biomass at the sample level for the three indigenous tree species were successfully fitted. The results from an estimation of above-ground tree biomass of the three indigenous tree species, based on criteria of the coefficient of determination (R^2), showed that *Vepris lanceolata* had the highest R^2 values (0.8021) followed by *Rapanea melanophloeos* (0.7517) and *Celtis africana* (0.6345).

The geometric approach to estimate oven dry biomass proposed by Seifert and Seifert (2014) was a function of stem volume multiplied by basic wood density. Stem biomass was calculated by using Smalian's formula (Seifert and Seifert, 2014). The basic density reported by Carsan et al. (2012) was 640-820 kg/m^3 for *Celtis africana*, 740-1060 kg/m^3 for *Vepris lanceolata* and 680-845 kg/m^3 for *Rapanea melanophloeos*. In comparison the average basic density obtained by the CT scanner method was 879 kg/m^3 for *Celtis africana*, 1039 kg/m^{3}for *Vepris lanceolata*, and 806 kg/m^3 for *Rapanea melanophloeos*. The total tree biomass was equal to summation of biomass of components (wood, foliage) and biomass of stem volume (stem with bark) (Parresol, 2001).

4.2.5.8 Conclusion

This study produced the equations to estimate the above ground tree biomass of the three indigenous tree species (*Celtis africana*, *Vepris lanceolata*, and *Rapanea melanophloeos*). Different models were developed to estimate the biomass for tree component level and total tree level. The model statistics of total tree biomass of *Celtis africana, Vepris lanceolata, and Rapanea melanophloeos* was significant $p < 0.05$. The diameter at breast height (dbh) associated with the slope was significant $P < 0.001$; however the independent parameter tree height was not significant in this study. The results from linear regression of branch diameter explained 91% of the variation of *Celtis africana*, 94% of the variation for *Vepris lanceolata* and 86% of the variation for *Rapanea melanophloeos*. The results revealed that the *Vepris* *lanceolata* had the highest biomass per dbh, while *Rapanea melanophloeos* and *Celtis africana* were lower but similar.

4.3 Hydro-meteorological Findings

4.3.1 Climate

Analysis of the synthesis of observed rainfall at Buffeljagsrivier indicated a MAP of 636 mm (Figure 4.15). The lowest rainfall year recorded was 1882 with 308 mm and a maximum of 1045 mm in 1906. Nearby stations were checked to see if there were inconsistencies in these extreme years.

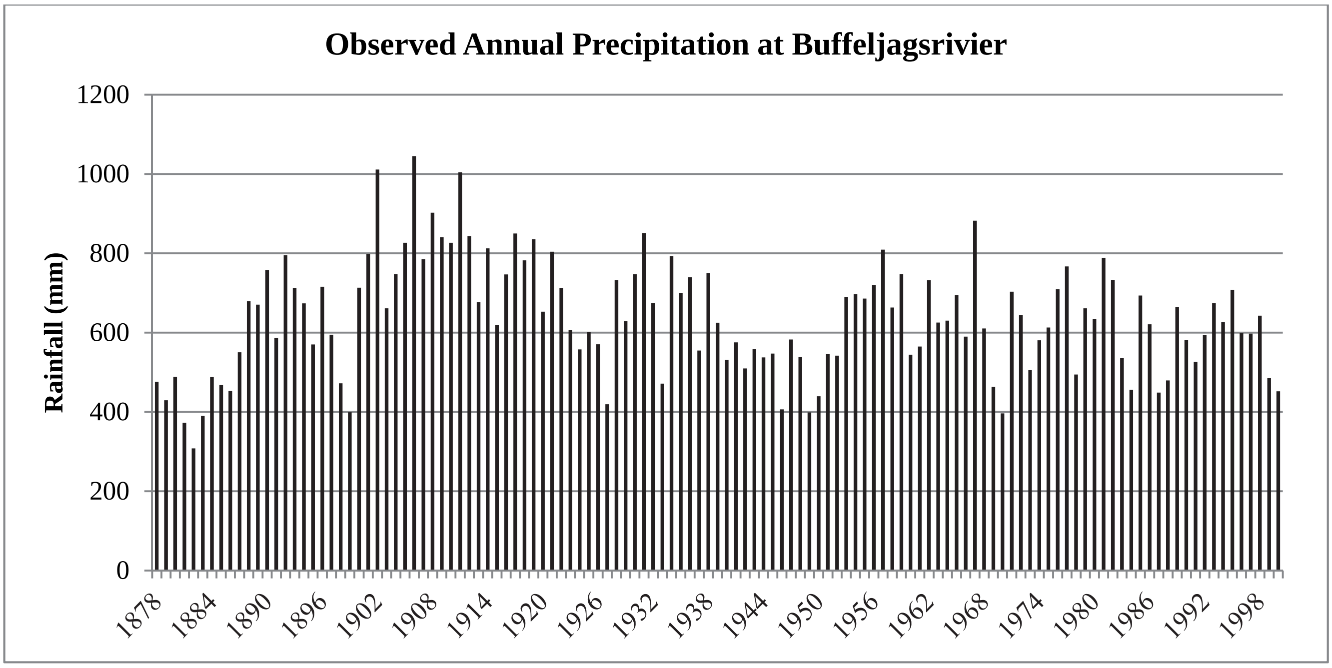


Figure 4.15 Annual precipitation recorded at rainfall stations near Buffeljagsrivier (1878 to 2000)

Climate data is important for the interpretation of tree water-use measurements. The climate data is used to "patch" any periods with missing sapflow data, using relationships developed with the vapour pressure deficit and solar radiation, which are both strongly correlated to hourly sapflow. The measurements were also used to calculate reference evapotranspiration (ET_O) (Allen, et al., 1998). The data collected from the Buffeljagsrivier station were of high quality. Hourly and daily data (Figure 4.16 to Figure 4.17) were collected during the measurement period.

The rainfall at Buffeljagsrivier (Figure 4.16) showed that although there was an increase in rainfall during the winter period, the difference was small and the rainfall was fairly uniform throughout the year. Between the periods of 25th January 2012 and 12th December 2013, 1903 mm of rainfall fell. For the hydrological year (1st October 2012 to the 1st October 2013), 902 mm of rainfall was recorded. In mid-October, when the solar radiation had reached its maximum, there was the greatest amount of rainfall. There were numerous days of high hourly rainfall demonstrating the prevalence of high intensity storms at the site. The solar radiation peaked at 1000 W.m^{-2}, where the seasonal trend showed that the lowest radiation period was during June and the highest during January and December.

The Vapour Pressure Deficit (VPD) is the difference between the amount of moisture in the air and the amount of moisture the air can potentially hold at saturation. VPD was calculated using Relative Humidity (RH) and average temperature. The RH ranged from 20% to 90%, with little seasonal trend (Figure 4.17). When RH was at its lowest, VPD was at its highest. During these periods, the atmospheric demand was high causing the transpiration to peak. The VPD was closely related to plant water-use.

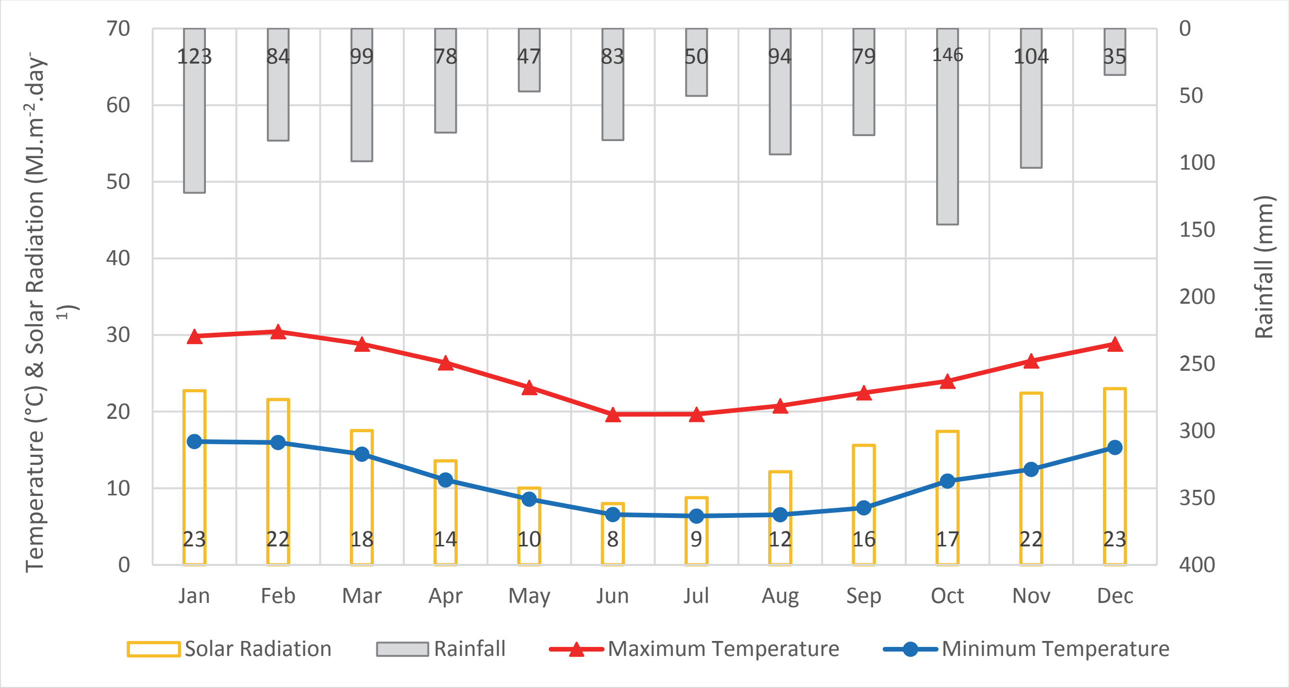


Figure 4.16 Aggregated monthly values of maximum and minimum temperatures (°C), rainfall (mm) and solar radiation (MJ.m^{-2}.day^{-1}) at Buffeljagsrivier

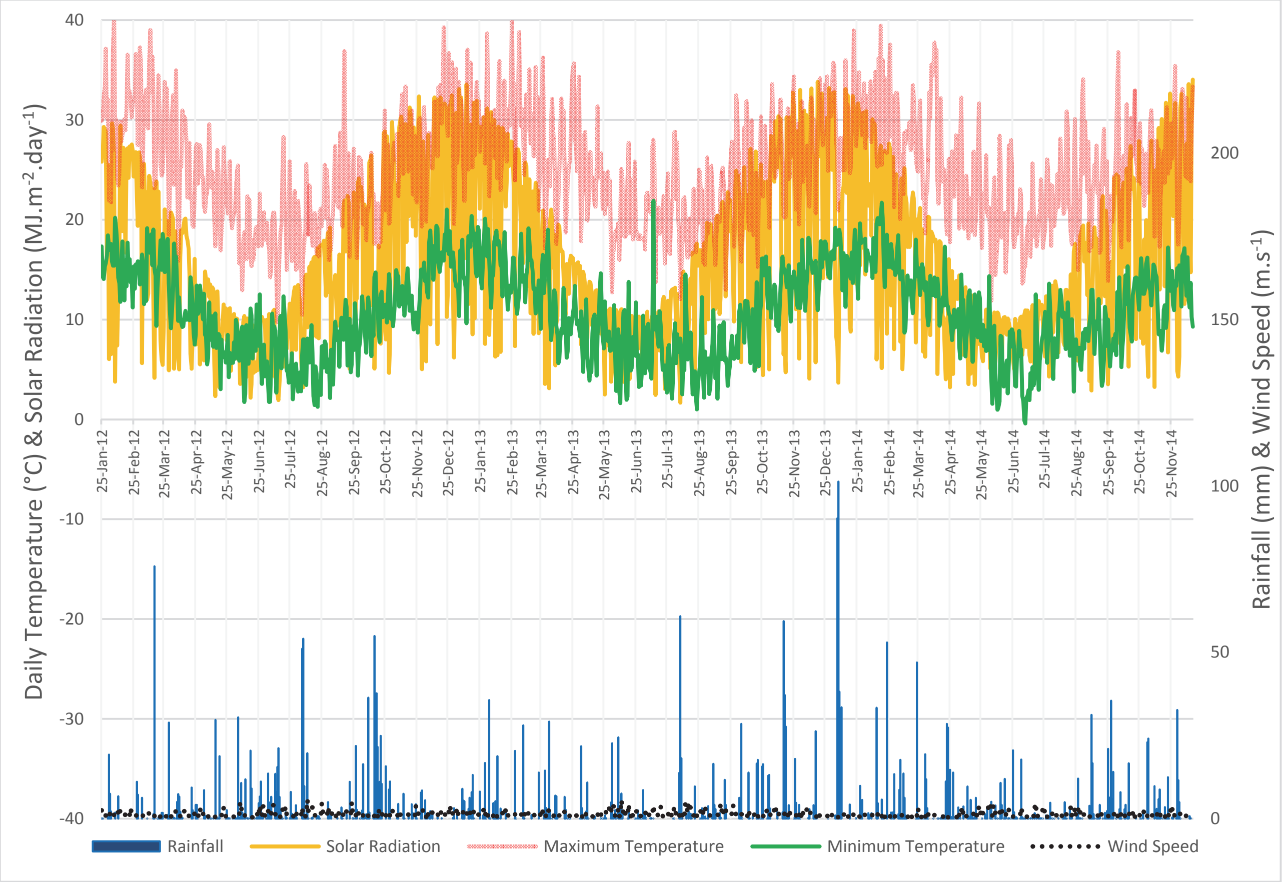


Figure 4.17 Daily values of maximum and minimum temperatures (°C), solar radiation (MJ.m^{-2}.day^{-1}), rainfall (mm) and windspeed (m.s^{-1}) at Buffeljagsrivier from January 2012 to November 2014

An average daily temperature of 22.1 ºC was recorded at Buffeljagsrivier in the summer months. During these months, daily maximum temperatures reached in excess of 40 ºC. During the wet winter months, the temperatures averaged 12.1 ºC due to numerous days of low solar radiation during this period. Periods of low solar radiation corresponded to rainfall (and cloudy days) and would likely result in little to no transpiration occurring. The average daily wind speed peaked at 5.7 m.s^{-1}, which is approximately 20.5 km hr^{-1}.

The daily ET$_o$ average from approximately 1 mm in the winter period to 4 mm during summer. The daily ET$_o$ peaked at 7.5 mm, which is considered high for reference evaporation. When the temperature was at its highest, the ET$_o$ was also at its peak due to a greater atmospheric demand. Due to these findings, the water-use measurements were expected to be high during this period.

The volumetric water content in the alien stand at Buffeljagsrivier (Figure 4.18) was generally very low. During high rainfall events the soil-moisture content exceeded 20% and was close to the field capacity (FC) of 15% (sandy-clay-loam). All the horizons showed a rapid but short response to rainfall, showing that the soil water moves through this horizon rapidly. However, very little water was stored in the lower profile. The shallow rooting observed in the soil profile indicates that water was available to the roots in the shallow horizons. This was particularly evident in the alien stand where fallen *Acacia mearnsii* trees were common, revealing a very shallow and dense rooting system characteristic of aggressive pioneer species. Due to the high porosity of the soil (very sandy texture) the infiltration drained vertically very quickly.

In the indigenous stand (Figure 4.19), the middle TDR probe (0.3 m) showed the highest water content. This was evident in the soil samples taken where there was a high organic content below the Orthic-A horizon. During the warmest period (December 2012 to April 2013) there was very little water in the horizons (even after rainfall events). This would suggest that the deeper roots from the indigenous species were readily using this water. In contrast, the alien stand upper soil profile was more responsive to the same rainfall events suggesting that interception (throughfall and stemflow) played a significant role when comparing these stands. The data from these pits were used to derive relationships between the actual transpiration measured using the HPV system.

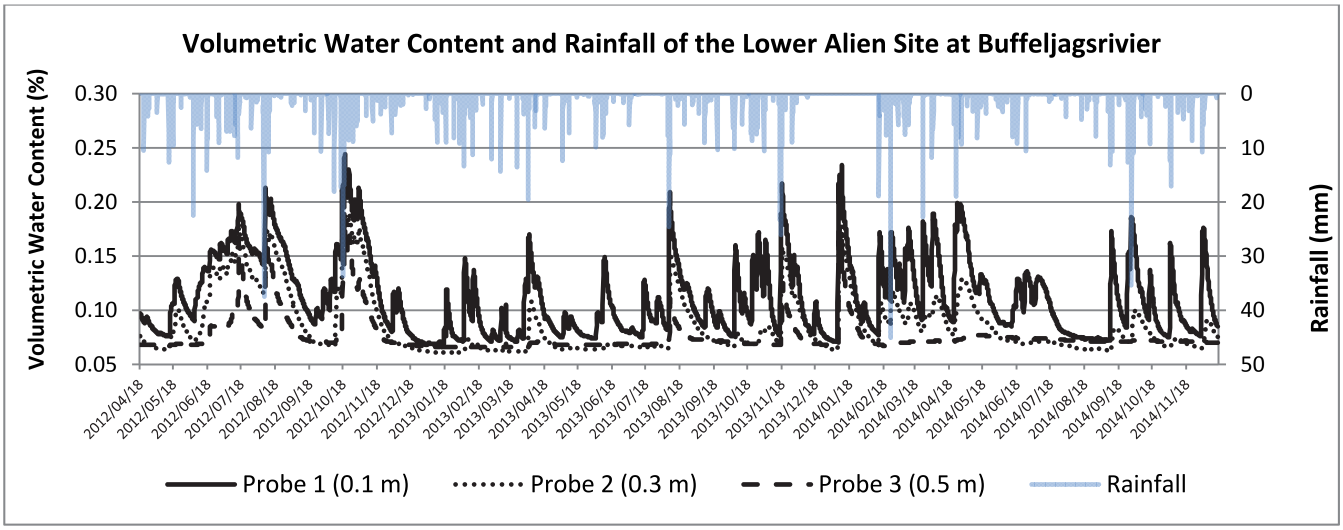


Figure 4.18 Three hourly volumetric water content of the upper indigenous stand corresponding to the three hourly accumulated rainfall at Buffeljagsrivier (April 2012 to December 2014)

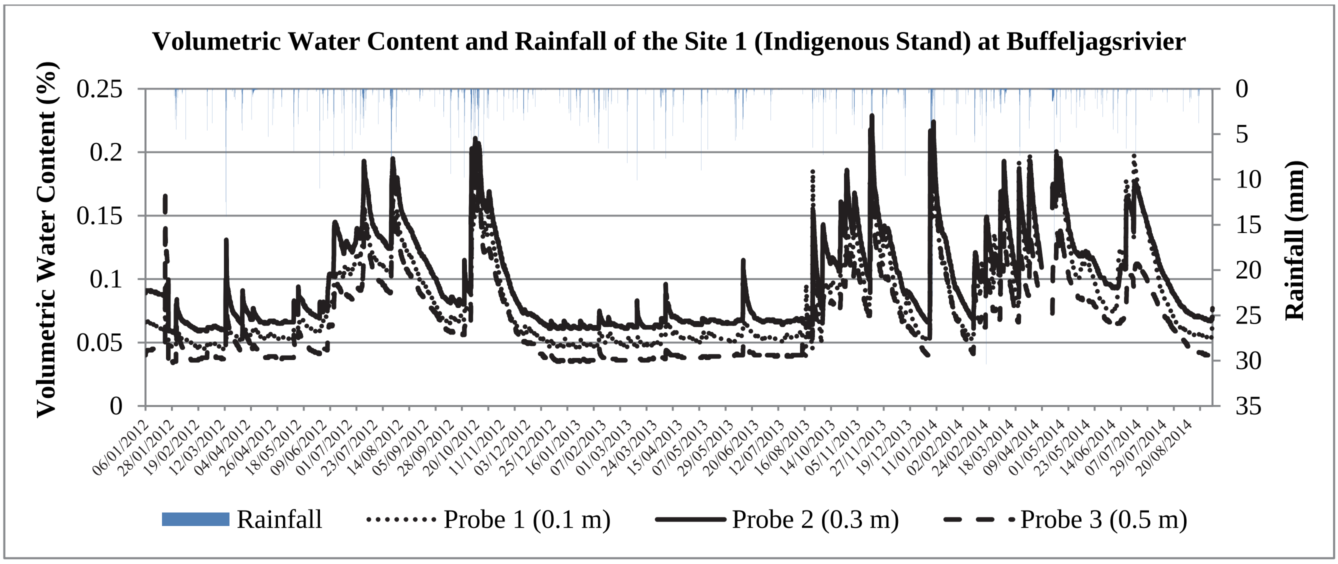


Figure 4.19 Hourly volumetric water content of the upper indigenous stand corresponding to the hourly rainfall at Buffeljagsrivier (June 2012 to December 2014)

The water quality results are presented in Table 4.12. Salinity was a measure of the total amount of dissolved salts in water, measured in parts per thousand (‰). The initial result of 0.17 ‰ indicated that the sample was fresh water. The total dissolved solids (TDS), which is a measure of the organic and inorganic substances contained in the water, was well within the global drinking standard of not more than 500 mg.L^{-1}. The conductivity (measure of the ability of a volume of water to conduct electricity), which is linked to TDS, was also in the fresh water range at 25.8 µS.cm^{-1}. Dissolved oxygen (waste product of photosynthesis) is harmful to aquatic life if the levels exceed 110%. The pH was determined by the concentration of hydrogen ions in a solution. It is an important indicator of water quality as heavy metals can be toxic under certain pH levels. An interesting finding was the difference between the pH in the river and the alien stand borehole which indicated a more acidic environment under the alien stand.

Table 4.12 Water quality measurements of samples taken from the Buffeljagsrivier

	Temperature	Atmospheric Pressure	Dissolved Oxygen		Conductivity	Total Dissolved Solids	Salinity	pH
	ºC	mmHg	%L	mg.L^{-1}	µS.cm^{-1}	Mg.L^{-1}	‰	
Site 1	12.2	753.1	63.0	6.69	258.7	222.3	0.16	7.79
Site 2	11.8	753.1	62.4	6.68	257.0	222.9	0.17	7.74
Site 3	11.8	753.1	63.8	6.84	256.8	222.9	0.17	7.72
River	11.3	753.1						7.05
Borehole	16.5	753.1						5.86

*borehole depth measured at 3.76 m and an ORP of -71 mV

4.3.2 Water-use

Although the initial probe insertion depths were determined by the analysis of a core sapwood sample, some probes had to be readjusted after analysis of the initial sap flow results. It is likely that these complications were due to asymmetrical sapwood profiles, resulting in the last probe being installed into the heartwood where little or no sapflow occurs. The first month of measurements allowed for the insertion depths to be adjusted to the correct depth.

Regular maintenance of the equipment was undertaken as the probes were susceptible to movement/damage following storms and animal disturbance. With the heavy storms that occurred during the measurement period, the probes in some of the trees moved or were damaged. If any broken equipment was found, it was replaced during the site visits. The *Celtis africana* trees at Buffeljagsrivier (Figure 4.20) were highly acidic and resulted in corrosion of the heater probes. A new protective brass sheath was developed to prevent this corrosion and was installed in February 2014.

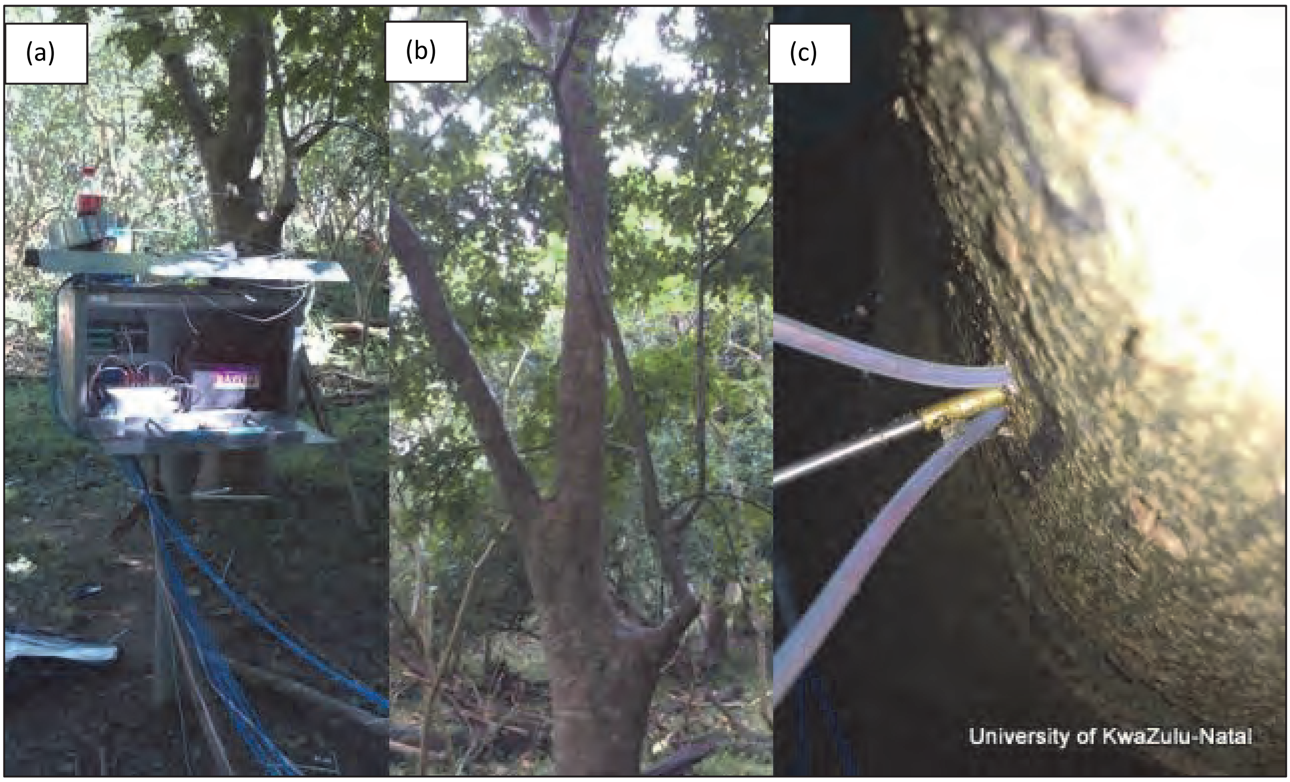


Figure 4.20 Acidic *Celtis africana* (a: Tree 10), the HPV system (b) installed at the extended *Celtis* site and the brass sleeves installed (c) at Buffeljagsrivier

For comparative purposes the water-use of similar sized *Vepris* and *Acacia* trees were analysed. During the dry summer month of January, the *Vepris lanceolata* tree sapflow exhibited smooth bell shaped curves indicative of the clear sunny days typical at this time of year in the winter rainfall region. The midday peak heat pulse velocity was between 6 and 12 cm.hr^{-1} on cool and hot days respectively. During the 24 hour rainfall period on the 24/01/2012 there was little to no water-use in this tree (< 1 cm.hr^{-1}) due to the low evaporative demand and wet canopy. The highest midday sap flows (8-12 cm.hr^{-1}) were measured at the probes installed 0.5 and 1.5 cm below the bark. In the deeper probes, sap flows were consistently lower with maximum rates between 2-6 cm.hr^{-1}. The data generally showed a decrease in sap flow towards the heartwood in the older xylem vessels.

The ability to insert probes at precise depths is an advantage of the instruments used in this study. The smooth shape of all the probe data on clear days indicated that they were all positioned within the sapwood area. These data illustrate the importance of distributing the probes at all depths within the sapwood to accurately represent the variable nature of the water flow across the sapwood. Probes inadvertently inserted into the heartwood where no conductance occurred were gradually moved back during the installation period to just obtain flow in the deepest portion of the sapwood.

In comparison, the *Acacia mearnsii* tree at the same site had maximum heat pulse velocities between 10 and 22 cm.hr^{-1}, almost double the sapflow rates found in the *Vepris lanceolata* tree (Figure 4.21). The water-use was also low during the rainfall period but still higher than that of the indigenous tree. As the sapwood depth varied between size and species of trees, it was important to compare the water-use per tree for all four probes to include the variability in sapflow rates across the sap wood. Comparing the four probes provides an insight into how the sapflow rates vary across the tree (radial profile). Scaling-up the total tree water-use measurements is important for understanding the stand water-use of each community (e.g. a canopy of an indigenous tree may cover more area than a canopy of an introduced tree). Sapwood depth, density and moisture content measurements were taken from similar sized trees to those of the selected trees in order to obtain individual tree water-use estimates. Although the highest sapflow of the *A. mearnsii* tree was also at 1.5 cm, there was an opposite trend to *Vepris* with sapflow increasing with depth.

During the wet winter period all trees except the *Celtis* cluster still had a high LAI. The indigenous patch in the wattle site had an LAI of 3.4 which was higher than the LAI of 3.1 under the nearby *A. mearnsii* trees. The indigenous trees in the upper reach indigenous site had an LAI of 3.6. Comparison of the tree water-use showed that the *Vepris* tree was transpiring at lower rates (peaks of 12 cm.hr^{-1}) than the *A. mearnsii* tree (peaks of 20 cm.hr^{-1}). *Vepris* was more responsive than the *A. mearnsii* tree to a 18.8 mm rainfall event (18/05/2012). This indicated that the introduced tree was using more water in the lower soil horizon, possibly due to a deeper root system, suggesting that the introduced tree had better access to water than the indigenous tree.

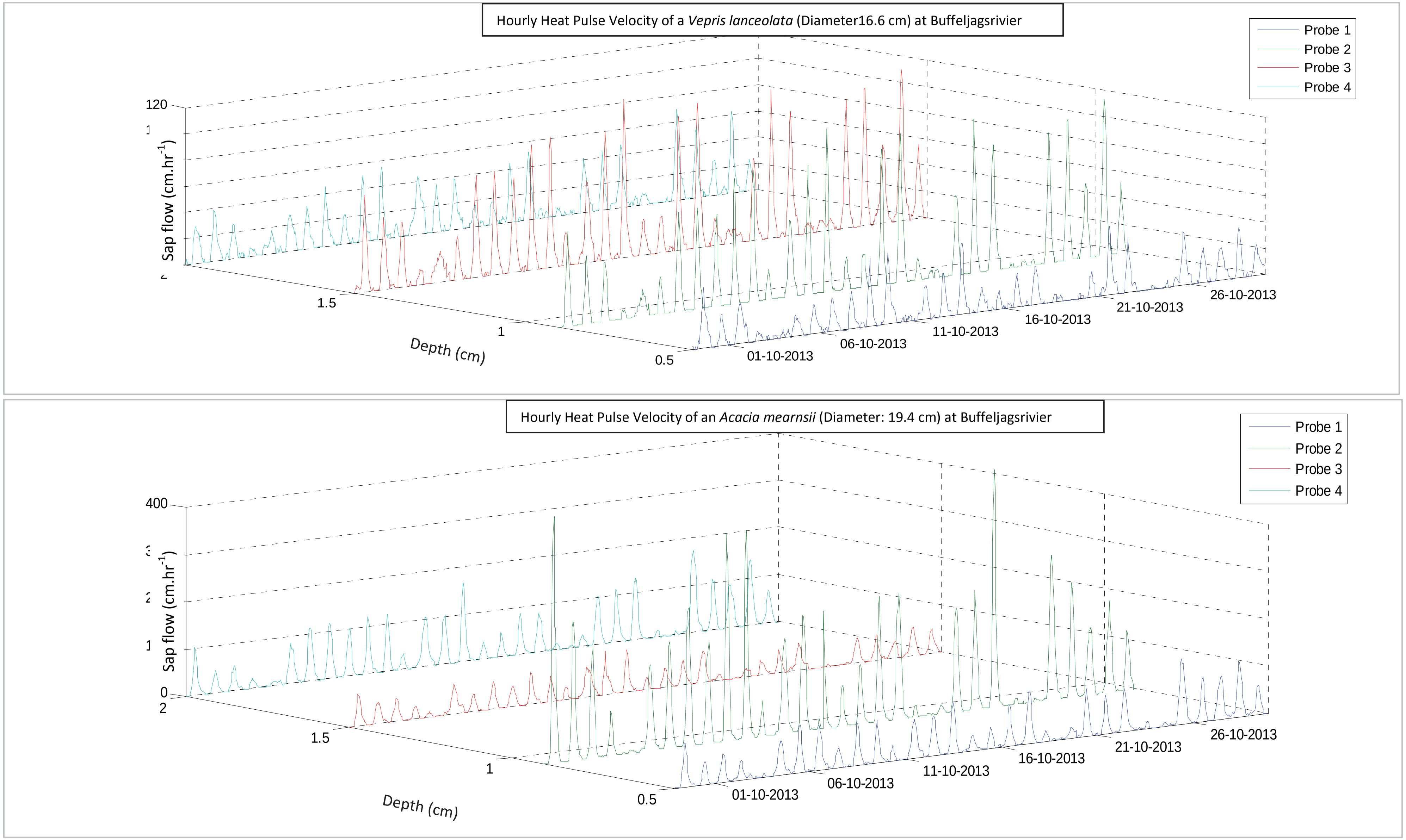


Figure 4.21 Radial sap flow profile for a *Vepris lanceolata* (Lower site) and an *Acacia mearnsii* (lower site) at Buffeljagsrivier

The three indigenous trees (Tree 1, 2 & 3) in the lower reach wattle stand at Buffeljagsrivier (Figure 4.22) showed significant differences in their daily sap flow rates. During the first 6 months of measurements, Tree 1 in the alien stand averaged 16 L.day^{-1}, compared to 15 L.day^{-1} from the slightly smaller tree 2 and 32 L.day^{-1} from the bigger Tree 3. Sap flow rates reduced distinctly in May and June for most of the trees, dropping from approximately 20 L.day^{-1} in April to 5 L.day^{-1} in June for Tree 2. This was attributed to there being less available energy at this time of year to drive the transpiration process. There was also a shorter period of energy available due to less daylight hours in the winter months. From November 2012 to March in 2013, all three trees showed a significant increase (doubling) in water-use during this hot summer period (Figure 4.22).

The water-use in the *Acacia mearnsii* trees (Figure 4.23) showed a distinct peak in transpiration during the months of March 2012, September 2012 and February 2013. During March 2012, there were high average temperatures (21.45 ºC), a 76 mm rainfall event and high daily vapour pressure deficits (VPD) (average of 1.26 kPa) which is an indication of high atmospheric demand. Under a high VPD and high soil water, the trees would be expected to use more water. The average daily sap flow ranged from 35 L (Tree 4) to 25 L (Tree 5) and 15 L (Tree 6). The low values for Tree 6 could be due to poor health or competition for light and soil water.

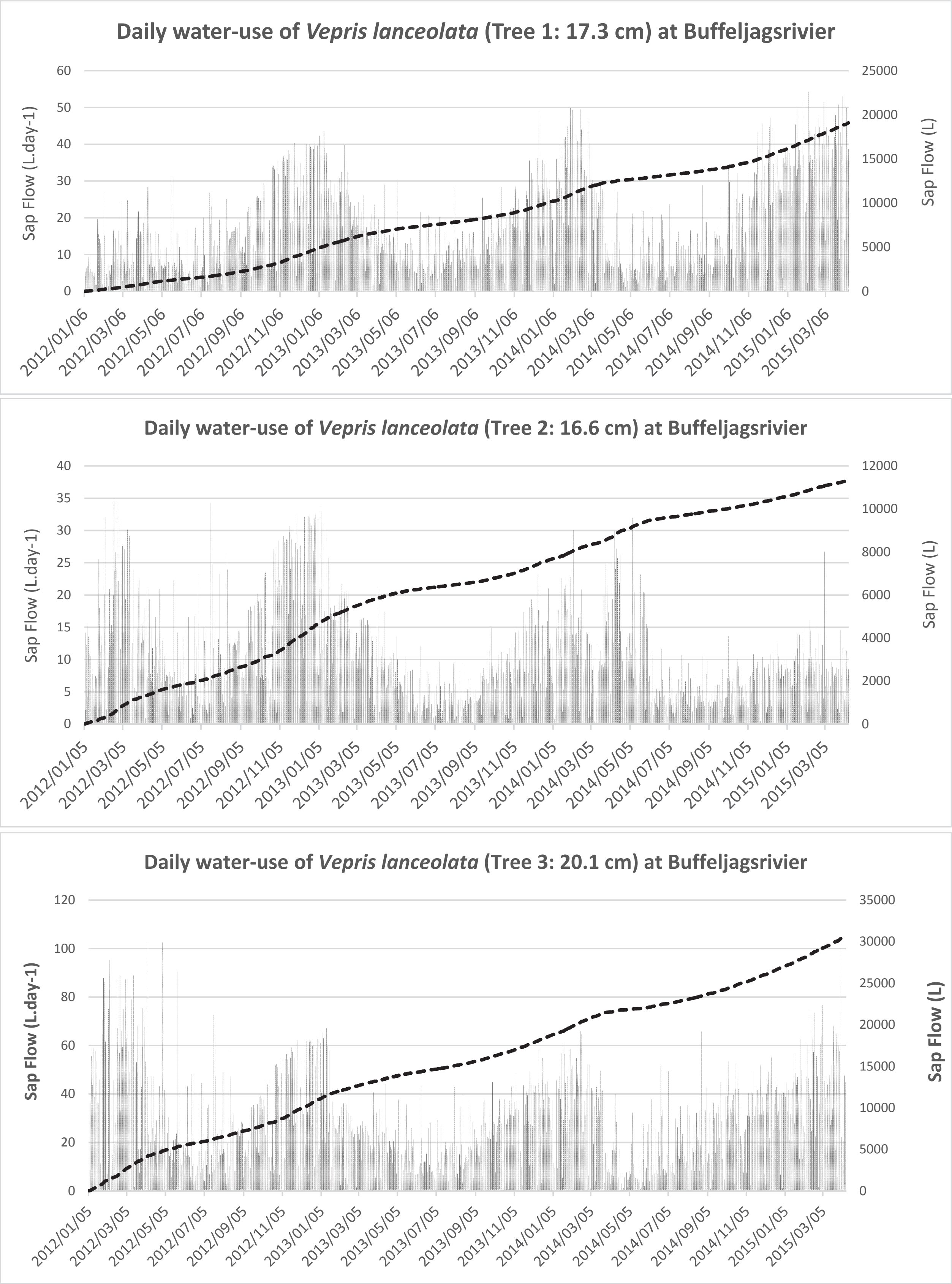
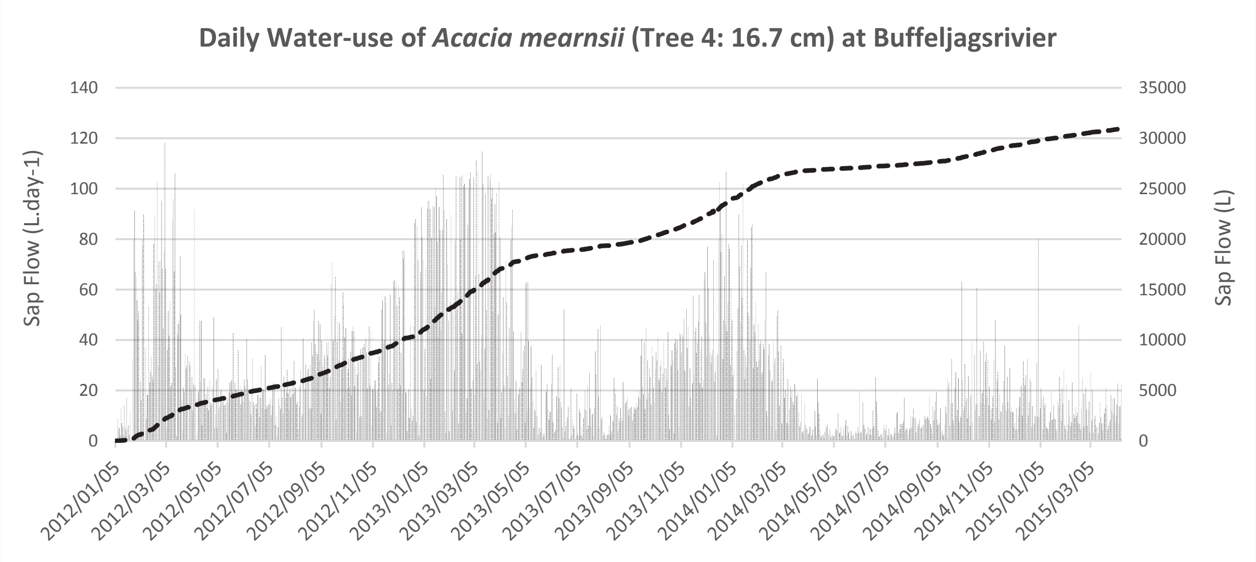
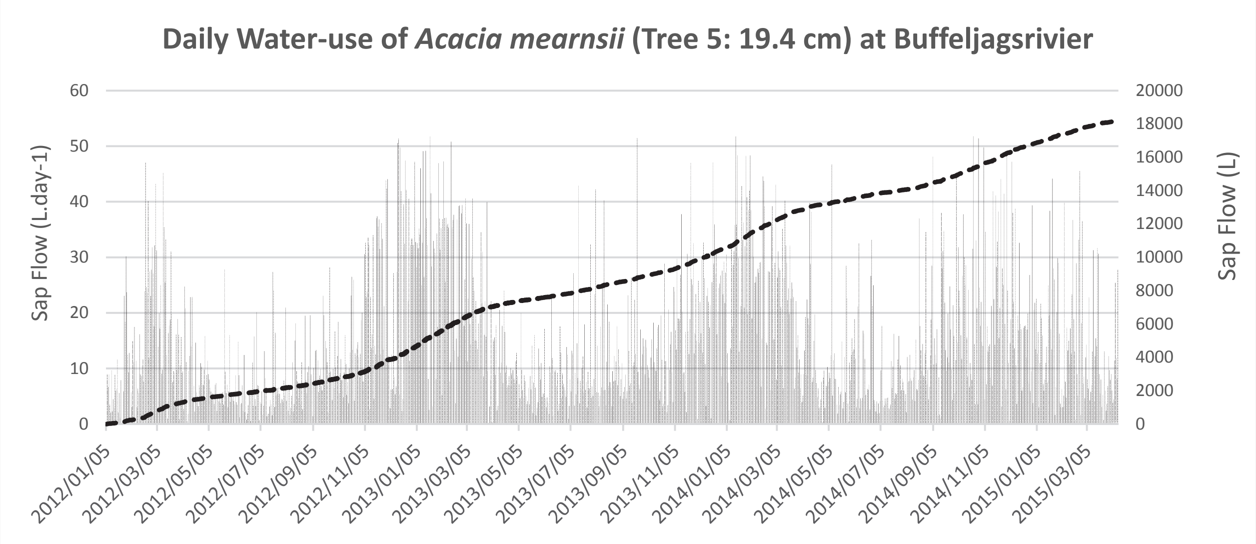


Figure 4.22 Sap flow (daily and accumulated) from three *Vepris lanceolata* (Trees 1, 2 & 3) in the lower reach alien stand at Buffeljagsrivier (January 2012 to March 2015)


Daily Water-use of *Acacia mearnsii* (Tree 4: 16.7 cm) at Buffeljagsrivier


Daily Water-use of *Acacia mearnsii* (Tree 5: 19.4 cm) at Buffeljagsrivier

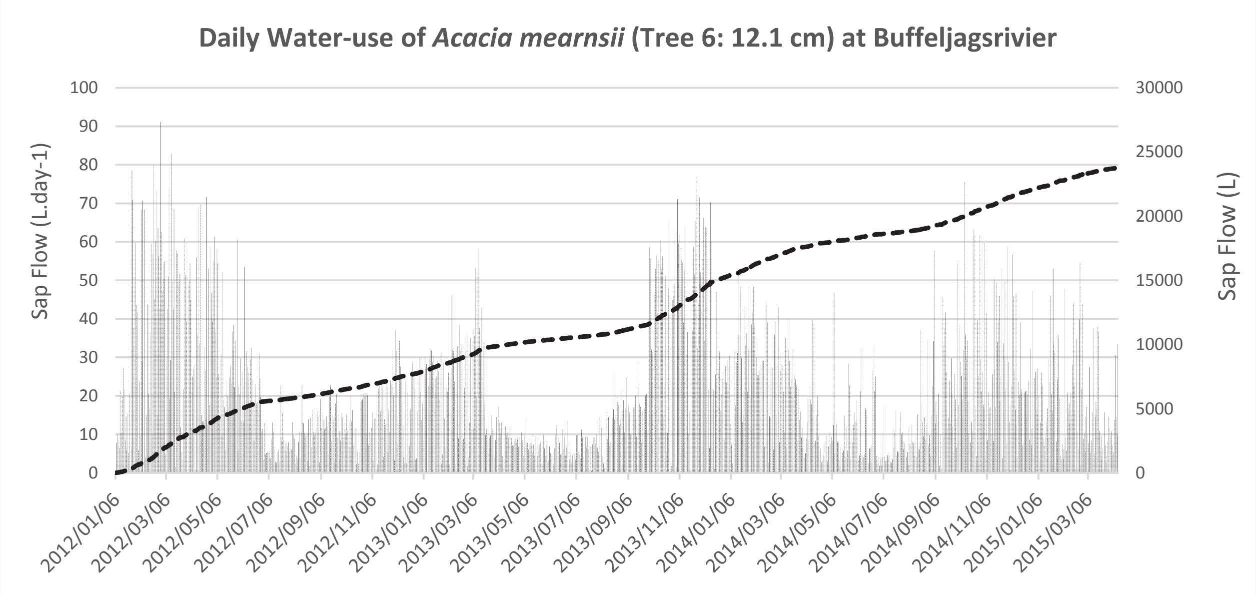

Daily Water-use of *Acacia mearnsii* (Tree 6: 12.1 cm) at Buffeljagsrivier

Figure 4.23 Sap flow (daily and accumulated) from three *Acacia mearnsii* species (Tree 4,5 & 6) in the lower reach alien stand at Buffeljagsrivier (January 2012 to March 2015)

The daily water-use of two of the *Vepris lanceolata* trees in the indigenous stand showed high water-use with an average of 18 L (Tree 7) and 42 L (Tree 8, Figure 4.24). The high water-use in tree 8 is ascribed to its large size and deep rooting system which is presumed to have had easy access to groundwater at this site due to the proximity to the river. This was verified with the borehole and a brief root analysis at the site. The water level ranged from 3.2 m to 4.8 m at the site where roots were observed to 5 m while installing the borehole. The water-use of the *Rothmannia capensis* (Tree 9) had two periods of missing data from baboon damage. The data from this tree was patched with the AWS data.

The *Celtis africana* example displays a high water-use during the summer period (Figure 4.26). As this is a deciduous tree, no water is used during leaf fall. This particular tree has the highest canopy area and is the largest tree at the site. Approximately 11 400 L of water has been used by this tree during the measurement period and its water-use is conservative when compared to the evergreen trees.

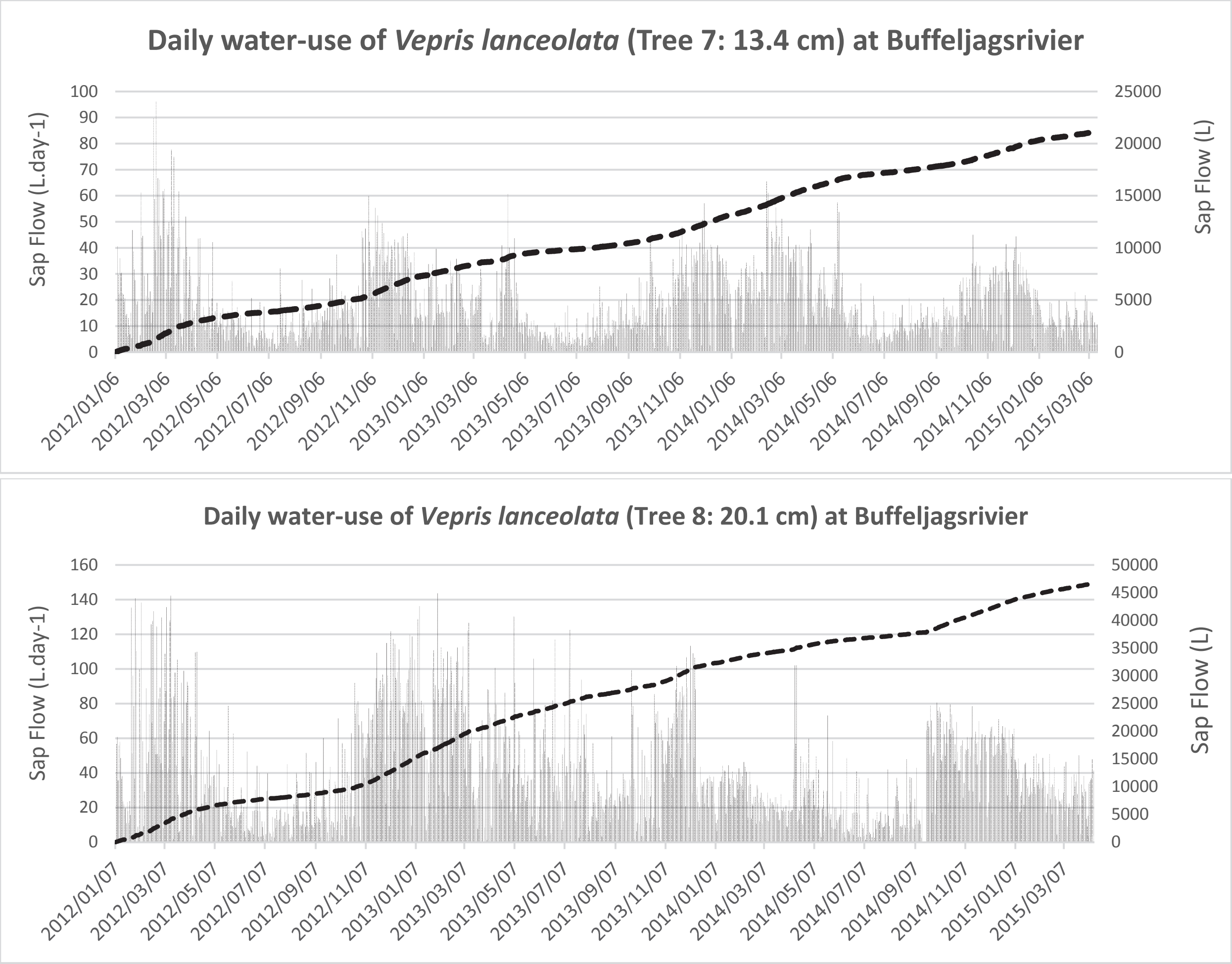


Figure 4.24 Sap flow (daily and accumulated) from two *Vepris lanceolata* (Trees 7 & 8) in the upper reach indigenous stand at Buffeljagsrivier

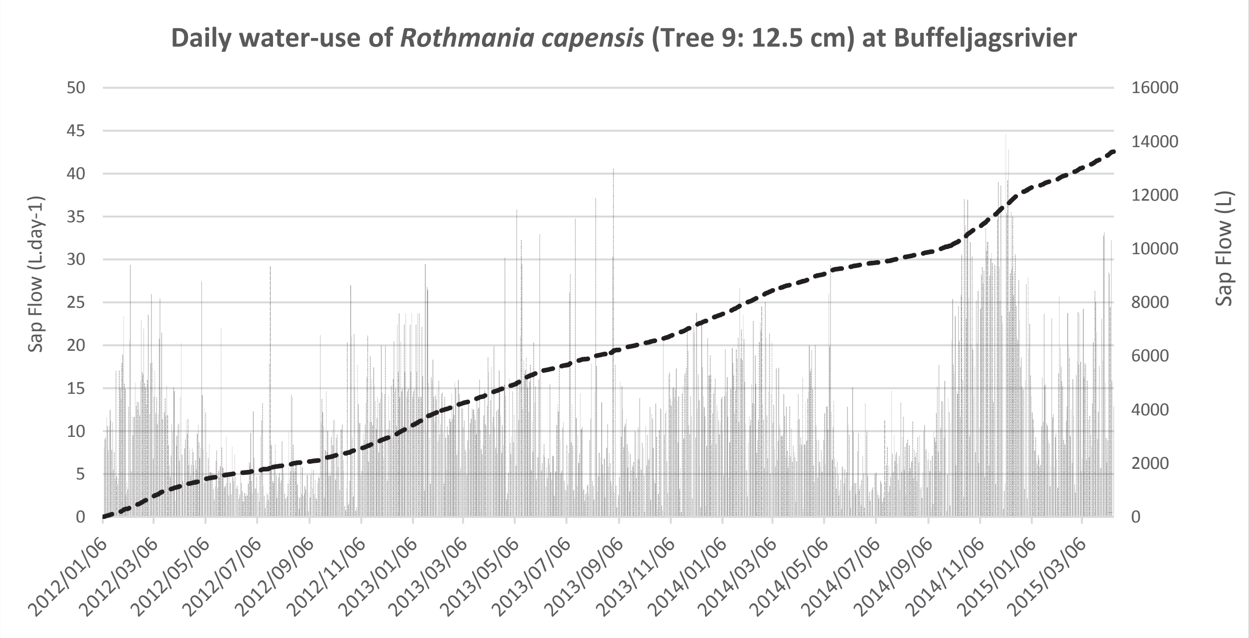


Figure 4.25 Sap flow (daily and accumulated) from *Rothmania capansis* (tree 9) in the upper reach indigenous stand at Buffeljagsrivier (January 2012 to March 2015)

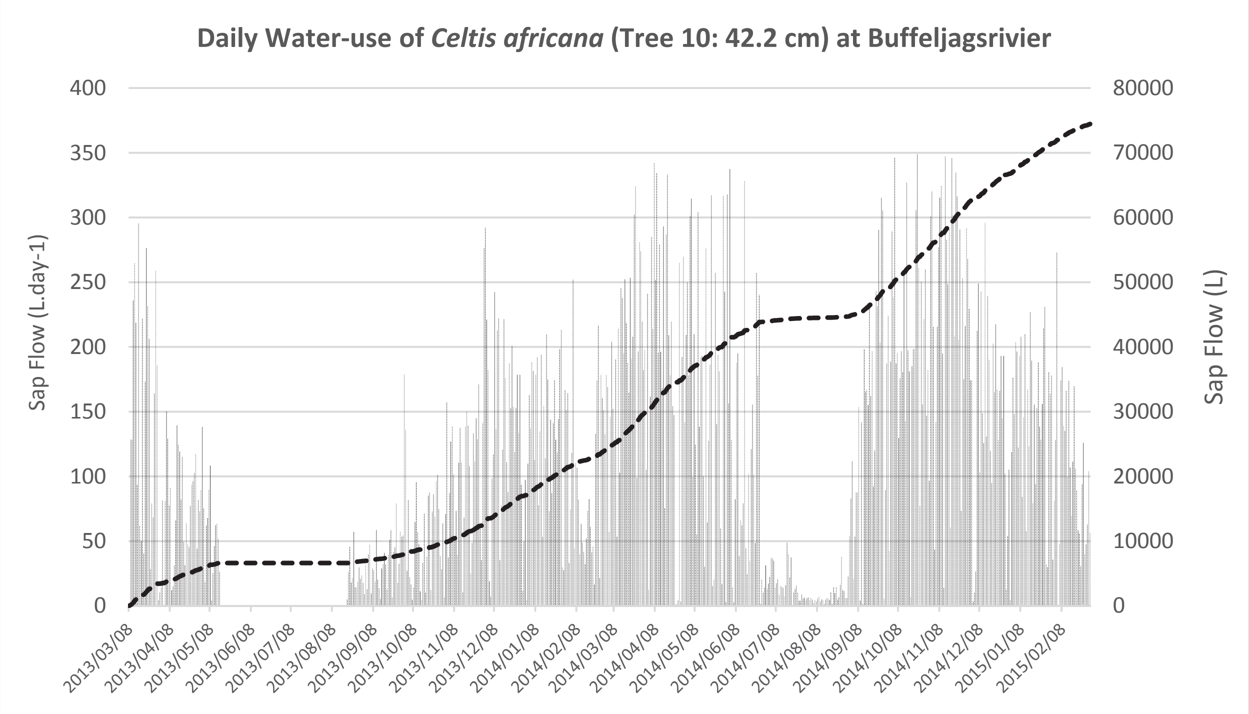


Figure 4.26 Sap flow (daily and accumulated) from a *Celtis africana* species (Tree 10) in the lower reach alien stand at Buffeljagsrivier (March 2013 to March 2015)

4.3.3 Evaporation modelling

As described in the methods, the *ACRU* and *SWAT* models were run for the Buffeljagsrivier catchment area. These models were validated using the available streamflow data at the outlet of Buffeljags dam (H7H013, Buffeljags River @ Eenzamheid). The results showed that neither model predicted the streamflow with great accuracy with an R^2 of 0.44 for *ACRU* and 0.49 for *SWAT* (Figure 4.27). The *ACRU* model generally did not respond to rainfall events, underestimating streamflow for all events. This was particularly noticeable during the winter period (Figure 4.27). The *SWAT* model simulated the trends well but did not simulate the peak flows accurately. This requires further investigation if detailed hydrological findings are to be made. The reason for these differences was attributed to the highly variable catchment, where half of the catchment was represented by the steep Langeberg mountain range which was poorly gauged. This area would have quick peak flows and was likely to have a significantly higher rainfall than the rest of the catchment area. The validation study did, however, show that these models were of sufficient accuracy to use for scenario based modelling. It must be noted that each year during the measurement period for this site experienced a higher than average volume of rainfall.

**note – streamflow was converted from mm.day^{-1} to m^3.s^{-1} using the catchment area for both models*

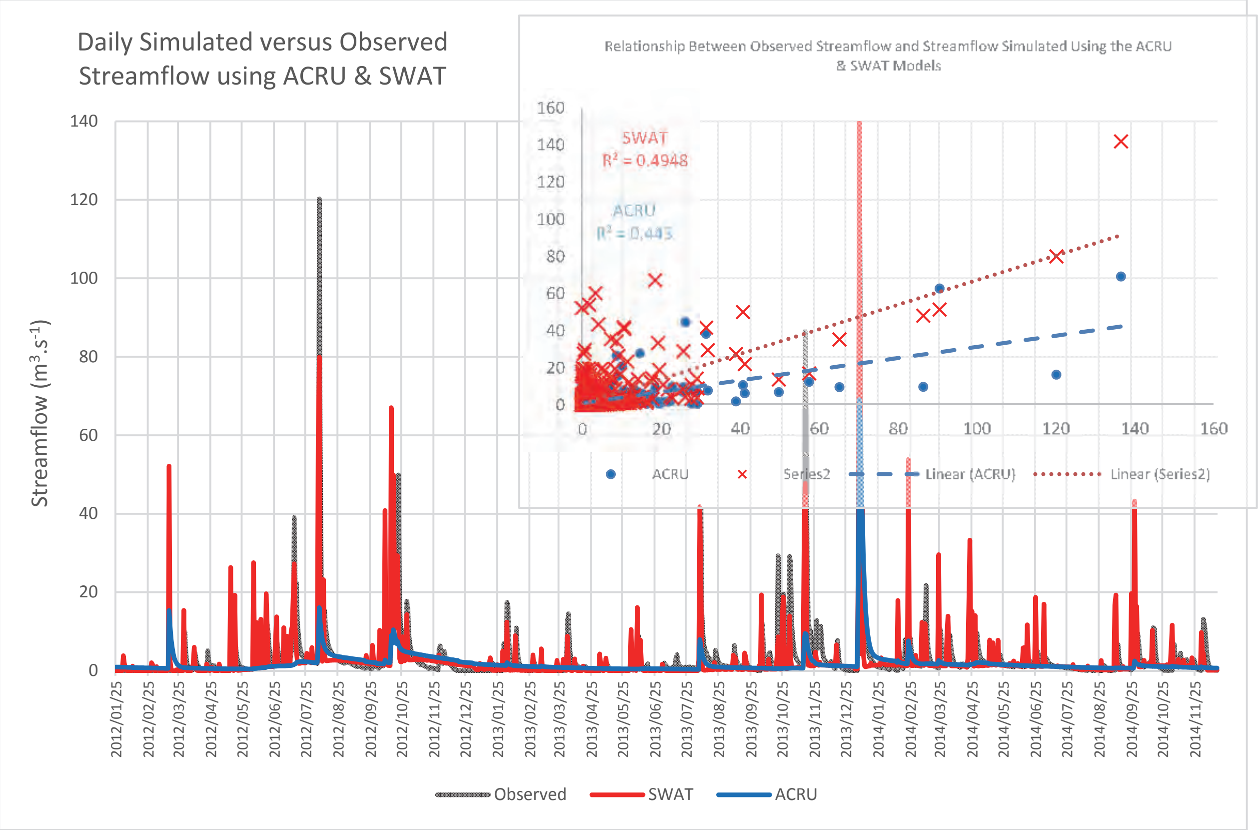


Figure 4.27 Model validation of the *ACRU* and *SWAT* models using observed streamflow (January 2012 to December 2014)

A summary of the baseline scenario (current state) of the *SWAT* water balance showed for the riparian HRU that 56% of the precipitation was returned to the atmosphere through total evaporation (Figure 4.28). 40% of the remaining precipitation contributed to the catchment streamflow in the form of surface runoff, lateral flow and return flow.

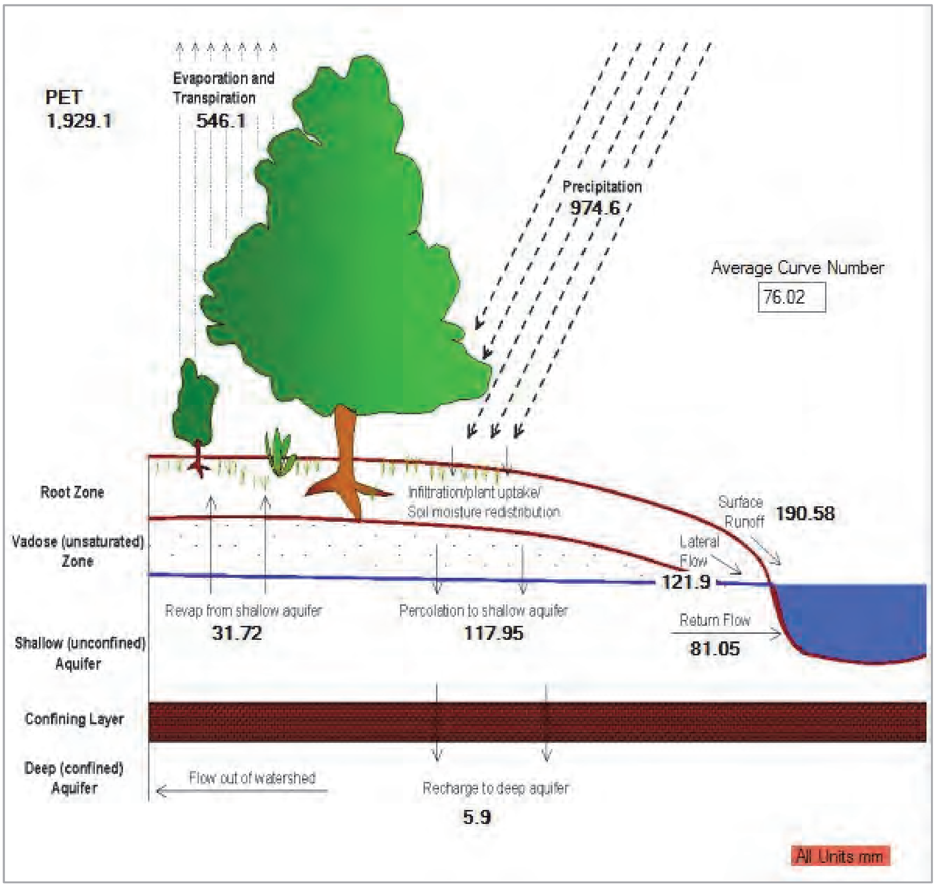


Figure 4.28 Modelled water balance for Quaternary Catchment H70E using the *SWAT* model

On a daily basis ACRU predicted daily evaporation values for the invaded scenario which were almost double the pristine scenario during the 50 year validation period. The differences in water-use between indigenous and invaded riparian zones were also reflected in the runoff components where the streamflow reduction in the entire catchment was approximately 1 478 m^3 over the 50-year simulation period (results not provided). Over the study period, accumulated streamflow was reduced by 127 mm (Figure 4.29).

The *SWAT* model showed clear differences between an HRU that was invaded and a pristine state. The total evaporation was approximately 35% less under the pristine state where the streamflow differed by 100 mm over the three year period. Directly scaling up the actual tree water-use data using SWAT showed similar findings with the impact of clearing the *Acacia mearnsii* showing clear water balance benefits.

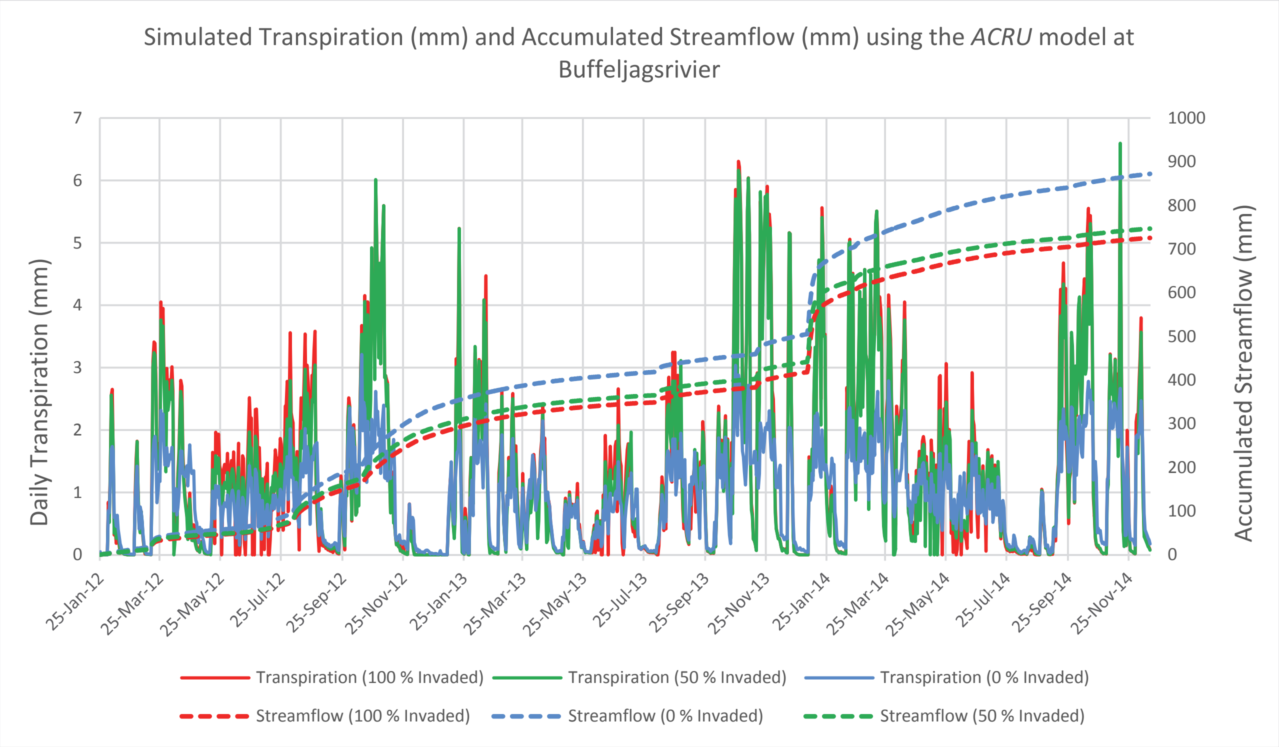


Figure 4.29 ACRU modelled transpiration (mm) and accumulated streamflow (mm) between the baseline scenario (present state) and the pristine and degraded (invaded) scenarios at Buffeljagsrivier for an individual HRU (25th January to 16th December 2014)

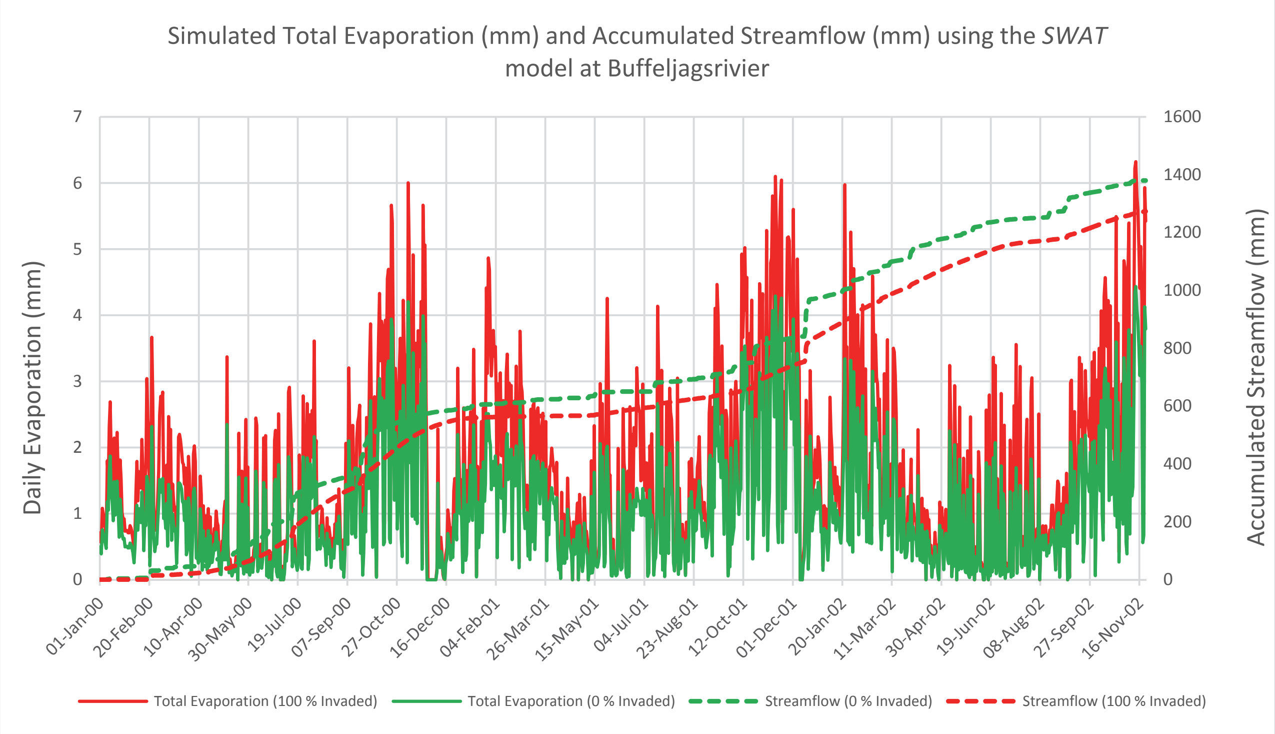


Figure 4.30 *SWAT* modelled total evaporation (mm) and accumulated streamflow (mm) between the pristine and degraded (invaded) scenarios at Buffeljagsrivier for an individual HRU (1st January 2000 to 16th November 2002)

4.4 Discussion and Conclusion

The results from the hydrological and ecological components of the Buffeljagsrivier site were used to determine an actual annual water-use per unit area between the invaded and pristine sites. The findings are summarised as follows:

- The stem density of *Acacia mearnsii* was 650 stems.ha^{-1} for the small size class, 200 stems.ha^{-1} for the medium size class and 50 stems.ha^{-1} for the large size class.
- The annual water-use of *Acacia mearnsii* was 5879 L for the small size class, 7639 L for the medium size class and 9981 L for the large size class.
- Therefore the *Acacia mearnsii* stand used approximately 5.85 ML.ha^{-1}.year^{-1} (585 mm.yr^{-1}).
- The stem density of combinations of *Vepris lanceolata*, *Rothmania capensis, Celtis africana* and *Rapanea melanophloeos* was 120 stems.ha^{-1} for the small size class, 65 stems.ha^{-1} for the medium size class and 24 stems.ha^{-1} for the large size class.
- The annual water-use of the indigenous clusters was 1209 L for the small size class, 6321 L for the medium size class and 18900 L for the large size class.
- Therefore the indigenous stand uses approximately 1.01 ML.ha^{-1}.year^{-1} (101 mm.yr^{-1}).
- From the above we concluded that, annually, the alien stand uses nearly six times more water per unit area than the indigenous stand.

*Note: The results provided are transpiration (assuming a closed canopy) and exclude understorey, surface and canopy evaporation.

The annual tree water-use, as provided in the conclusion (Figure 7.1), showed the high variability both within and between species tree water-use. For example, the annual water-use of *A. mearnsii* ranged between a low of 5879 L.year^{-1} and a high of 9981 L.year^{-1}. These data highlight the importance of good replication of a representative sample of size classes. Despite the fact that an individual *Celtis africana* tree can use 24000 L of water per year (14 000 L more than the largest *A. mearnsii*) it is the high density of the invaded species which becomes important in the scaling up of the canopy water-use.

5. EASTERN MISTBELT FOREST

The Eastern Mistbelt forest site (referred to as New Forest) was chosen to represent a summer rainfall forest area that has been under pressure historically by commercial forestry and agricultural lands. The particular forest used in this study was an example of a heavily degraded site. Important ecological and hydrological findings for this site are presented in this chapter.

5.1 Study Site

The New Forest riparian area falls under the Eastern Mistbelt forest type. The surrounding natural areas are covered by Highland Sourveld (Acocks' 1988) or Drakensberg Foothill Moist Grasslands (Mucina and Rutherford, 2006). Due to the close proximity to the University of KwaZulu-Natal, the abundance of indigenous species and the ease of access, this site was chosen to be a high intensity monitoring site, with up to 18 trees being monitored with HPV systems. Numerous saplings were monitored for growth under various shading and grazing conditions. No plant water-use research had previously been carried out in the New Forest or Upper Umgeni catchment area. However, interest had recently been placed on the land due to a proposed housing development and the water balance project being undertaken by WWF. The study site is typical of invasive alien plant (IAP) invasion, whereby plantations have been grown in traditionally fire dominated grasslands and have subsequently invaded the surrounding riparian areas.

Figure 5.1 shows a patch of cleared Bug Weed in the New Forest area (a) and the indigenous riparian forest (b). A detailed background for this site is provided in the following section.

Figure 5.1 Cleared Bug Weed patch (a) and the indigenous riparian forest (b)

The New Forest riparian site is at latitude 29°28’30” S and longitude 29°52’48” E at approximately 1760 m above sea level. The riparian area occurs along a tributary to the upper Umgeni River, within Quaternary Catchment (QC) U20A and Quinary Catchment (QnC) 3737 (Figure 5.2). Eastern Mistbelt forests can be characterised by cool, tall inland forests (Pooley, 2003). These forests, have in the past, been exploited for timber uses and are well known for their rich species diversity and the presence of large yellowwoods (Pooley, 2003). The mountain slopes of the area consist of fractured dolorite dykes and basaltic outpourings (Crowson, 2008). The soils show evidence of high precipitation and age with shallow mispah soils occurring on the slopes and katspruit soils dominating the low lying areas.

Approximately 80% of the precipitation occurs in the summer months, which mostly consists of orographically-induced and squall-line thunderstorms (Schulze, 1982). Interception from mist makes a large contribution to the seasonal precipitation and determines the distribution of the mistbelt forest. The Mean Annual Precipitation is between 980 and 1000 mm. There is a distinct dry season from May to August. Average temperatures range from 25.2 °C in the summer to 16.9 °C in the winter, with the highest temperatures occurring on the North-facing slopes. Cool mountain winds occur at night with warm up-valley winds occurring during the day (Crowson, 2008). Strong berg (westerly) winds are prevalent during August to September and play a significant role in the spread of fire (Schulze, 1982).

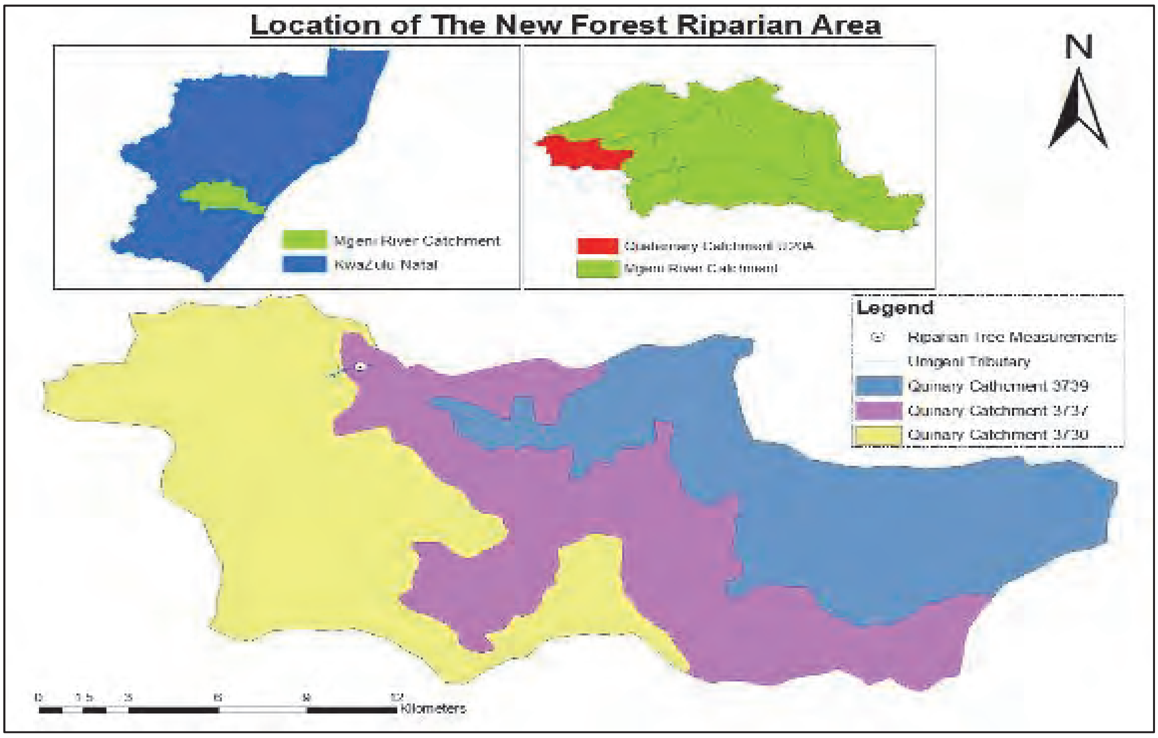


Figure 5.2 New Forest study site, showing the measurement site in relation to KwaZulu-Natal and the Mgeni River Catchment

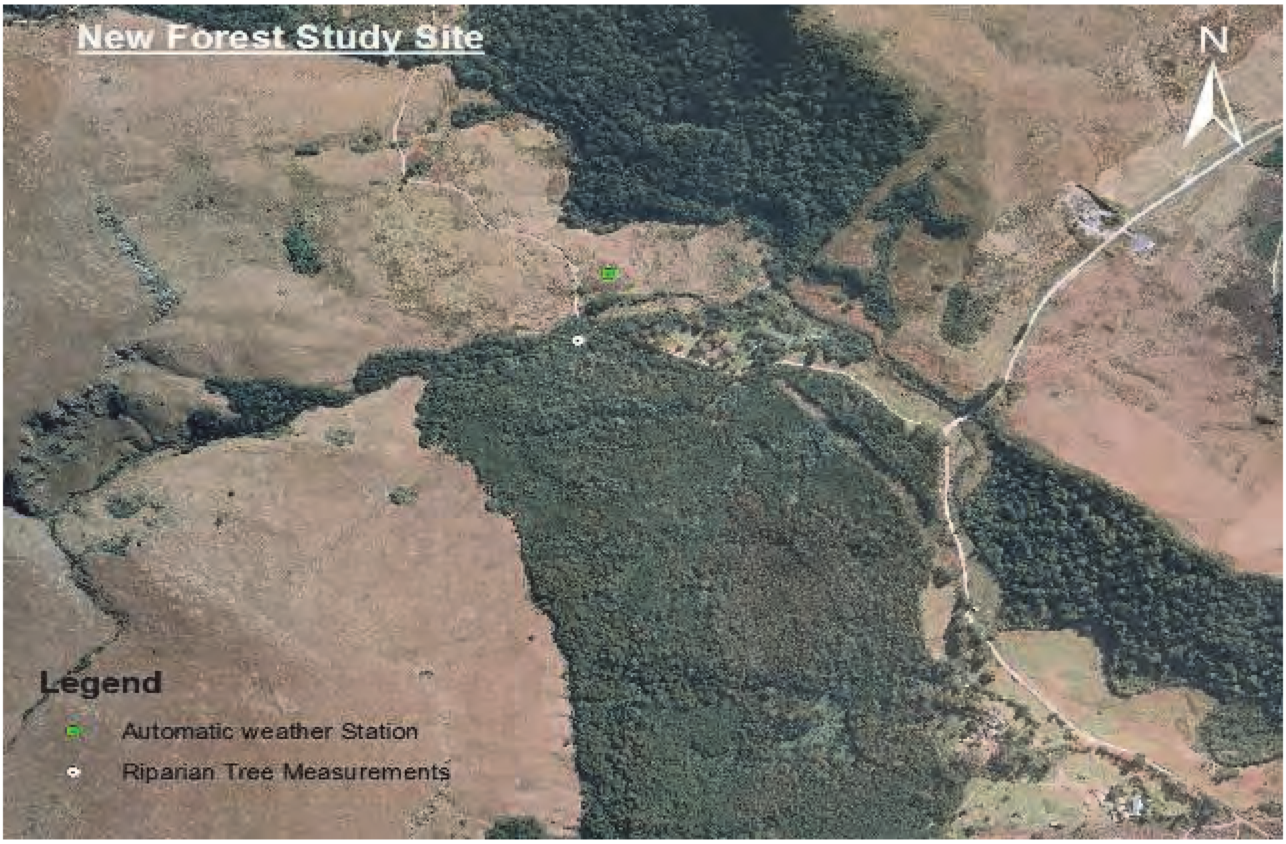


Figure 5.3 Location of the research areas within the New Forest farm

New Forest farm is privately owned. The area south of the Umgeni tributary (Figure 5.3) has been planted with *Acacia mearnsii* and *Pinus patula* over the last 50 years. Historical photographs suggest that the indigenous trees in the riparian area have spread up the north-facing slope due to fire protection from the planted trees. The change in the plantation size from 1944 (Figure 5.4 a) to 1984 (Figure 5.4b) can be seen, where only a small area of pine trees were visible from the 1944 period. The riparian area has since been heavily invaded with *Acacia mearnsii*, *Eucalyptus grandis* and *Solanum mauritianum*. Common indigenous tree species present in the forest are *Celtis africana*, *Podocarpus latifolius*, *Halleria lucida*, *Leucosidea sericea* and *Buddleja salvifolia*. Riparian invasive alien tree clearing has been ongoing in the area by WfW. The land owners started clearing the alien stand on the farm in August 2012, but agreed to leave a band of trees in order to accommodate the water-use experiments.

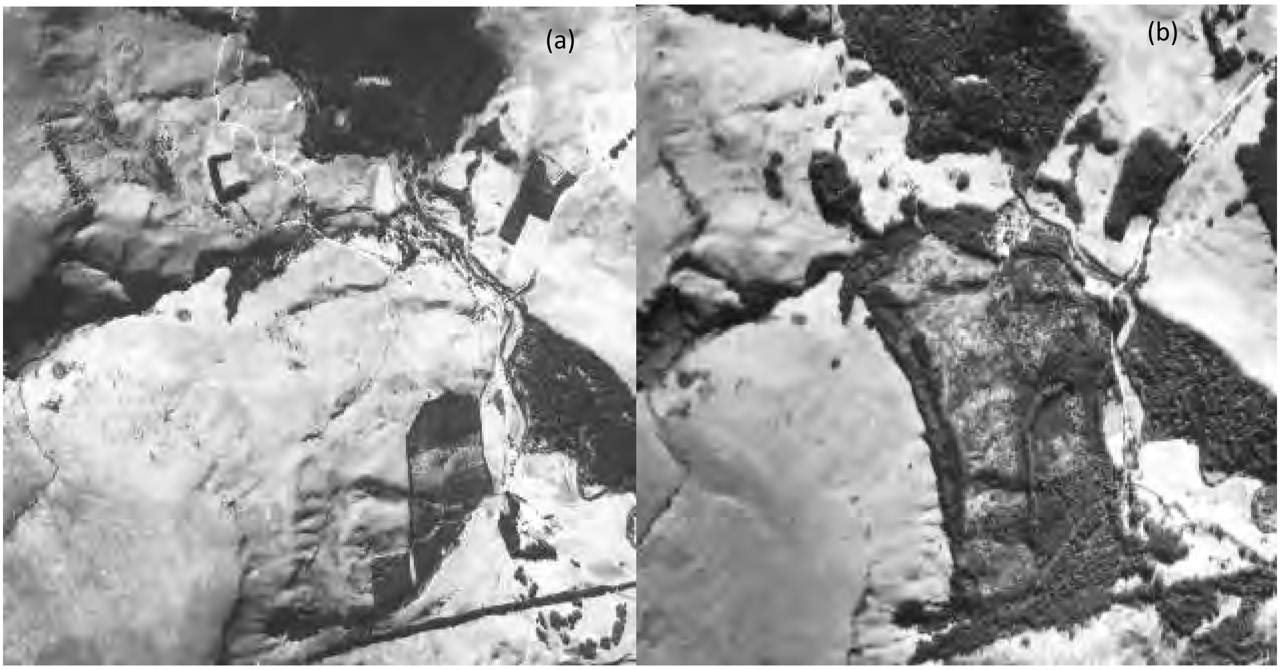


Figure 5.4 Historical imagery for New Forest farm from 1944 (a) to 1984 (b)

5.2 Ecological Findings

5.2.1 Floristic attributes of native forest regeneration

5.2.1.1 Native Forest communities of New Forest

In total, 58 species were recorded on the 15 plots sampled within the natural forest at New Forest. Forest areas were differentiated into two broad stand types, namely mature forest and mixed regrowth forest. The ordination in Figure 5.5 shows the mature forest plots tightly clustered on the left and the regrowth forest scattered in small groupings in the centre and right of the ordination. The nature of this grouping firstly illustrated the difference between regrowth forest and mature forest, and secondly showed a range of variation in the mixed regrowth forest. The differences among the mixed regrowth forest plots illustrated the different types of regrowth which were sampled at New Forest. Grouping RE1 was an old *Acacia melanoxylon* (R.Br.) stand that had been cut down and was regenerating within a mixture of *Leucosidea sericea*. RE2 was similar to RE1 and was a young forest edge or ecotone regrowth dominated by *Leucosidea sericea*. RE3 was an older type of disturbed regrowth forest which was now mixed with invasive species.

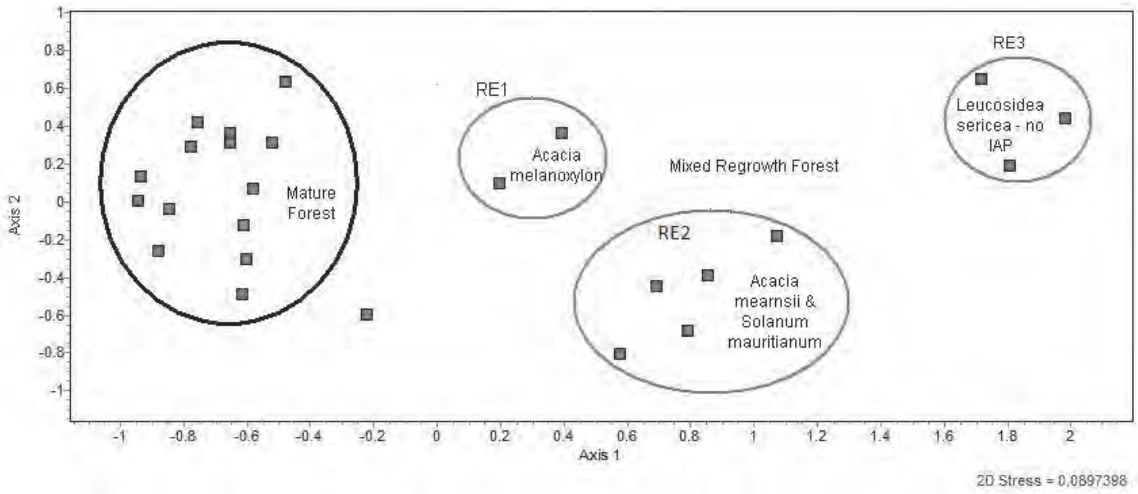


Figure 5.5 **NDMS ordination showing the difference between mature forest and regrowth forest at New Forest. Blocks represent plots in ordination space. 2D stess = 0.089.**

In the mature forest, large canopy forest trees had a mean DBH of 42 cm and the dominant species were: *Ptaeroxylon obliquum, Scolopia mundii, Celtis africana, Maytenus peduncularis, Podocarpus latifolius and Kiggelaria africana*. Other large canopy species which stood out were: *Chionanthus* foveolatus (E.Mey.) Stearn, *Ilex mitis, Olinia emarginata, Podocarpus falcatus, Calodendrum capense* (L.f.) Thunb., and *Scolopia* zeyheri (Nees) Szyszy Less robust species which were present in both the canopy (of low forest) or as sub-canopy (in tall forest) were: *Clausena anisata* (Willd.) Hook.f. ex Benth, *Euclea natalensis* (A.DC.) *and Eugenia zuluensis* (Appendix 4, Table 12).

Importance values (IVs) of the forest sub-canopy showed common understory species as: *Gymnosporia harveyana* (Loes.), *Diospyros whyteana* (Hiern) and *Eugenia zuluensis* and uncommon but present sub-canopy species *Allophylus dregeanus* (Sond.) De Winter, *Canthium mundianum, Maytenus albata* (N.E.Br.) E.Schmidt bis & Jordaan *Gymnosporia devenishii* (Jordaan). Dominant lianas were *Scutia myrtina* (Burm.f.) Kurz (often recorded as dense understorey shrub, but eventually develops into a large canopy liana), *Strophanthus speciosus* and *Combretum edwardsii* (Exell.).

A further ordination of the mature forest plots by NMDS revealed three basic floristic groupings (Figure 5.6), which related to localised biogeographic affinities. The plots grouped on the right of the ordination were low lying or flood plain forest plots, the centre grouping were slope forest plots and the grouping on the left were from steep riparian gully plots. All three communities had similar canopy composition with *Celtis africana, Ptaeroxylon obliquum Scolopia mundii* and *Podocarpus latifolius* being distinct characteristic species.

The presence of *Kiggelaria africana* and *Euclea natalensis* in the canopy differentiated the low lying community from the other two communities and the presence of *Maytenus peduncularis* (Loes.) rendered the riparian gully community distinctive from the low lying and the slope forest communities. In the sub-canopy, the dominance of *Gymnosporia buxifolia* and *Euclea natalensis* was unique to the low lying forest, as was the high value of *Eugenea zuluensis* (Gard.) in slope forest. (Appendix 4, Table 13).

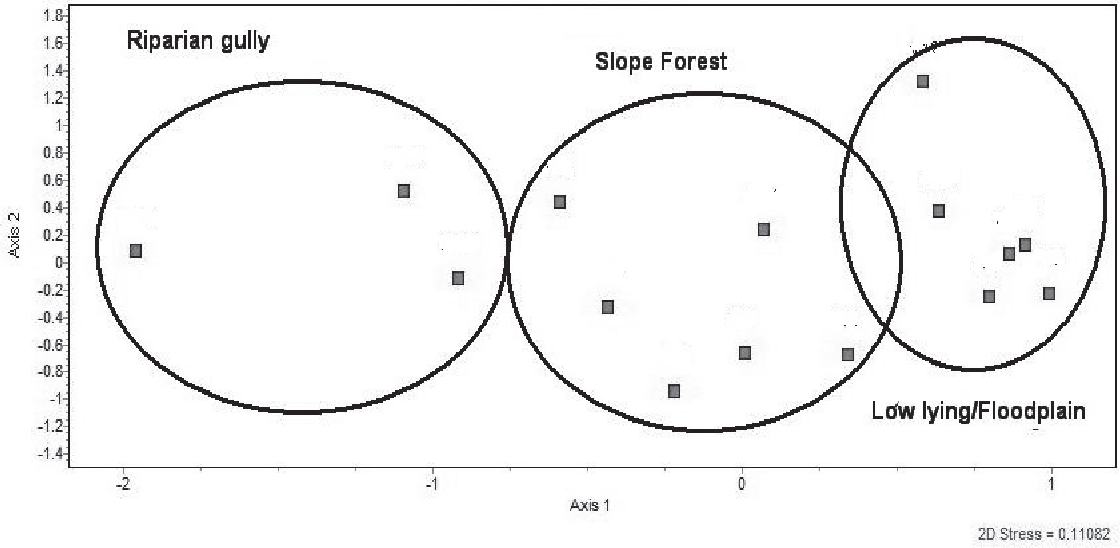


Figure 5.6 Separation of floristic canopy communities of species >5 cm DBH at New Forest. Blocks represent plots in ordination space.

5.2.1.2 Analysis of regeneration communities in mature forest, mixed regrowth forest and IAP invasive stands

The most important species from each respective community were tabulated according to the ecological role (Appendix 4, Table 14). Indicator species are presented in Appendix 4, Table 15. IV values with at least one species >20 from each community are presented in (Appendix 4, Table 16). The grouping of the regeneration data when subjected to NDMS was interpreted along a linear gradient on Axis-1 (Figure 5.7). Most plots fitted into four groupings which were defined as regeneration communities. Analysis of species composition in these groupings showed a successional pattern from pioneer to mature forest along a linear gradient moving from right (pioneer) to left (mature forest). Axis 2 was thought to represent variance in individual groupings. Bar charts (Figure 5.8 and Figure 5.9) are presented to illustrate the change in native species richness and density between communities.

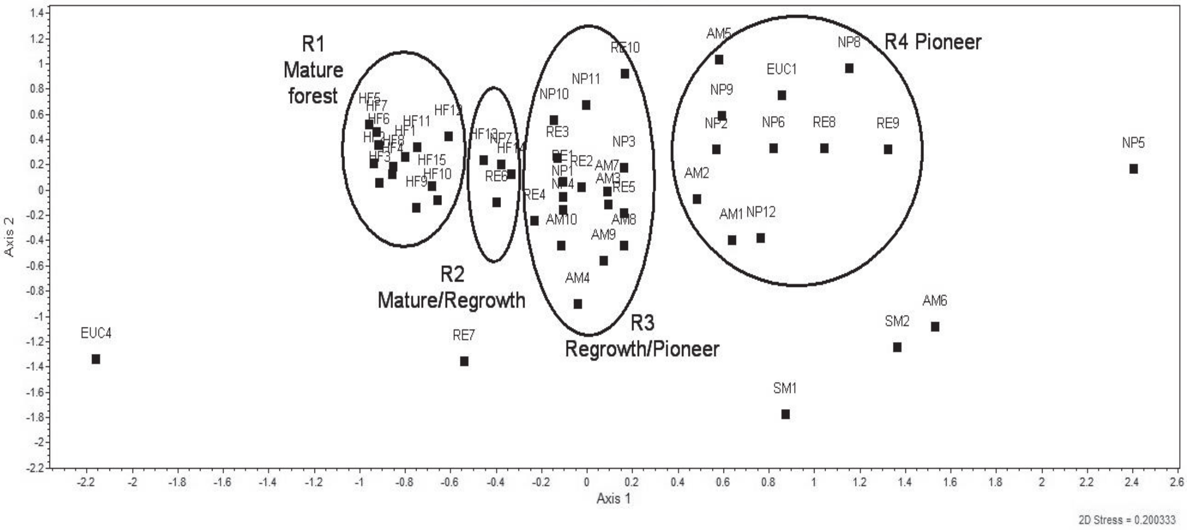


Figure 5.7 NMDS of regeneration community species composition at New Forest. Blocks represent plots in ordination space

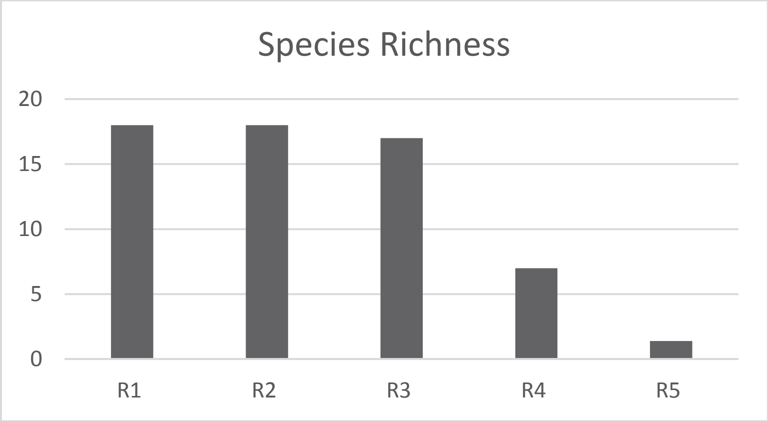


Figure 5.8 **Bar chart showing the species richness of native species within regeneration communities. R5 is not an actual community and contained outlier data.**

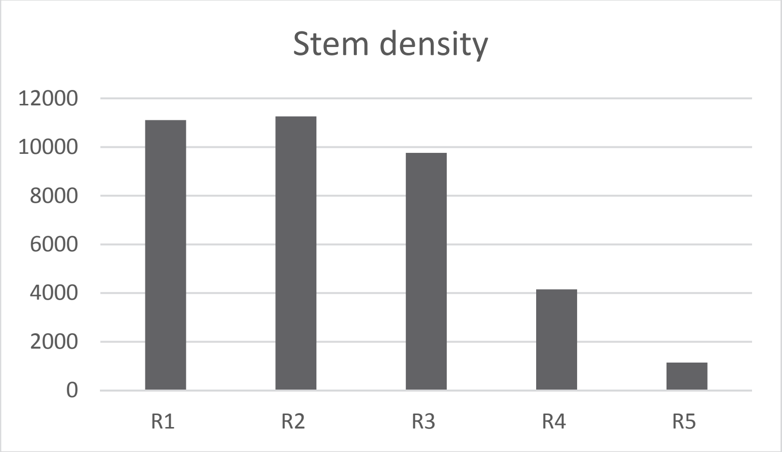


Figure 5.9 **Bar chart showing the stem density of native species within regeneration communities. R5 is not an actual community and contains outlier data.**

The plots that were not associated with any groupings contained extremely low regeneration stem density (1140 stems ha^{-1}) and species richness (1.4 species). These plots were judged to be in an initial pioneer phase and were discounted from any community grouping. On the right of the ordination, community R4 appeared to be in a general pioneer regeneration phase which had a regeneration density of 4175 stems ha^{-1} and species richness of 7.7 species per plot. The canopy composition (i.e. stems >5 cm dbh) of this community was mostly invasive species (90%). Species with the highest IVs in this community were *Celtis africana*, *Halleria lucida, Searsia dentata* (Thumb.) Barkley and *Searsia pyroides*, and the indicator species was *Halleria lucida*.

The next community grouping R3 was judged to be a late successional pioneer and early regrowth forest community. This community had canopy species from both mixed regrowth forest and invasive stands (71% IAP), with more than twice the density (9764 stems ha^{-1}) and species richness (17 species) in the regeneration layer than in community R4. The species with the highest IVs were *Searsia pyroides, Scolopia mundii, Celtis africana, Gymnosporia buxifolia, Euclea natalensis* and *Canthium ciliatum*. Indicators for this community were *Euclea natalensis, Canthium ciliatum* (Klotzsch) Kuntze and *Searsia pyroides*.

Community R2 was a mix between late successional regrowth forest and mature forest species. The canopy composition in this stand type was again a mixture of native and IAP species, though less IAPs (37%) than native species. Regeneration density (11260 stems ha^{-1}) and species richness (18) was not much higher than community R3. The species with the highest IVs were *Carissa bispinosa, Clausena anisata, Canthium ciliatum, Scolopia mundii* and *Scolopia zeyheri*. The highest indicators for this community were *Scolopia* zeyheri, *Carissa bispinosa*, and forest gap specialists *Buddleja auriculata* (Benth.), *Grewia occidentalis* (L.) and *Lauridia tetragona*. (L.f.) R.H.Archer. The presence of these forest gap species showed the pioneer element in the successional pathway to mature forest in this regeneration community.

In community R1, the mature trees in the canopy were mostly indigenous species, sub-canopy regeneration was density (11107 stems ha^{-1}) and richness (18 species per plot). The most important species were *Canthium ciliatum, Celtis africana, Clausena anisata, Gymnosporia harveyana* and *Scutia myrtina,* while the highest indicator species were *Diospyros whyteana*, *Strophanthus specious (Ward & Harv.) Reber*, and *Dovyalis rhamnoides* (Burch. ex DC.) Burch. & Harv.

5.2.1.3 Discussion

The dominance of *Scolopia mundii* at New Forest (listed as an important Afrotemperate forest species in Mucina and Geldenhuys, 2006) and the rarity of the *Podocarpus henkelii* at New Forest (a near Eastern Mistbelt endemic according to Mucina and Geldenhuys, 2006) suggested that New Forest is a high altitude Eastern Mistbelt forest that is separated floristically between the Eastern Mistbelt forests and the Drakensberg Afrotemperate forests. In addition, the absence of *Ocotea bullata, Xymalos monospora and Cryptocarya myrtifolia* indicated that species richness at New Forest was in line with the general trend that species richness decreases with an increase in altitude and consequently Afrotemperate forests are less species rich than Eastern mistbelt forest (Lawes et al., 2007). Further sampling and analysis into other higher altitude forests, such as Fort Nottingham are required to establish if there is a consistent floristic difference between low and high altitude Eastern Mistbelt forests or if these differences are related to other biogeographical influences.

The floristic composition of New Forest showed that mature forest areas were relatively homogenous and differences in forest composition were a result of the same species growing in different combinations. Some of the mature forest areas at New Forest may be ‘newly developed’ mature forest, as indicated by some of the lower lying communities represented by pioneer forest species with large stem diameters. The difference between mature forest and regrowth forest was also apparent. Regrowth forest contained mostly pioneer species, but interestingly also species that could be considered mature forest species, e.g. *Celtis africana*. This may have been due to the multi-functional attributes of these species or that their greater density in mature forest areas influenced representation in regrowth forest.

The combined riparian plots and the abandoned plantation plots contained 43 native species which was slightly lower when compared to a study by Geldenhuys (1997) in the Northern Province which recorded 62 tree species. This may have been because the forests sampled in that study were at lower altitude or that the regeneration was in a more advanced successional stage. Young native species in invasive stands showed distinct community groupings which were representative of a native forest successional process. The differences in species richness and stem density in the different regeneration communities showed the potential for regeneration across the different communities. These similarities were similar in mature forest and mixed regrowth forest communities, but less in young pioneer communities. This data also suggested a link between species richness and stem density, as communities that had more species also had higher stem densities. Some plots were not defined into a particular community due to very low stem densities, but still showed that stands with 99% invasive canopy cover had native regeneration stem densities of 1000 stems ha^{-1}.

5.2.1.4 Conclusion

This research showed that there were differences in regeneration between mature forest stands, mixed regrowth forest stands and invasive forest stands at New Forest. Mature forest and mixed regrowth regeneration communities were more species rich than invasive stand communities, though invasive stand communities did contain both pioneer and mature forest species. *Celtis africana, Scolopia mundii* and *Podocarpus falcatus* had at least two ecological roles, i.e. as a pioneer species in young developing IAP and regrowth forest stands, and secondly as a component in mature forest. Ensuring these species develop into maturity will ensure good development of mixed regrowth forest.

5.2.2 Influence of distance to seed source on native forest regeneration

5.2.2.1 Trends between distance to seed source and native regeneration

In total 52 natural forest tree or shrub species were recorded growing as either woody seedlings or saplings within the abandoned plantation or invasive stand plots, at an average density of 5700 stems ha^{-1} (± 831) with 11 (± 0.87) native species per plot. Regeneration stem density ($P=\leq 0.01$, $r^2 = 0.31$) and species richness ($P=\leq 0.01$, $r^2= 0.21$) declined linearly with increasing distance to nearest seed source (DNSS) ($P=\leq 0.01$, $r^2 = 0.21$). This supported the first hypothesis of the study and is illustrated in Figure 5.10 and Figure 5.11. This response was weak, with a wide scatter of points about the fitted linear response.

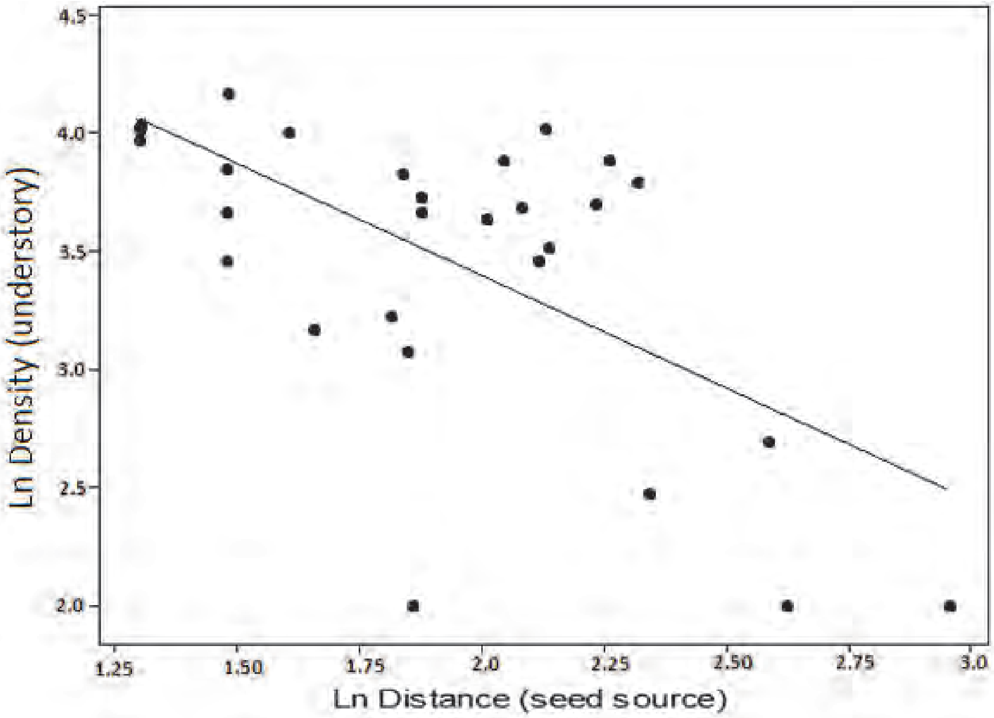


Figure 5.10 The relationship between distance from forest edge (seed source) and woody regeneration of natural forest species. $P=\leq 0.01$, $r^2 = 0.31$, Density = 4.7 – 0.59 Distance. Ln= log10.

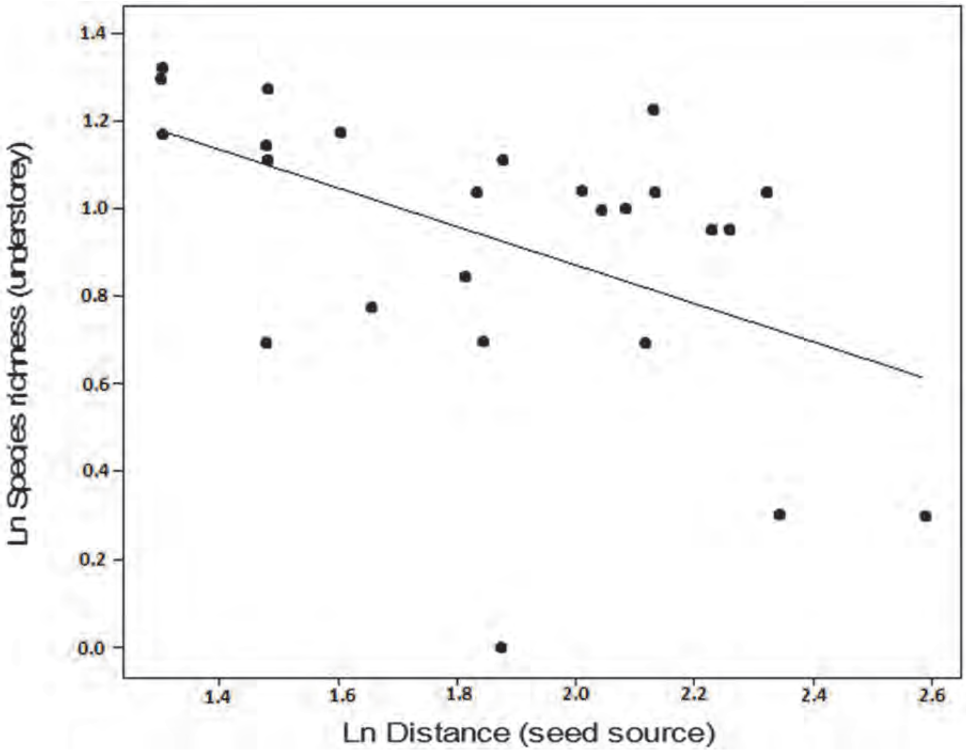
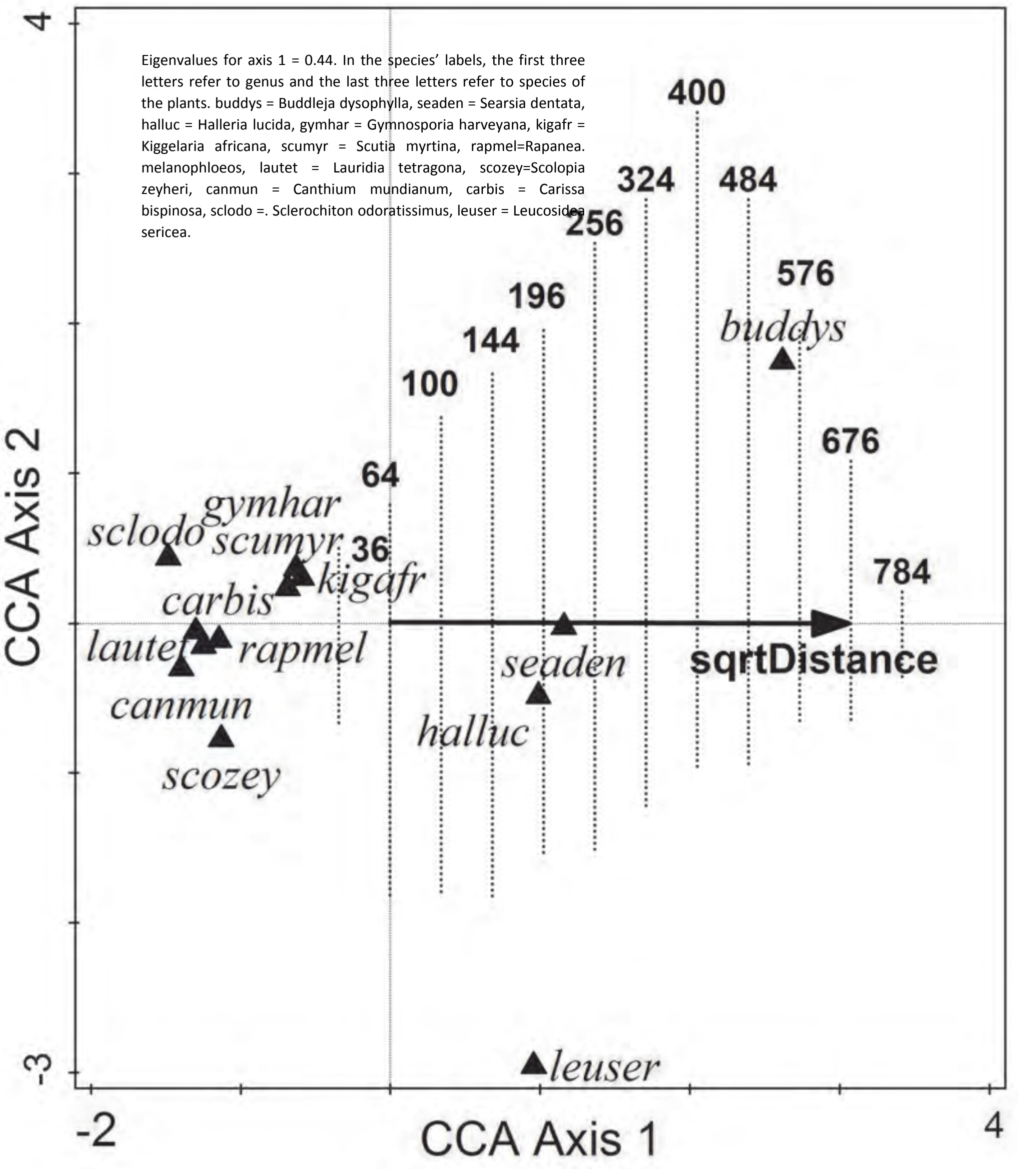


Figure 5.11 The relationship between ln distance from the forest edge and ln species richness. P = ≤0.01, r^2 = 0.21, Species richness = 1.74-0.43 Distance. Ln = log10.

Only 12 native forest species had at least 5% of their variance accounted for by the distance gradient in the CCA (Figure 5.12) The distribution of the responsive species along the distance gradient ranged from those with their estimated centroid, or centre of abundance, proximate (i.e. <36 m) to native forest patches (e.g. *Rapanea melanophloeos*), to distant (i.e. >500 m) such as *Buddleja dysophylla*. Species with centroids at an intermediate distance were found to be most abundant between 200 and 250 m from native seed source (e.g. *Searsia dentata*, *Halleria lucida* and *Leucosidea sericea*)



Eigenvalues for axis 1 = 0.44. In the species' labels, the first three letters refer to genus and the last three letters refer to species of the plants. buddys = Buddleja dysophylla, seaden = Searsia dentata, halluc = Halleria lucida, gymhar = Gymnosporia harveyana, kigafr = Kiggelaria africana, scumyr = Scutia myrtina, rapmel=Rapanea. melanophloeos, lautet = Lauridia tetragona, scozey=Scolopia zeyheri, canmun = Canthium mundianum, carbis = Carissa bispinosa, sclodo =. Sclerochiton odoratissimus, leuser = Leucosidea sericea.

Figure 5.12 Centroids of species along the first two axes of a canonical correspondence analysis (CCA) of the species composition of regenerating forest in relation to square-root transformed distance-to-native-seed-source (sqrtDistance)

The proximal zone (<36 m) contained two exclusive mature forest understorey species (*Carissa bispinosa* and *Gymnosporia harveyana*), three mature forest and regrowth forest canopy species (*Rapanea melanophloeos*, *Scolopia zeyheri* and *Kiggelaria africana*), two regrowth forest understorey species (*Canthium mundianum* and *Sclerochiton odoratissimus* (Hillard)), and two lianas (*Scutia myrtina* and *Lauridia tetragona*). The intermediate zone (180-250 m) zone contained three species *Halleria lucida*, *Searsia dentata* and *Leucosidea sericea* which are known pioneer species. The only species in the distant zone was *Buddleja dysophylla*, it is a pioneer species often found in forest ecotone areas.

5.2.2.2 Discussion

The study's objective was to analyse the relationship between native forest patches and native species which were noted to be colonising within invasive alien plant (IAP) stands. This investigated the spatial distribution of native forest colonisation and entailed looking at stem density, species richness and the pattern of species distribution of native species within IAP stands.

The role of distance from seed source in colonisation native forest within invasive alien stands

The outcome of this study found that the closer to native forest (either mature forest or established regrowth forest) the greater native species colonisation will be within IAP stands. This supports similar findings in the literature (Geldenhuys, 1997; Senbeta and Teketay, 2001) and predictions by island biogeographical theory (MacArthur and Wilson, 1967). Forests are not one dimensional and there are likely to be many abiotic and biotic factors which influence the colonisation process such as age and density of the invasive species, which affects resources such as light, water and nutrients (Geldenhuys, 1997; Powers et al., 1997) plant allelopathy (Tassin et al., 2009), the species of invasive plant, the number of browsing or grazing ungulates in the area (Atsame-Edda, 2014), soil substrate, aspect, and the amount of local wildlife that act as seed dispersal agents.

It was clear that the strength (or source) of the native colonisation was from mature forest areas and this in turn demonstrated that at New Forest the native forest has the ability to expand into areas which were historically grassland and are now covered in woody invasive species. This was consistent with other literature which predicts that forest has the potential to persist in fire dependent grassy ecosystems with over 650 mm rainfall (Bond et al., 2002). Other studies which look at the cluster effect of forest colonisation in invasive plant stands (Atsame-Edda, 2014) should not be ignored. They hypothesise that forest clusters develop within invasive plant stands and create self-perpetuating effects for forest expansion. Although this theory is plausible, this did not appear to be the case at New Forest since the invasive area was likely to be too young and contained very few trees which were of reproductive age in the invasion areas themselves.

Although both the regressions which tested the relationship between distances to nearest seed source and native colonisation were statistically significant, their wide scatter and the low coefficient of determination revealed that other factors were likely to have influenced native forest regeneration. This may have been a combination of factors which were simply a product of being in 'close proximity to a forest seed source', i.e. a better chance of regeneration success because of a greater amount of seeds and being closer to an established forest area (which would likely contain a different microclimate, structure and fauna than invasive stands). Thus linking forest colonisation to some of these biotic and abiotic factors would lead to a more complete picture of what drives and limits this process.

The spatial distribution of colonising species showed that most species which colonised within 36 m of native forest patches were common in mature forest (e.g. *Scolopia zeyheri*) and that true pioneer species colonised furthest away (>250 m) from the seed source (e.g. *Buddleja dysophylla*). However some species located on the edge of native forest patches within invasive stands have multi-functional ecological roles in Eastern Mistbelt Forest, meaning that they functioned both as colonizing pioneer species and as mature species on the site. This further complicated understanding the colonisation process. For example, *Rapanea melanophloeos* is an important canopy component of mature Eastern Mistbelt Forest but also a pioneer species in secondary or regrowth forest. The colonisation process seemed to be indicative of natural forest colonisation processes, due to the fact that areas of increasing distance from native seed sources contained forest species indicative of their respective functions, i.e. shade tolerant slow mature forest species growing close to mature forest and quick growing species colonising further afield in perceivably extreme pioneer environments.

Reproductive characteristics and distribution

It was apparent that trees with different fruiting characteristics were located at different distances from seed sources. From the results it could be hypothesised that smaller wind dispersed species tended to regenerate further from the seed source (e.g. *Buddleja dysophylla*) than fruiting species with larger seeds (e.g. *Rapanea melanophloeos*). The dispersal agent and method of dispersal of seeds are known to influence their colonisation distance (Howe and Smallwood, 1982), and a recent study on seed rain in Thailand found that bats were likely to be the dispersal agents for tree species which grew furthest away from the seed source (Sritongchuay et al., 2014). Colonising in close proximity to the seed source were some species which contained fleshy arils and it was thought that in this case the seeds were ballistically dispersed. In the spatially intermediate area from seed sources, species with small prolific fleshy berries (i.e. *Searsia dentata* and *Halleria lucida*) were likely to have been dispersed by bats and birds. These species are fed on by generalist bird species (e.g. Cape White Eye, *Zosterops virens*) and the Egyptian fruit bat (*Rousettus aegyptiacus*) which prefer second growth habitats as opposed to core forest and are known to move between forest patches to feed at New Forest (Scott, 2012). The Chacma baboon (*Papio ursinus*) may have been responsible for slightly longer distance seed dispersal of larger seeding tree species as during sampling some larger seeding species (e.g. *Rapanea melanophloeos*) were noted in the distant zone in relation to seed sources. This fact reveals the difficulty in predicting the mechanisms of forest colonisation and emphasizes the point that there is always an exception to the rule.

Forest regeneration is a complex process that is influenced by many variables; this study showed that at New Forest distance to nearest seed source was one of these variables. Species distribution pattern, density and species richness of native species in invasive stands were influenced by the distance from seed source. However, these results also showed that distance to seed source was not the only variable to affect regeneration and that other unmeasured variables were also likely to have influenced the colonisation ability of native species in invasive alien stands.

Rehabilitation managers are often faced with limited budgets and enormous quantities of alien species to control. In such circumstances, should invasive stands growing adjacent to native forest be deemed young second growth forest which is ecologically connected to the core or mature native forest? Alternatively, should these types of areas be interpreted by managers as a threat to native forest and be completely removed? In this context there is merit to allowing a contuum of the natural ecological process based on research such as D'Antonio and Meyerson (2002) and Geldenhuys (2013) who argue that alien species provide ecosystem services in rehabilitation projects.

It is likely that mixtures of invasive species and native forest ecotones will be permanent features in the modern landscape, especially in increasing fragmented and altered areas of habitat. Although this study suggests that native forest species are colonising stands of invasive alien trees (specifically on the forest edge) it does not determine if the forest is expanding specifically because of the presence of alien plant stands. The ecological pattern of this forest expansion could be attributed to 'woody encroachment' which is thought to occur because of a number of factors such as a change in fire regime (Geldenhuys, 2013) and increasing CO^2 levels (Bond, 2008; Bond and Parr, 2010) as there are many ecological similarities between the encroachment of native woody species and invasive alien plants in grassland areas.

The results from this study have practical implications for land use managers. Understanding how variables affect regeneration of native species in invasive stands and knowing which areas have the potential to develop into natural forest, will provide tools for natural resource managers in complex ecological areas. For example, it is especially important to understand the spatial potential of native rehabilitation in relation to distance to nearest seed source by knowing how many and which species are likely to regenerate near or far from the seed source. It is also important to understand these patterns if rehabilitation activities aim to achieve a forest rehabilitation response which can be influenced by management activities. This information could be assimilated into IAP clearing methodology, fire management and future tree planting programmes. Research such as this provides ecological insight into forest successional processes and species colonisation patterns, and will ensure that natural resource managers partner with the natural flow of forest ecology and not work against it.

5.2.3 The relationship between invasive stand structure and native forest regeneration

5.2.3.1 Self-thinning of invasive stands

A correlation between stem density and stem diameter across the invasive stands was observed. Plots with an average of larger stems had generally lower stem density, and plots with an average of smaller stems had generally higher stem density. For example, the plot with highest overhead stand density (i.e. stems ≥ 5 cm dbh) contained 2675 stems ha^{-1} and had a corresponding mean DBH of 9.4 cm, whereas the plot with lowest density contained 450 stems ha^{-1} and had a mean DBH of 14.5 cm DBH. A linear regression between Ln density and Ln mean DBH revealed a significant negative regression slope (P=≤0.001) illustrated in Figure 5.13. This demonstrated that invasive stands were undergoing self-thinning which was in line with the first objective of the study.

Further analysis revealed that the slope of the regression otherwise known as the 'self thinning coefficient' was -0.37. This indicated that the stand self-thinning ratio was determined by plants growing allometrically (that is plants that change shape during growth and determined by a regression coefficient of -0.33). This is opposed to the stands which contain plants growing isometrically (that is plants that do not change shape and determined by a slope of -0.66) (Osawa and Allen, 1993; Bagchi, 2007). Allometric growth is characteristic of natural forests and this consequently revealed that the self-thinning invasive stands at New Forest showed a potential similarity to the self-thinning process of natural forest pioneer stands.

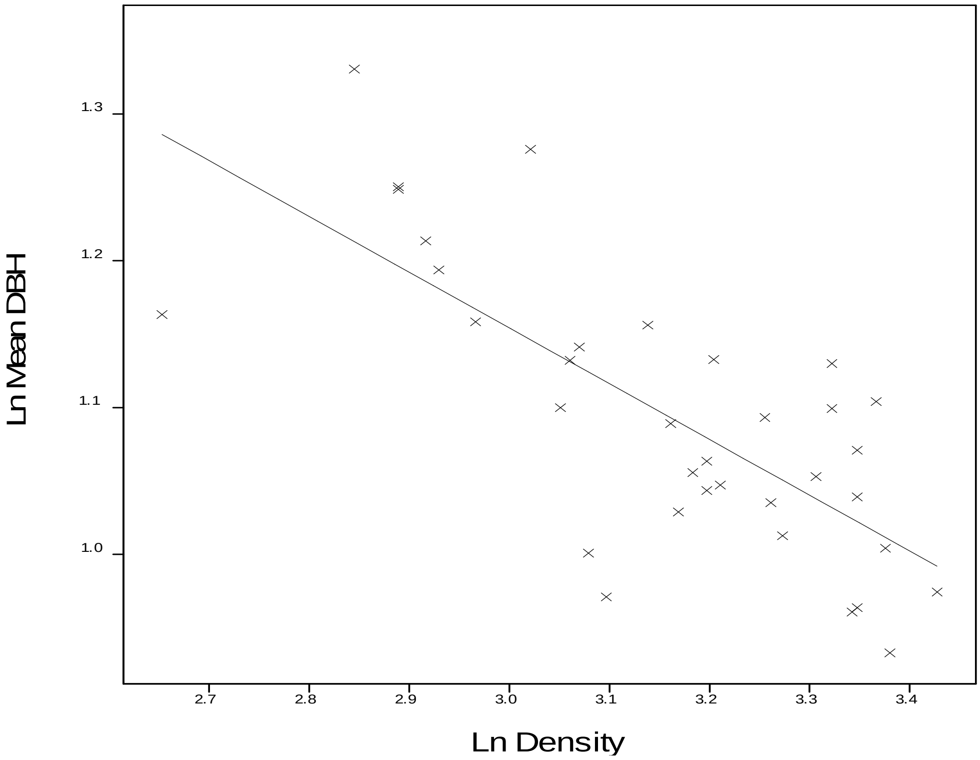


Figure 5.13 A linear regression between density (no. of trees per plot) and trees size (mean DBH) to estimate self-thinning of trees p= ≤0.001; R^2= 0.52; y= -0.37x +2.

5.2.3.2 The relationship between stand types and native regeneration

There was a general trend that stands with greater stem diameters had the highest regeneration stem density and species richness (Table 5.1). Mixed regrowth stands in general seemed to be the most successful stand types for recruitment, followed by abandoned plantation stands, riparian invasion stands, *Eucalyptus* spp. and then *Solanum mauritianum* stands. Eleven plots in the data set contained native regeneration densities of >10 000 stems ha^{-1} (five plots each from mixed regrowth and abandoned plantation plots and one plot from the riparian plots). The four *Eucalyptus* spp. stands were the lowest recruiters. The mean of their native species regeneration density was 1800 stems ha^{-1} (though this included one stand with 1500 stem ha^{-1}). The abandoned plantation and riparian invasion plots generally had similar regeneration densities (± 6000 stems ha^{-1}) but species richness was higher in abandoned plantation (42) as opposed to 32 species in the riparian invasion plots. The mean DBH for both stand types was 12.3 cm. There were also differences in the native regeneration of older and younger mixed regrowth forest plots. Older mixed regrowth forest contained 37 species, as opposed to the 19 species in young regrowth.

Table 5.1 Density (stems ha^{-1}) and species richness of woody regeneration in relation to structural attributes of invasive species stand types

Stand Type	Mean DBH (cm) of invasive stand	Mean stem density of invasive stand (ha^{-1})	Density of native regeneration (stems ha^{-1})	Native regeneration richness (no of species)	Upper canopy cover Braun-blanquet %	Lower canopy cover Braun-blanquet %
Old mixed regrowth (7 plots)	13.4	1308	9157	37	52	46
Young mixed regrowth (3 plots)	9.5	2150	14033	19	38	31
Abandoned plantation (12 plots)	12.3	1541	6758	51	65	38
Riparian invasion (10 plots)	12.3	1632	6090	32	61	24
Eucalyptus (4 plots)	12.7	1233	425	17	50	37
Solanum (2 plots)	8.0	1337	2600	2	63	36

The results from Braun-blanquet cover values of lower and upper canopies of different stand types revealed that all stand types had relatively broken upper canopies between 48-60% cover. The riparian invasion plots were the group with the lowest cover of the lower canopy, and this was attributed to periodic flooding from the river which may have cleared the lower structural elements of the forest.

5.2.3.3 Relationship between stand structure and native regeneration

Nonlinear regressions between invasive species stand density and native regeneration revealed no significant relationships; it therefore appeared that stand density did not influence native species regeneration. However, this may be because of the varying distances of each plot from the seed source of the natural forest. A weak relationship was observed between the mean DBH of the invasive species stand and the amount of native species regeneration (measured as species richness and stem density) and are detailed in Figure 5.14 and Figure 5.15. In both regressions there were outlier plots that demonstrated high leverage in the regressions. This indicated that the age of the invasive stands had an influence on the amount of native forest regeneration.

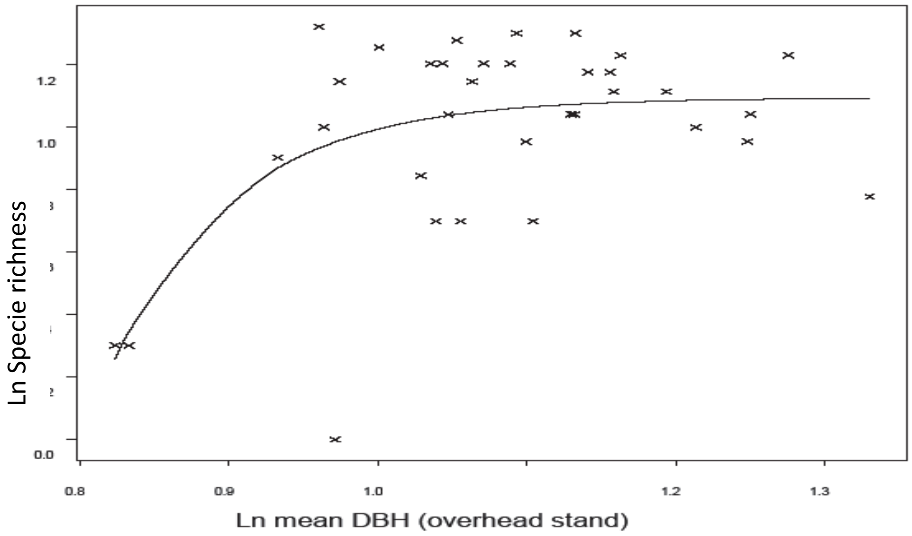


Figure 5.14 The relationship between mean DBH (Tree size) and species richness (no. of native species per plot) P = ≤0.001, R^2 = 0.31. Ln richness= -1 + 16562 x Ln DBH 0.00000061. Five plots were removed due the low number of species in these plots (3 eucalypt plots, 1 abandoned plantation plot 1 Bugweed plot).

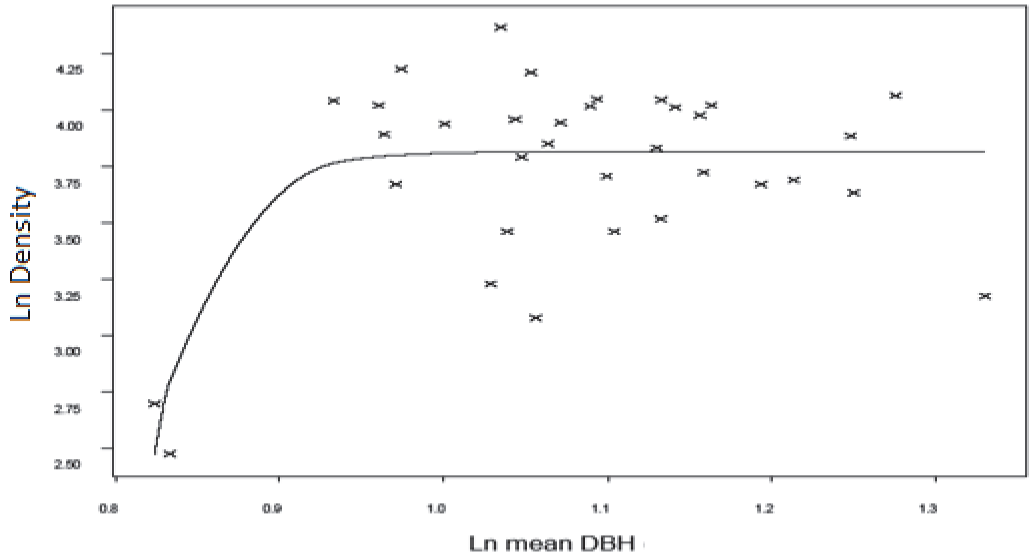


Figure 5.15 The relationship between mean DBH (size of trees) and understory native stem density (no of stems ≥5 cm). P =≥0.001, R^2 = 0.43, Ln density = -3.8 + 5.76E+10 x Ln DBH 1.25E-13. Three plots were removed due to low stem density.

The study therefore determined that the hypothesis that the structure of invasive stands influenced native species regeneration is only partially confirmed. This was because it was found that only mean DBH of invasive stands had a weak influence on native forest regeneration. Although stand density has a strong inverse relationship with mean stand DBH, and that this relationship determines the amount of light, and possibly also soil moisture, the relationship between stand density and native forest regeneration was not significant.

5.2.3.4 Discussion

Self-thinning of invasive stands

The study revealed that trees in invasive stands were self-thinning. This aligned with the first objective of the study and was in line with the general theory of the study which relied on the fact that IAP stands undergo a self-thinning process during their development (Geldenhuys, 2013). The slope of the regression showed self-thinning to be consistent with allometric stand growth which was typical of natural forest environments as they reflect changes in individual tree structure (Bagchi, 2007).

The fact that the invasive stands at New Forest were self-thinning and that their growth was allometric underlines the idea of a natural successional development process. This was because changing structure during stand development and fewer but larger trees in a forest stand could provide ecological opportunity for native forest species to colonise within invasive stands.

The relationship between stand types, stand structure and regeneration

Differences in native species in both the regeneration layer and sub canopy/canopy tree layers in the different stand types followed the successional pattern that native species were more abundant and species rich in older stands than in younger stands.

This supported the second hypothesis of the study and was aligned with results from previous studies (Geldenhuys, 1997). The stand type with most native regeneration was mixed regrowth forest which was separated into two types. Secondary regrowth stands were the oldest stand type and had trees with the largest stem diameters. These plots were from heavily disturbed and invaded regrowth forest areas and were generally the most species rich with highest regeneration stem density. This was attributed to the immediate seed source from many mature individual trees which were characteristic of its late successional stage.

Primary mixed regrowth plots were located on forest margins in grassland areas. Young regeneration in these stands was denser than the secondary mixed regrowth stands, though the species richness was less in both the canopy and regeneration layers. This was attributed to the dominance of the native pioneer *Leucosidea sericea* which accounted for most of the regeneration in these plots. The abandoned plantation forest and riparian invasion stands had similar species richness and stem density of their regeneration. Native stem density was comparable with results from a similar study from an Eastern Mistbelt Forest of 6000 stems ha (Geldenhuys and Delvaux, 2006) though species richness was considerably higher at New Forest. The lowest regeneration was seen in the *Eucalyptus* spp. and *Solanum mauritianum* stands and this was thought to be from allelopathic influences (Ruwanza et al., 2013) or distance to seed source in the *Eucalyptus* stands and the young stage of the *Solanum* stands. Not enough plots were sampled to be certain of this. However, that native species were present in these plots showed the capacity of native plants to grow in environments that did not seem favourable to colonisation by native forest species.

Forest successional process and the potential for application

Even though the results were not clear on the actual successional stages which controlled the native regeneration, the results corresponded with other literature on the subject (Geldenhuys, 1997, 2013;

Powers et al., 1997; Geldenhuys and Delvaux, 2006) and provide a meaningful addition to this branch of ecological research.

The fact that invasive stands were determined to be self-thinning and native regeneration increased with stand age is a clear demonstration of an ongoing forest successional process within invasive stands. A better understanding of this process which considers micro site factors such as soil substrate, pH, nutrients, and other controlling factors such as distance to seed source and/or browing, is required if manipulation of this process is to be successful. Two broad examples of the successional stages were determined in this study:

i. The abandoned plantation and riparian invasion stands were determined to be in a successional stage 2, as they contained a young regeneration layer, but very few native species in the canopy. Young mixed regrowth stands were also judged to be in a stage 2 (Figure 5.16) of the successional process as they also had very few native species besides *Leucosidea sericea* in the canopy.

ii. Older mixed regrowth stands were deemed to be of successional stage 4 (Figure 5.16), this was because they contained many older stems of 30 tree species in the canopy. It must be noted, however, that the older mixed regrowth forest did not follow the successional process from pioneer invasive stand to mixed regrowth forest as it was a path of existing disturbed forest which was invaded. However it was deemed a likely representation of this stage and a good example of what stage 4 regeneration might portray. The area sampled was most likely a severely disturbed regrowth forest in which the large open gaps became invaded by alien plants. IAPs subsequently self-thinned within these forest gaps and thus joining the successional process at a later stage as there were many sources of seed for native regeneration in the immediate vicinity.

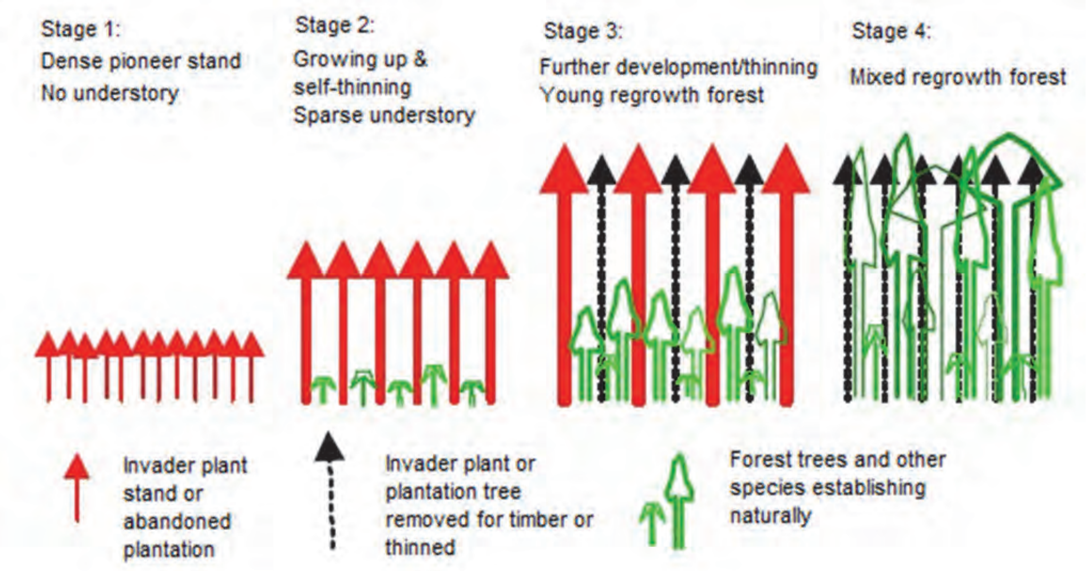


Figure 5.16: A hypothesis of mixed regrowth forest development within alien invasive stands

During invasive plant control, applying the understanding of succession stages could be conducted in areas of abandoned plantation and riparian invasive stands where young native regeneration has established. A thinning regime could be implemented to promote the transition from successional stage 2 to successional stage 3, rather than reversing the successional process by cutting down the entire invasive stand.

5.2.3.5 Conclusion

Stand structure did affect native regeneration at New Forest, but in many different ways and it was not only structure that influenced regeneration. This research revealed that marginally shade tolerant native pioneer species were not smothered by mass recruitment of invasive plants when growing within the shaded environment of invasive stands; in fact, in most circumstances invasive species were too shade intolerant and required large disturbance such as a tree fall, flood or tree felling to recruit prolifically. Invasive stands provided the ecological opportunity for native species to develop in nurse conditions along a forest successional gradient and that manipulating forest structure to align with the natural successional process could be a viable IAP treatment.

Shortcomings in this study were that it did not sample stands along the entire forest successional process and that the various invasive stand types made it difficult to assess a clear regeneration pathway. However, the gap between the young successional stages (in abandoned plantation and riparian invasive plots) and advanced successional stages (in secondary mixed regrowth forest) was clear. Further research should look at (1) manipulating young invasive plant stands within an experimental design, which would control some variables while allowing testing the effects of other regeneration influences and (2) Identifying and sampling sites which show evidence for stage 3 and 4 successional processes without forest manipulation.

5.3 Hydro-meteorological Findings

5.3.1 Climate

The Mean Annual Precipitation observed between 1906 and 2001 at New Forest was 941 mm (Figure 5.17). It is also clear from these records that the rainfall has become more variable in the last 30 years, where as little as 459 mm (2000) and as much as 1458 mm (1991) have been observed in a year.

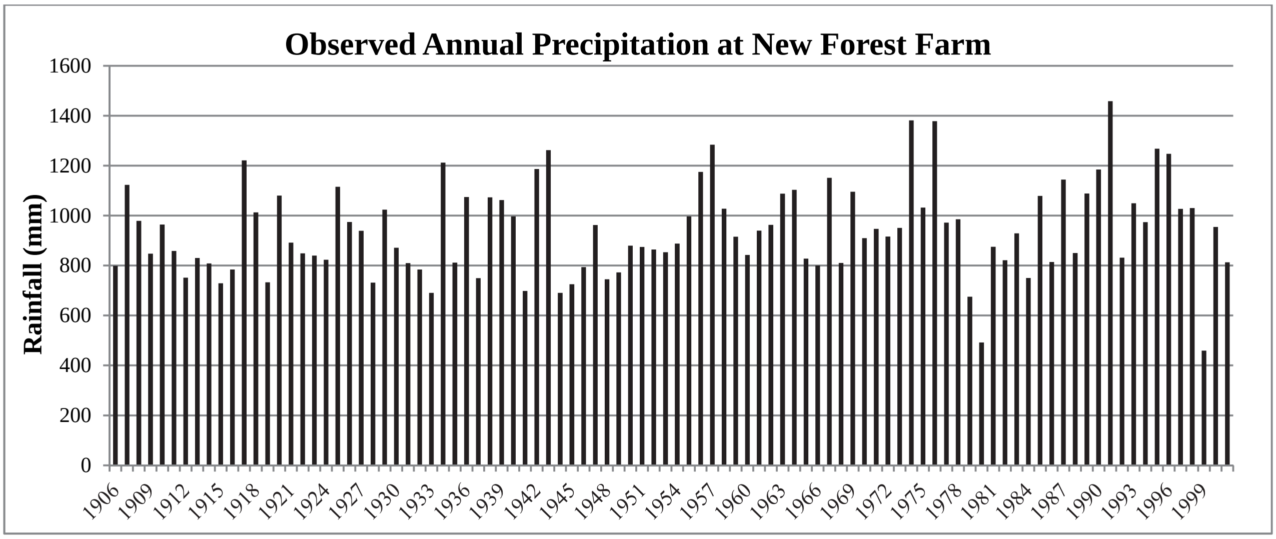


Figure 5.17 Annual precipitation recorded at rainfall stations near New Forest farm (1906-2001)

An average daily temperature of 18.4 ºC was recorded at New Forest in the summer months during the study period. During these months, daily maximum temperatures reached in excess of 30 ºC. During the dry winter months, the temperatures averaged 11.7 ºC due to numerous days of low solar radiation during this period and the cold nights. Periods of low solar radiation correspond to rainfall (and cloudy days) and would likely result in little to no transpiration occurring. The daily ET_o peaked at 6.1 mm, which was expected for this area (Figure 5.18). When the temperature was at its highest, the ET_o was also at its peak due to a greater atmospheric demand. Thus during summer the water-use measurements were expected to be highest.

The hourly rainfall and solar radiation showed that there were numerous days of high hourly rainfall. This indicated that intense rain storms were prevalent at the site. On cloudless days the solar radiation peaked at 39.5 MJ day^{-1} in summer and dropped to 15 MJ day^{-1} in winter. The typical summer rainfall zone radiation trends for this area can be clearly seen in Figure 5.18.

The monthly data (Figure 5.18) indicated a peak rainfall month exceeding 400 mm in November. Average monthly temperature ranged from 12 °C to 19 °C. The total rainfall during this period was 1118 mm. The daily solar radiation reached up to 40 $MJ.m^{-2}.day^{-1}$ (Figure 5.19) while reference total evaporation reached up to 5.6 mm per day.

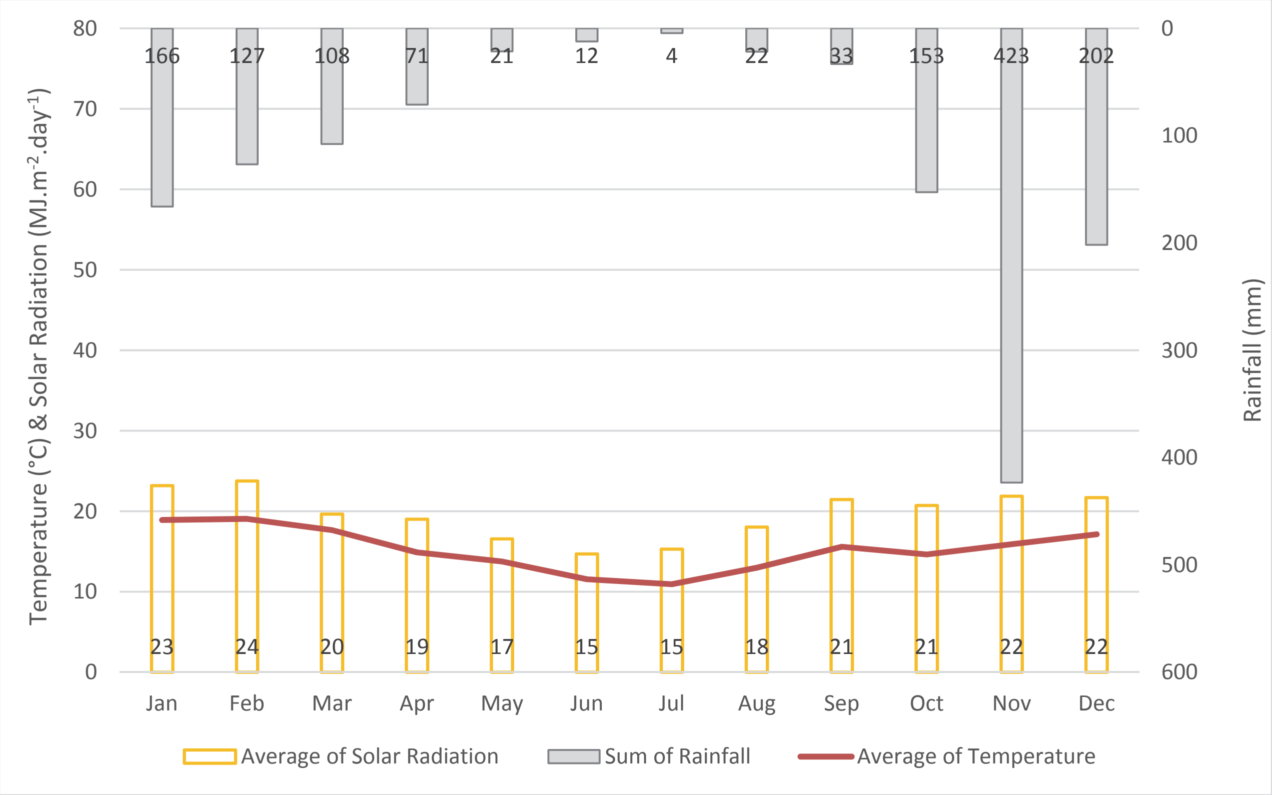


Figure 5.18 Aggregated monthly values of average temperature (°C), rainfall (mm) and solar radiation ($MJ.m^{-2}.day^{-1}$) at New Forest

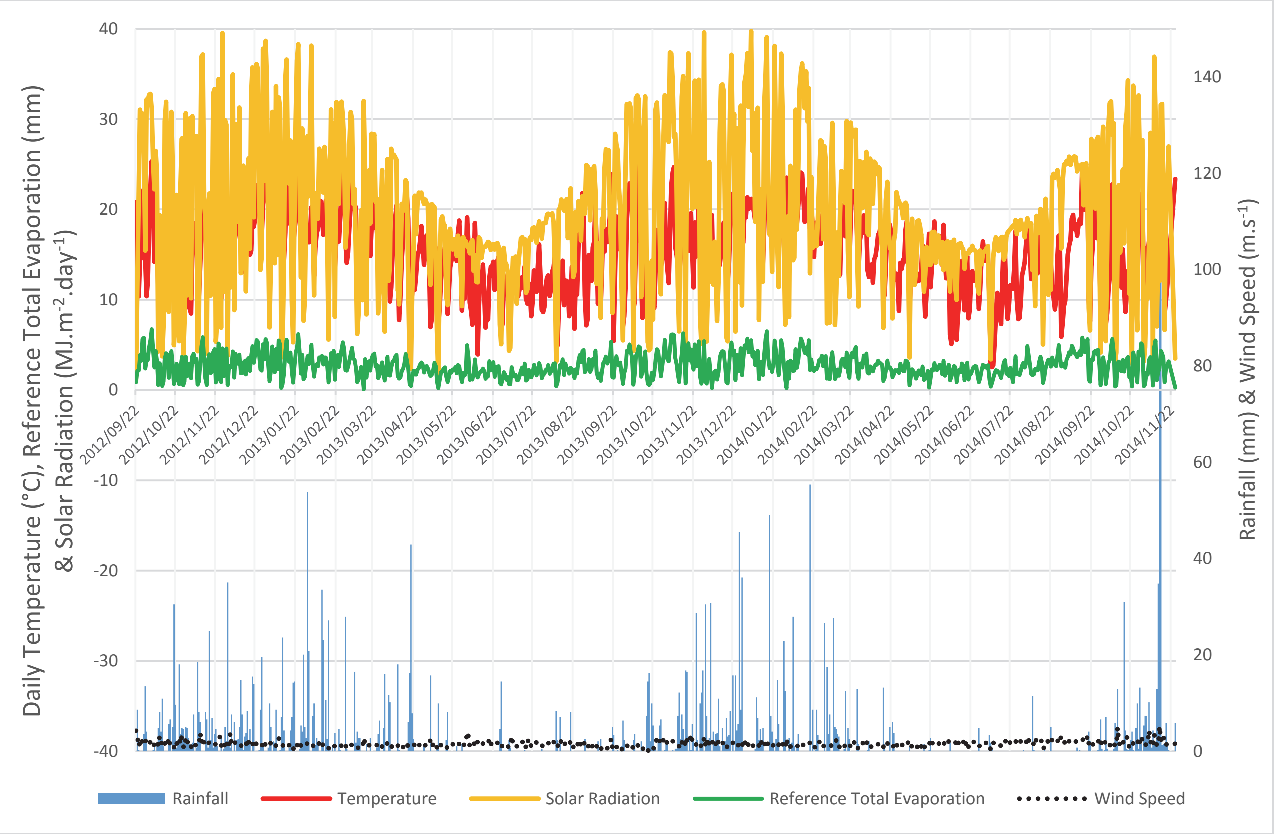


Figure 5.19 Daily values of maximum and minimum temperatures (°C), reference total evaporation, solar radiation (MJ.m^{-2}.day^{-1}), rainfall (mm) and windspeed (m.s^{-1}) at New Forest

The water contents at the New Forest sites were high (approximately 35% during the wet season). On the 27th of January 2013, 20 mm of rainfall occurred. The response to this event can be seen at all the depths, but markedly in the first 0.1 m at the lower site (Site 1, Figure 5.20). The deeper probes (0.5 m) were the least responsive to this event. This suggests that most of the water from rainfall events was stored in the topsoil and was then taken up by the roots and/or runoff into the nearby stream. The shallow rooting profile observed in the soil profile supports this theory. In addition, the upper probes dried out quickly and returned to their original water content, whereas the lower profile stayed wetter for longer after a rainfall event. The higher clay content in the lower profile would most likely store more water than the Orthic soil in the upper profile.

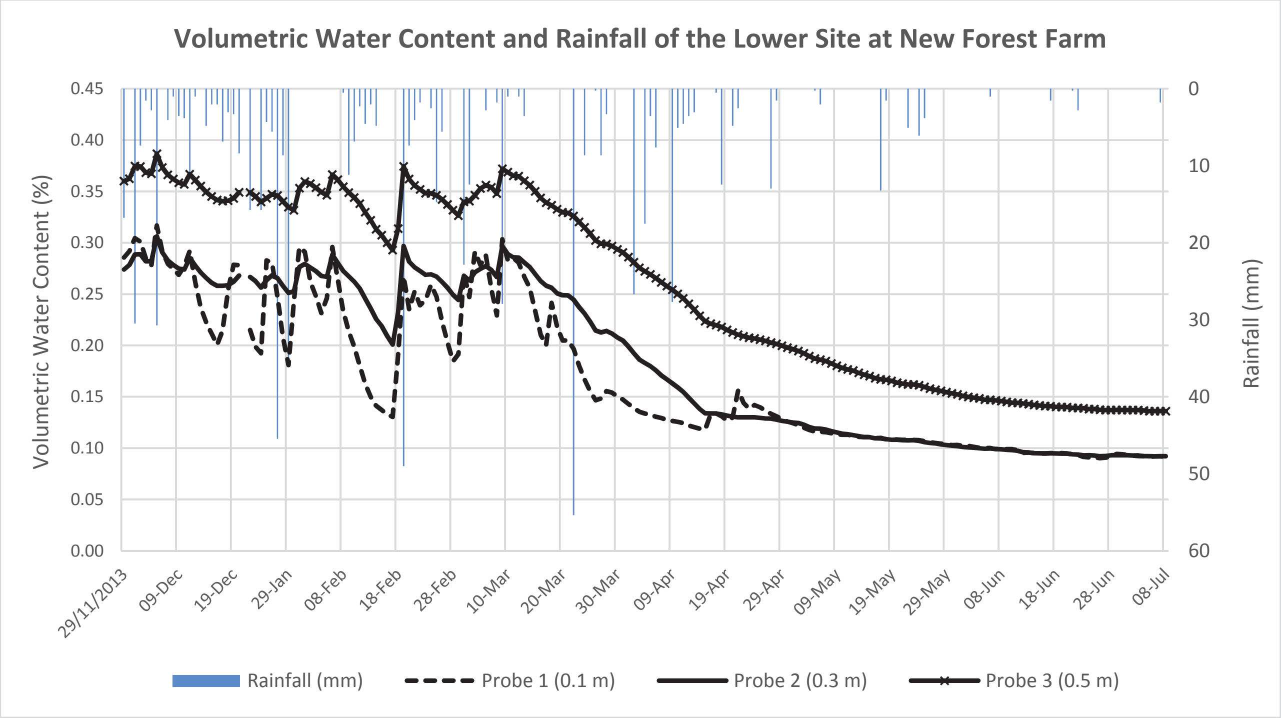


Figure 5.20 Volumetric water content of Site 2 during the summer period at New Forest farm

During the dry winter period (Figure 5.21), only the upper probe (0.1 m) responded to rainfall events. This was most likely due to dry antecedent soil moisture conditions, where the tree roots readily absorbed available water during these low rainfall events.

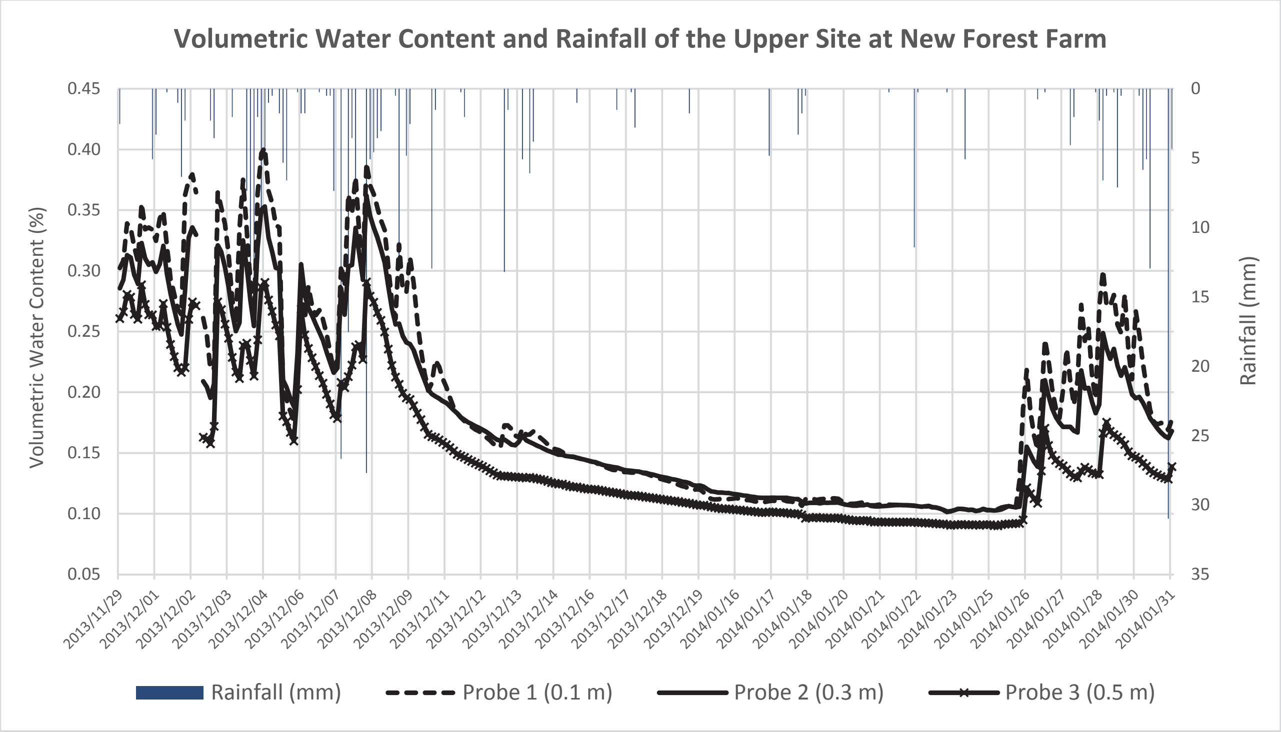


Figure 5.21 Volumetric water content of Site 2 during the measurement period at New Forest farm

Table 5.2 Water quality measurements of samples taken from New Forest farm on the 19th July and the 26th September 2013

New Forest 19/06/2013 Tributary	Temperature	Atmospheric Pressure	Dissolved Oxygen		Conductivity	Total Dissolved Solids	Salinity	pH
	ºC	mmHg	%L	Mg/L	uS/cm	Mg/L	ppt	
Site 1	7.9	639.4	63.5	6.34	23.4	22.8	0.02	8.81
New Forest/ Mgeni 26/09/2013	Temperature	Atmospheric Pressure	Dissolved Oxygen		Conductivity	Total Dissolved Solids	Salinity	pH
	ºC	mmHg	%L	Mg/L	uS/cm	Mg/L	ppt	
Site 1	15.1	649.0	57.1	4.91	26.8	21.5	0.01	6.84
Site 2	15.0	649.0	60.2	5.18	26.6	21.5	0.01	6.77
Site 3	15.1	649.0	60.9	5.24	26.6	21.5	0.01	6.80

Soil samples analysed in the laboratory yielded the following results:

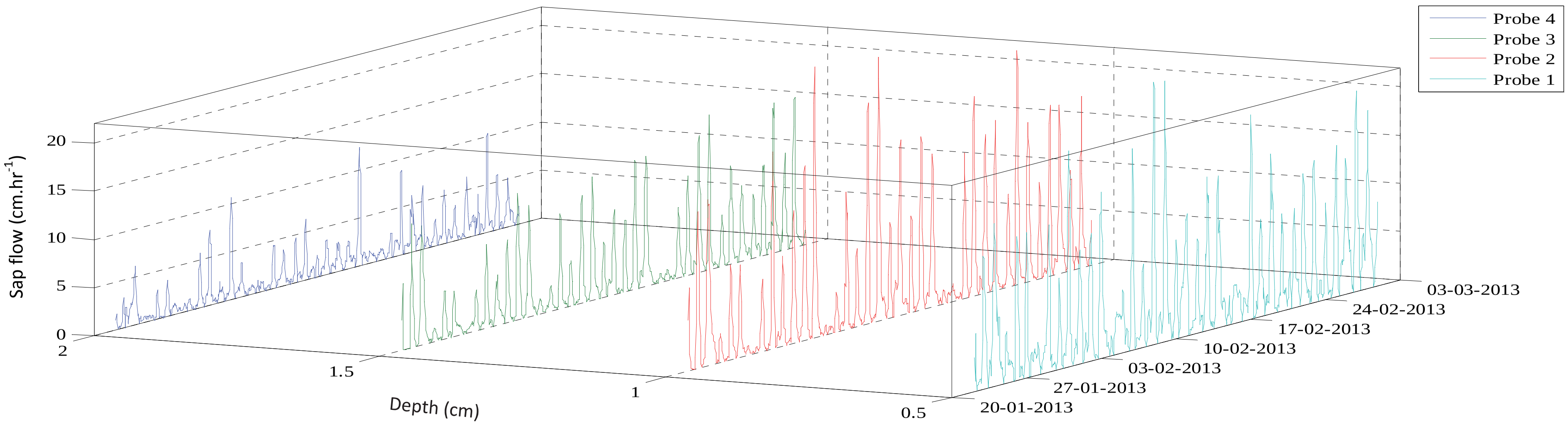
Bulk density (*Db*):	1.22 g.cm^{-3}
Particle density (*Dp*):	2.54 g.cm^{-3}
Porosity (*P*):	0.52%

5.3.2 Water-use

Heat pulse velocity measurements from a selection of the trees at New Forest have been provided in Figure 5.22. The results showed that the peak sapflow rates occurred at midday. Sapflow only occurred on days when the solar radiation was high. An offset was needed for some of these trees to adjust for the difference in baseline readings. The sapflow rates between the *Maytenus peduncularis* and the *Acacia mearnsii* (Figure 5.22) were similar, with the peak sapflow occurring at approximately 20 cm.hr^{-1} for both trees. These trees were of a similar stem diameter.

The results from an *Acacia mearnsii* (Figure 5.22) showed that the highest sap flow occurred in the third probe (2.5 cm). The sap flow reached 25 cm.hr^{-1} at this depth, whereas it was approximately 3 cm.hr^{-1} and 15 cm.hr^{-1} for the *Searsia* and the *Gymnosporia* respectively. The anatomy of these trees was clearly very different. It can also be seen that the sap flow had a strong relationship with the reference total evaporation calculated from the AWS. This was important for patching and modelling for this catchment.

Hourly Heat Pulse Velocity of an *Maytenus peduncularis* (Diameter: 11.4 cm) at New Forest Farm



Hourly Heat Pulse Velocity of an *Acacia mearnsii* (Diameter: 19.0 cm) at New Forest Farm

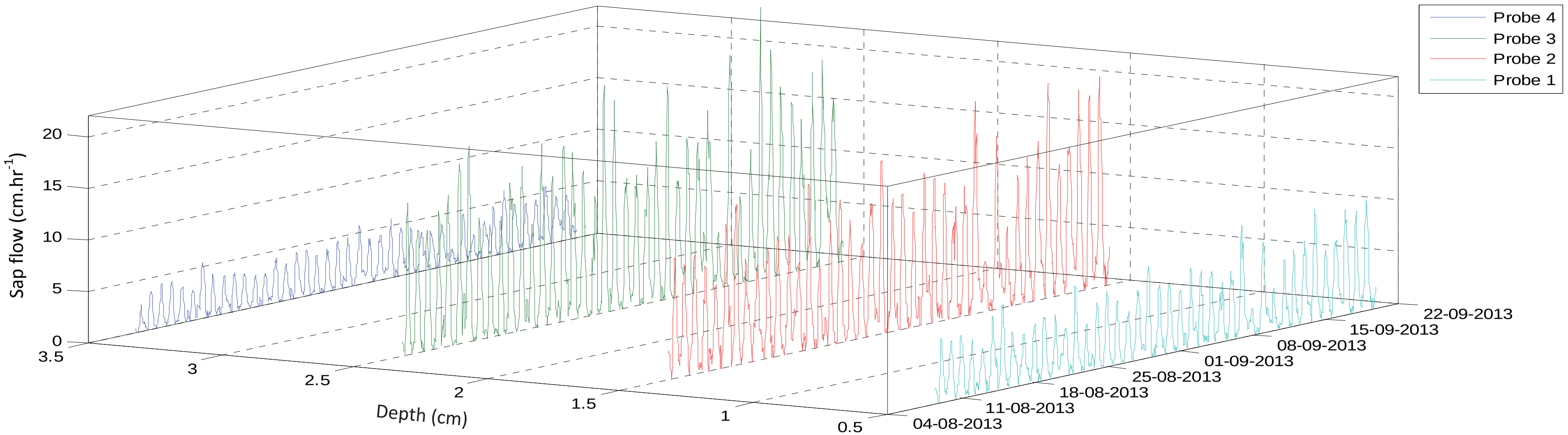
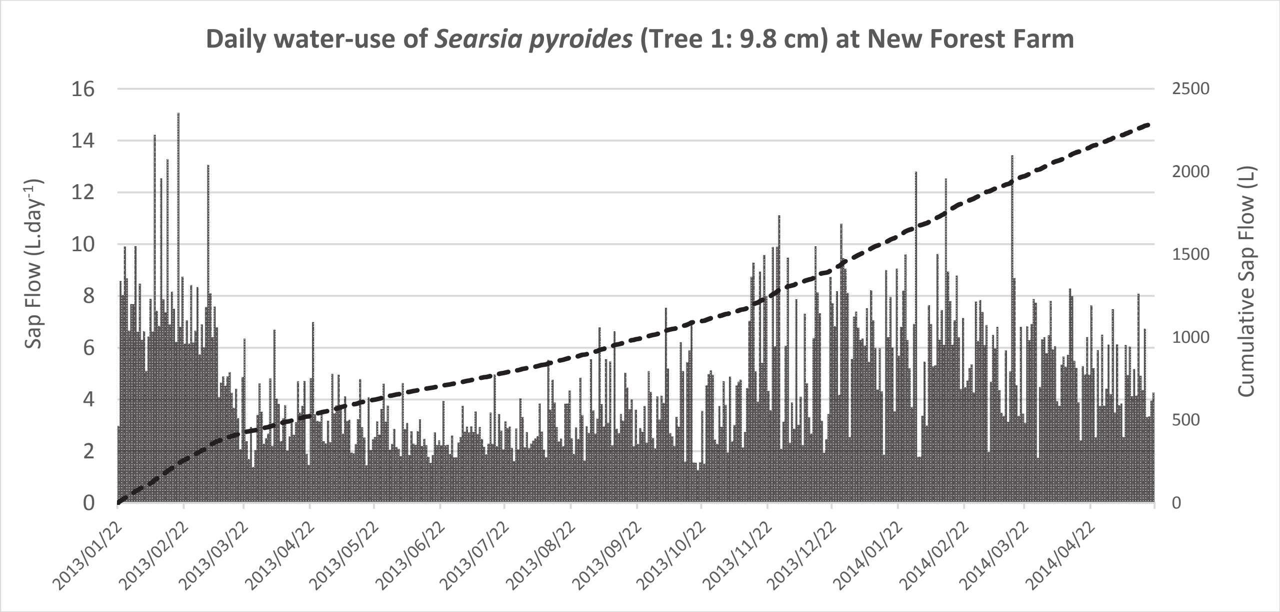
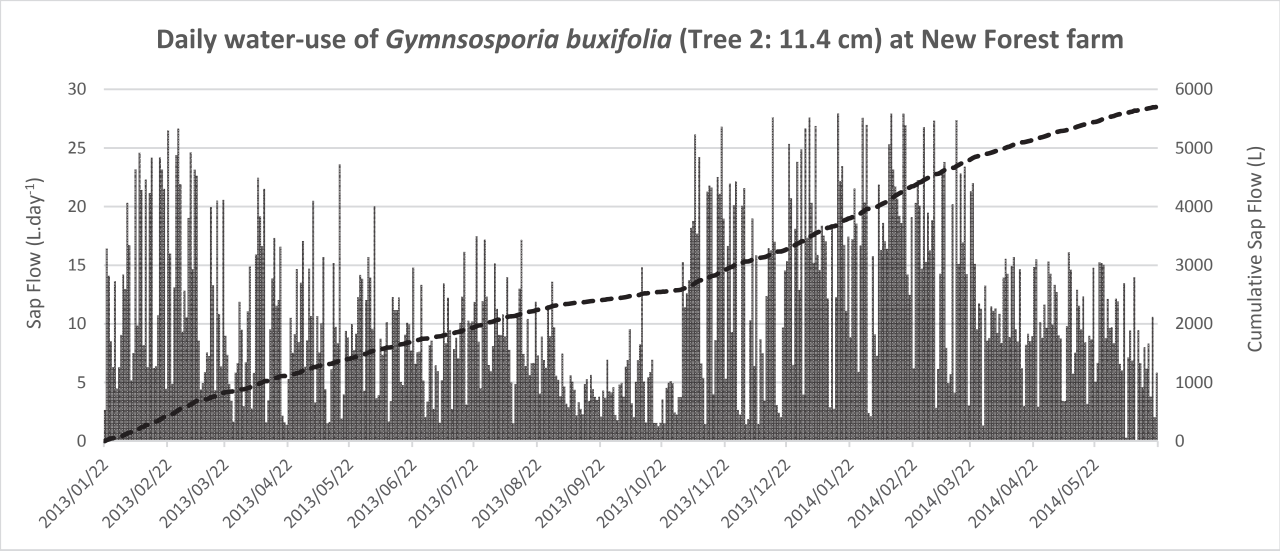


Figure 5.22 Radial sap flow profile for a *Maytenus peduncularis* (Site 1) and an *Acacia mearnsii* (Site 2) at New Forest farm

The information in Figure 5.21 is useful to determine where the peak flows are occurring and whether the sapwood depth is being accurately represented. The tree (*Kiggelaria africana*, Tree 6,) displayed a fairly high sapflow rate (results provided separately), considering its size (5 cm diam.) and young age.

The three trees at New Forest were semi-deciduous species (*Searsia pyroides*, *Gymnosporia buxifolia* and *Acacia mearnsii*), losing some leaves in winter but remaining evergreen throughout the year (Figure 5.23). The daily water-use of *Searsia pyroides* averaged 8 L.day^{-1} in summer compared to 3 L.day^{-1} in winter, resulting in an accumulated total water use of 2265 L between 22nd January 2013 and 22nd April 2014. By contrast, *Gymnosporia buxifolia* used approximately 25 L.day^{-1} in summer compared to 12 L.day^{-1} in winter, resulting in an accumulated total water use of 5649 L over the same period. Despite the similar size in the indigenous species, the *Gymnosporias buxifolia* used nearly twice the amount of water than the *Searsia pyroides*. The alien *Acacia mearnsii* of similar stem diameter showed little seasonal variation. This tree averaged 60 L.day^{-1} throughout the measurement period. This summed up to 15 383 L over the year which was very high in comparison to the indigenous species and is comparable to other large introduced species measured throughout South Africa. The *Celtis africana* used a relatively high amount of water, despite being deciduous, and used more water than the other indigenous trees by approximately 2000 L.year^{-1} (7713 L accumulated water use).





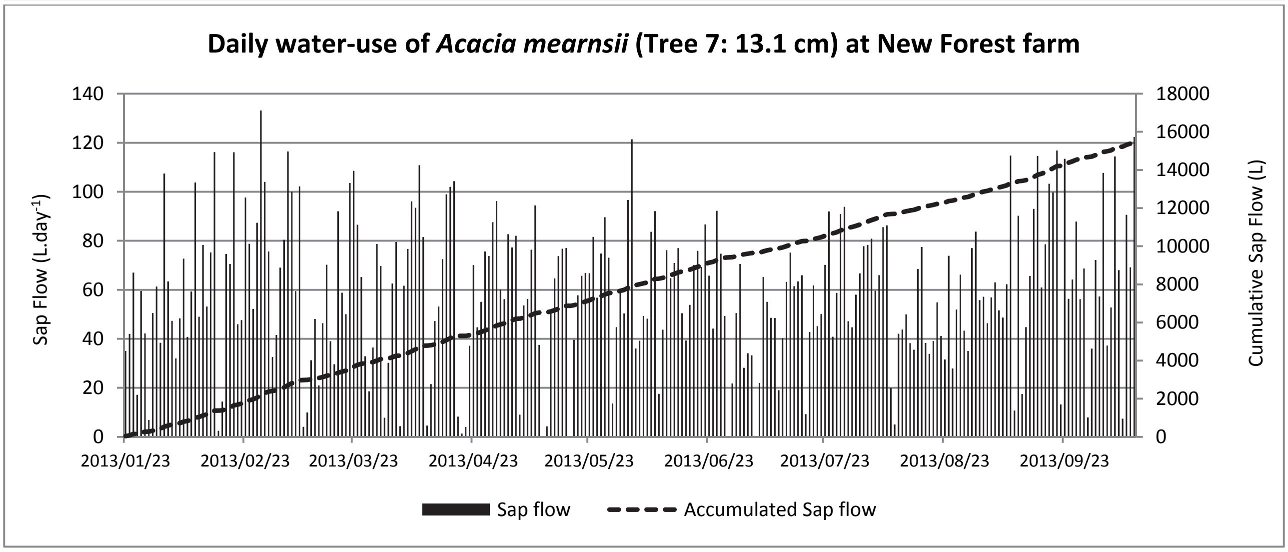


Figure 5.23 Daily sap flow from a *Searsia pyroides* (Tree 1), a *Maytenus peduncularis* (Tree 2) and an *Acacia mearnsii* (Tree 7) at New Forest farm

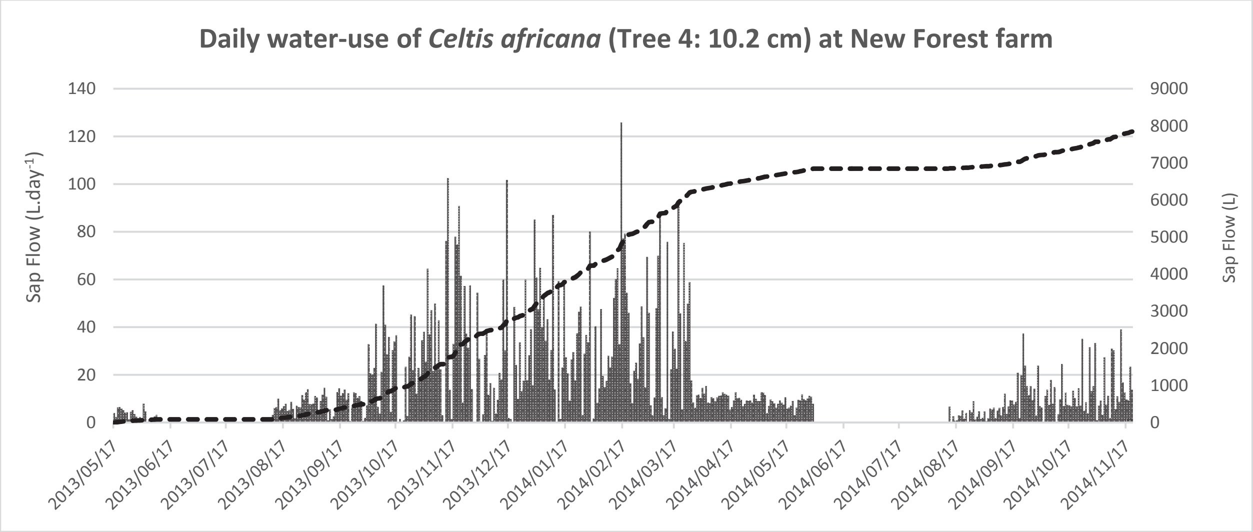


Figure 5.24 Daily sap flow from a *Celtis africana* (Tree 4) at New Forest farm

Using the Dynamax pot trials, which were set up inside a greenhouse at the University of KwaZulu-Natal, the *K* values for the stem and the sheath were calculated. This equipment was then moved to New Forest farm (Figure 3.21). The observations from these trials highlighted some interesting findings. The first, and most important, was that *Buddleja salviifolia* and *Leucosidea sericea* were suitable species for measurement with this technique. Secondly, there was no correlation between stem size and transpiration. It is likely that transpiration is linked to the position of the stem in relation to the direction of the incoming light. When comparing similar sized stems from the two different species, it was clear that *Buddleja salviifolia* had a much higher transpiration than *Leucosidea sericea.* Results from the equipment running at New Forest yielded some interesting comparisons. The *Buddleja* stems summed together (Figure 5.25) had higher flows (averaging 6 L.day^{-1}). In comparison, the smaller *Solanum mauritianum* and the *Acacia mearnsii* used considerably less water (Figure 5.25). The *Acacia mearnsii* was particularly sensitive to hourly changes in solar radiation when hourly values were observed.

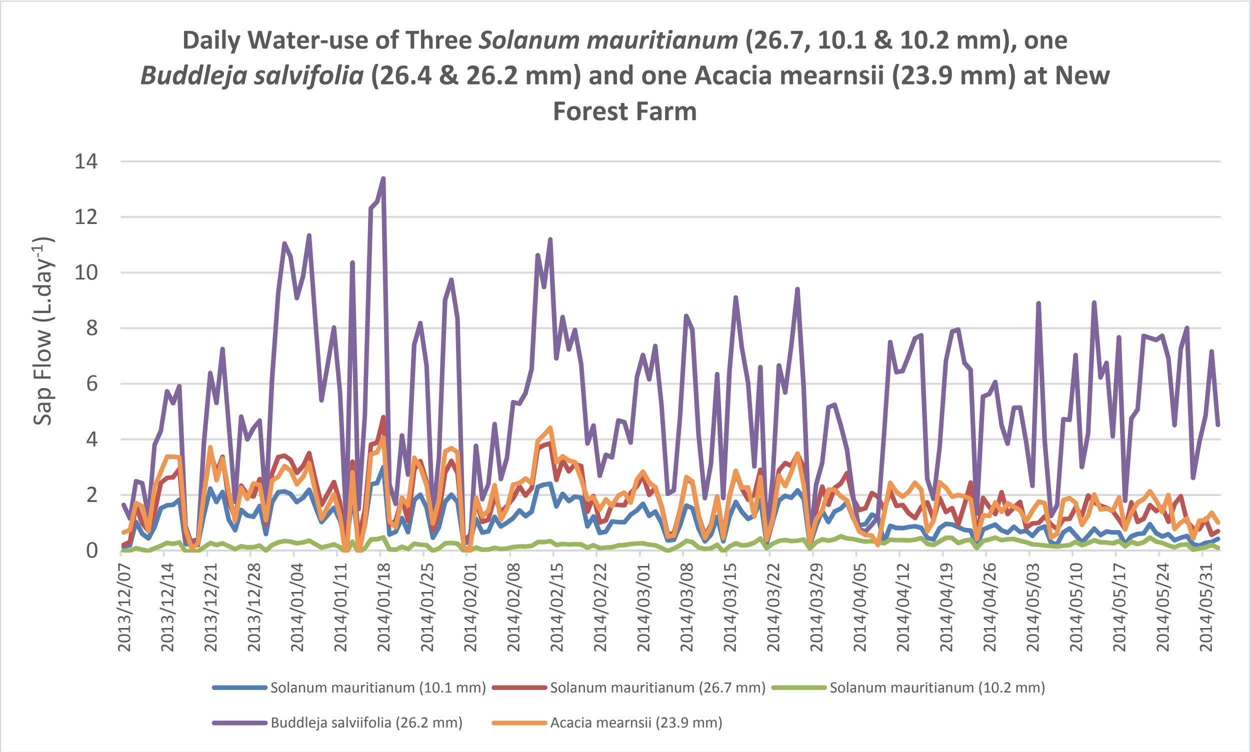


Figure 5.25 Daily water-use for three *Solanum mauritianum* stems, multiple stems of *Buddleja salvifolia* stems and an *Acacia mearnsii* using the SSS technique at New Forest from July 2013 to February 2014

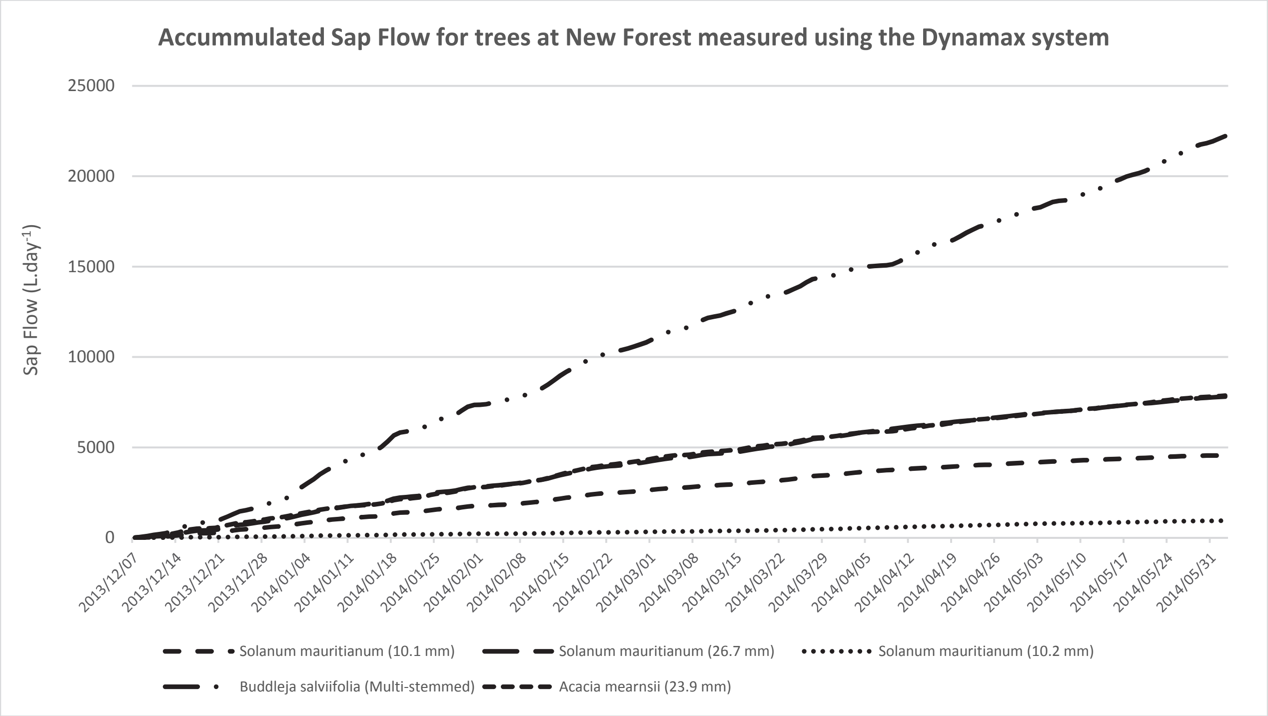


Figure 5.26 Accumulated hourly sap flow some of the tree stems measured using the SSS technique at New Forest from July 2013 to February 2014

5.3.3 Evaporation modelling

Both transpiration and streamflow were modelled for New Forest for three scenarios (current, invaded and pristine) using the *ACRU* and *SWAT* hydrological models. Daily modelled transpiration was approximately 20% higher in the invaded scenario (~5 mm) when compared with the pristine condition (~4 mm). This resulted in an accumulated streamflow reduction of 610 mm over the 50-year simulation period (Figure 5.28).

The catchment water balance for the current condition scenario using the SWAT model showed that during this high precipitation period (3 year simulation), less than half was returned to the atmosphere (Figure 5.27). The contribution of precipitation to streamflow (surface runoff, lateral flow and return flow) was 44%.

On a daily basis ACRU predicted daily evaporation values for the invaded scenario which were 20% higher than the pristine scenario during the 50 year validation period. The differences in water-use between indigenous and invaded riparian zones were also reflected in the runoff components although the loss in streamflow was very slight. The *SWAT* model showed differences between an HRU that was invaded and a pristine state. The total evaporation was approximately 4% less per annum under the pristine state where the streamflow differed by 93 mm over the three year period (Figure 5.29). Much like the Western Cape site, directly scaling up the actual tree water-use data using SWAT showed similar findings with the impact of clearing the *Acacia mearnsii* showing clear water balance benefits.

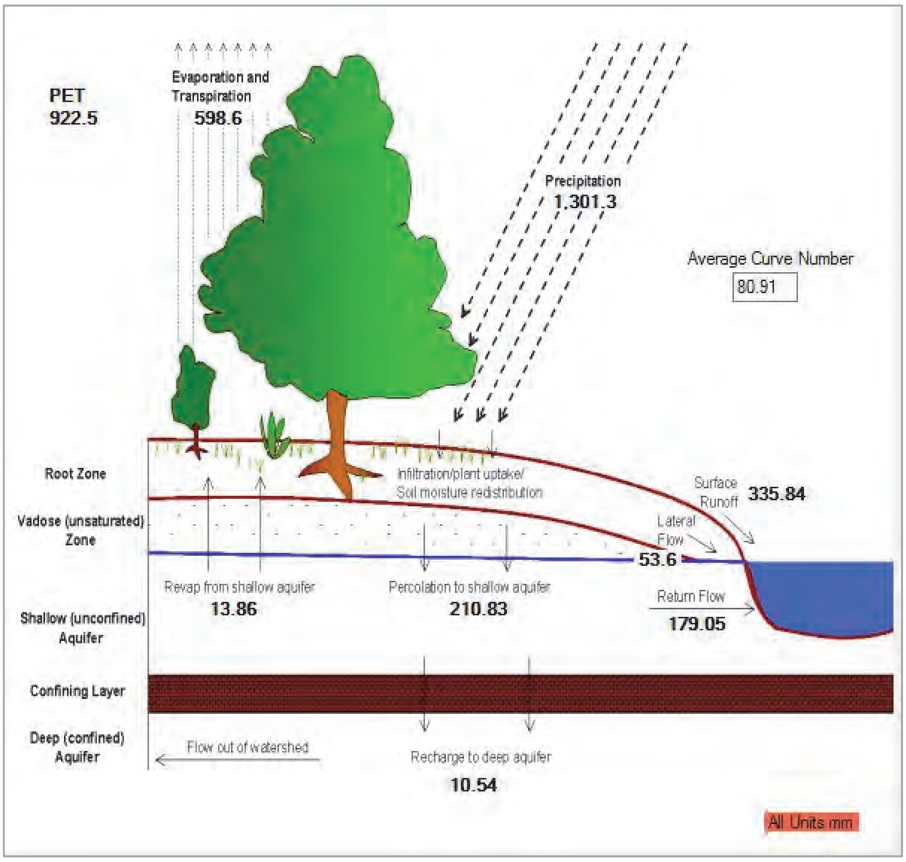


Figure 5.27 Modelled water balance for the baseline scenario (current state) of Quaternary Catchment U20A using the *SWAT* model

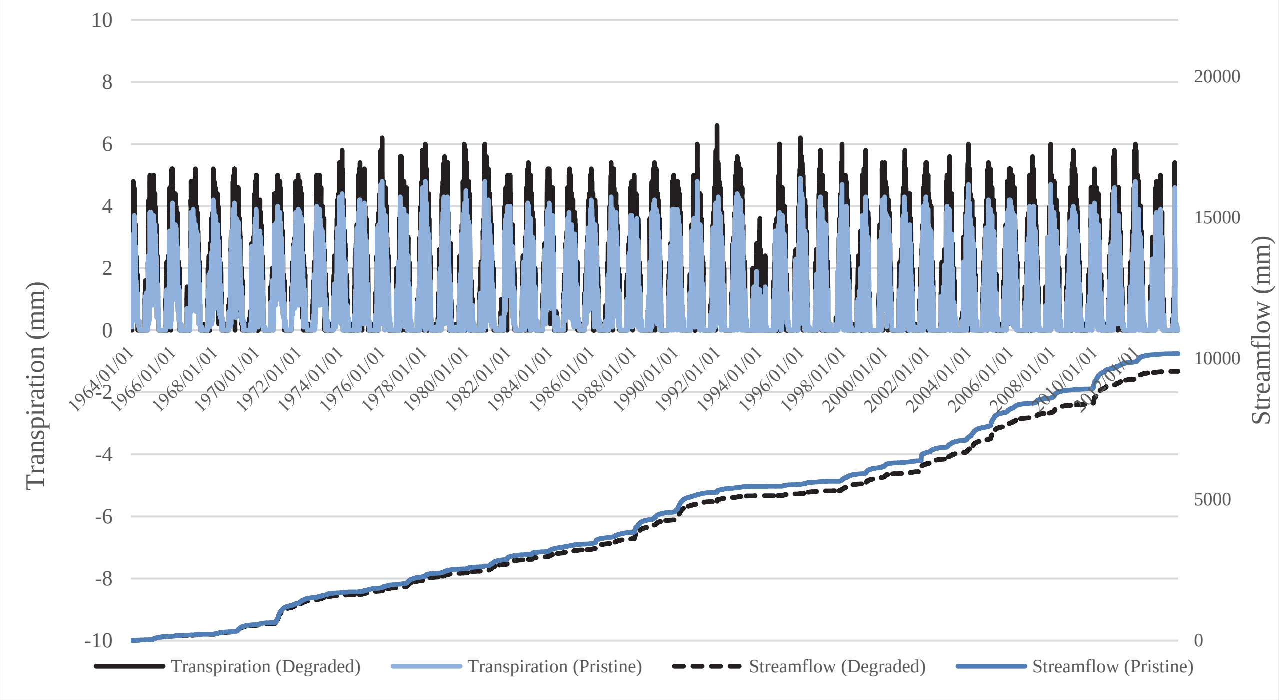


Figure 5.28 *ACRU* Modelled transpiration (mm) and accumulated streamflow (mm) between the pristine and degraded (invaded) scenarios at New Forest for an individual HRU for a 50 year period

The accumulated streamflow and evaporation after three years of *SWAT* simulation showed accumulated differences of 83 and 129 mm respectively for the pristine vs the invaded scenario (Figure 5.31).

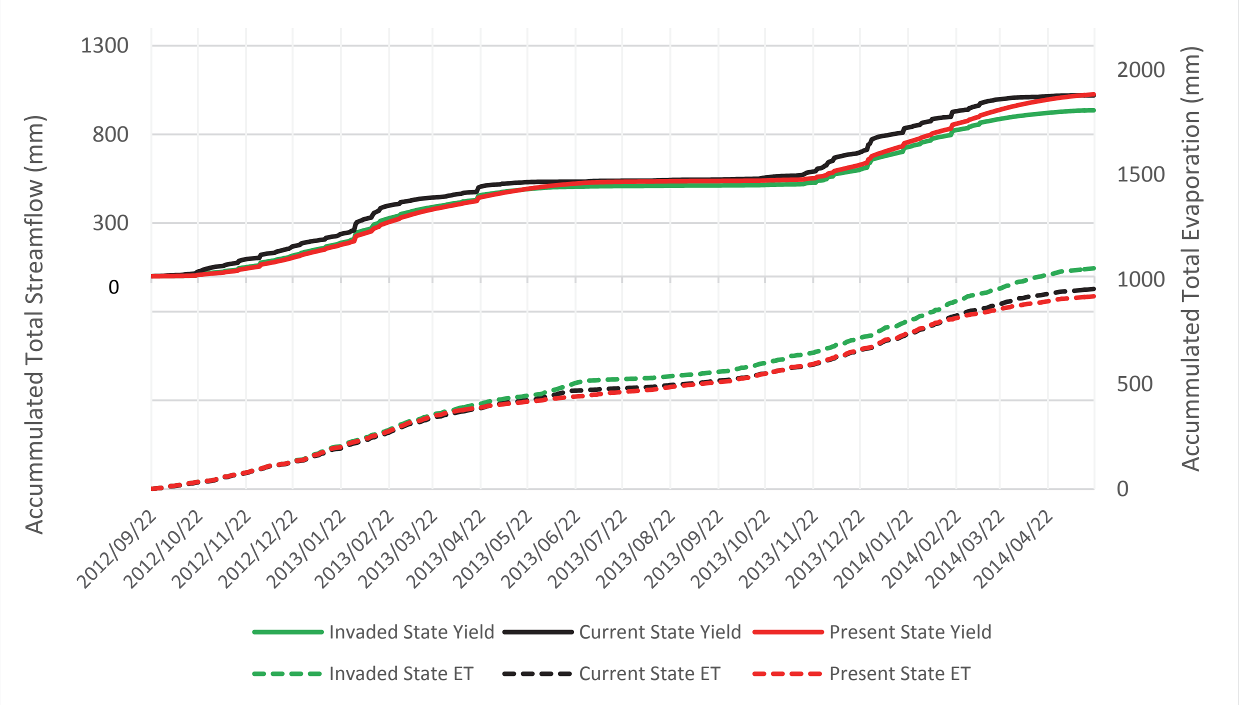


Figure 5.29 *SWAT* Modelled total evaporation (mm) and accumulated streamflow (mm) between the pristine and degraded (invaded) scenarios at New Forest for an individual HRU over a three year period

5.4 Conclusion

Results from the Eastern Mistbelt Forest region (New Forest) generally showed lower water-use measurements when compared to that of the indigenous species at the Western Cape site, apart from the *Acacia mearnsii* which were relatively high at each site considering their size classes. This was expected as the site had a much shorter indigenous canopy with higher disturbance. During the monitoring period, snow broke most of the *Acacia* trees, fire burnt through the understory, cattle broke many of the smaller indigenous species and some of the species died due to stress. This meant a continually changing light and competition dynamic. The SSS technique showed that the understory species such as *Solanum* used significant amounts of water once accumulated to stand density (~2L.day^{-1}). The high variation in this stand made it difficult to model. However, at a catchment scale, clearing of IAPs would make an important contribution to the total water balance.

6. MAPUTALAND COASTAL BELT

The Maputaland Coastal Belt was not originally identified as an option for this project. However, as the project developed, Vasi Pan which is surrounded by the Manzengwenya plantation, became important due to severe water shortages and a lack of knowledge in both ecological and hydrological components. This is a groundwater driven site that has changed drastically over the last decade.

Pine (*Pinus elliottii)* was planted in the surrounding Manzengwenya plantations in the early 1950s. These plantations were subsequently planted to *Eucalyptus grandis* which grew better in the warmer climate. The plantations have been handed over to the Ngonyama Trust which is leased back to the Department of Agriculture, Forestry and Fisheries (DAFF). This transfer is the biggest land reform project in the history of South African forestry (SA Forestry Magazine, 2014) to date.

6.1 Study Site

The Vasi North area falls under the Indian Ocean Coastal Belt Biome and is classified as Maputaland Coastal Belt (CB 1, Mucina and Rutherford, 2006; Scott-Shaw and Escott, 2011). The surrounding natural areas are covered by a mixture of densely forested areas, interspersed dry grasslands (dominantly palm veld), hygrophilous grasslands and thicket. Due to the importance of the site and the abundance of indigenous species, nine tree species were selected to be fitted with the heat pulse velocity systems. In addition, Dynamax collars were chosen to measure the irregularly shaped palm species. No plant water-use research has previously been carried out in the Vasi pan area. However, research on the groundwater interactions of the peat systems in the area is currently being undertaken (Grundeling *et al.* ongoing). Discussions have been held to collaborate research with the students working in the area.

Figure 6.1 shows the indigenous fringe area along Vasi North with the Pine species that have invaded the grassland areas.

Figure 6.1 Fringe forest at Vasi North showing the presence of Pine species

The Vasi North site is at latitude 27°10’50” S and longitude 32°41’22” E at approximately 68 m above sea level. The pan area is just inland of the greater Isimangaliso Wetland Park protected area, within Quaternary Catchment (QC) W70A and Quinary Catchment (QnC) 5525 (Figure 6.2). The surrounding areas have in the past been exploited for timber uses. The soils show evidence of high precipitation and leaching with the deep tertiary sands and pliocene/miocene beds overlaying cretaceous mudstone. The soils in the area are known to be generally infertile and of low agricultural potential. Approximately 80% of the precipitation occurs in the summer months. The Mean Annual Precipitation is between 750 and 800 mm. There is a distinct dry season from May to August. Average temperatures range from 28.7 °C in the summer to 11.5 °C in the winter.

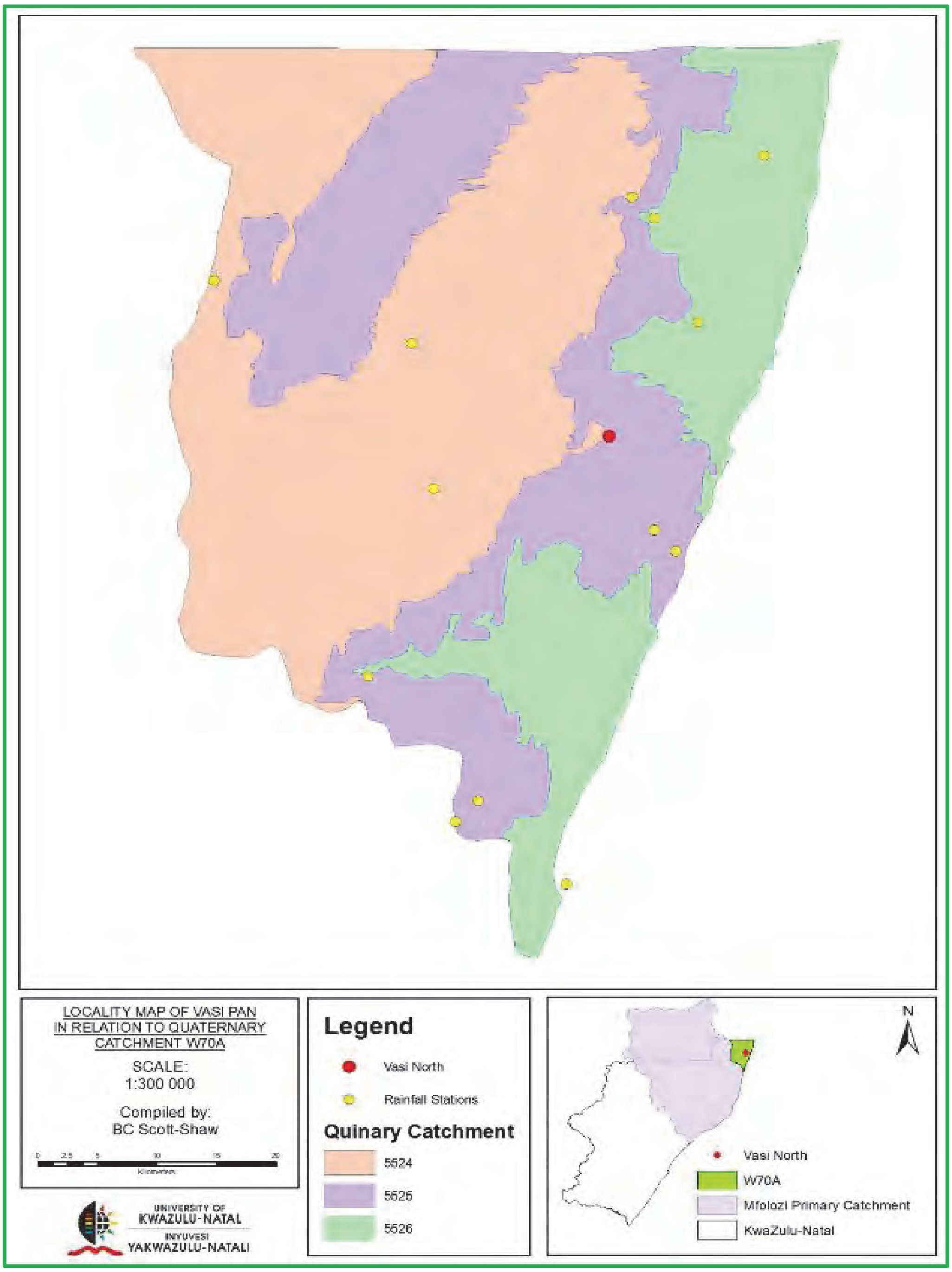


Figure 6.2 Vasi North study site, showing the measurement site in relation to KwaZulu-Natal and the Mfolozi Catchment

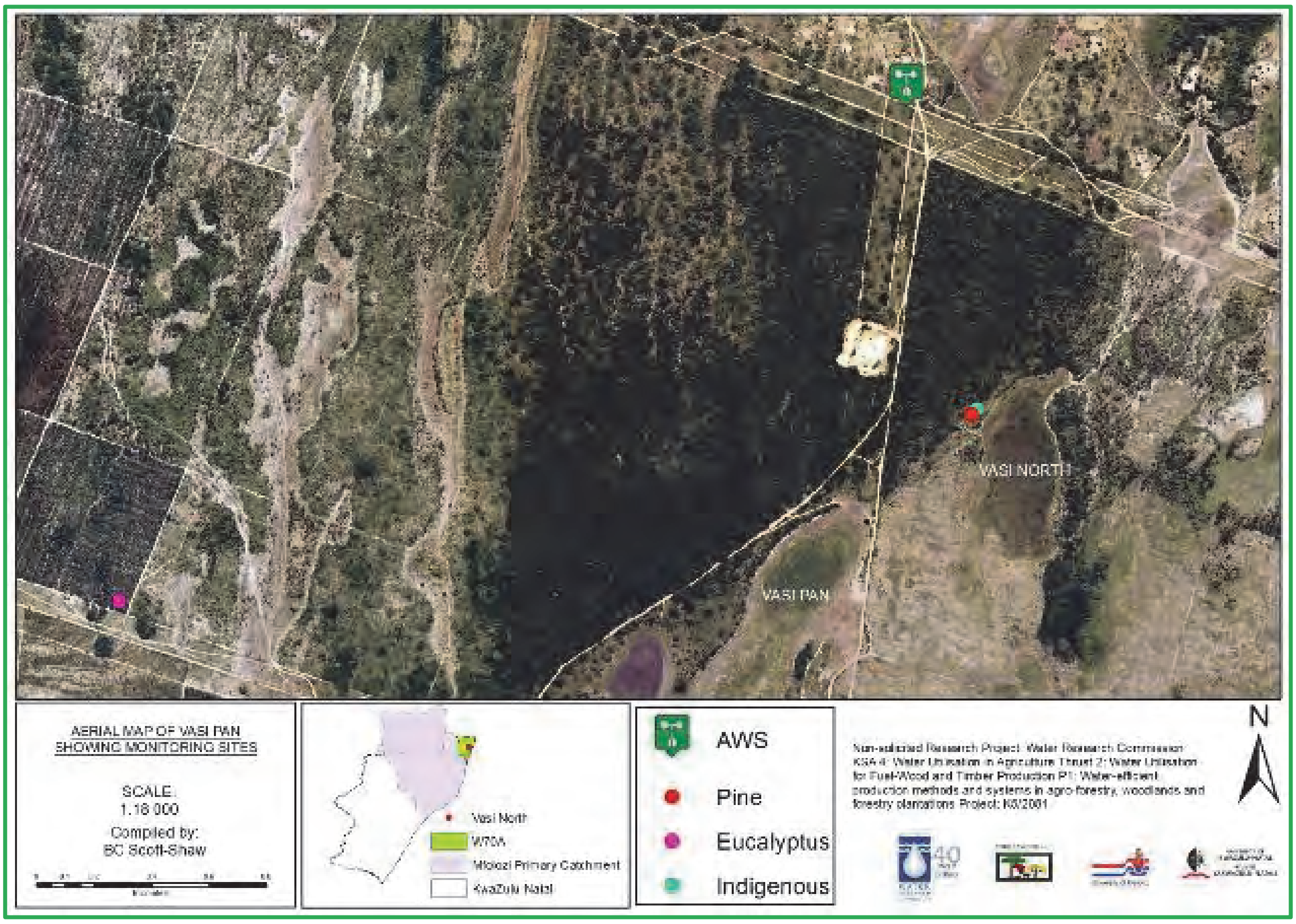


Figure 6.3 Locality map of the monitoring sites in relation to Vasi North

The historical analysis shows the study site (Figure 6.4) before the introduction of pine species. There was very little (if any) tree species present, but rather scattered bush areas. It is likely that the protection of fire in the area, linked to the commercial plantations, has allowed for bigger woody species to grow.

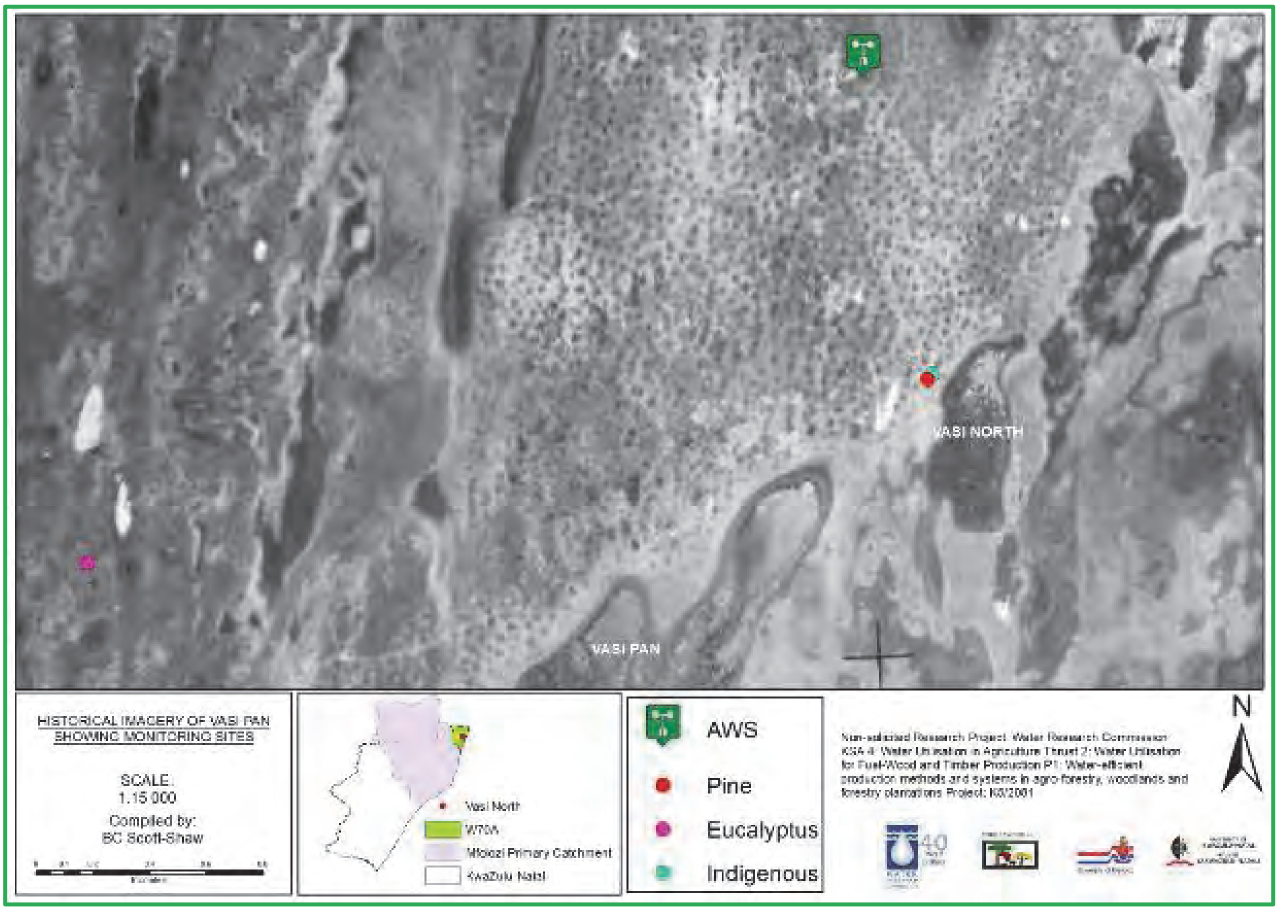


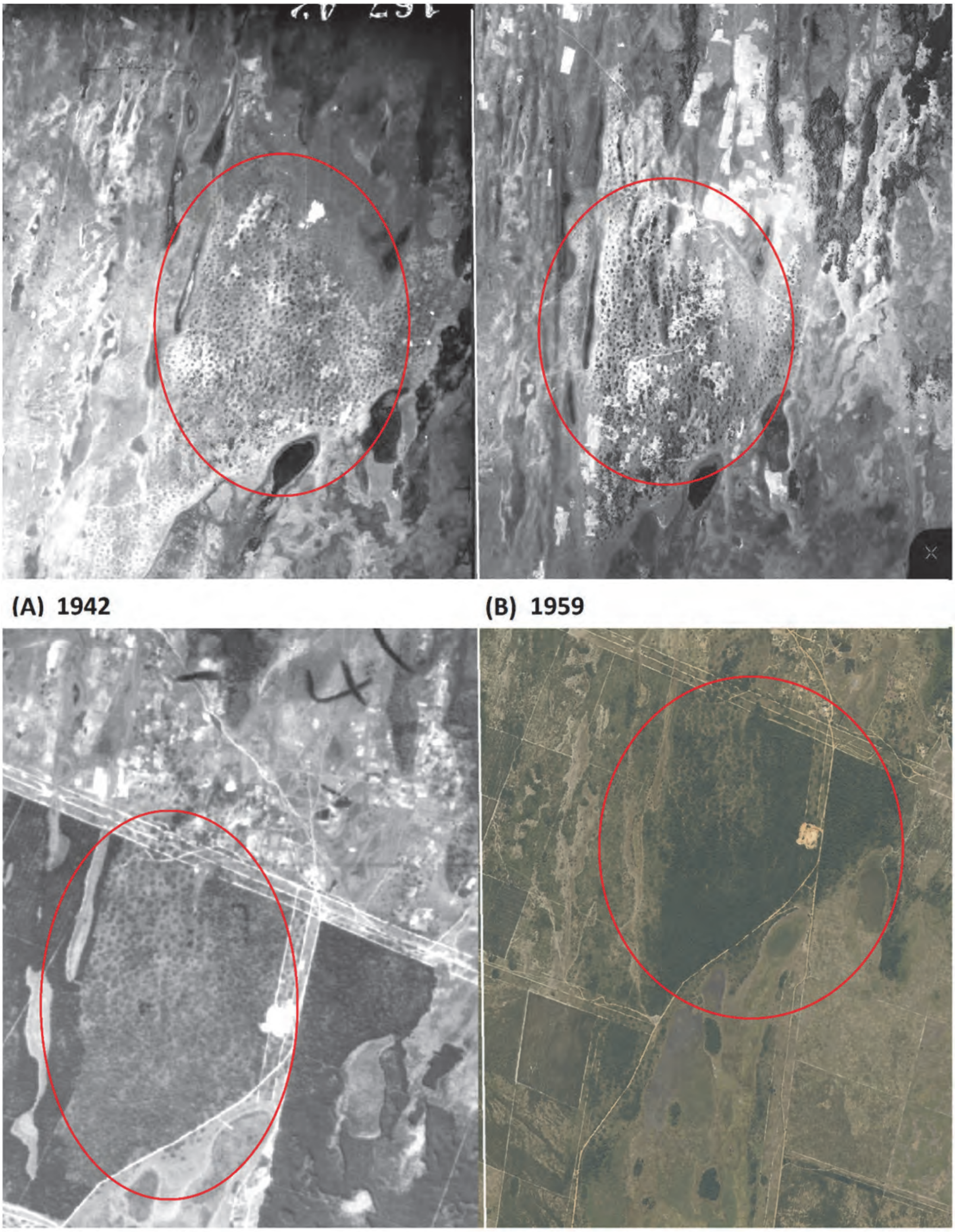
Figure 6.4 Historical imagery for Vasi North from 1944

6.2 Ecological Findings

6.2.1 Floristic and structural analysis of regrowth forest and woodland at Vasi Pan

6.2.1.1 Analysis of aerial imagery

Historical aerial imagery from 1942 and 1959 (Figure 6.5) revealed that the study area did not originally contain forest and was likely grassland with intermittent bush clumps, termed Maputaland woody grassland (CB2) (Mucina and Rutherford, 2006). Imagery from 1959 showed that the study area had been disturbed and represented a mixture of cultivated land, grassland and bush clumps. The imagery in Figure 6.5 indicated that the actual study site was not formally cultivated as a commercial plantation, though the surrounding areas were planted. A few old pine stumps and a small living population of pines were noted during fieldwork, though these were likely to have been as a result of invasion rather than cultivation. The occurrence of closed canopy natural forest appears to have developed because of less frequent fires which was a consequence of being enclosed within a fire-protected estate. This forest naturalisation process which involved the development from bush clumps in grassland into closed canopy regrowth forest, provided a good opportunity to look at forest development processes in the absence of frequent fire events. The site conditions at Vasi over the last 60 years are representative of the conditions of what much of the eastern Maputaland Coastal plain is exposed to at present. That is, increasing fragmentation, timber plantation activities and fire suppression. Conclusions drawn from the aerial imagery suggest that the original bush clumps indicated as (a) and (b) in Figure 6.5 expanded and formed closed canopy regrowth forest (c) and (d), in much the same way the forest clusters were thought to expand within the invasive plant stands at Buffeljagsrivier and New Forest. The hydrological relevance is that understanding the processes and dominant forest species which were dominant in the forest expansion will provide insight into the water-use associated with the change from grassland into forest which under today's conditions appears to be the prevalent vegetation pattern in the Maputaland landscape.



(A) 1942 **(B) 1959**

(C) 1990 **(D) 2009**

Figure 6.5 Development of natural regrowth forest at Vasi Pan from 1942 until 2009. The red circles indicates the general study area

6.2.2 Floristic analysis

In total, 47 native tree or shrub species from 27 families were recorded within 15 regrowth forest plots, and 13 species from 9 families were recorded in the 10 woodland plots. The floristic and density (number of stems ha^{-1}) data were subjected to ordination using non-metric multidimensional scaling. The clustering of the plots in ordination space provided insight into similarities and differences of the regrowth forest and woodland communities. There was a clear difference between most regrowth forest plots which occupied the negative side of axis 1 and the woodland plots on the positive side. There were three noteworthy interpretations from the ordination (Figure 6.6): (1) regrowth forest plots appeared to form a cohesive grouping, suggesting that these plots represented the core composition of the regrowth forest; (2) the woodland plots were less cohesively distributed and therefore less akin with each other in comparison to the regrowth plots; and (3) there appeared to be a mixture of regrowth and woodland plots located in the centre of the ordination, suggesting that woodland may develop towards regrowth forest with forest species becoming established within developing woodland.

Analysis of the importance Values (IVs) calculated for the forest regrowth and woodland communities (Table 6.1) revealed that similar species (*Brachylaena discolor*, *Apodytes dimidiata*, *Sclerocroton integerrimum* and *Strychnos spinosa* (Lam)) dominated the species composition of both the regrowth forest and the woodland communities. This suggested that these four species played an important role in conversion of woodland into forest. The less dominant species in the regrowth forest community such as *Hymenocardia ulmoides* (Oliv.), *Antidesma venosum* E.Mey. ex. Tul., *Trichilia emetica* and *Albizia adianthifolia* (Schumach.) W.Wight were deemed to be characteristic pioneer forest trees. Woodland specialist species *Sclerocarya birrea* (which was the most dominant species in the woodland community), *Dichrostachys cinerea* (L.) Wight & Arn. and *Vangueria infausta* (Burch.) are known to be fire tolerant savanna species and that accounted for their presence in the woodland community.

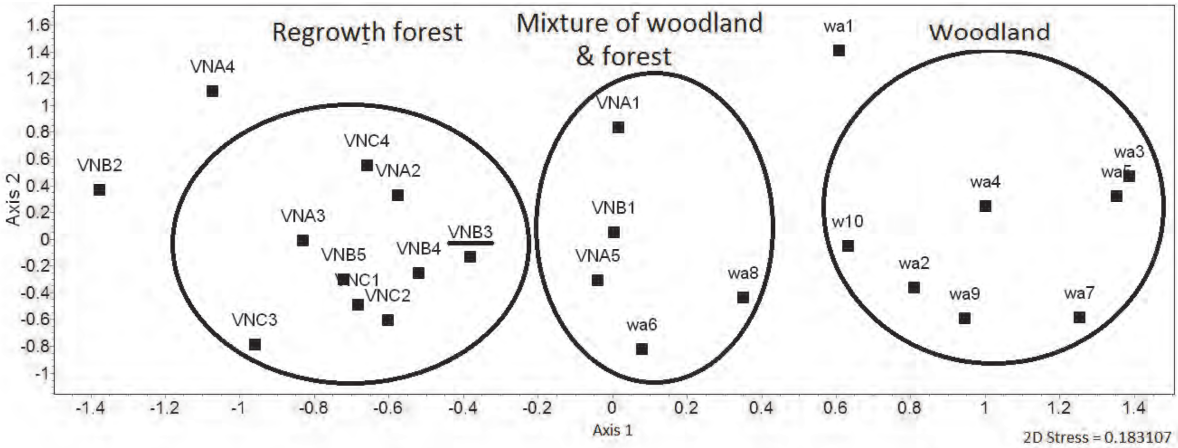


Figure 6.6 Clustering of the regrowth forest (VN) and woodland plots (W) into three broad groupings at Vasi Pan, using non metric multidimensional scaling.

Table 6.1 Importance Values of regrowth forest species

Species	IV Regrowth forest	IV Woodland
Brachylaena discolor (Silver Oak)	38	19
Apodytes dimidiata (White pear)	36	38
Sclerocroton integerrimus (Duiker Berry)	26	35
Strychnos spinosa (Monkey apple)	23	24
Hymenocardia ulmoides (Redheart tree)	22	
Schrebera alata (Wild Jasmin)	20	
Sclerocarya birrea (Marula)		42
Vangueria infausta (Velvet Wild-medlar)		19
Antidesma venosum (Tassel berry)	19	
Strychnos madagascarensis (Black monkey orange)	19	
Trichilia emetica (Natal Mahogany)	18	
Albizia adianthifolia <20 cm DBH (Flat crown)	17	13
Albizia adianthifolia (large) >20 cm DBH (Flat crown)	16	
Dalbergia obovata (Flat bean)	15	
Dichrostachys cinerea (Sickle bush)		13

6.2.3 Structural analysis

Canopy height, stem density and stem size class distribution were described to analyse structural differences between regrowth forest and woodland. The height of regrowth forest was on average 5.6 m taller than woodland and the stem density of regrowth forest was on average 1106 more stems ha^{-1} than woodland. Regrowth forest had a higher height (mean 8.9 m ±1.2) than woodland (mean 3.2 m ±0.4). Average density of regrowth forest was 1333 stems ha^{-1} (±408) and woodland 225 stems ha^{-1} (±112). Stem diameter class distributions for the regrowth and woodland plots were calculated within cohorts of 5-10 cm, 10-20 cm and >20 cm dbh. Analysis of the highest ranked IV species showed that small trees (5-10 cm) dominated both the forest regrowth and woodland plots. Most species showed inverse-J shaped stem diameter distribution, with many small stems and fewer larger stems (Figure 6.7). *Albizia adianthifolia* showed a different pattern which reflected a J-curve in the plots, with few small stems and many larger stems (Figure 6.8).

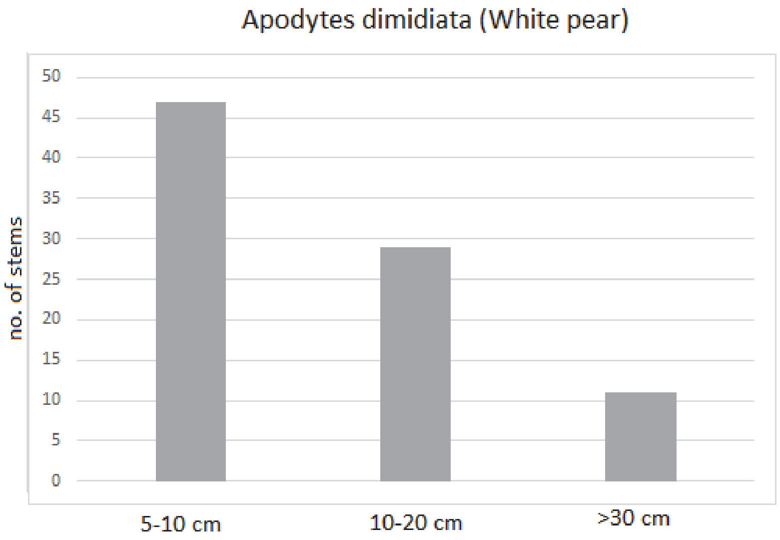


Figure 6.7 Typical inverse-J curve of most pioneer species sampled in regrowth forest and woodland.

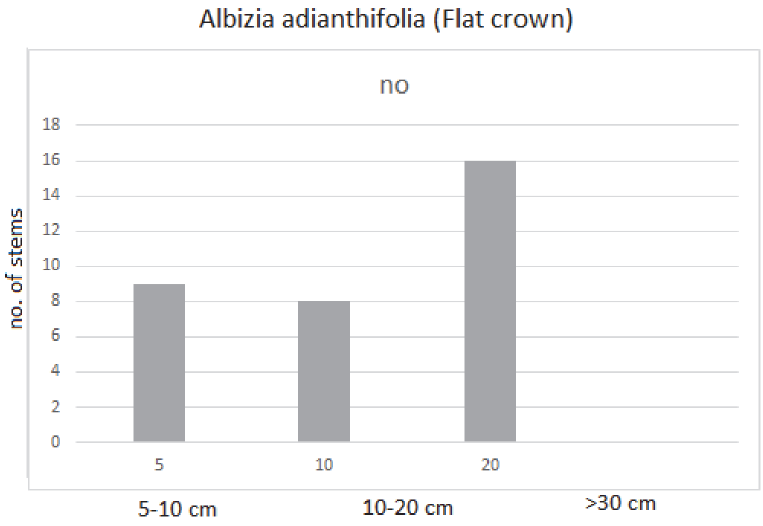


Figure 6.8 J-curve stem class distribution of Albizia adianthifolia.

6.2.4 Discussion

The forest site at Vasi pan was thought to be relatively young and analysis from historical imagery showed the site was previously grassland with a small woody component. The absence of floristically and structurally mature forest across much of the site attests to the development process of the forest from a pioneer stage, which would have likely developed from multiple regenerating clusters rather than from an expansion of historical 'mature' core forest patches. It appeared that clusters of regeneration joined to form what presently could be considered 'core' areas of the forest. This rationale was further motivated by the somewhat patchy network of different aged forest areas within the inner or central areas on the site. For example, plots such as B3 ordinated similarly to woodland plots but were located in the central area of the forest (Figure 6.6). No evidence of a distinct 'mature' forest area at one point and younger forest leading away from it was noted. This would have been expected if forest had developed from 'mature' core areas. It is however important to note the so called 'core' areas of the forest created by expanding clusters should not be thought of as mature forest, but rather an development stage of regrowth forest.

It was noted during sampling that some areas of the site appeared floristically but not structurally younger than the ‘core’ regrowth forest. This could represent a transition state between woodland and regrowth forest, i.e. primary forest growth stage. It may be that a different sampling strategy is required to distinguish fine scale regrowth stages, as opposed to the broad scales of mature, regrowth and woodland forest which are referred to in the literature (Corrigan et al., 2010). It should again be emphasised that the term core forest in this context does not refer to mature or old growth core forest (as there was none at Vasi), rather to a core of regrowth forest which was initiating forest expansion, into grasslands via woodland expansion.

Evidence for this development stage (between woodland and regrowth forest) was broadly noted in the ordination (Figure 6.6). Firstly, there was a broader variation in woodland plots opposed to the regrowth plots indicating woodland may be in a greater transition phase to regrowth forest, possibly due to quite a fast transition stage from open to closed canopy communities in the absence of fire. Secondly, the ordination showed some woodland and regrowth forest plots were associated with the centre of axis 1, while the nucleus of the regrowth forest and woodland plots were positioned within the positive and negative sectors respectively. These central plots were not quite forest or woodland and are likely evidence of a pioneer growth stage discussed in the previous paragraph. Some of these plots were located on the forest edge which again pointed tentatively to the evidence of a ‘primary’ forest growth, as opposed to the nucleus of regrowth forest plots which would then be termed as a secondary growth stage.

Analysis of the floristics clearly showed the difference between the regrowth forest and woodland communities. Regrowth forest contained more species (47 species) to the woodland communities (9 species). Interestingly the woodland and forest communities shared the same dominant species, except for fire tolerant species such as Marula. This was interpreted as evidence of cluster expansion, in two ways. Firstly, the dominant woodland species were spreading out and colonising grassland areas, and secondly, they appeared to persist into a later successional stage as regrowth forest. These results are similar to the observations made in the Limpopo forests with expansion into developing woodland within former grassland (Geldenhuys and Venter, 2002). It was also worth investigating less common forest species within the regrowth forest areas. The presence in some plots of characteristically mature forest species such as *Hymenocardia ulmoides*, *Dialium schlechteri* (Harms.) and *Manilkara discolor* (Sond.) J.H. Hemsl. (Though all in very small size class distributions) pointed towards the development of regrowth forest into mature forest and the likely disappearance of any pioneer regrowth or woodland species in those areas.

The height and stem class distribution of the regrowth forest said a lot about its age. One would expect old growth coastal forest to exceed 20 m in height and consist of many large stems with diameters >30 cm. This was not the case. In fact only 2.3% of trees in the data set were >30 cm dbh of which more than half were *Albizia adianthifolia*. This was reflected in the stem class distributions of the dominant trees sampled which all showed an inverse-J curve and *Albizia* with a J curve, with a clear differentiation in data of the stem density and height between regrowth forest and woodland. Differences within the structural attributes of the regrowth forest which might have differentiated between forest edge and slightly older core forest were small and not apparent.

It was challenging to determine the exact role that alien plants or plantation forests had in the establishment of the forest in this area. Though it was clear from the evidence of some old pine stumps and some standing trees, pines had a significant vegetation presence at some point in the last 60 years. There are two points to be made here: (1) the historical imagery before plantation activities indicated that although the area was dominated by grassland, some minimal woody cover was present. These woody elements are likely to have proliferated in the absence of fire within the confines of the plantation environment. (2) Did invading pine trees into the area affect the development of forest?

6.2.5 Conclusion

The forest at Vasi Pan was seen to develop along transitional stages towards mature Northern Coastal Forest. The forest was considered to be in an advanced regrowth phase and expanding into adjacent fallow secondary grassland through the process of both pioneer forest and savanna woodland establishment. It was evident from the analysis that the canopy layer of the 'core' forest areas were dominated by so called pioneer species for example, *Brachyleania discolor*. However the presence of characteristically mature forest canopy species as well as species in the understorey, for example *Isoglossa woodii* (C.B Clarke)*,* in these 'core areas' indicated that they were undergoing a transition from regrowth forest to mature forest. Forest expansion was being driven by younger and older regrowth areas and it was understood that because of the absence of regular fire events (which is an ecological symptom of life within a plantation) that the forest developed through the inception of woodland and then expansion of clusters into a congruent regrowth forest core. Evidence of four transitional stages from woodland establishment to mature forest were recorded on the site. These stages were: (1) The expansion of forest into grassland through the occurrence of woodland; (2) The transition from open canopy woodland into young regrowth forest; (3) The transition from 'pioneer or young' regrowth forest into 'core' regrowth forest; and (4) the transition from core regrowth forest into mature forest. Understanding such transitional development in vegetation cover under certain conditions will provide ecological insight into the water-use ramifications of an increasingly fragmented and fire retardant broader landscape of a former wooded grassland matrix with bush clumps of various woody species.

6.3 Hydro-meteorological Findings

6.3.1 Climate

The rainfall which was measured at Vasi Pan was added to the long term data record at the end of the study. Any inconsistencies between these data and the data recorded at the nearby sites were corrected using a relationship derived between the overlapping data of the historical records. These data were used for the modelling component of the study, as well as to link the tree growth (determined from anatomy analysis) to the last 30 years of rainfall.

The Mean Annual Precipitation observed since 1914 at Vasi Pan was 926 mm (Figure 6.9). As little as 427 mm and as much as 1689 mm has been observed in a hydrological year (high variation).

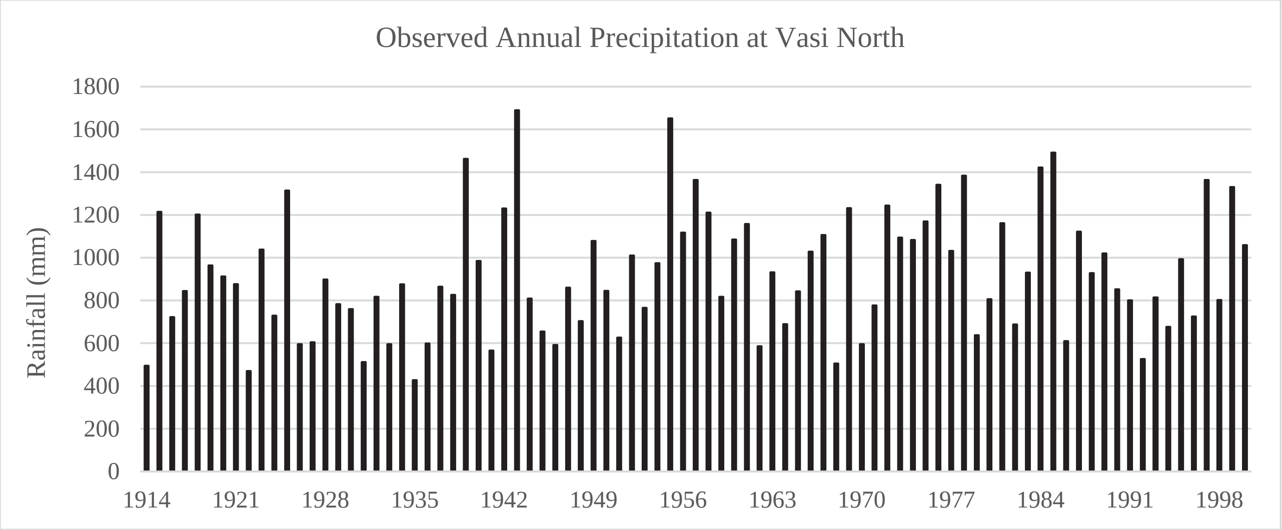


Figure 6.9 **Annual precipitation recorded at rainfall stations near Vasi Pan**

An average daily temperature of 23 ºC was recorded at Vasi Pan during the monitoring period. During these months, daily maximum temperatures reached in excess of 35 ºC. During the dry winter months, the temperatures averaged 18ºC. Periods of low solar radiation correspond to rainfall (and cloudy days) and would likely result in little transpiration occurring. The Daily ET_0 peaks at 3.4 mm, which is high for South Africa. Solar radiation reached up to 33 $MJ.m^{-2}.day^{-1}$ in February (Figure 6.10). When the temperature is at its highest, the ET_0 is also at its peak due to a greater atmospheric demand.

The daily rainfall and temperature (Figure 6.11) has been provided. There were two periods of high rainfall. This suggests that intense storms are prevalent at the site.

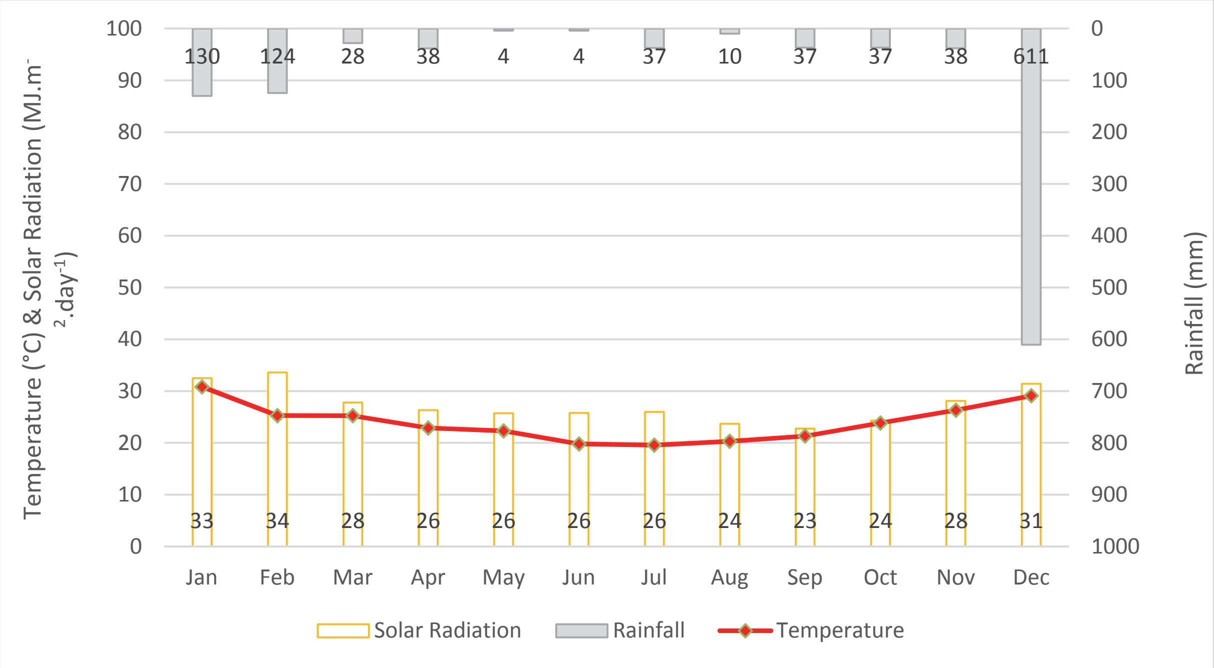


Figure 6.10 **Hourly values of average temperature (ºC) and reference total evaporation (mm) at Vasi Pan from the 30th November 2014 to the 21st January 2015**

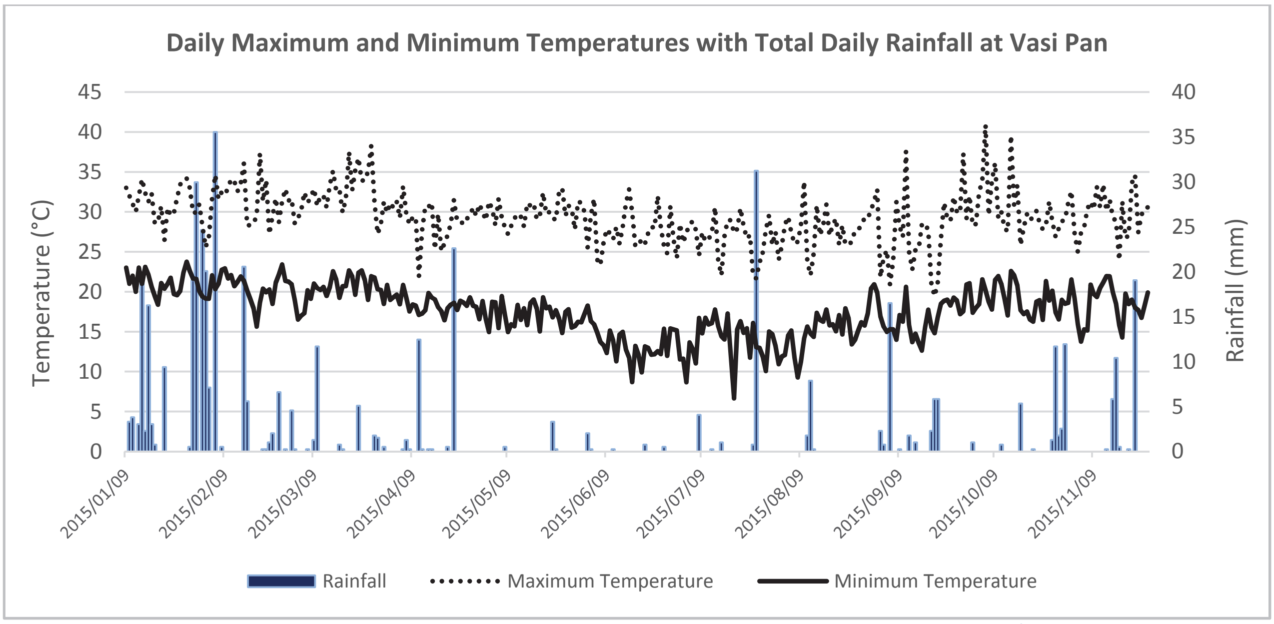


Figure 6.11 **Hourly values of rainfall (mm) and solar radiation (W.m^{-2}) at Vasi Pan from 30th November 2014 to the 20th December2014**

The soil water contents at the Vasi Pan sites were low (between 4 & 6% during the observed during the wet season). The response to rainfall events can be seen at all the depths with little variation throughout the profile (Figure 6.12). The deeper probes (0.8 m) were generally less responsive to these events. The presence of sandy soils and the quick draw-down suggests that little water was stored in this profile and that the infiltration was quick. At site 2, which is further away from the pan and within the *Eucalyptus* plantation, the deepest probe showed no response to rainfall events (Figure 6.13). Rainfall events did not infiltrate to this depth, most likely due to the water uptake by the gum trees. It is likely that responses will be visible during high rainfall events.

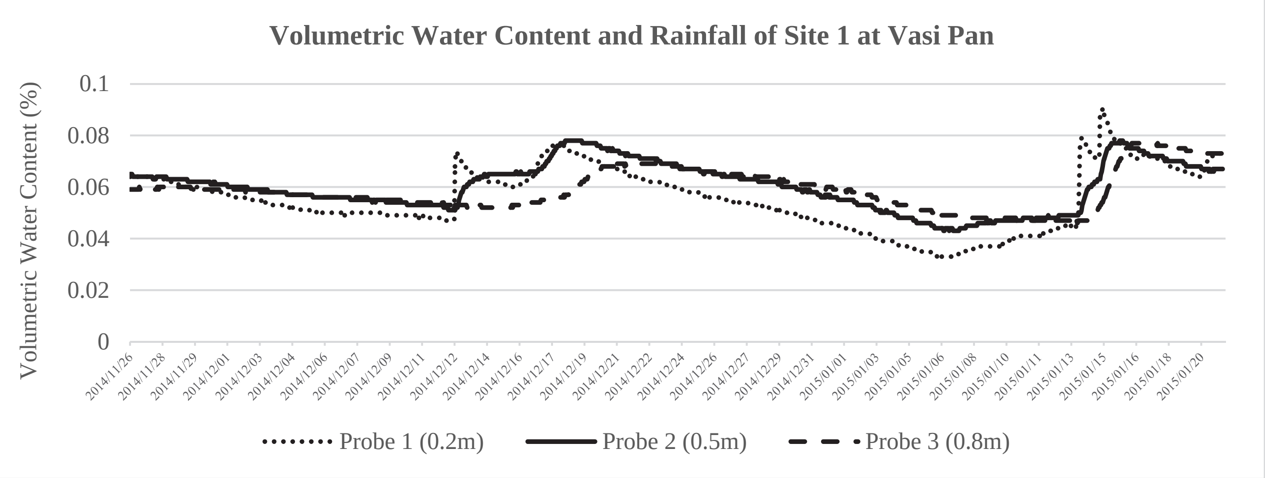


Figure 6.12 **Volumetric soil water content of Site 2 during the summer period at New Forest farm**

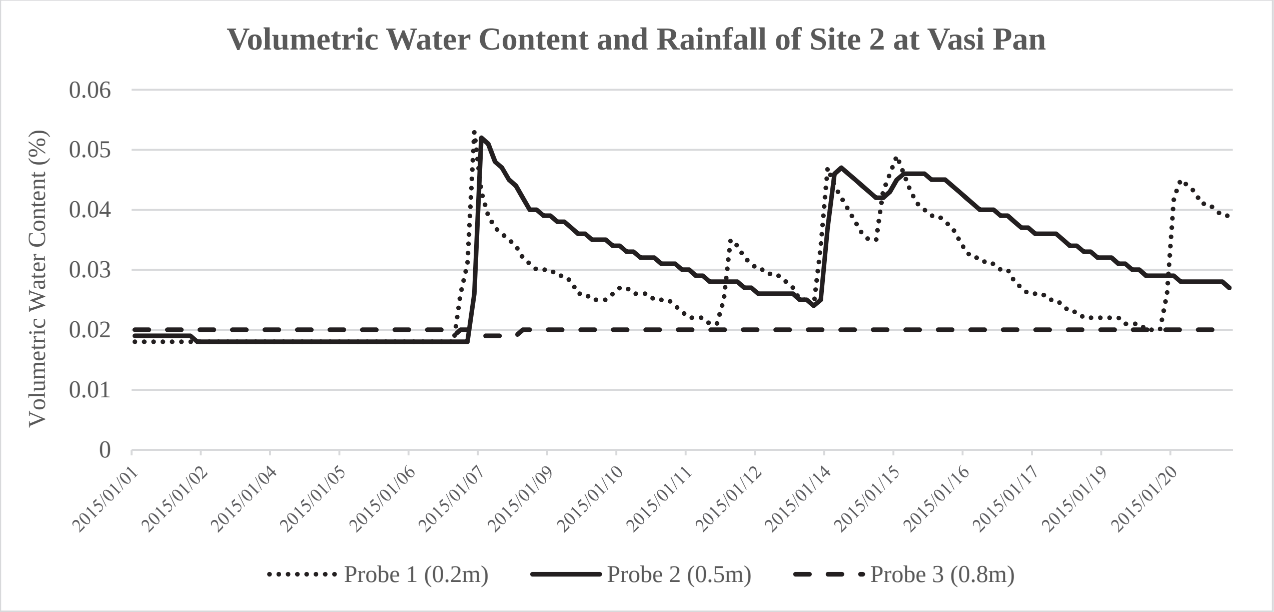


Figure 6.13 Volumetric water content of Site 1 during the winter period at New Forest farm

6.3.2 Water-use

An example of heat pulse velocity measurements from the *Eucalyptus* trees has been provided in Figure 6.14. The results showed that the peak sapflow rates occurred at midday. Sapflow only occurred on days when the solar radiation was high. An offset was used for some of these trees to adjust for the difference in baseline readings. The sap flow peaked at approximately 20 cm.hr^{-1} for the *Pinus elliottii* trees, at 10 cm.hr^{-1} for the *Shirakiopsis ellipticum* trees and at approximately 20 cm.hr^{-1} for the *Eucalyptus grandis* trees during the short measurement period. Figure 6.26 illustrates an example of the radial sap flow in one of the *Eucalyptus* species.

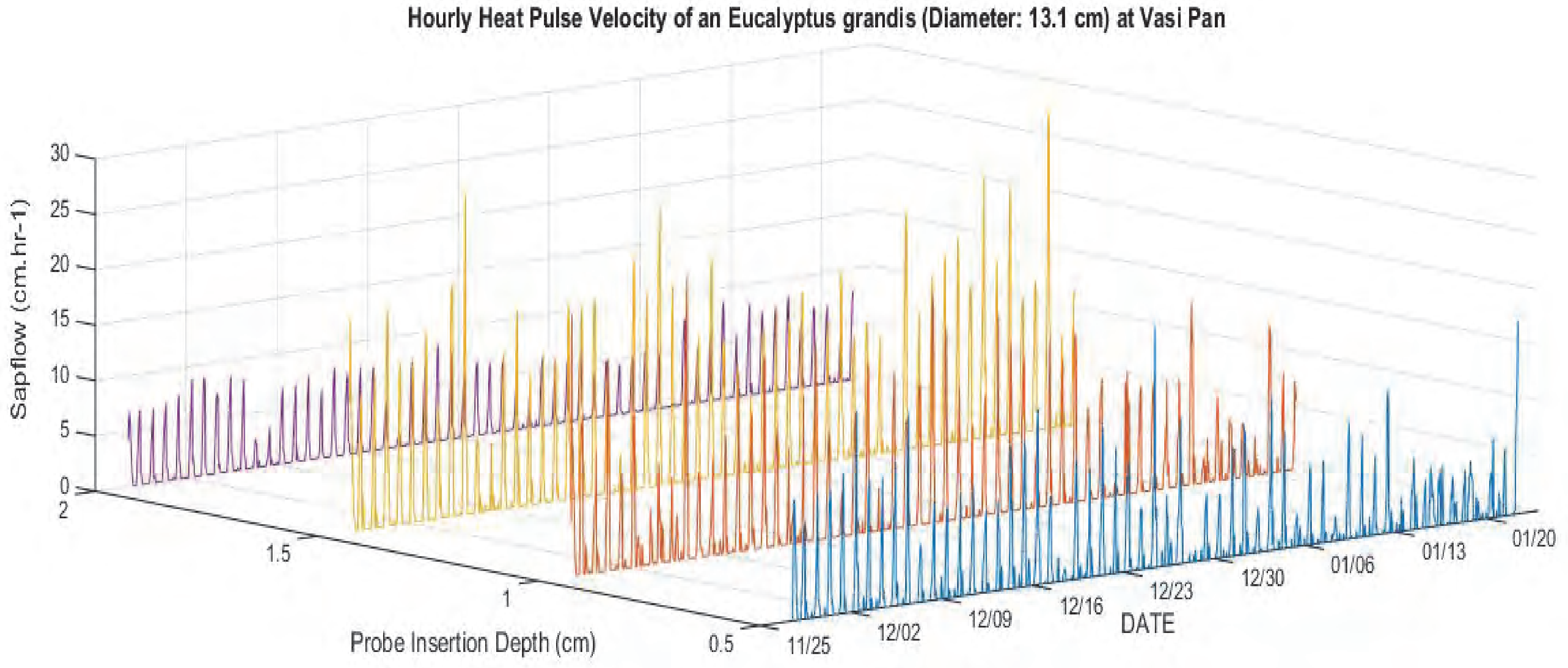


Figure 6.14 Radial sap flow profile for a *Eucalyptus grandis* (Site 2) at Vasi Pan.

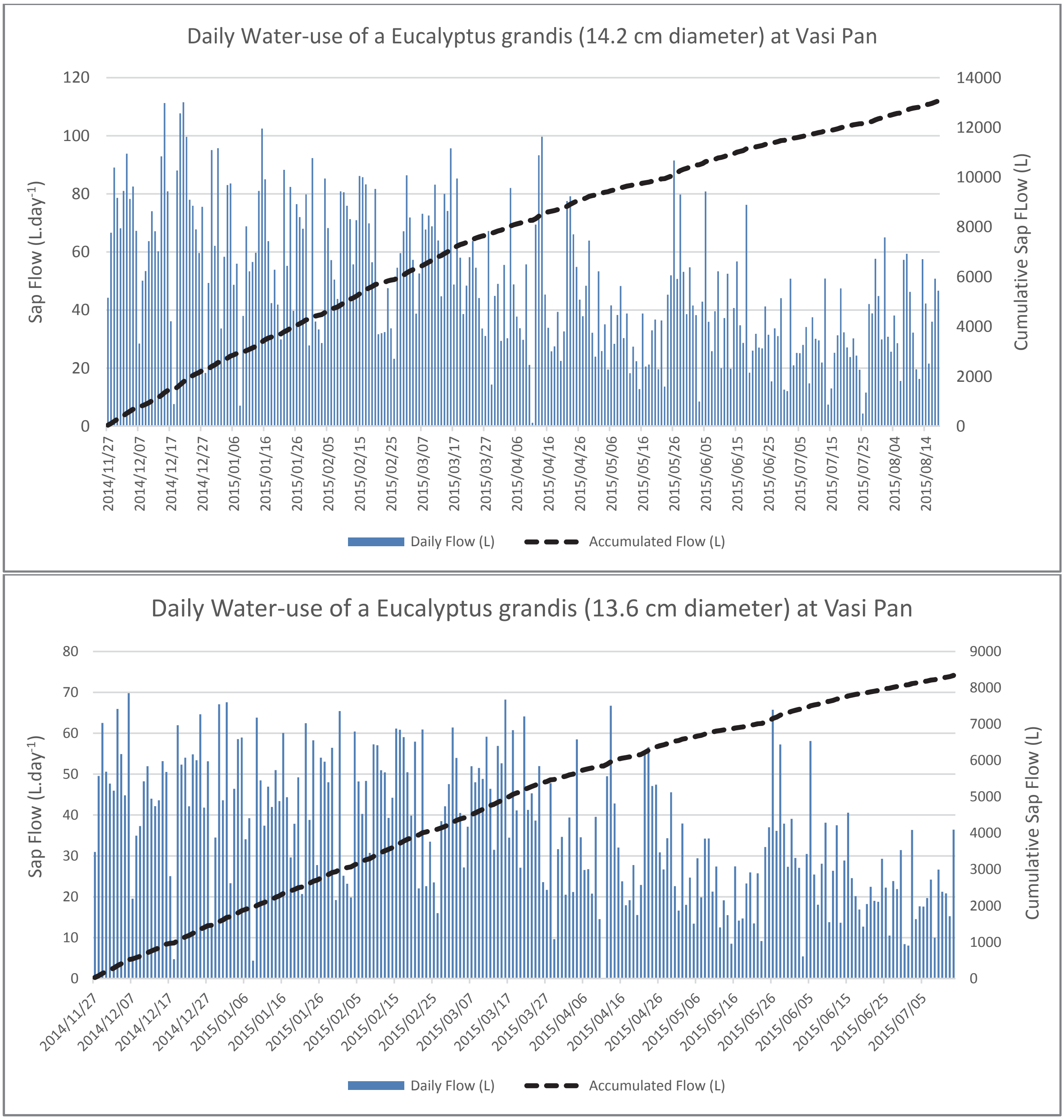


Figure 6.15 Daily Sap Flow for two Eucalyptus grandis trees (Site 2) at Vasi Pan

A fire occurred in mid-October within the Eucalyptus stand (Site 2). Unfortunately the HPV probes were damaged and some of the data was lost. However, the logger was not damaged and data from the period leading up to the fire was recovered (Figure 6.16).

Figure 6.16 Fire damage within the *Eucalyptus* stand at Vasi Pan

The field measurements (Figures 6.17 & 6.18) showed the hourly heat energy balance for *Phoenix reclinata* and *Pinus elliottii*. The results showed that although the pine species uses much more water individually, the *Phoenix* species uses only slightly less once extrapolated to the number of fronds in the individual palm.

Figure 6.17 Dynamax EXO skin collar used on irregular/asymmetrical stems

Figure 6.18 *Phoenix reclinata* stand within the Manzengwenya pine plantation that was implemented with the new EXO collars

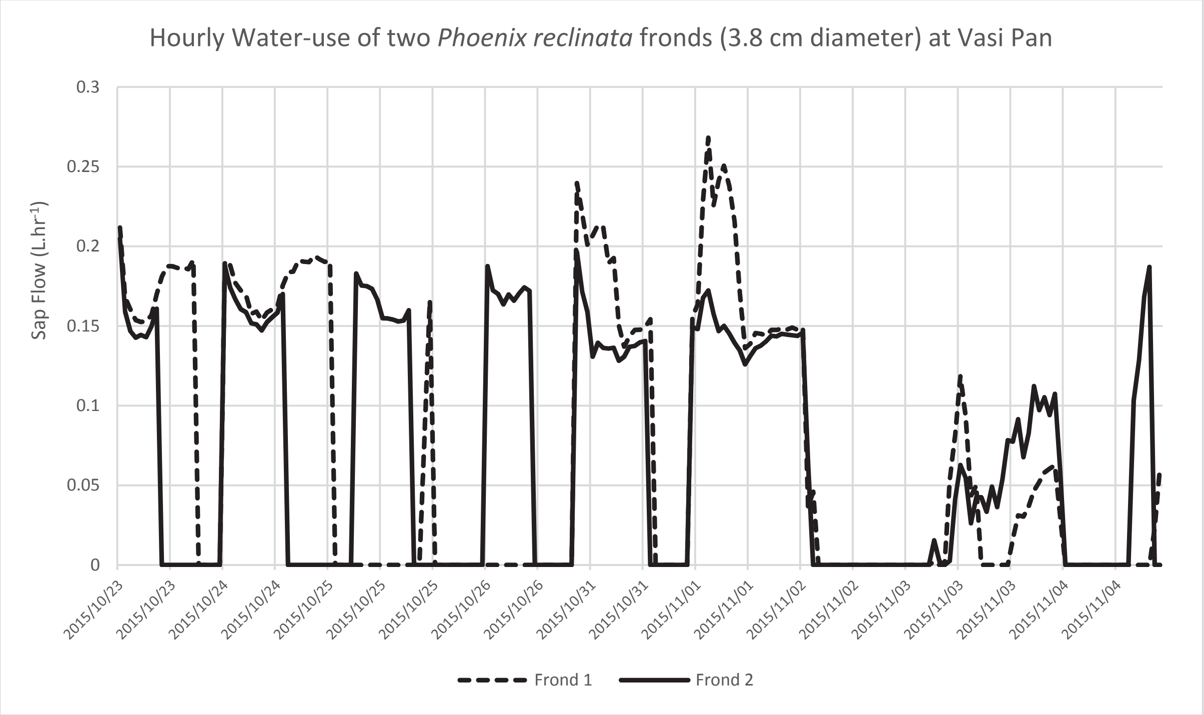


Figure 6.19 Hourly sap flow of two *Phoenix reclinata* fronds at Vasi Pan

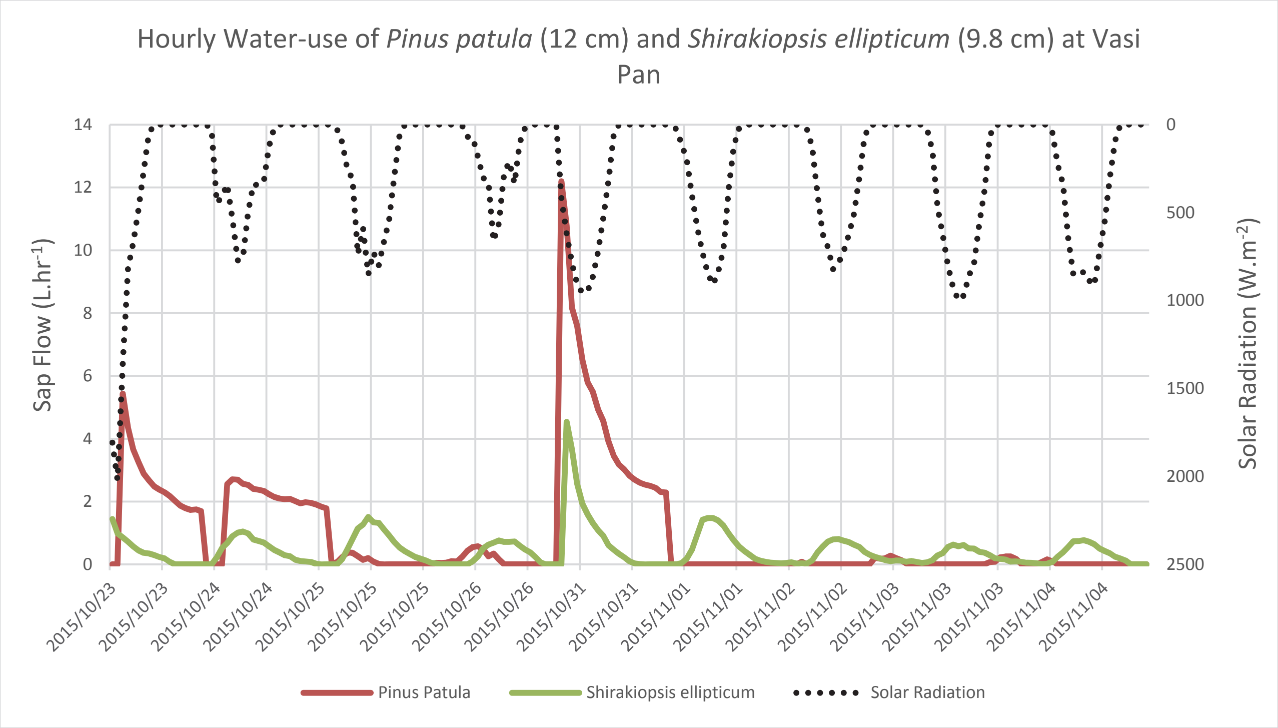


Figure 6.20 Hourly sap flow of *Pinus elliottii* and *Shirakiopsis ellipticum* at Vasi Pan

6.3.3 Evaporation modelling

6.3.3.1 Sensitivity studies

To understand the impacts of various inputs on relevant outputs, a number of sensitivity studies were undertaken. Inputs were varied one at a time, while the others remained the same. For every trial there are results for a catchment under natural vegetation with shallow roots (from now on called Trial-1) and under forest plantations with deep roots (from now on called Trial-2). The inputs were modelled using 50 years of daily climate data and the results shown below are either averages of monthly values for the outputs of SIMWTD and SUMDD, or the sum of all the monthly values over 50 years for SUR, AET and ATRAN.

6.3.3.2 The influence of the initial shallow groundwater depth, represented by the ACRU variable OBSWTD, on drawdown, recharge, total evaporation and transpiration

Trials were run with varying initial groundwater depths (OBSWT), while the other inputs remained unchanged. The expected result is that with an increased initial groundwater depth, the simulated groundwater level should also increase. This is hypothesised to be more so for the deep root than the shallow root scenarios. Transpiration from the deeper levels (ATRAN 3 and 4) was expected to reduce as the groundwater depth increased, as it might be below the reach of the plant roots. Transpiration from the A and B horizon was expected to be the same for varying groundwater depth, but higher for forest plantation than for the natural vegetation selected. Table 6.2 shows the results after a 50 year simulation on water table depth (SIMWTD), drawdown (SUMDD), recharge (SUR2, SUR3 and SUR), total evaporation (AET) and transpiration from the A, B and intermediate zone horizons (respectively ATRAN1, ATRAN2 and

ATRAN3) and from the capillary zone above the groundwater table (ATRAN4), with deep root runs shaded (Results from Trial 25-27).

Table 6.2 The influence of the initial observed shallow groundwater depth (OBSWTD)

Trial No	OBSWTD (m)	Average SIMWTD (mm)	Average SUMDD (mm)	Sum SUR2 (mm)	Sum SUR3 (mm)	Sum SUR (mm)	Sum AET (mm)	Sum ATRAN1 (mm)	Sum ATRAN2 (mm)	Sum ATRAN3 (mm)	Sum ATRAN4 (mm)
27_1	10	12305	0	4192	1443	18328	27879	15275	6582	0	672*
25_1	25	30387	0	4192	0	16885	29268	15275	6582	0	2061**
26_1	30	36500	0	4192	0	16885	29751	15275	6582	0	2544**
27_2	10	16372	5636	3333	0	15948	44838	20430	8521	3156	11090
25_2	25	32024	2793	3333	0	15948	40078	20430	8521	1915	7572
26_2	30	37705	2576	3333	0	15948	39645	20430	8521	1623	7430

* All from the first year ** All from the first two years

With an increasing initial groundwater depth (OBSWTD) from 10 m to 25 m to 30 m the simulated average depth of the groundwater table increased as well, and more so for the runs with deep roots than for the runs with shallow roots. The drawdown (SUMDD) by the plantation decreased as the initial groundwater level increased. Drainage out of the intermediate zone (SUR3) occurred only from the shallowest initial groundwater trial run with shallow roots.

Transpiration via deep roots in the intermediate and capillary zone (ATRAN3 and ATRAN4) decreased as the initial groundwater level increased. Transpiration for the A and B horizon (ATRAN1 and ATRAN2) remained steady. Transpiration with deep roots was consistently higher than from shallow roots. The shallow root runs showed values for ATRAN4 for the first two years. The deeper the impervious layer, represented by the *ACRU* input variable of DEPIMP, the smaller the simulated water table depth, but the drawdown and the transpiration via deep roots were larger, due to increased transpiration from the capillary zone above the groundwater level (ATRAN4).

6.3.3.3 The influence of the size of the plantation, represented by the variable SIZEHA, simulated groundwater table depth, recharge and transpiration

The variable SIZEHA was changed. The original runs were done with the size according to national land cover 2000 data of 24 560 ha plantations for Quaternary Catchment W30A. A trial was undertaken with SIZEHA = 0 for the first catchment with shallow roots, but *ACRU* does not accept a zero plantation size. SIZEHA for Trials_1 were then set at 1 ha and 24 560 ha, while those for Trail_2 were set to 10 ha, 100 ha, 1 000 ha and 24 560 ha. The expected result is that the size of the plantation should not influence the results for Trial_1 under shallow roots. For the Trial_2s it is expected that with an increase in plantation size, the simulated groundwater depth should increase, so should the drawdown and so should the transpiration. Results are shown in Table 6.3.

Changing SIZEHA for Trial_1 did not make a difference for the outputs for Trial_1, nor did it affect the outcomes of Trial_2. Increasing SIZEHA for Trial_2 increased the simulated groundwater table depth and the drawdown. The drainage remained the same as did ATRAN1 and ATRAN2. ATRAN3 increased, while ATRAN4 decreased.

Table 6.3 Influence of the size of plantation on simulated groundwater table depth, recharge and transpiration from A, B and intermediate zone horizons and from the capillary fringe above the groundwater table, with results from the deep root runs shaded.

Trial No	SIZEHA (ha)	Average SIMWTD (mm)	Average SUMDD (mm)	SUM SUR2 (mm)	SUM SUR3 (mm)	SumSUR 1+2+3 (mm)	Sum ATRAN1 (mm)	Sum ATRAN2 (mm)	Sum ATRAN3 (mm)	Sum ATRAN4 (mm)
27_1	24560	12305	0	4192	1443	18328	15275	6582	0	672
31_1	1	12305	0	4192	1443	18328	15275	6582	0	672
27_2	24560	16372	5636	3333	0	15948	20430	8521	3156	11090
31_2	24560	16372	5636	3333	0	15958	20430	8521	3156	11090
33_2	10	11099	362	3333	0	15948	20430	8521	1664	18745
32_2	100	12039	1301	3333	0	15948	20430	8521	1865	17837
34_2	1000	14425	3688	3333	0	15948	20430	8521	2485	14703

The size of the plantation input (SIZEHA) in Trial_1 did not affect the outcomes, but should be set to at least 1. A recommendation would be to make it equal to SIZEHA in Trial_2. The size of the plantation in Trial_2 influenced the simulated groundwater depth, with the larger the plantation, the bigger the simulated level of the groundwater table, as was to be expected. The drainage was not affected by the size of the plantation; neither was transpiration from the A and B horizons. Modelled transpiration from the intermediate zone increased as the size of plantation increased, while modelled transpiration from the capillary zone decreased as the size of plantation increased.

This could be explained by the drawdown increasing the groundwater depth with less water being available for capillary action. However, the question remains, what happened to the water that was drawn down? For which areas were the transpiration values valid? Is it the area of the plantation only, or is it over the whole catchment? More studies would need to be done in this regard.

6.3.3.4 The influence of taproot depth (DEPROT) on the relevant simulated outputs

Various taproot depths (DEPROT) were input, both for natural vegetation, assuming shallow roots, and for plantations. It would be expected that a larger rooting depth would result in a larger simulated groundwater table depth, a larger drawdown, and a higher transpiration from below the B horizon. Results are shown in Table 6.4.

Table 6.4 Influences of various taproot depths on simulated groundwater table depth, recharge, total evaporation and transpiration from the A, B and intermediate zone horizons and from the capillary fringe above the groundwater (OBSWTD = 10), with the deep root runs shaded

Trial No	DEPROT (mm)	Average SIMWTD (mm)	Average SUMDD	Sum SUR2 (mm)	Sum SUR3 (mm)	SumSUR1+2+3 (mm)	SumAET (mm)	Sum ATRAN1 (mm)	Sum ATRAN2 (mm)	Sum of ATRAN3 (mm)	Sum of ATRAN4 (mm)
29_2	0	11257	634	3333	868	16816	31452	20430	8521	0	859
27_2	5000	16372	5636	3333	0	15948	44838	20430	8521	3156	11090
28_2	10000	11380	646	3333	0	15948	32688	20430	8521	1718	378
30_2	15000	15583	4847	3333	0	15948	42446	20430	8521	2699	9154

An increase of taproot depth from 0 to 5 m resulted in an increase of simulated depth of the groundwater table. A further increase resulted in a reduction in simulated groundwater table depth, while a further increase resulted in an increase again, but still below the groundwater level with 5 m root inputs. Drainage from the intermediate zone (SUR3) only occurred for a 0 m taproot depth. For shallow roots, all the various ATRAN1-4 were the same, as was to be expected. ATRAN3 was 0, which was to be expected. ATRAN4 did not equal 0, but gave an unchanged value. This seems to be an omission in the model code, possibly an initialisation not included, and is made up of the first 11 month results, which were all > 0 and were between 31.8 and 90.7 mm. In the *ACRU* model, the modelled output of transpiration was made up of transpiration from the A horizon (ATRAN1), from the B horizon (ATRAN2), from the intermediate zone (ATRAN3) and from the groundwater zone (ATRAN4).

It needs to be checked why there were figures for ATRAN4 for shallow roots. A way around this could be to only start analysing results from month 12 onwards. Similarly, for the trials with deep roots the first 7 months produced much higher ATRAN4 values than thereafter. For plantation inputs accumulated ATRAN1 and ATRAN2 were the same for all variations of DEPROT, with ATRAN1 = 20430 mm and ATRAN2 = 8521, for trials 2_27 – 2_30. For DEPROT = 0, ATRAN3 =0, which was to be expected, but ATRAN4 gave a value beyond the first few lines.

The simulated groundwater level, drawdown and transpiration did not follow a trend and this result was unexpected. One reason could be that the initial observed groundwater depth was set for 10 m in those trials, which was equal to the rooting depth in trial 28_2. It was likely that this caused problems. A trial on rooting depth was repeated using an observed initial water depth of 25 m and the results are shown in Table 6.5.

Table 6.5 Influence of various taproot depths on simulated outcomes, with OBSWTD = 25, and Trial_2 results shaded.

Trial No	DEPROT (mm)	Average SIMWTD (mm)	Average SUMDD (mm)	Sum SUR2 (mm)	Sum SUR3 (mm)	Sum SUR1+2+3 (mm)	Sum ATRAN1 (mm)	Sum ATRAN2 (mm)	Sum of ATRAN3 (mm)	Sum of ATRAN4 (mm)
37_2	2000	30186	1063	3333	0	15948	20430	8521	559	3620
25_2	5000	32024	2793	3333	0	15948	20430	8521	1915	7572
35_2	10000	34229	4997	3333	0	15948	20430	8521	2789	12340
36_2	15000	35434	6202	3333	0	15948	20430	8521	3202	14788

As the taproot depth increased, so did the simulated groundwater depth, the recharge, as well as transpiration from the intermediate zone and capillary zone. With an increase in taproot depth, the simulated shallow groundwater table depth increased, so did ATRAN3 and ATRAN4, as was expected. Compared with the trial shown in Table 6.5, which did not give the expected results, it seems that the routine cannot cope well if the roots directly reach the groundwater table level. Inputs therefore need to be set so that DEPROT < OBSWTD.

6.3.3.5 The influence of the saturated hydraulic conductivity variable (VALUEK) on groundwater related responses over a 50 year period of climate input

In this sensitivity study the input values of saturated hydraulic conductivity (VALUEK) were changed, while the other inputs remain unchanged. In contrast to the previous trials, the vegetation inputs of arid grassland and the soil inputs of sandy soil were used here, with an OBSTWTD of 25 m. Simulated results are shown in Table 6.6.

Table 6.6 The influence of saturated hydraulic conductivity on various relevant outputs, with other inputs for arid grassland, sandy soils and the depth of the groundwater table remaining constant, and with Trial_2's results shown shaded

Trial No	VALUEK (mm/h)	Average SIMWTD (mm)	Average SUMDD (mm)	Sum SUR2 (mm)	Sum SUR3 (mm)	Sum SUR1+2+3 (mm)	Sum AET (mm)	Sum ATRAN 1 (mm)	Sum ATRAN 2 (mm)	Sum ATRAN 3 (mm)	Sum ATRAN4 (mm)
24_1 **	61	28609	n/a	5289	623	18704	28703	14041	4731	0	1723
23_1 **	150	27739	n/a	5289	447	18527	28922	14041	4731	0	1943
21_1 **	210	27208	n/a	5289	350	18430	29067	14041	4731	0	2087*
24_2	61	30726	4534	3333	0	15948	42195	20432	8521	1067	9933
23_2	150	27907	3318	3333	0	15948	47178	20432	8521	1067	15521
21_2	210	26415	2705	3333	0	15948	48771	20432	8521	836	17324

* Made up from the first 10 years only

** Shallow roots, arid grassland vegetation inputs and sandy soil inputs

An increase of saturated hydraulic conductivity resulted in a decrease of simulated groundwater table depth and a decrease of drawdown. Recharge into the intermediate zone (SUR3) decreased with an increase in saturated hydraulic conductivity in Trial_1, while there was zero simulated groundwater recharge for Trial_2. Transpiration from the intermediate zone (ATRAN3) for Trial_2 first remained constant and then decreased, while ATRAN4 increased. An increase of the saturated hydraulic conductivity variable led to an increase of the sum of total evapotranspiration, mainly due to an increase in transpiration from the capillary fringe above the groundwater table. It, however, also led to a reduction in average simulated groundwater table depth and a reduced drawdown. A question that remains for future research is to explain the anomalie that ET increased while the water table rose?

Following on from the sensitivity study, analyses of the 50 year time series of rainfall were used as an input for the runs which appear below.

6.3.4 ACRU Shallow Groundwater Runs

To be able to set up the *ACRU* Shallow Groundwater Routine for Catchment W70A, various trials with the *ACRU* model were run. For most model runs, the inputs from the South African Quinary Database for the Quaternary W70A were used (Quinaries 5524-5526), including the driver rainfall with 50 year of daily historical climate data (1950 to 1999), as well as soil and vegetation information. The dominant soil texture class is "loamy sand" and the dominant vegetation is "Coastal forest thornveld". The quaternary catchment's area was taken as the study catchment size (2624 km^2). The forest plantation size of 24 560 ha for the study catchment was extracted from the National Land Cover information (NLC 2000). However the routine requires various inputs that could not be established from published information and therefore assumptions were made. This includes, for example, the depth of the impenetrable layer, tap root depth and initial groundwater table levels. The latter were going to be taken from the Sibaya Lake weir levels (DWS, 2015, https://www.dwa.gov.za/Hydrology/HyDataSets.aspx?Station=W7R001). However those levels showed a near-steady increase from 2 m in 1967 to over 18 m in 1999 and were assumed not to be reliable enough for use here, and they were therefore discarded. In this section results from selected *ACRU* trials are shown. Various trials gave slightly different results, depending on the input variables chosen.

The monthly precipitation can be compared with the modelled recharge beyond the B horizon, which is calculated by the sum of the recharge out of the B horizon (*ACRU* Output SUR2) and the recharge out of the intermediate zone to groundwater (*ACRU* output SUR3). Results from a selected trial are shown in Figure 6.21.

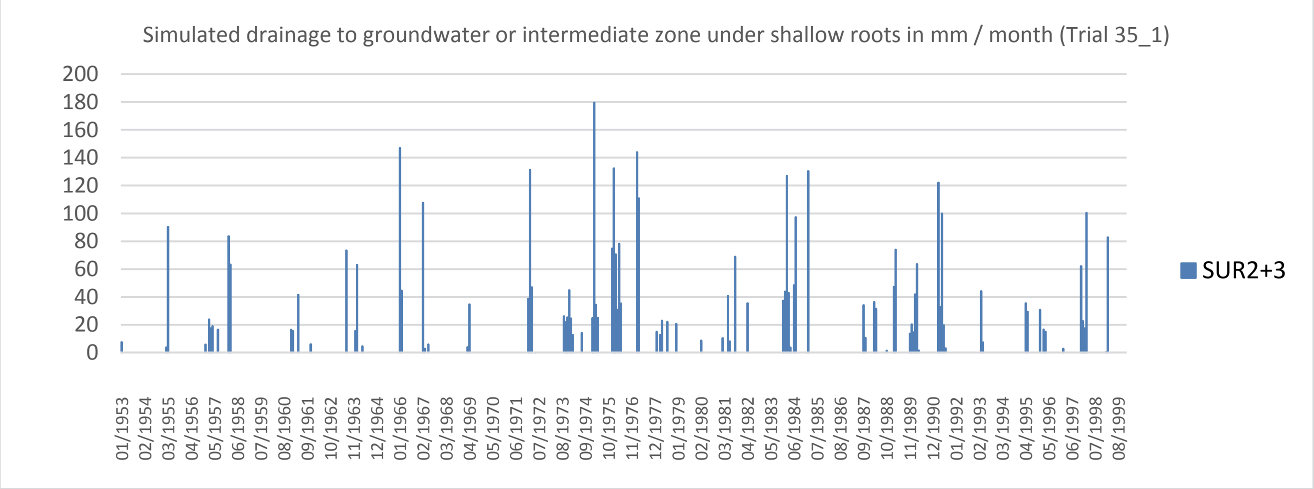


Figure 6.21 Recharge into the intermediate zone and/or the groundwater (SUR2 + SUR3) under shallow rooted vegetation in mm / month.

The result show that recharge only takes place when there are high rainfall months. The simulated intermediate and groundwater zone recharge as well as utilisation by deep roots from the intermediate zone or groundwater (ATRAN3 + ATRAN4) are compared in Figure 6.22.

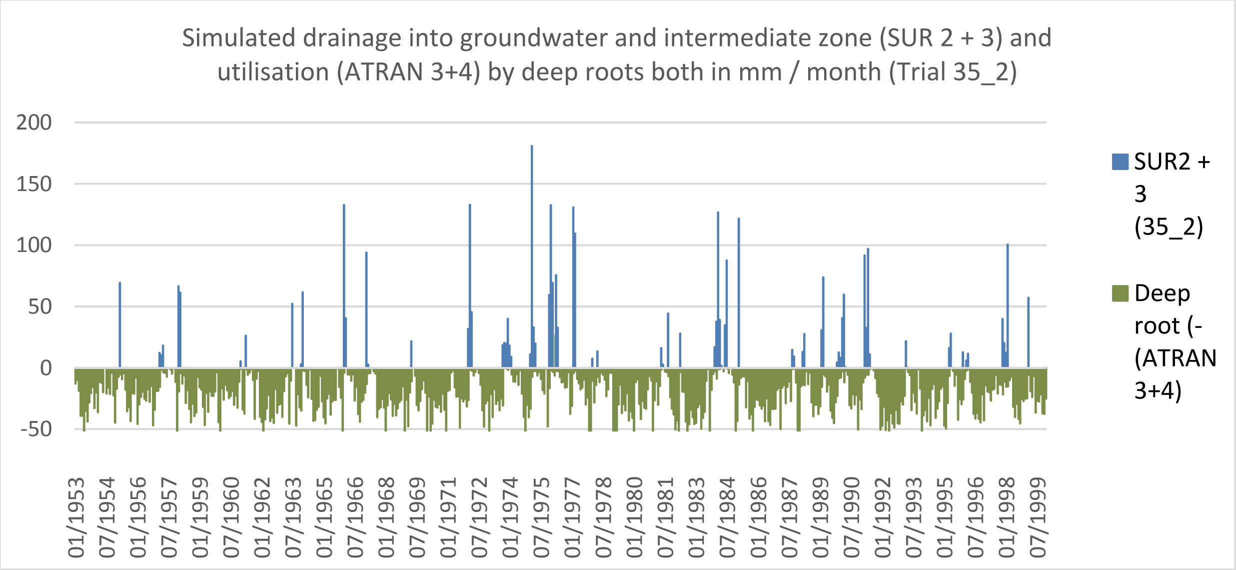


Figure 6.22 Simulated drainage into the intermediate zone and groundwater under shallow roots in mm / month. Results are shown for Trial 35_2

The expected result is that the drainage into intermediate zone and groundwater would be higher under shallow rooted than under deep rooted vegetation, and this is what can be seen when results from Figures 3 and 4 are compared. The groundwater table levels under shallow roots and under deep roots of a forest plantation were simulated, as was the drawdown under deep roots, with results from Figure 6.23 shown for Trial 35.

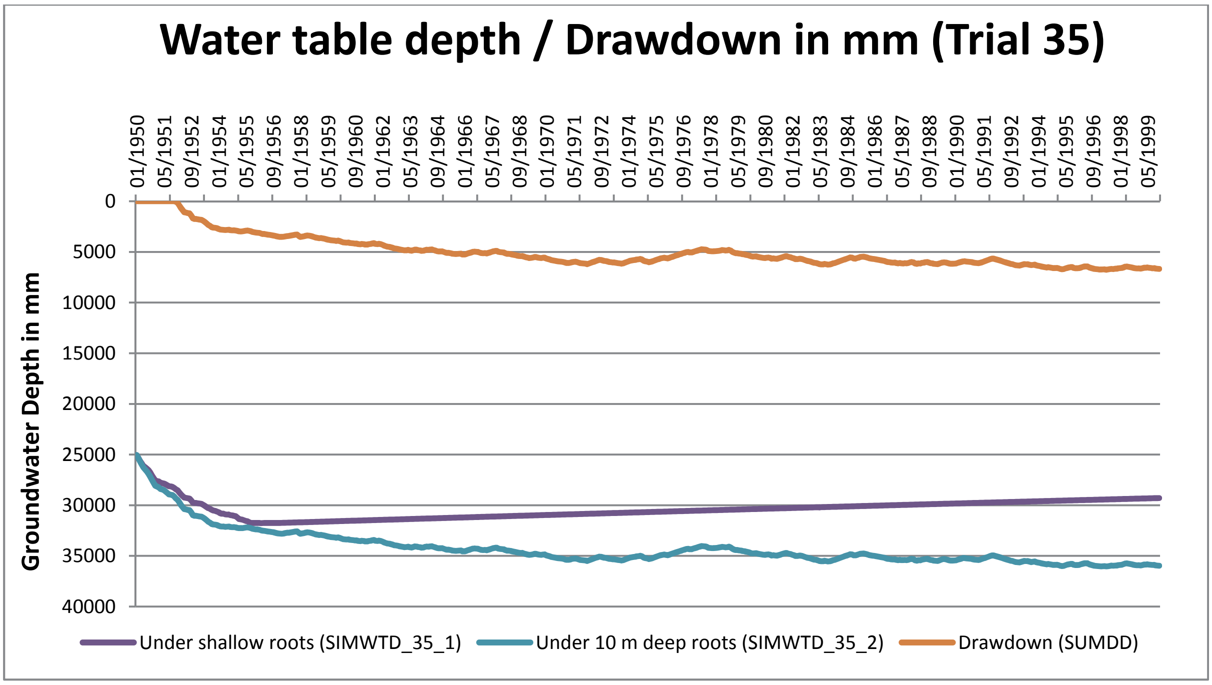


Figure 6.23 Simulated water table depth under shallow roots and water table depth as well as drawdown under 10 m deep roots, assuming an initial groundwater table depth of 25 m.

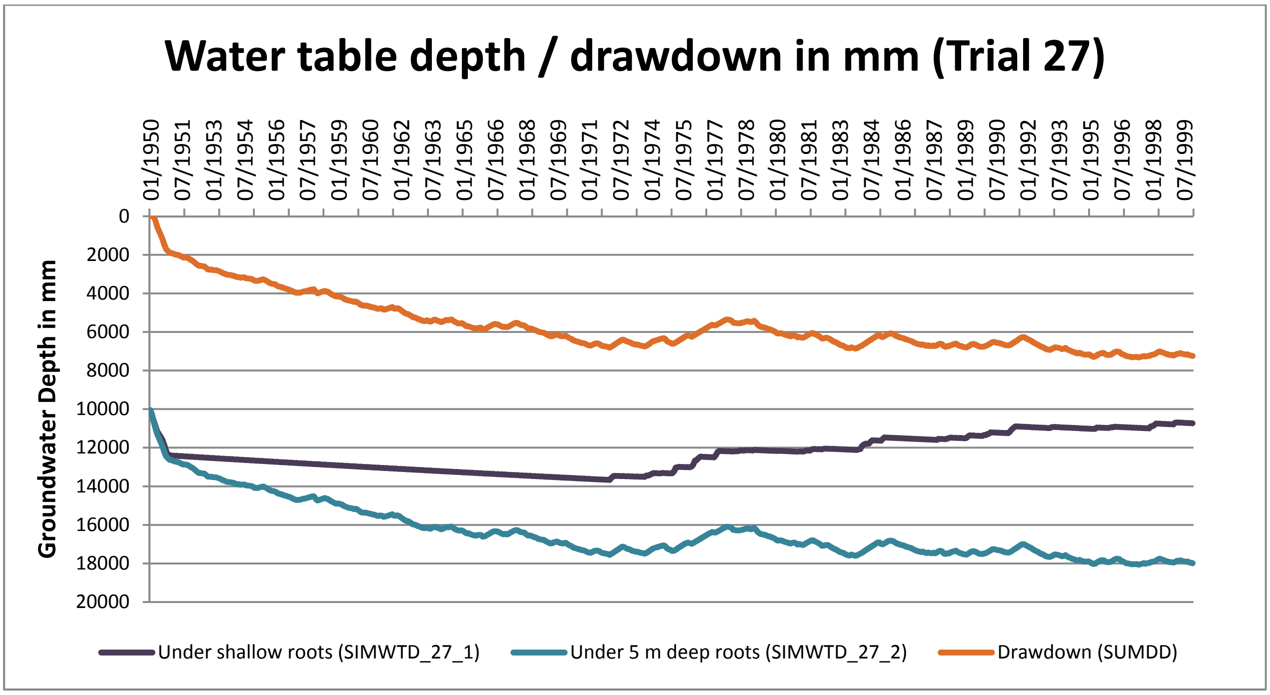


Figure 6.24 Simulated water table depth under shallow roots and water table depth as well as drawdown under 5 m deep roots, assuming an initial groundwater table depth of 10 m.

Both simulations (Figure 6.23 and Figure 6.24) show a drawdown due to deep roots. Both simulations under shallow roots showed an initial drawdown and after that a slow but steady increase in water table level. This correlated with the increase in the driver rainfall, which was shown in Figure 1. It is, however, also likely that the natural vegetation has roots beyond the B-horizon and therefore would also draw a certain amount from the intermediate and capillary zones, which was not accounted for in the simulation. The initial steep drawdown and step drop in water table level seems to be related to the model computational code’s initialisations and occurred in all trials. It also needs to be noted that the simulation results shown in Figure 6.23 and Figure 6.24 had different initial groundwater table level inputs, and thus the resulting simulated groundwater levels should be seen as relative, rather than absolute.

6.4 Conclusion

In conclusion, plausible results were obtained with the ACRU shallow groundwater routine.The Vasi Pan site is a highly sensitive and important area. ACRU modelling results showed that the site is a high water demanding area that is largely dependent on groundwater. With recent droughts in the area there is a need for continued research in the catchment.

7. CONCLUSION AND RECOMMENDATIONS

Parts of South Africa experience up to 87% alien tree invasions (Working for Water, 2011), with most of these being in the riparian area that have readily available water and are difficult to manage. In South Africa there is a limited understanding of the extent to which tree species (particularly those in the riparian area) contribute to total evaporation. As such, it is difficult for government organizations and scientists to justify alien tree removal and rehabilitation unless a known hydrological benefit can be seen. This study set out to provide actual values of riparian tree water-use (both indigenous and alien) while, at the same time, monitoring these dynamics under rehabilitation stages guided by the ecological component. Results are provided for long-term tree water-use of various tree species, soil water content, as well as local meteorological conditions at Buffeljagsrivier in the Western Cape, New Forest in the KwaZulu-Natal midlands and Vasi Pan in the Maputaland coastal area. The findings add to a continually growing database of tree water-use. Furthermore, the HPV system has been validated and improved during this study. The ecological component of the study showed that some natural forest species (mostly pioneers but also old growth forest species) have the potential to regenerate (in previously forested areas) or colonise (in historically grassland/fynbos) within the confines of invasive plant stands. A hydrological modelling study was undertaken to support the extrapolated ecological observations. Given the availability of two observed variables (up-scaled transpiration and streamflow), model inputs could be refined for pristine and invaded riparian forests. Importantly, the *SWAT* model has been applied in a South African context using the refined input variables.

7.1 General Conclusions of the Hydro-meteorological Component

The aims of the hydro-meteorological component were to:

1. To investigate the water-use (transpiration rates) of a selection of pioneer indigenous tree species suitable for forest expansion, rehabilitation programmes and riparian zone rehabilitation following invasive alien clearing or manipulation.
4. Incorporate the data into a modelling framework for temporal and spatial extrapolation of water-use predictions.
5. Provide guidelines and recommendations for the management of water-efficient indigenous tree species for use in land rehabilitation programmes.

An extensive knowledge review was undertaken to gain understanding on current *status quo*, gaps in the available literature that could be explored, expert scientists that could be consulted (both locally and internationally), tree species that have been measured or suggested for measurement and the techniques used in various locations throughout South Africa. There is a widespread belief (which has been supported by numerous studies: Olbrich et al., 1996; Dye et al., 2001; Everson et al., 2007; Dye et al., 2008; Gush and Dye, 2008; Gush and Dye, 2009; Gush and Dye, 2015) in South Africa that indigenous tree species, in contrast to the introduced trees species, use less water and should be planted more widely in land rehabilitation programmes. Little research has been undertaken on the riparian area which excludes water limitations (except in severe drought conditions). The knowledge review highlighted the need to understand this riparian zone component as well as to expand the species measured which are usually diverse in these ecosystems. A key recommendation from the literature, which has been emphasized in a recent study by Gush and Dye (2015), is that indigenous tree stand management research is needed in South Africa. This could be in the form of manipulated stands (agroforestry), stands that have been successfully rehabilitated and government linked research stands. This study addresses part of this recommendation.

Riparian tree water-use was determined using the Heat Pulse Velocity (HPV) technique and validated using the Stem Steady State (SSS) and Thermal Dissipation (TD) techniques. A modelling component allowed this data to be extrapolated and for the ecological component (species density and specific clearing approaches) to be incorporated into these findings. The techniques chosen were site specific due to limitations in fetch, accessibility and stand dynamics/variability. The results obtained and presented in this study provide long term water-use for three different forest types and therefore climatic areas, each at differing levels of rehabilitation. Many of the species measured had not been measured prior to this study. A lack of information on riparian tree water-use existed prior to this study, which has subsequently been documented, based on the most accurate and modern techniques and models available to the authors.

The results showed that indigenous trees in an established riparian stand in a Western Cape Afro-temperate forest can use high volumes of water throughout the year (little seasonal rainfall change in this region). The variability of water-use between species and tree size was large as this variable is largely dependent on location, tree condition and light dynamics. This further highlights the need for measurement replication. The comparison between individual trees indicates that the largest trees (*Celtis* and *Vepris*) used the most water. However, when extrapolated by stem density, the alien species (*Acacia mearnsii*) used significantly more water per unit area (up to five times more water in certain stand locations). The modelling results revealed that a significant amount of water can be conserved if alien invaded forest stands are rehabilitated. The results provided were based on a catchment where the area of forest only contributed 5% of the total catchment area. This suggests that catchments with larger areas of forests will be much more responsive to rehabilitation programmes.

Of particular importance, during the wetter season (May to August), the deciduous trees were not using any water. This is in contrast to the deciduous species in the Eastern Mistbelt region and the Maputaland coastal belt that are dormant during the dry season when water is most scarce. In the Western Cape area, it is recommended that evergreen species be used for forest rehabilitation as they use less water than the deciduous trees during the drier months when water is needed the most.

The results for the Eastern Mistbelt forest, which had a highly disturbed/invaded stand, showed very low water-use volumes in comparison to the Western Cape site. Given the disturbances present, this stand was in a constant state of recovery. Most species did not grow vertically which is a sign of disturbance. Furthermore, the alien species present in the stand exceeded double the height of the majority of indigenous species. In contrast to the seasonal rainfall trend, the alien species showed little variation in their annual water-use. The alien species used significantly more water than the indigenous species, which had approximately the same stem density in the measurement area. Extrapolation was difficult in this stand due to the large variability in species and density. A key finding from this site was the water-use results of smaller trees in the understorey of pioneer species such as *Buddleja (indigenous)*, *Solanum* and *Acacia* (introduced) ranging in diameter between 1 and 2.5 cm. These species used up to 4 $L.day^{-1}$ individually. This showed that a substantial amount of water was used from these understorey species and this component should not be ignored for future up-scaling studies or in clearing programs. The *A. mearnsii* trees can act as understory as well as climax canopy species with the results proving that these species are using a significant amount of water from a very small size. In this area, it is recommended that deciduous species in addition to low consumptive evergreen species be used for forest rehabilitation as they use very little water during the drier winter months when water is needed the most. A summary of the annual water-use has been provided in Figure 7.1.

The results from the Maputaland Coastal belt revealed that the alien species (*Eucalyptus grandis* and *Pinus elliottii*) used significantly more water than the short forest that it invaded. Although the measurement of the *Eucalyptus* was in a commercial stand, the site still has direct access to groundwater as the entire area is within close proximity to depression wetlands. The monitoring period at the Vasi Pan site allowed for the HPV technique to be improved and calibrated for smaller tree species. The site also provided an opportunity for the authors to validate the HPV system against the SSS technique. A key recommendation for this site is that more detailed research be undertaken given the environmental, political, social and hydrological importance of the site. This site is also important due to its history of extensive plantations and its link to drought amplification in the major freshwater systems nearby, where uncertainty exits as to the future of these systems and the trade-off between wood production, water security and environmental concerns. The modelling component investigated a relatively untested *ACRU* groundwater routine. Some interesting preliminary results were obtained. However, due to the complexity of the groundwater systems and its movement to the freshwater lakes, it was concluded that more research is required on this component.

Although modelling was not the primary focus of this study, unique input attributes for mixed riparian forests have been derived for the *ACRU* and the *SWAT* models. This is an important step forward for future modelling (upscaling) as it allows users to accurately model these riparian systems that have constant access to water. The *SWAT* model is not commonly used in South Africa as the input parameters are not easily available nor are they easily transferable from one model to another. This model was run successfully using entirely site specific inputs and used to test various scenarios at each site and the model showed that it has the potential to provide a powerful tool for understanding the impact of various land use scenarios.

The contribution to new knowledge and the extent to which the aims have been addressed are as follows:

- Quantification and comparison of long-term measurements of transpiration have been provided for various riparian tree species in different rainfall regions (Objective 1);
- An investigation of the most appropriate water-use measurement techniques as well as a validation of these techniques was carried out (Objective 1);
- A modelling assessment was undertaken to extrapolate the water-use measurements both temporally and spatially (Objective 4);
- A model validation assessment was undertaken to determine if the ACRU and SWAT models could be used in riparian systems and if newly derived inputs were accurately simulating streamflow and total evaporation (Objective 4);
- Recommendations were provided on whether catchment water would be conserved under rehabilitation programmes (Objective 5); and
- Guidelines have been provided on the methods and best species to use for rehabilitation programmes (incorporated with the ecological component – Objective 5).

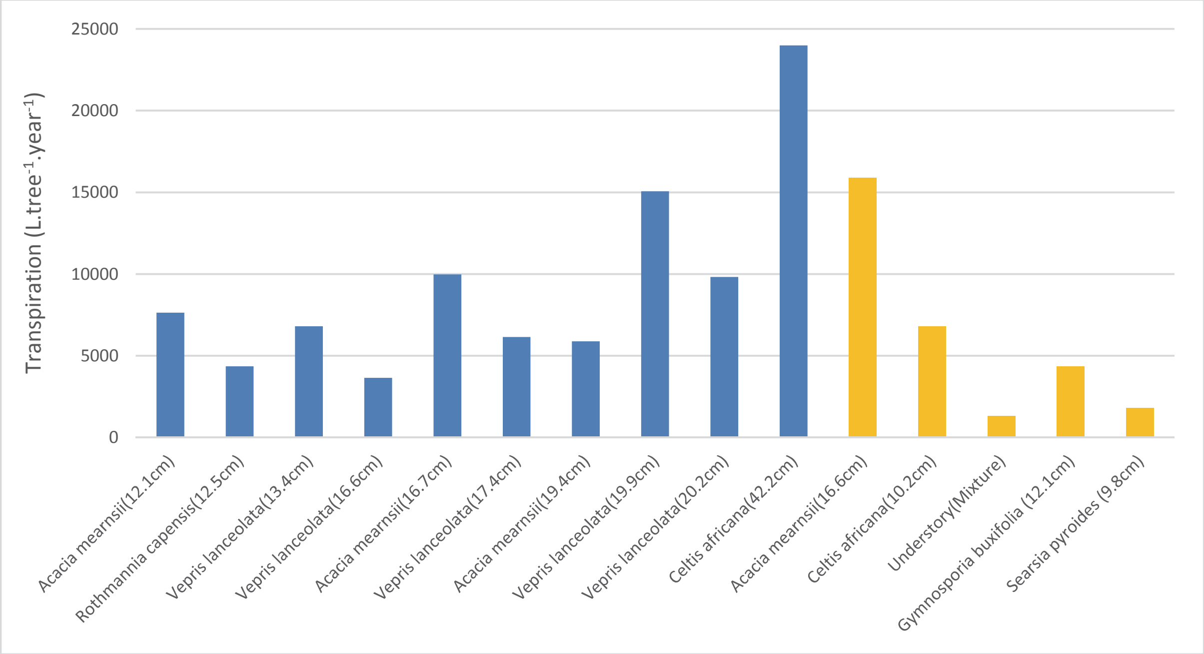


Figure 7.1 Annual water-use for species measured at Buffeljagsrivier (blue bar) and New Forest (yellow bar)

7.2 General Conclusions of the Ecological Component

The study investigated the influence of alien plant stand conditions (i.e. distance from seed source) and the development processes (i.e. cluster expansion) in which forest growth occurred. This challenged the perception that invasive plants nullify the capacity of native species to grow within IAP vegetation systems. The aim of study was to further the knowledge of how shade tolerant native forest species are dispersed, grow and develop within the confines of an IAP canopy. Two broad development processes (i.e. cluster development and edge expansion) were noted from the results of the ecological studies at Buffeljagsrivier and New Forest and they both appear to be present at Vasi Pan. Several hypotheses on forest development processes were tested to provide a sound scientific rationale into the ecology of indigenous tree species establishing in IAP stands, particularly the development and expansion of clusters of native forest species, and the influence of distance to native seed sources. Further to this, the study focused on the floristic composition (on mostly regrowth forest) of Southern Afrotemperate forest, Eastern Mistbelt and Northern Coastal forest and also investigated how native forest development was related to the structural components of alien plant stands. The intention was to use the information from the study to improve on the guidelines on how to rehabilitate stands of IAPs towards natural forest in the natural forest environment.

Two in-depth ecological studies and one preliminary ecological study were conducted within alien plant stands and natural forest within the vicinity of riparian forest areas. This study in general addressed three important questions: Do natural forest species establish within stands of IAP species? What are the underlying processes of natural forest species spreading into the IAP stands? Can invasion of invader plant stands by natural forest species be managed to facilitate natural forest recovery? A forest patch was defined as a natural forest stand adjacent to an IAP stand. A forest cluster was defined as a group of one to several natural forest trees growing on a limited area within the IAP stand. A cluster had to include at least one reproductively mature tree that could attract dispersal agents.

Forest expansion process within alien plant stands

The study at Buffeljagsrivier focused on cluster development and because it looked at cluster development at distance from natural forest patches it provided an insight into forest edge expansion. This analysis showed that the successful establishment of natural forest species in clusters within the introduced invasive wattle occurred in different numbers and sizes according to distance from natural forest patches. Large clusters were most common closer to natural forest and smaller clusters most common further away from natural forest patches.

This points to forest establishment through an edge expansion process. A similar expansion process was recorded within an Eastern Mistbelt Forest, which showed that forest establishment <40 m from a mature forest patches within a mixed Eucalyptus, Black Wattle and Pine stand, contained a greater density of plants, higher species richness and characteristic mature forest species compared to areas sampled further away.

Importantly, the study found that clusters (which contained mature individual trees) were expanding self -perpetually and thus did not require the seed source from the initial forest patches to expand. This could be interpreted as a type of edge expansion in itself. The nearest (proximal) zone to the natural forest patches had the highest number of large natural forest clusters, followed by the intermediate distant zones. In contrast, the distant zone had the highest number of small, newly establishing clusters. The unequal distribution of forest clusters suggested a directional process in the establishment of natural forest clusters within the IAP stand. In terms of the forest succession process, most of the trees first established near to potential seed sources, formed clusters and as they mature, they facilitated the progressive establishment of new small clusters to the distant zone, via the intermediate zone. Insight into this process was supported by the analysis from the study at New Forest in Eastern Mistbelt forest. It showed by CCA that at intermediate and far distances from forest patches (i.e. between 200 and 600 m) pioneer forest species such as *Searsia dentata*, *Halleria lucida* and *Buddleja dysophylla* were likely to be recruited, the latter being wind dispersed. However, at Buffeljagsrivier, the arrival of forest species at points furthest away from the seed source areas also related to the characteristics of the dispersal agents. For example, some species that were absent from the proximal and/or intermediate zones, such as *Ocotea bullata*, *Apodytes dimidiata* and *Olinia ventosa,* arrived in the distant zone because the baboons may have taken them there.

There were two distinct ways in which natural forest was recorded establishing within alien plant stands (1) Edge expansion and (2) Cluster development. During an initial forest expansion process, the edge of the forest would have expanded laterally, and then through clusters to further reaches of the alien plant stand. The growth in the edge expansion had more mature species and was of a higher density than that of the clusters. However once a self-perpetual process began with the forest development process and the clusters became 'reproductive' they too take on an edge expansion function which (1) joined to form larger clusters, (2) joined to increase the edge expansion of the initial forest patch, and (3) contributed to the longer distance expansion of the forest by forming new clusters at greater distances from the initial forest patch.

The influence of the alien plant stand structure on forest expansion

The New Forest study investigated how invasive plant stand structure might affect the establishment of the natural forest. The study showed that the IAP stands which were sampled were self-thinning, i.e. their density decreased with an increase in the age or mean stem diameter of the stand. This finding supported the theory outlined in the knowledge review of the project, which was that self-thinning and further manipulation of alien plant stands can facilitate the development of natural forest. The theory outlined in the knowledge review relied on the concept that young IAP stands undergo a natural self-thinning during Stage 1 of the development process. The finding further confirmed that stand manipulation is not necessarily required during the Stage 1 development phase, while manipulating stands are recommended during development Stage 2 and 3 to speed up the process. The study looked at the relationship between IAP stand density and forest development and found no relationship. Analysis into these results revealed that because the plots were located at varying distances from the natural forest patch, this was likely to have influenced the result and indicated that distance may have had a stronger influence on forest development than IAP stand structure.

Many mature native forest specimens sampled at Buffeljagsriver were >5 cm DBH and many areas had begun the forest self-perpetual expansion process. New Forest however, contained very few (<5%) trees >5 cm DBH, even though there were many young plants. This was thought to be because the forest development process at New Forest was in a much younger phase (initial cluster expansion) due to persisting disturbances (such as fire and/or timber harvesting) in the study area. Understanding why there was such a low conversion from young plants (primary cluster development) to older plants (self-perpetual cluster expansion) is a topic for future research. In contrast at Vasi Pan (Northern Coastal Forest), Results from the study at Vasi Pan (Northern KZN Coastal Forest) showed another aspect of forest expansion, i.e. through the consequence of the changed ecological conditions of a plantation environment through fire exclusion of a grassland environment. Similarities in the process of cluster expansion of grassland bush clumps and the self-perpetual expansion of clusters at Buffeljagsriver and New Forest were noted.

Floristic composition of natural forest expansion

The differences in species composition between forest patches and alien plant stands conveyed a lot of information about the state of the development of the expanding forest. At Buffeljagsrivier and New Forest, the forest development process was in terms relatively young. This was determined by the presence of expanding forest clusters within the alien plant stands. Most of the species within the clusters were pioneer marginally shade tolerant forest species, while mature forest species were noted on the expanding edges of the forest patches. In that sense, mature forest patches could easily be separated from forest clusters. The development process which occurred at Vasi Pan, appeared to be slightly different and this was reflected in the floristic composition of the forest. At Vasi there were essentially no mature forest patches, rather a mosaic of 'core' regrowth forest surrounded by younger pioneer forest and woodland, which originated from bush clumps. The process whereby the bush-clumps developed into closed canopy regrowth forest was interpreted to be similar to the cluster development within alien plant stands.

It is important to understand the genera of plant species within the forest, particularly with reference to the characteristics of the dominant pioneer species. The forest floristics at the three study sites in many ways represented the geographic location or the forest type of each forest and geographic area contained different dominant forest species. However, there were some obvious dominant species in the process, for example, *Celtis africana* (White stinkwood) was present and common in all three sites. It was furthermore interesting that some of these species functioned as both pioneer and old growth forest species, e.g. *Celtis africana* and *Rapanea melanophloeos* (Cape Beach) which were recorded as dominant pioneer species and old growth forest species at New Forest and Buffeljagsrivier. Such species become established in large gaps or degraded forest and then persist into the canopy where they then nurse the regeneration and establishment of more shade-tolerant forest species This trend was also noted at Vasi Pan for example with *Hymenocardia ulmoides* (Redheart Tree). From a hydrological perspective understanding the water-use of such widespread species would be important for choosing suitable species for rehabilitation programs.

The study showed that the forest expansion processes were more or less similar (i.e. edge expansion and cluster development) throughout the three study sites. An in-depth analysis of forest development at Buffeljagsrivier and New Forest and a preliminary study conducted at Vasi Pan confirmed this. This showed the ability of the natural forest to initiate a self-perpetual reproductive process within areas of present or historical invader plant stands. The study revealed the dominant pioneer genera within each site, and where they are most likely to occur during the forest development process. This is critical from a water-use perspective as these data can be synthesised with the hydrological data and incorporated into models of the water-use for riparian catchments. The conversion from invader plant stands into natural regrowth forest is a process, which can occur naturally but can also be facilitated by manipulation to benefit the developing natural forest. A practical guideline document has been provided as part of this project which guides the natural resources managers on this process. Further research into this topic could focus on the development phases of forest development and reactions to different treatment methods. This should be done on a long term basis to obtain meaningful results.

7.3 Future Research

Any gaps or shortcomings of the research undertaken during this study have been brought forward as areas needing future research. From the hydrological component, the following areas were identified:

- More replications are needed for tree water-use measurements. This is limited by time and cost but is essential in accurately representing a larger area;
- Spatial estimates of evapotranspiration are required but are difficult to obtain in remote areas with limited reach. Remote sensing could be one area where this could be useful given appropriate validation;
- Management dynamics are important in these environments. Management needs to be properly controlled (such as grazing in the forest) in order to reduce the uncertainty in the measurement and modelling of water-use; and
- The Maputaland Coastal belt has been identified as an area of priority of research by DWS, DAFF and DEA. A strong focus on groundwater modelling coupled with tree water-use, meteorological and management techniques should be considered if any work continues in the area.

The ecological component identified the following areas for future research:

- Investigation into development phases of forest establishment in invasive alien plant stands. This should be looked at along the lines of variables such as structure, light, nutrients and differences between development stages.
- Long term investigation of natural forest development in browsing exclusion plots
- Investigation into the concept of forest cluster development and investigation into self-perpetual process of forest expansion. Why does there appear to be low conversion from saplings (primary cluster development) to older trees (cluster development) and could this be facilitated by management intervention?

- Understand with accuracy the water-use of plantation forestry and indigenous species within a commercial, community woodlot and mixed plantation or agroforestry environment in Maputaland.
- Understand the ecological pattern and water-use of natural vegetation systems that could be incorporated in agroforestry systems in Maputaland.
- Develop and evaluate groundwater models of the Maputaland Coastal Aquifer to determine the impacts of land-use in context to plantation forestry, natural vegetation systems and a mixed plantation environment.
- Long term manipulation experiments of invasive alien plant stands, which would monitor the response of native forest development to different thinning regimes – linked with plant diversity change and impacts on water use.

8. REFERENCES

Aerts, R., Negussie, A., Maes, W., November, E., Hermy, M. and Muys, B. 2007. Restoration of Dry Afromontane Forest Using Pioneer Shrubs as Nurse-Plants for *Olea europaea* ssp. cuspidata. Restoration Ecology. 15, 129-1

Allen, S.J. and Grime, V.L. 1994. Measurements of transpiration from savannah shrubs using sap flow gauges. Agricultural and Forest Meteorology. 75. 23-41.

Armstrong. A.J. and Van Hensbergen, H.J. 1996. Impacts of afforestation with pines on assemblages of native biota in South Africa. South African Forestry Journal 175. 35-42.

Arnold, J.G. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrological Processes. 19. 563-572.

Askey-Dorin, M., Petit, N., Robins, L. and McDonald, D. 1999. The role of vegetation in riparian management. In: Riparian Land Management Technical Guidelines. Vol. 1. Principles of Sound Management. Eds. S. Lovett and P. Price. LWRRDC Canberra. pp. 97-120.

Atsame-Edda, A. 2014. Regeneration dynamics of natural forest species within a stand of the invasive alien *Acacia mearnsii* along the Buffeljagsrivier, Swellendam, South Africa. MSc Thesis. Stellenbosch University.

Aylward, B.A. and Barbier, E.B. 1992. Valuing environmental functions in developing countries. Biodiversity Conservation. 1, 34-50.

Bagchi, S. 2007. Relationship between size hierarchy and density of trees in a tropical dry deciduous forest of western India. Journal of Vegetation Science. 18, 389-394.

Baker, J. and van Bavel, C. 1987. Measurement of mass flow of water in the stems of herbaceous plants. Plant, Cell & Environment. 10, 777-782.

Baldocchi, D.D., Hincks, B.B. and Meyers, T.P. 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology. 69, 1331-1430.

Baldocchi, M.M. 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology. 9, 1-14.

Banskota, M., Papola, T.S. and Richter, J. 2000. Growth, poverty alleviation and sustainable resource management in the Mountain areas of South Asia. International Centre for Integrated Mountain Development, Nepal.

Bazzaz, F.A. 1979. The physiological ecology of plant succession. Annual Review Ecological Systems. 10, 351-371.

Berliner, D. 2005. Systematic conservation planning for the forest biome of South Africa. Department of Water Affairs and Forestry (DWAF), Pretoria.

Berliner, D. 2009. Systematic Conservation Planning for South Africa's Forest Biome: An assessment of the conservation status of South Africa's forests and recommendations for their conservation. PhD, University of Cape Town.

Birkhead, A.L., Olbrich, B.W., James, C.S. and Rogers, K.H. 1997. Developing an Integrated Approach to Predicting the Water Use of Riparian Vegetation. Water Research Commission Report No. 474/1/96.

Blignaut, J., Mander, M., Schulze, R., Horan, M., Dickens, C., Pringle, C., Mavundla, K., Mahlangu, I., Wilson, A., McKenzie, M. and McKean, S. 2010. Restoring and managing natural capital towards fostering economic development: Evidence from Drakensberg, South Africa. Ecological Economics. 69, 1313-1323.

Bond, W.J. 2008. What Limits Trees in C-4 Grasslands and Savannas? Annual Review of Ecological Evolution. 39, 641-659.

Bond, W.J., Midgley, G.F. and Woodward, F.I. 2002. What controls South African vegetation — climate or fire? South African Journal of Botany. 69, 79-91.

Bond, W.J. and Parr, C.L. 2010. Beyond the forest edge: Ecology, diversity and conservation of the grassy biomes. Biological Conservation. 143, 2395-2404.

Boon, R. 2010. Trees of Eastern and Southern Africa. Flora and Fauna Publications Trust, Durban.

Bradshaw, A.D. 1987. The reclamation of derelict land and the ecology of eco-system. In: W.R. Jordon (Editor), Restoration Ecology.

Brady, N.C. 1996. Alternatives to slash-and-burn: A Global imperative. Agriculture, Agroecosystems and Environments. 58, 3-11.

Bray, J.R. and Curtis, J.T, 1957. An ordination of the upland forest communities of southern Wisconsin. Ecological Monographs. 27, 325-349.

Brown, D.R. 2004. A spatiotemporal model of forest cover dynamics and household land use decisions by subsistence farmers in southern Cameroon. PhD thesis, Cornell University, United States.

Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. Food & Agriculture Org. (FAO *Forestry* Paper-134), FAO, United Nations, Rome.

Burgess, S.O., Adams, M.A., Turner, N.C., Beverly, C.R., Ong, C.K., Khan, A.A.H. and Bleby, TM. 2001. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiology. 21, 589-598.

Campbell Scientific. 1998. Tripod weather station installation manual: Campbell Scientific models CM6, CM10 tripods. Revision: 4/98.Logan, Utah, USA.

Carbutt, C. and Edwards, T.J. 2006. The endemic and near-endemic angiosperms of the Drakensberg Alpine Centre. South African Journal of Botany. 72, 105-132.

Carsan, S., Orwa, C., Harwood, C., Kindt, R., Stroebel, A., Neufeldt, H. and Jamnadass, R. 2012. African wood density database. World Agroforestry Centre, Nairobi.

Cawe, S.G. and Geldenhuys, C.J. 2007. Resource status and population dynamics of target species in natural forests of the Port St Johns Forest Estate: A basis for sustainable resource use. Report for Project 2006-397. Pretoria.

Čermák, J. and Kuæera, J. 1987. Transpiration of mature stands of spruce (Picea abies (L.) Karst.) as estimated by the tree trunk heat balance method. In: Proceedings of the Forest Hydrology and Watershed Management Symposium. Vancouver, Canada, IAHS Publ. No. 167, 311-317.

CES 2008. The boundary survey and demarcation of indigenous forests in the Wild Coast. Report for BID 2/FY/09, Eastern Cape Parks, East London.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J-P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B. and Tamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests: Oecologia. 145, 87-99.

Chehbouni, A., Watts, C., Lagouarde, J.P., Kerr, Y.H., Rodriguez, J.C., Bonnefond, J.M., Santiago, F., Dedieu, G., Goodrich, D.C. and Unkrich, C. 2000. Estimation of heat and momentum fluxes over complex terrain using a large aperture scintillometer, Journal of Agricultural and Forest Meteorology. 105, 215-226.

Cienciala, E., Kuèera, J., Ryan, M.G. and Lindroth, A. 1999. Water flux in boreal forest during two hydrologically contrasting years; species specific regulation of canopy conductance and transpiration. Annuals of Forest Science. 55, 47-61.

Clements, F.E. 1936. Nature and structure of the climax. Journal of Ecology. 24, 252-284.

Clulow A.D. 2008. The long-term measurement of total evaporation over *Acacia mearnsii* using large aperture scintillometry. MSc. thesis, University of KwaZulu-Natal, South Africa. 91 pp.

Coates Palgrave, M. 2002. Trees of Southern Africa, 3rd ed. Struik, Cape Town.

Cohen, Y., Fuchs, M. and Green, G.C. 1981. Improvement of the heatpulse method for determining sap flow in trees. Plant, Cell Environ. 4,391-397.

Cooper, K.H. 1985. The conservation status of indigenous forests in Transvaal, Natal and OFS, South Africa. Wildlife Society of South Africa.

Corrigan, B.M., Kneen, M., Geldenhuys, C.J. and Wyk, B. Van, 2010. Spatial changes in forest cover on the KwaNibela Peninsula, St Lucia, South Africa, during the period 1937 to 2008 Spatial changes in forest cover on the KwaNibela Peninsula, St Lucia, South Africa. Southern Forests. 72, 37-41.

D'Antonio, C. and Meyerson, L.A., 2002. Exotic plant species as problems and solutions in ecological restoration: A synthesis. Restoration Ecology. 10, 703-713.

Dahm, C., Cleverly, J., Coonrod, J., Thibault, J., McDonnell, D. and Gilroy, D. 2002. Evapotranspiration at the land/water interface in a semi-arid drainage basin. Freshwater Biology. 47, 831-84.

Drake, J. A., Mooney, H.A., Di castri, F., Groves, R.H., Kruger, F.J., Rejma´nek, M. and Williamson, M. 1989. Biological invasions. A global perspective. SCOPE 37. John Wiley & Sons, Chichester, UK.

Dufrêne, M. and Legendre, P. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs. 67, 345-366.

Dunn, G.M. and Connor, D.J. 1993. An analysis of sap flow in mountain ash (Eucalyptus regnans) forests of different age. Tree Physiology.13, 321-336.

Dye, P. 1996. Climate, forest and streamflow relationships in South African afforested catchments. Commonwealth Forestry Review.75, 31-38.

Dye, P. and Jarmain, C. 2004.Water Use by Black Wattle (*Acacia mearnsii*): Implications for the Link Between Removal of Invading Trees and Catchment Streamflow Response. South African Journal of Science. 100, 40-44.

Dye, P., Moses, G., VilakazI, P., Ndlela, R. and Royappen, M. 2001. Comparative Water Use of Wattle Thickets and Indigenous Plant Communities at Riparian Sites in the Western Cape and KwaZulu-Natal. Water SA 27: No. 4, 529-538.

Dye, P.J.2001.Modelling growth and water use in four Pinus patula stands with the 3-PG process-based model. Southern African Forestry Journal.191, 53-63.

Dye, P.J. and Poulter, A.G.1995.Field demonstrations of the effect on streamflow of clearing invasive pine and wattle trees from a riparian zone. South African Forestry Journal. 173, 27-30.

Dye, P.J. and Jarmain, C. 2004. Water-use by Black Wattle (*Acacia mearnsii*): Implications for the Link between Removal of Invading Trees and Catchment Streamflow Response. South African Journal of Science. 100, 40-44.

Dye, P.J. and Poulter, A.G. 1995. Field demonstrations of the effect on streamflow of clearing invasive pine and wattle trees from a riparian zone. South African Forestry Journal. 173, 27-30.

Dye, P.J., Gush, M.B., Everson, C.S., Jarmain, C., Clulow, A., Mengistu, M., Geldenhuys, C.J., Wise, R., Scholes, R.J., Archibald, S. and Savage, M.J. 2008. Water-use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. Water Research Commission Report No. 361/08. Water Research Commission, Pretoria, RSA.

Dye, P.J., Jarmain, C., Le Maitre, D., Everson, C.S., Gush, M. and Clulow, A. 2008. Modelling vegetation water-use for general application in different categories of vegetation. Water Research Commission Report No. 1319/1/08. Water Research Commission, Pretoria, RSA.

Dye, P.J., Moses, G., Vilakazi, P., Ndlela, R. and Royappen, M. 2001. Comparative Water-use of Wattle Thickets and Indigenous Plant Communities at Riparian Sites in the Western Cape and KwaZulu-Natal. Water SA 27: No. 4, 529-538.

Dye, P.J. 1996. Climate, forest and streamflow relationships in South African afforested catchments. Commonwealth Forestry Review. 75, 31-38.

Dye, P.J. 2001. Modelling growth and water-use in four Pinus patula stands with the 3-PG process-based model. Southern African Forestry Journal. 191, 53-63.

England, J.R. and Attiwill, P.M. 2007. Changes in sapwood permeability and anatomy with tree age and height in the broad-leaved evergreen species Eucalyptus regans. Journal of Tree Physiology. 27, 1113-1124.

Everson, C.S., Gush, M., Moodley, M., Jarmain, C., Govender, M. and Dye, P. 2007. Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources. Water Research Commission Report No. 1284/1/07. Water Research Commission, Pretoria, RSA.

Everson, C.S., Clulow, A.D. and Mengitsu, M. 2009. Feasibility study on the determination of riparian evaporation in non-perennial systems. Water Research Commission Report No. TT424/09. Water Research Commission, Pretoria, RSA.

FAO 2005. Global forest resources assessment 2005: Progress towards sustainable forest management. Forestry Paper No. 147, FAO, Rome.

Feely, J.M. 1987. The early farmers of Transkei, Southern Africa, before A.D. 1870. Cambridge Monographs in African Archaeology 24, BAR International Series 378. 142 pp.

Fetene, M. and Beck, E.H. 2004. Water relations of indigenous versus exotic tree species, growing at the same sit in a tropical montane forest in southern Ethiopia. Trees. 18, 428-435.

Finegan, B., 1984. Forest succession. Nature. 312, 109-114.

Ford, C.R., McGuire, M.A., Mitchell, R.J. and Teskey, R.O. 2004. Assessing variation in the radial profile of sap flux density in Pinus species and its effect on daily water-use. Tree Physiol. 24, 241-249.

Geldenhuys, C.J. and Berliner, D. 2010. Estimation of the carbon sequestration potential of the natural forests of the Wild Coast. FW-02/10, FORESTWOOD cc, Pretoria. 29 pp.

Geldenhuys, C.J. 1998. Long-term monitoring plots show trends in the composition, growth and mortality of mixed evergreen forest in South Africa. In: F. Dallmeier & J.A. Comiskey (eds). Forest Biodiversity Research, Monitoring and Modeling: Conceptual background and Old World Case Studies. Man and the Biosphere Series, Volume 20. UNESCO, Paris & Parthenon Publishing. pp. 457-479.

Geldenhuys, C.J. 2000. The need for monitoring recruitment, growth and mortality in the indigenous forests: Examples from Northern Province. In: Seydack, A.H.W., Vermeulen, W.J. & Vermeulen, C. (eds). Towards sustainable management based on scientific understanding of natural forests and woodlands. Proceedings: Natural Forests and Woodlands Symposium II, Knysna, South Africa, 5-9 September 1999. pp. 17-28.

Geldenhuys, C.J. 1986. Costs and benefits of the Australian blackwood *Acacia melanoxylon* in South African forestry, in: Macdonald, I.A., Kruger, F. and Ferrar, A. (Eds.), The Ecology and Management of Biological Invasions in South Africa. Oxford University Press, Cape Town, pp. 275-284.

Geldenhuys, C.J. 1993a. Composition and dynamics of plant communities in the Southern Cape forests. Department of water affairs and forestry. Forestek. Pretoria.

Geldenhuys, C.J. 1993b. Floristic composition of the south Cape forests with an annotated check-list. South African Journal of Botany. 1, 26-44.

Geldenhuys, C.J. 1996a. Forest management systems to sustain resource use and biodiversity: examples from the southern Cape, South Africa, in: The Biodiversity of African Plants. Springer, pp. 317-322.

Geldenhuys, C.J. 1996b. Fruit/seed characteristics and germination requirements of tree and shrub species of the southern Cape forests. Pretoria, South Africa.

Geldenhuys, C.J. 1996c. The Blackwood Group System: its relevance for sustainable forest management in the southern Cape. South African Forestry Journal. 177, 7-21.

Geldenhuys, C.J. 1997. Native forest regeneration in Pine and Eucalypt plantations in Northern Province, South Africa. Forest Ecology and Management. 99, 101-115.

Geldenhuys, C.J. 2004. Meeting the demand for Ocotea bullata bark : implications for the conservation of high-value and medicinal tree species, in: Lawes, M.J., Eeley, H.A.C., Shackleton, C.M., Geach, G.B. (Eds.), Indigenous Forests and Woodlands in South Africa: Policy, People and Practice. University of KwaZulu-Natal Press, Pietermaritzburg, pp. 1-30.

Geldenhuys, C.J. 2010. Managing forest complexity through application of disturbance-recovery knowledge in development of silvicultural systems and ecological rehabilitation in natural forest systems in Africa. Journal of Forest Restoration. 15, 3-13.

Geldenhuys, C.J. 2013. Converting invasive alien plant stands to natural forest nature’s way. Overview, Theory and Practice. In: Jose, S., Singh, H.P., Babish, R.D., Kohli, R.K. (Eds.), Invasive Plant Ecology. Taylor & Francis Group, Boca Raton, pp. 217-237.

Geldenhuys, C.J., Assede, P.S.E., Cawe, S.G., Kutta, S., Litye, K., Mengqani, N.K. and Stemele, X. 2013. Phase 2 Report for the study to Review the Nqabarha Management Plan and to Develop Natural Resource Use Guidelines: Forest resource assessment. Report number FW-02/13, FORESTWOOD cc, Pretoria. 65 pp

Geldenhuys, C.J. and Bezuidenhout, L. 2008. Practical guidelines for the rehabilitation of forest-related streambank vegetation with removal of invader plant stands along the Berg River, Western Cape. Forestwood cc, Pretoria.

Geldenhuys, C.J. and Delvaux, C. 2006. The *Pinus patula* plantation – A nursery for natural forest seedlings, in: Bester, J., Seydack, A.H.W., Vorster, T., Van der Merwe, I.J., Dzivhani, S. (Eds.), Multiple Use Management of Natural Forests and Woodlands: Policy Refinement and Scientific Progress. Natural forests and savanna woodland symposium IV, 15-18 May 2006, Port Elizabeth, Port Elizabeth, pp. 94-107.

Geldenhuys, C.J. and Macdevette, D.R., 1989. Conservation status of coastal and montane evergreen forest, in: Huntley, B. (Ed.), Biotic Diversity in Southern Africa: Concepts and Conservation. Oxford University Press, Cape Town, pp. 224-238.

Geldenhuys, C.J. and Venter, S. 2002. Plant communities and biodiversity of the Limpopo Province forests: relevance and management options. In: Seydack, A.H.W., Vorster, T., Vermeulen, W.J. & Van der Merwe, I.J. (Ed.), Multiple Use Management of Natural Forests and Savanna Woodlands: Policy Refinements and Scientific Progress. Proceedings of Natural Forests & Savanna Woodlands Symposium III, 6-9 May 2002, pp. 23-37.

Gibbs, R.D. 1958. Patterns in the seasonal water content of trees. In: Thimann, KV. ed. The physiology of forest trees. New York: Ronald Press, pp. 43-69.

Gillham, S. and Haynes, M. 2001. Is the clearing of riparian invasive alien vegetation a viable water resources management strategy? Regional Management of Water Resources, Proceedings from the Sixth IAHS symposium, The Netherlands.

Görgens, A.H.M. and Van Wilgen, B.W. 2004. Invasive alien plants and water resources: an assessment of current understanding, predictive ability and research challenges. South African Journal of Science 100, 27-33.

Granier, A., Bobay, V., Gash, J.H.C., Gelpe, J., Saugier, B. and Shuttleworth, W.J. 1990. Vapor flux density and transpiration rate comparisons in a stand of Maritime pine (Pinus pinaster Ait.) in Les Landes forest. Agricultural and Forest Meteorology. 51, 309-319.

Granier, A., Loustau, D. and Bréda, N. 2001. A Generic Model of Forest Canopy Conductance Dependent on Climate, Soil Water Availability and Leaf Area Index. Annuals of Forest Science. 57, 755-765.

Grime, V.L. and Sinclair, F.L. 1999. Sources of error in stem heat balance sap flow measurements. Agricultural and Forest Meteorology. 94, 103-121.

Guevara, S., Purata, S.E. and Van der Maarel, E. 1986. The role of remnant forest trees in tropical secondary succession. Vegetation. 66, 77-84.

Gush, M.B. and Dye, P.J. 2008. Water-use Measurements of Selected Woodland Tree Species Within the Kruger National Park. CSIR, % Agrometeorology, School of Environmental Sciences, University of KwaZulu-Natal, Scottsville, South Africa.

Gush, M.B. and Dye, P.J. 2009. Water-Use Efficiency Within a Selection of Indigenous and Exotic Tree Species in South Africa as Determined Using Sap Flow and Biomass Measurements. CSIR, % Agrometeorology, School of Environmental Sciences, University of KwaZulu-Natal, Scottsville, South Africa.

Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E, Hallowes, L.A. and Görgens, A.H.M. 2002. A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. South African Forestry Journal. 196, 27-36.

Hardwick, K., Healey, J., Elliott, S., Garwood, N. and Anusarnsunthorn, V. 1997. Understanding and assisting natural regeneration processes in degraded seasonal evergreen forests in northern Thailand. Forest Ecology and Management. 99, 203-214.

Hatton T., Dyce P., Zhang L. and Dawes W. 1995. WAVES – An Eco hydrological model of the surface energy and water balance: sensitivity analysis. Technical Memorandum 95.2, Division of Water Resources, CSIRO, Australia.

Hatton, T.J., Moore, S.J. and Reece, P.H. 1995. Estimating Stand Transpiration in a Eucalyptus populnea Woodland with the Heat Pulse Method: Measurement Errors and Sampling Strategies. Journal of Tree Physiology. 15, 219-227.

Henderson, L. 2001. Alien weeds and invasive plants: A complete guide to declared weeds and invaders in South Africa. Plant Protection Research Institute Handbook No. 12, Agricultural Research Council, Pretoria.

Hobbs, R.J. 2007.Setting effective and realistic restoration goals: key directions for research. Restoration Ecology. 15, 354-357.

Holmes, P.M., Esler, K.J., Richardson, D.M. and Witkowski, E.T.F. 2008. Guidelines for improved management of riparian zones invaded by alien plants in South Africa. South African Journal of Botany. 74, 538-552.

Hooper, E., Legendre, P. and Condit, R. 2005. Barriers to forest regeneration of deforested and abandoned land in Panama. Journal of Applied Ecology. 42, 1165-1174.

Horst, T.W. and Weil, J.C. 1992. Footprint estimation for scalar flux measurements in the atmospheric boundary layer. Boundary-Layer Meteorology. 59, 279-296.

Howe, H.F. and Smallwood, J, 1982. Ecology of seed dispersal. Annual Review of Ecological Evolution and Systematics. 13, 201-228.

Instone, L. 2003. Shaking the ground of shifting cultivation: Or why (do) we need alternatives to slash-and-burn? Resource management in Asia-Pacific Program Working Paper No.43. Resource Management in Asia-Pacific Program, Research School of Pacific and Asian Studies, The Australian National University, Canberra.

Jarmain, C., Everson, C.S., Savage, M.J., Clulow, A.D., Walker, S. and Gush, M.B. 2008. Refining tools for evaporation monitoring in support of water resource management. Water Research Commission Report No. 1567/1/08. Water Research Commision, Pretoria, RSA.

Jarmain, C., Govender, M. and Everson, C.S. 2004. Improving the basis for predicting total evaporation from natural veld types in South Africa: A Focus on Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland. Water Research Commission Report No. 1219/1/04. Water Research Commission, Pretoria, RSA.

Jewitt, G.P.W., Horan, M.C. and Meier, K. B.2002. A compensatory forestry approach to clearing alien invasive vegetation from riparian zones in a South African basin. Fourth International Conference on FRIEND (Flow Regimes from International Network Data), Cape Town, South Africa, 18-22 March 2002. Wallingford, UK: 1AHS Press. pp. 397-405.

Keeton, W.S. and Franklin, J.F. 2005. Do remnant old-growth trees accelerate rates of succession in mature Douglas-fir forests? Ecological Monographs. 75, 103-118.

Kindt, R. and Coe, R. 2005. Tree diversity analysis. A manual and software for common statistical methods for ecological and biodiversity studies. Nairobi: World Agroforestry Centre (ICRAF).

Kipp and Zonen, Pty Ltd. 2007. Instruction Manual to the Large Aperture Scintillometer, Kipp and Zonen, Delft, Holland.

Knowles, O.H. and Parrotta, J.A. 1995. Amazonian forest restoration: an innovative system for native species selection based on phenological data and field performance indices. Commonwealth Forestry Review. 74, 230-243.

Kotze, D.J. and Lawes, M.J. 2007. Viability of ecological processes in small Afromontane forest patches in South Africa. Austral Ecology. 32, 294-304.

Kozlowski, T.T. 1971. Growth and Development of Trees, Vol I: Seed germination, ontogeny, and shoot growth. Academic Press, New York, New York, USA

Kromhout, C.P. 1975. ‘n Sleutel vir die mikroskopiese uitkenning van die vernaamste inheemse houtsoorte van Suid-Afrika. Bulletin no 50, Departement van Bosbou.140pp.

Ladefoged, K. 1963. Transpiration of forest trees in closed stands. Plant Physiology. 16, 378-414.

Lamaddalena, N., Shatanawi, M., Todorovic, M., Bogliotti, C. and Albrizio, R. 2007. Water-use Efficiency and Water Productivity. Proceedings of 4th WASAMED (WAter SAving in MEDiterranean agriculture). Centre International de Hautes Etudes Agronomiques Méditerranéennes.

Lawes, M.J., Aide, H., Eeley, H.A., Koetze D.J., Wethered R. 2007. An Assessment of the forests of the Maloti-Drakensberg Transfrontier Bioregion, with reference to important ecosystem processes. Forest Biodiversity Research Unit, School of Biological and Conservation Sciences, University Of KwaZulu-Natal, Pietermaritzburg.

Le Maitre, D.C., Van Wilgen, B.W., Gelderblom, C.M., Bailey, C., Chapman, R.A. and Nel, J.A. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. Forest Ecology and Management. 160, 143-159.

Le Maitre, D.C., Versfeld, D.B. and Chapman, R.A. 2000. The Impact of Invading Alien Plants on Surface Water Resources in South Africa: A Preliminary Assessment. Water SA. 26, 397-408.

Lepš, J. and Šmilauer, P. 2005. Multivariate analysis of ecological data using CANOCO. Bulletin of the Ecological Society of America. 86, 246-248.

Lorentz, S., Goba, P. and Pretorius, J. 2001. Hydrological Processes Research: experiments and measurements of soil hydraulic characteristics. Water Research Commission Report No. K5/744, Water Research Commission, Pretoria, RSA.

Loumeto, J.J. and Huttel, C. 1997. Understory vegetation in fast-growing tree plantations on savanna soils in Congo. Forest Ecology and Management. 99, 65-81.

Lübbe, W. and Mostert, G.P. 1991. Rate of *Ocotea bullata* decline in association with *Phytophthora cinnamomi* at three study sites in the southern Cape indigenous forests. South African Forestry Journal. 159, 17-24.

Lugo, A. 1997. The apparent paradox of re-establishing species richness on degraded lands with tree monocultures. Forest Ecology and Management. 99, 9-19.

MacArthur, R.H. and Wilson, E.O. 1967. The theory of island biogeography, Princeton University Press Princeton USA Major RE Kendal CE, Monographs in Population Ecology. Princeton University Press.

MacDonald, I.A.W., Kruger, F.J. and Ferrar, A.A. 1986. The ecology and management of biological invasions in southern Africa. Oxford University Press.

Mala, A.W. 2009. Knowledge systems and adaptive collaborative management of natural resources in southern Cameroon: Decision analysis of agro-biodiversity for forest-agriculture innovations. PhD thesis, University of Stellenbosch, Stellenbosch, South Africa.

Malan, F.S. 2005. The effect of planting density on the wood quality of South African-grown Eucalyptus grandis. South African Forestry Journal. 205, 31-37.

Mantel, N. 1967. Ranking procedures for arbitrarily restricted observation. Biometrics. 23, 65-78.

Marais, C. and Wannenburgh, A.M. 2008. Restoration of water resources (natural capital) through the clearing of invasive alien plants from riparian areas in South Africa- costs and water benefits. South African Journal of Botany. 74, 526-537.

Martínez-Garza, C., Peña, V., Ricker, M., Campos, V. and Howe, H.F. 2005. Restoring tropical biodiversity: Leaf traits predict growth and survival of late-successional trees in early-successional environments. Forest Ecology and Management. 217, 365-379.

Mather, A. 1993. Afforestation. Policies, planning and progress. Belhaven Press, London.

Medellin, R.A. and Gaona, O. 1999. Seed Dispersal by Bats and Birds in Forest and Disturbed Habitats of Chiapas, Mexico. Biotropica. 31, 478-485.

Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC.

Monteith J. L. 1981. Evaporation and surface temperature. Quarterly Journal of the Royal Meteorological Society. 107, 1-27.

Mucina, L. and Geldenhuys, C.J. 2006. Afrotemperate, subtropical and azonal forests. In: The vegetation of South Africa, Lesotho and Swaziland. Mucina, L. & Rutherford, M.C. (Eds.) Strelitzia. 19, 584-614.

Mucina, L. and Rutherford, M.C. 2006. The vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria, Pretoria.

Nel, W. and Summer, P.D. 2005. First rainfall data from the KZN Drakensberg escarpment edge (2002 and 2003). Water South Africa. 31, 399-402.

NWA. 1998. National Water Act of South Africa. RSA Government Gazette No. 36 of 1998: 26 August 1998, No. 19182. Cape Town, RSA.

Olbrich, B., Olbrich, K., Dye, P.J. and Soko, S. 1996. A Year-Long Comparison of Water-use Efficiency of Stressed and Non- Stressed E. grandis and P. patula: Findings and Management Recommendations. CSIR report FOR-DEA 958. CSIR, Pretoria, South Africa.

Osawa, A. and Allen, R.B. 1993. Allometric Theory Explains Self-Thinning Relationships of Mountain Beech and Red Pine. Ecology. 74, 1020-1032.

Otsamo, R. 2000. Secondary forest regeneration under fast-growing forest plantations on degraded Imperata cylindrica grasslands. New Forests. 19, 69-93.

Parresol, B.R. 2001. Additivity of nonlinear biomass equations. Canadian Journal for Forest Research. 31, 865-878.

Parrotta, J.A., Turnbull, J.W. and Jones, N. 1997. Catalyzing native forest regeneration on degraded tropical lands, in: Forest Ecology and Management. 99, 1-7.

Paw U., K.T., Baldocchi, D.D., Meyers, T.P. and Wilson, K.B. 2000. Correction of eddy-covariance measurements incorporating both advective effects and density fluxes. Boundary-Layer Meteorology. 97, 487-511.

Phillips, N., Oren, R. and Zimmermann, R. 1996. Radial patterns of xylem sap flow in non-, diffuse- and ring-porous tree species. Plant Cell Environment. 19, 983-990.

Phiri, D. 2013. Biomass modelling of selected drought tolerant eucalypt species in South Africa. Department of Forest and Wood Science. MSc Thesis. University of Stellenbosch. Stellenbosch.

Powers, J., Haggar, J. and Fisher, R. 1997. The effect of overstory composition on understory woody regeneration and species richness in 7-year-old plantations in Costa Rica. Forest Ecology and Management. 99, 43-54.

Prinsloo, F.W. and Scott, D.F. 1999. Streamflow responses to the clearing of alien invasive trees from riparian zones at three sites in the Western Cape Province. South African Forestry Journal. 185, 1-7.

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ramakrishnan, P.S., Rao, K.S., Kothyari, B.P., Maikhuri, R.K. and Saxena, K.G. 1992. Deforestation in Himalaya: Causes, consequences and restoration. In: J.S. Singh (Editor), Restoration of degraded land: concepts and strategies, Rastogi Publications, Meerut, pp. 271-289.

Rawat, Y.S., Vishvakarma, S.C.R. and Todaria, N.P. 2009. Fuel wood consumption pattern of tribal communities in cold desert of the Lahaul valley, North-Western Himalaya, India. Biomass and Bioenergy. 33, 1547-1557.

Richardson, D.M. 1998. Forestry Trees as Invasive Aliens. Journal of Conservation Biology. 12, 18-26.

Richardson, D.M., Rouget, M., Ralston, S.J., Cowling, R.M., VAN Rensburg, B.J., and Thuiller, W. 2005. Species richness of alien plants in South Africa: Environmental correlates and the relationship with indigenous plant species richness. Ecoscience. 12, 391-402.

Rosenberg N.J., Blad B.L. and Verma S.B., 1983. Microclimate: The Biological Environment, 2nd ed. New York, Wiley, 495 pp.

Rutherford, M.C. and Westfall, R.H. 1986. Biomes of southern Africa – an objective categorization. Memoirs of the Botanical Survey of South Africa. 54, 1-98.

Ruwanza, S., Gaertner, M., Esler, K.J. and Richardson, D.M. 2013. Both complete clearing and thinning of invasive trees lead to short-term recovery of native riparian vegetation in the Western Cape, South Africa. Applied Vegetation Science. 16, 193-204.

Savage M.J., Everson, C.S., Odhiambo, G.O., Mengistu, M.G. and Jarmain, C. 2004. Theory and practice of evaporation measurement, with a special focus on SLS as an operational tool for the estimation of spatially-averaged evaporation, Water Research Commission Report No. 1335/1/04. Water Research Commission, Pretoria, RSA.

Savage, M.J. 2008. Estimation of evaporation using a dual-beam surface layer scintillometer and component energy balance measurements. Agricultural and Forest Meteorology. 149, 501-517.

Savage, M.J., Graham A.D.N. and Lightbody, K.E. 2000. An investigation of the stem steady state heat energy balance technique in determining water-use by trees. Water Research Commission. 348, 1-168.

Savage, M.J. and Everson, C.S. 1997. Evaporation measurement above vegetated surfaces using micro-meteorological techniques. Water Research Commission Report No. 349/1/97. Water Research Commission, Pretoria, RSA.

Saxena, K.G., Rao, K.S., Sen, K.K., Maikhuri, R.K. and Semwal, R.L. 2001. Integrated natural resources management: approaches and lessons from the Himalaya. Conservation Ecology. 5, 1-14.

Schmid, H.P. 1994. Source areas for scalars and scalar fluxes. Boundary-Layer Meteorology. 67,293-318.

Scholes, R.J and Biggs, R. 2004. Ecosystem Services in Southern Africa: A Regional Assessment. The Regional-Scale Component of the Southern African Millennium Ecosystem Assessment. Council for Scientific and Industrial Research, Pretoria, RSA.

Schultze, R.E. 1995. Hydrology and Agrohydrology: A Text to Accompany the ACRU-3.00 Agro-Hydrological Modelling System. Water Research Commission Report No. TT 69/95, Pp 552, Water Research Commission, Pretoria, RSA.

Schurr, U. 1998. Xylem sap sampling – new approaches to an old topic. Trends in Plant Science. 3, 293-298.

Schwärzel, K., Häntzschel, J., Grünwald, T., Köstner, B., Bernhofer, C. and Feger, K-H. 2007. Fundamentals of the spatially distributed simulation of the water balance of forest sites in a low-range mountain area. Advances. S in Geoscience. 11, 43-47.

Scott, R. L., Cable, W.L., Huxman, T.E., Nagler, P.L., Hernandez, M. and Goodrich, D.C. 2008. Multiyear riparian evapotranspiration and groundwater use for a semiarid watershed. Journal of Arid Environments 72, 1232-1246.

Seaby, R. and Henderson, P. 2007. Community Analysis Package 4.0. Pisces Conservation LTD, United Kingdom.

Seifert, T. and Seifert, S. 2014. Modelling and simulation of tree biomass, in: Bioenergy from Wood. Springer, pp. 43-65.

Senbeta, F. and Teketay, D. 2001. Regeneration of indigenous woody species under the canopies of tree plantations in Central Ethiopia. Tropical Ecology. 42, 175-185.

SER. 2004. The SER Primer on Ecological Restoration, Version 2. Society for Ecological Restoration Science and Policy Working Group. http://www.ser.org/reading_resources.asp.

Seydack, A.H.W. and Vermeulen, W.J. 2004. Timber harvesting from southern Cape forests. The quest for sustainable levels of resource use. Indigenous Forests and Woodlands South Africa. Policy, people practice. University. KwaZulu-Natal Press. Pietermaritzburg. pp. 309-336.

Smith, D.M. and Allen, S.J. 1996. Measurement of sap flow in plant stems. Journal of Experimental Botany. 47, 1833-1844.

Smith, R.E., Moses, G. and Versfeld, D.B. 1992. Verification of the heat pulse velocity technique for *Acacia mearnsii*. South African Forestry Journal. 163, 1-4.

Smithers, J.C. and Schulze, R.E. 2004. ACRU Agro-Hydrological Modelling System: User Manual, Version 4.00. School of Bioresources Engineering and Environmental Hydrology. University of KwaZulu-Natal, Pietermaritzburg, RSA.

Snyman, H.A. 1999. Soil erosion and conservation. In: Tainton, N.M. (Ed.), Veld Management in Southern Africa. University of Natal Press, Scottsville, South Africa, 472pp.

Spellerberg, I.F. and Sawyer, W.D. 1996. Standards for biodiversity: a proposal based on biodiversity standards for forestry plantations. Biodiversity and Conservation. 5, 447-459.

Spicer, L. and Gartner, B.L. 2001. The effects of cambial age and position within the stem on specific conductivity in Douglas-fir (*Pseudotsuga menziesii*) sapwood. Trees – Structure and Function. 15, 222-229

Sritongchuay, T., Gale, G.A., Stewart, A. and Kerdkaew, T. 2014. Seed Rain in Abandoned Clearings in a Lowland Evergreen Rain Forest in Southern Thailand. Tropical Conservation Science. 7, 572-585.

Street, W. and Hempstead, H. 2011. An introduction to statistical methods in GenStat. VSN International, Hemel Hempstead.

Syampungani, S., Geldenhuys, C.J. and Chirwa, P.W. 2010. Age and growth rate determination using growth rings of selected miombo woodland species in charcoal and, slash and burn regrowth stands in Zambia. Journal of Ecology and the Natural Environment. 2, 167-174.

Tabacchi, E., Lambs, L., Guilloy, G., Planty-Tabacchi, A.M, Muller, E. and de´Camps, H. 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes. 14, 2959-2976.

Tassin, J., Medoc, J.M., Kull, C.A., Riviere, J.N. and Balent, G., 2009. Can invasion patches of Acacia mearnsii serve as ´union colonizing sites for native plant species on Reunion (Mascarene archipelago)? African Journal of Ecology. 47, 422-432.

Ter Braak, C.J.F., 1986. Canonical correspondence analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology. 67, 1167-1179.

Thorburn, P.J., Hatton, T.J. and Walker, G.R. 1993. Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests. Journal of Hydrology. 150, 563-587.

Turpie, J.K., Marais, C. and Blignaut, J.N. 2008. The Working for Water Programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. Journal of Ecological Economics. 65, 788-798.

Van Aarde, R.J., Ferreira, S.M., Kritzinger, J.J., Van Dyk, P.J., VOGT, M., and Wassenaar, T.D. 1996. An evaluation of habitat rehabilitation on coastal dune forests in northern KwaZulu-Natal, South Africa. Restoration Ecology. 4, 334-345.

Van Bavel, M. G. 2005. Flow4 Manual: This manual refers to Flow4 version 6.5(and above) and user interface version 6.0 (and above) with notes on upgrades to later versions. Dynamax inc.

Van Daalen, J.C., 1981. The dynamics of the indigenous forest-fynbos ecotone in the Southern Cape. South African Forest Journal. 119, 14-23.

Van Laar, A. and Geldenhuys, C.J. 1975. Tariff tables for indigenous species in the South Cape Province. Forestry in South Africa. 17, 29-37

Van Wilgen, B.W., Cowling, R.M. and Burgers, C.J. 1996. Evaluation of Ecosystem Services: A Case Study from South African Fynbos Ecosystems. Bioscience. 46, 184-189.

Van Wilgen, B.W., Reyers, B., Le Maitre, D.C., Richardson, D.M. and Schonegevel, L. 2008. A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. Journal of Environmental Management. 86, 336-349.

Van Wyk, G.F., Everard, D.A. and Geldenhuys, C.J. 1995. Forest ecotone development and succession: experimental results and guidelines for forest rehabilitation and protection. Report FOR-DEA 867, Division of Forest Science and Technology, CSIR, Pretoria. 40 pp.

Vann, D.R., Palmiotto, P.A. and Strimbeck, G.R. 1998. Allometric equations for two South American conifers: test of a non-destructive method. Forest Ecology and Management. 106, 55-71.

Versfeld, D.B. 1994. The forest industry and management for water conservation. In: Southern African Forestry Handbook, 657-674. South African Institute of Forestry, Pretoria.

Von Maltitz, G.P., Van Wyk, G.F. and Everard, D.A. 1996. Successional pathways in disturbed coastal dune forest on the coastal dunes in north-east KwaZulu-Natal, South Africa. South African Journal of Botany. 62, 188-195.

Walters, D.J.J., Kotze, D.C. and O'Connor, T.G. 2006. Impact of land use on vegetation composition, diversity, and selected soil properties of wetlands in the southern Drakensberg mountains, South Africa. Wetlands Ecology and Management. 14, 329-348.

Werk, K.S., Oren, R., Schulze, E-D., Zimmerman, R. and Meyer, J. 1988. Performance of two Picea abies (L.)Karst.stands at different stages of decline. Oecologia. 76, 519-524.

Wilson, A-L. and Downs, C.T. 2012. Fruit nutritional composition and non-nutritive traits of indigenous South African tree species. South African Journal of Botany. 78, 30-36.

Wilson, K.B., Hanson, P.J. and Baldocchi, D.D. 2000. Factors controlling evaporation and energy partitioning beneath a deciduous forest over an annual cycle. Agricultural and Forest Meteorology. 102, 83-103.

Wunder, S. 2005. Payments for environmental services: some nuts and bolts, CIFOR Occasional Paper No. 42, Center for International Forestry Research, Bogor.

Xu X., Zhang, H. and Zhang, O. 2004. Development of check-dam systems in gullies on the Loess Plateau, China. Environmental Science & Policy 7, 79-86.

Yarranton, G.A. and Morrison, R.G. 1974. Spatial dynamics of a primary succession: nucleation. Journal of Ecology. 62. 417-428.

Zhang, L., Dawes, W.R. and Walker, G.R. 1999. Predicting the Effect of Vegetation Changes on Catchment Average Water Balance. Technical Report 99/12, Cooperative Research Centre for Catchment Hydrology, CSIRO, Canberra.

Zobel, B.J., Van Wyk, G. and StahL, P. 1987. Growing exotic forests. John Wiley & Sons, New York.

9. APPENDICES

9.1 Appendix 1 Capacity Building and Technology Transfer Report

9.1.1 Capacity building

The capacity building and technology transfer activities included the scientific training of students for postgraduate qualifications, scientific papers delivered at regional and overseas conferences and numerous informal study group sessions by local and international visitors to the trial sites.

The building of research capacity was achieved through the registration of students at the University of Stellenbosch and the University of KwaZulu-Natal. The following table indicates the students who have completed their qualifications as well as those who are in the process of completing them.

Table 1: Candidates for postgraduate qualification

NAME	DEGREE	STATUS
Angeline Edda	MSc – Univ. Stellenbosch	Complete
Robert Mwamba	MSc – Univ. Stellenbosch	Complete
Hayden Jacobs	Hons – UKZN	Complete
Matthew Becker	Hons – UKZN	Complete
Allister Starke	MSc – UKZN	Complete
Bruce Scott-Shaw	PhD – UKZN	In Progress
Allister Starke	PhD – UP	In Progress
Margaret Mugure	MSc – UP	In Progress

9.1.1.1 Conference abstracts

The following presentations were made by project team members and students at local and international conferences:

World Forestry Congress 2015

Ecological and hydrological studies around the change from stands of Invasive alien plants to stands of natural forest at Buffeljagsrivier, Western Cape and New Forest, KwaZulu-Natal

Starke, A and Scott-Shaw, B.C

Center for Water Resources Research, School of Agriculture Earth and Environmental Science, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa

A study at Buffeljagsrivier in the Western Cape and New Forest in KwaZulu-Natal has shown that invasive alien plant stands (including Black wattle) in a natural forest environment can facilitate the recovery of such forests – challenging the general and global perception that invasive species threaten the biodiversity and functioning of natural vegetation systems. This abstract presents some results of how biodiversity and water-use change when invader plant stands are converted to natural forest. Indirectly the results have shown that this change could contribute to better stream bank stability and longer-term job creation for small entrepreneurs.

The ecological component of this study looked at how adjacent natural forest species ‘invade’ stands of alien plant species. Two different approaches were used to determine this process. At Buffeljagsrivier clusters of natural forest species were mapped within black wattle stands (*Acacia mearnsii*) whereas at New Forest, natural forest species were sampled in plots within mixed invasive stands (containing *Acacia mearnsii*, *Eucalyptus nitens* and *Pinus patula*). Sampling at New forest measured the distance to native forest seed source, the amount of native forest regeneration and the density of the invasive stands.

At Buffeljagsrivier 329 clusters of natural forest species were recorded and mapped within the wattle stand: 266 small clusters (1 to 3 reproductively mature trees), 36 medium-sized clusters (4 to 9 trees) and 27 large clusters (10+ trees). Large clusters were abundant in the zone close to the natural forest patches and the number of small clusters increased with increasing distance from the forest patches. While, at New Forest 38 plots of 400 m^2 were sampled to determine the stem density of mixed species invasive plots and 100 m^2 nested plots were used to count native species. Like at Buffeljagsrivier the study at New Forest determined that the further from native forest seed source the less native species regeneration was observed. Although the study at New Forest concluded that invasive species stands were self-thinning, the study determined the relationship between stem density of invasive species and native species regeneration to be inconclusive.

The hydrological study used several high-frequency monitoring techniques to measure water-use (sap flow or transpiration rates). Data have been obtained for 24 trees of eight species, to compare the water-use of the indigenous canopy trees with the Black wattle, gum species and bug-weed. A range of sizes were measured for each species. This is one of the longest running high frequency tree water-use monitoring studies in South Africa. There is a large variability in water-use between individual trees of the same species, different size classes and different species. As such, this study considered individual tree water-use, the canopy area and contributing stand density for each of the species measured. The results from both sites showed that daily sap flow rates of the indigenous trees in the varied between 30 L.day^{-1} for the smaller tree and 119 L.day^{-1} for the larger trees in the summer months, and dropped to between 15 L.day^{-1} and 25 L.day^{-1} in the winter months (less available energy during fewer daylight hours in winter to drive the transpiration process). Two (semi-deciduous) White Ironwood trees in the forest used a higher 77 and 140 L.day^{-1} in the summer. Water-use of the large deciduous White stinkwood trees (with highest canopy area) was high (approximately 190 L.day^{-1}) during summer. However, these trees use no water during leaf fall. Daily water-use of the Wattle trees ranged between 60 to 200 $L.day^{-1}$ in the summer months and between 20 $L.day^{-1}$ and 40 $L.day^{-1}$ in the winter months. The alien species were generally much thinner and taller than the indigenous species. In addition, the density of the alien species in comparison to the indigenous clusters was, on average, three time greater than the clusters and two times greater than the indigenous stand. Key findings from this study showed that introduced tree species can use up to five times more water than indigenous tree species. In addition, the three years of observed transpiration (beneficial water-use) data were used to validate the ACRU and SWAT models.

KZN-WILDLIFE Conservation Symposium 2015

EZEMVELO KZN WILDLIFE™
Conservation, Partnerships & Ecotourism

Native species from nearby seed source areas regenerate within invasive alien tree stands, New Forest, KwaZulu-Natal

A.P Starke[a], C.J Geldenhuys[b], C.E Everson[c], C.D Morris[d]

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Keywords: Alien invasive plants; distance to seed source; succession; native forest; afforestation; regrowth forest, ecological processes

Abstract

Invasive alien plant stands adjacent to Eastern Mistbelt Forest in KwaZulu-Natal, often persist due to a reduction in the areas natural fire regime, which would traditionally ensure that woody plant species were eliminated from historical grassland areas. This is an ecological consequence of habitat fragmentation and a ecotone shift from a forest-grassland tension zone (pre-fragmentation) to a forest-invasive stand tension zone (post fragmentation) is usually observed. These relatively young wooded invasive stands which persist on forest margins are gradually colonised by slower growing shade tolerant native forest species from surrounding areas of native forest. This study sampled native forest colonisation within alien stands of vegetation at varying distances from native forest and determined by canonical correspondence analysis and linear regression if distance to native seed source (DNSS) had an influence on native forest colonisation. Greater native forest growth (abundance and species richness) was noted closer to seed source than further away and most species colonised within 40 m of native forest areas. Species composition was the main response variable and inferences regarding the pattern of compositional change along DNSS showed tendencies of a native forest successional process. Analysis of the fruiting characteristics of native tree species determined that smaller and prolific seed producing

species were more likely to colonise further from seed source than larger less prolific seeding native forest species. Distance to seed source had a weak but significant effect on the species composition and abundance of natural forest species but other unmeasured factors also played a large role in determining the pattern of colonisation.

Poster Paper presented at the World Forestry Conference, September Durban 2015

APPLICATIONS OF SAP-FLUX DENSITY MEASUREMENTS FOR MONITORING TREE WATER-USE IN SOUTH AFRICAN CATCHMENTS

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For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Modelled estimates are frequently used without proper validation and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. Although the ET of the riparian zone vegetation (phreatophytic species) is a critical component of the overall catchment water balance, it is still poorly understood. Due to the availability of accurate techniques to quantify this large and often poorly understood component of the hydrological cycle, modelled estimates can be improved and therefore better understood, as can direct measurements. There is a need to expand current research and to include the water-use of indigenous trees used in forest expansion, the rehabilitation of degraded lands and riparian zones. This paper highlights the various sap-flow techniques available in South Africa, provides high frequency observations from a forested riparian area in the Western Cape, South Africa and concludes with the validation of a series of hydrological models. Key findings from this study showed that introduced tree species (*Acacia mearnsii* stand) can use up to five times more water than indigenous tree species. In addition, the three years of observed transpiration (beneficial water-use) data were used to validate the *ACRU* and *SWAT* models.

9.1.1.2 Journal abstracts

The following papers were published or have been submitted to peer reviewed journals:

APPLICATIONS OF SAP-FLUX DENSITY MEASUREMENTS FOR MONITORING TREE WATER-USE IN SOUTH AFRICAN CATCHMENTS

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For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Modelled estimates are frequently used without proper validation and the verification of the results is questionable, especially in dynamic and highly-sensitive riparian areas. Although the ET of the riparian zone vegetation (phreatophytic species) is a critical component of the overall catchment water balance, it is still poorly understood. Due to the availability of accurate techniques to quantify this large and often poorly understood component of the hydrological cycle, modelled estimates can be improved and therefore better understood, as can direct measurements. There is a need to expand current research and to include the water-use of indigenous trees used in forest expansion, the rehabilitation of degraded lands and the restoration of riparian zones. This paper highlights the various sap-flow techniques available in South Africa, provides high frequency observations from a forested riparian area in the Western Cape, South Africa and concludes with the validation of a series of hydrological models. Key findings from this study showed that introduced tree species (*Acacia mearnsii* stand) can use up to five times more water than indigenous tree species. In addition, the three years of observed transpiration (beneficial water-use) data were used to validate the *ACRU* and *SWAT* models.

An Overview of Techniques Used in the Measurement of Tree Water-Use in South Africa

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ABSTRACT

For many field and modelling applications, accurate estimates of total evaporation (ET) are required, but are often lacking. Modelled estimates are frequently used without proper validation and the verification of the results are questionable. In South Africa, the conversion of natural vegetation to agriculture is extensive and, as such, it is important to quantify the impact of these changes on the countries limited water resources. Tree water-use measurements have since become an important component of hydrological studies. There are several methods that can be used to measure the total evaporation (including productive transpiration and non-productive evaporation) of tree species and, therefore, their water-use. However, the selection of specific methods to obtain the required results is largely dependent on the location of the research to be done, the physical characteristics of the vegetation and the time and funds available to implement such research. Common techniques include empirical continuous methods, theoretical heat pulse methods and micrometeorological methods. This review suggests that, due to the variable nature of forested areas, there is no single ideal method that can be used to obtain long term measurements. Many of the major methods used to determine ET can be applied successfully to wetlands of uniform vegetation and adequate fetch, however, certain caveats apply. This paper highlights the various techniques used in the determination of tree water-use including the suitability of these techniques, as well as past and on-going research in South Africa.

Keywords: Total evaporation, transpiration, tree water-use, sap flow

COMPARISON BETWEEN INDIGENOUS AND INTRODUCED TREE SPECIES WATER-USE IN RIPARIAN FORESTS

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ABSTRACT

While extensive research has been undertaken on the water-use of terrestrial ecosystems, little is known about riparian tree water-use and growth for both indigenous and introduced tree species. This gap of knowledge has led to uncertainty and contention over riparian rehabilitation techniques. There is an increasing trend towards the promotion of indigenous trees with economic value that can be used to rehabilitate riparian forests. This research was undertaken in order to gain greater insights into understanding and quantifying riparian water-use. Common techniques to measure the total evaporation (including productive transpiration and non-productive evaporation) include empirical continuous methods, theoretical heat pulse methods and micrometeorological methods. The Heat Pulse Velocity (HPV) and the Stem Steady State (SSS) techniques were used to monitor tree water-use at three locations within South Africa.

The results indicate the introduced species can use up the three times more water per unit area. Furthermore, there are vast differences in the seasonal water-use which is largely dependent on the rainfall distribution of the areas. These results were used to validate and upscale model simulations for each site. Results from this study may facilitate the more realistic modelling of possible forest management approaches and may provide guidelines towards suitable indigenous alternatives.

9.1.1.3 Abstracts

The following section comprises the abstracts and summaries from the theses of the PhD and MSc candidates:

Robert Mwamba Mupemba

Modelling Aboveground Biomass of *Acacia mearnsii* and Competing Indigenous Species (*Celtis africana, Vepris lanceolata, Rapanea melanophloeos*) in South Africa

Thesis is submitted in partial fulfilment of the requirements for the degree of Master of Forestry at the University of Stellenbosch.
Supervisor: Professor Dr Thomas Seifert
Co supervisor: Professor Dr Coert Geldenhuys
2014

ABSTRACT

The species that covers a forest area can have a direct influence on the water-use and carbon sequestration. Biomass estimation serves as important base for all calculation used in this study below. Stands of invasive exotic species might differ substantially from indigenous forests in their biomass allocation. The aim of this study was to scale up aboveground biomass information from biomass to tree level, and at stand level for indigenous forest at Buffeljagsrivier, near Swellendam. The selected study area is a riverine area that has been invader by exotic black wattle (*Acacia mearnsii*) and slowly reclaimed by indigenous species. For this reason allometric biomass functions were developed for black wattle and three natural species (*Celtis africana, Vepris lanceolata and Rapanea melanophloeos*), that were found reclaiming areas in the wattle stands. They functions were developed to estimate aboveground biomass of the entire tree, based on dbh but also differentiated in different biomass components such as leaves, stem and branches. Non – destructive (minimal invasive) sampling method were applied. Since the indigenous species are protected, that prohibited felling. The result showed that the estimated biomass of *Acacia mearnsii* and *Vepris lanceolata* were still the equal, however biomass estimation of *Acacia mearnsii* and *Vepris lanceolata* is above than *Celtis africana* and *Rapanea melanophloeos*

Regeneration Dynamics of Natural Forest Species within a Stand of the Invasive Alien *Acacia mearnsii* along the Buffeljagsrivier, Swellendam, South Africa

Angeline Atsame-Edda

Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Forestry (Forest Science) in the Faculty of AgricSciences at Stellenbosch University
Supervisor: Prof. Coert Johannes Geldenhuys
Co-Supervisor: Prof. Thomas Seifert
2014

ABSTRACT

Several studies have shown that stands of invasive alien plants in the natural forest environment can facilitate the rehabilitation and recovery of such forests and challenged the general and global perception that such invasive species threaten the biodiversity and functioning of natural vegetation systems. The

aim of this study was to develop an understanding of the dynamics of the spread and establishment of natural forest species in a large stand of the invasive alien plant species *Acacia mearnsii* (Black wattle) along the Buffeljagsrivier, Western Cape, South Africa. Several patches of Moist forest, Dry forest and Riparian forest occur along the Buffeljagsrivier, above the Buffeljagsrivier dam. The stand of Black wattle consists of 90 ha for a distance of 3.12 km. The main objective was pursued through four specific objectives: (i) to map and assess the patterns in the distribution, size and species composition of the natural forest clusters within the Black wattle stand; (ii) to determine the relationship between natural forest clusters establishing within the Black wattle stand and the neighbouring natural forest patches as potential seed sources for the developing forest clusters; (iii) to determine the subsequent spread of natural forest species from the developing forest clusters into the rest of the Black wattle stand; and (iv) to synthesize the information on the dynamics of the spread and establishment of natural forest species into the Black wattle stand as a basis for developing general guidelines for the conversion of invasive alien plant stands in the forest environment towards regrowing natural forest.

In total, 329 clusters of natural forest species were GPS recorded and mapped (Arc-GIS) in three zones (Proximal, Intermediate and Distant in relation to the forest patches) within the Black wattle stand: 266 small clusters (one to three reproductively mature trees), 36 medium-sized clusters (four to nine trees) and 27 large clusters (more than 10 trees). Large clusters were abundant in the zone close to the natural forest patches and the number of small clusters increased with increasing distance from the forest patches. A total of 28 species of 20 families were recorded. Natural forest species are therefore able to establish within a Black wattle stand.

The relationship between natural forest clusters establishing within the Black wattle stand and the natural forest patches as potential seed sources was studied by sampling the stand composition along transects through the stands. A total of 55 rectangular plots (20 m x 10 m, 200 m^2) were sampled across forest patches and forest clusters. Hierarchical clustering analysis, using number of stems of a species per plot, identified three main groups and 10 sub-groups. All the sampled forest clusters were included in four of the five Riparian forest sub-groups. Most Moist and Dry forest species were absent from the forest clusters. The three main forest types differed in their general characteristics and site conditions, and this was supported by the ordination analyses: aspect, slope and canopy closure. The developing forest clusters within the Black wattle stand related more to the Riparian forest in terms of similar very gentle south-westerly slope and mean stem diameter. This suggested Riparian forest to be the primary seed source of the establishing forest clusters within the Black wattle stand. However, the large-sized stems of common species were not significantly different between Riparian forest patches and forest clusters, suggesting that large-sized stems in the forest clusters could be part of remnant forest patches, which could act as local seed sources. Detailed evaluation of species importance values and stem diameter distributions showed that some important Moist and Dry forest species are present in the forest clusters. The conclusion was that every type of forest patch contributes to a greater or lesser degree to the development of forest clusters within the Black wattle stand.

Seven large clusters were selected to sample the regeneration of natural forest species within 18 m from the forest cluster boundary. Two species lists were generated; one of species from adjacent natural forest patches, and another from 59 forest clusters of all sizes sampled throughout the wattle stand. The results indicated that (1) Mature trees of well-established forest clusters were the main seed sources for the cluster expansion in all directions; (2) Three different patterns were observed in terms of the distance of expansion of regeneration from the clusters: a decrease in regeneration with increasing distance from the cluster margin; increasing regeneration with increasing distance from the cluster; and no distinct pattern with a lack of regeneration of the dominant species of a forest cluster. The 40 species recorded

within the Buffeljagsrivier site include a wide range of fruit and seed characteristics. Four main groups of woody species were identified, based on their presence/absence in forest patches and forest clusters. The presence/absence of most species can be explained in terms of their fruit/seed characteristics and dispersal mechanisms. The majority of recorded woody species were most likely dispersed by birds and mammal, particularly Rameron pigeons and baboons.

In conclusion, a conceptual framework was developed to guide the rehabilitation of stands of light demanding invasive stands in the forest environment. Several topics for further research were identified.

Allister Patrick Starke

The potential for natural forest regeneration development within alien invasive stands at New Forest, Kwazulu-Natal, South Africa

Submitted in partial fulfilment of the requirements for the degree of Master of Science in Hydrology,
University of KwaZulu-Natal
2014

ABSTRACT

There is a growing body of evidence which supports the notion that indigenous forests have the potential to develop within Invasive Alien Plant (IAP) stands. This runs against the general perception that IAP stands are negative components in vegetation systems with limited ecological value. The aim of this study was to understand the variables that influence native species regeneration within IAP stands and test the hypothesis that natural forest has the potential to regenerate within invasive stands at New Forest. The study was conducted at New Forest, an Eastern Mistbelt Forest on the upper regions of the Umgeni River (29 ° 28’23.10 S; 29 °52’57.64 E) in the midlands of Kwazulu-Natal.

The aim of the study was pursued through four specific objectives namely to: (1) Determine the floristic relationship between the mature forest areas at New Forest and regeneration of natural forest species in the IAP stands (2) Understand how the distance to natural forest seed source influenced native species regeneration within invasive stands (3) Determine if self-thinning and invasive stand structure influenced native species regeneration (4) Synthesize results to provide guidelines for the management of invasive plants at New Forest.

Fifty two native and 10 invasive species were recorded in the 38 invasive stand plots. Non-metric Multi Dimensional Scaling (NMDS) grouped four regeneration communities and analysis of these communities suggested that native forest species in these communities followed a successional process from pioneer regeneration communities (in young invasive stands) through to communities which were dominated by mature forest species in core forest. The study also demonstrated that some tree species were present in the canopy of mature forest and also in younger successional forest stands such as regrowth forest and invasive stands. This revealed the multi-functional ecological aspects of key tree species at New Forest such as *Celtis africana* and *Scolopia mundii.*

Canonical correspondence analysis (CCA) determined that 13 native forest tree species showed a regeneration pattern which was influenced by their distance to forest seed source. This revealed a pattern in forest successional process, in that forest species regenerating closer to seed source contained greater mature forest species, while species regenerating further from seed source contained

characteristic pioneer forest species. The study also determined that increasing distance from seed source negatively influenced native regeneration.

Invasive stands were found to be self-thinning and the study determined the general trend that native species regeneration (measured as stem abundance and species richness) increased with the mean stem diameter (or age) of invasive stands. This indicated that invasive stand structure influenced native forest species regeneration and again underlined the occurrence of a forest successional process within invasive stands.

The study accepted the hypothesis in which invasive plant stands at New Forest have the potential to develop into mixed regrowth forest was credible and that native regeneration within invasive stands was influenced individually by a number of different factors. A conceptual framework and practical suggestions are given to guide the rehabilitation of invasive areas at New forest, and in addition topics for future research are identified.

9.1.1.4 Data storage

All processed data have been stored at:

School of Life Sciences
University of KwaZulu-Natal
Carbis Road
Scottsville
Pietermaritzburg
3209
South Africa

Carbis Road
Scottsville
Pietermaritzburg
3209
South Africa

9.2 Appendix 2 Schematic diagram of the heat pulse velocity (HPV) sensor, the thermal dissipation (TD) sensor and the heat field deformation (HFD) sensor, installed radially into a stem segment.

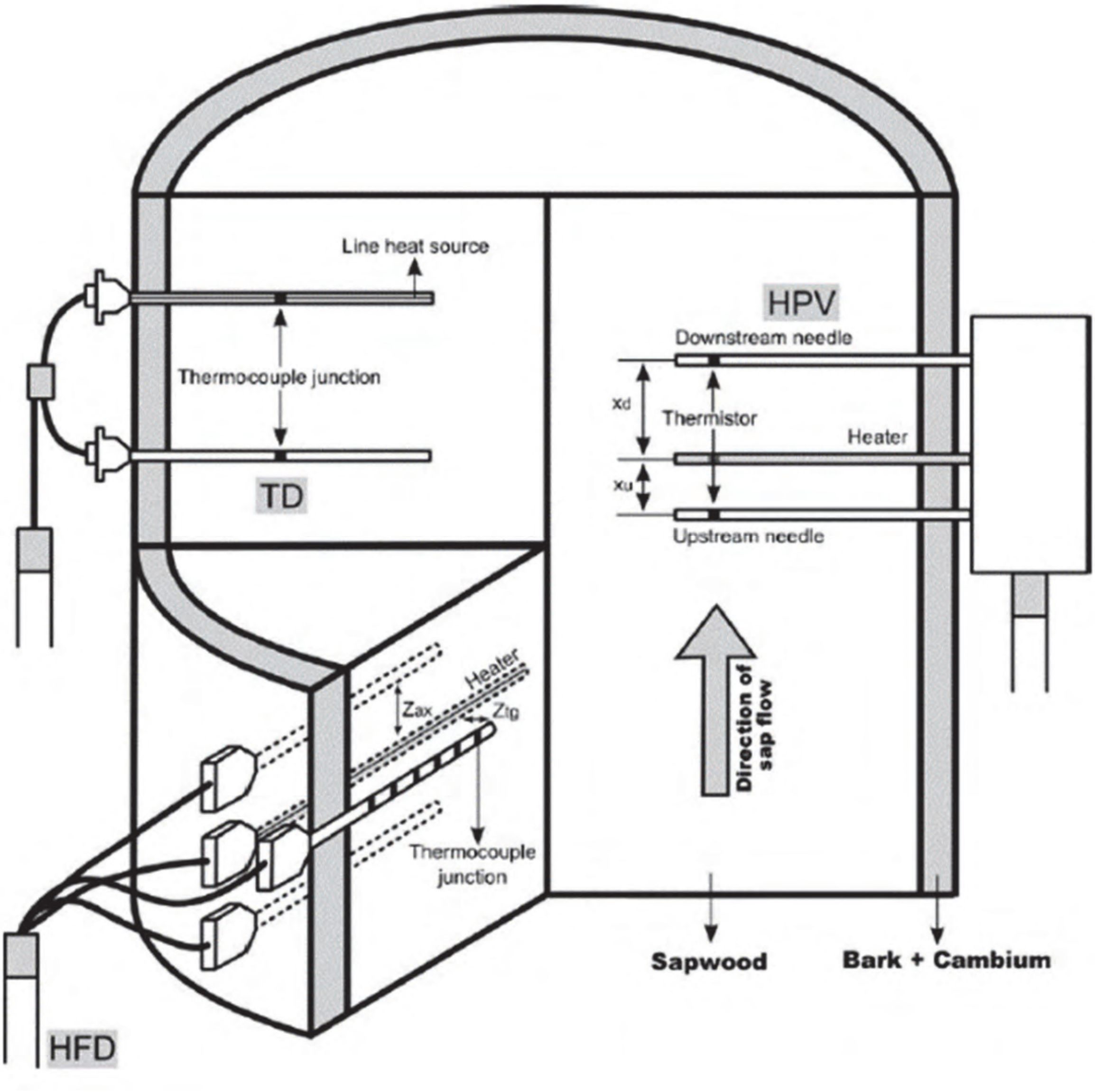


Figure 1: Symbols: xd and xu are the distances between the heater and the downstream and upstream needle of the HPV sensor, respectively; Zax and Ztg are the distances between the heater and the upper junction of the axial and tangential thermocouple of the HFD sensor, respectively (Steppe et al., 2010).

9.3 Appendix 3 Theory behind the Stem Steady State Energy Balance (SSS) after Taylor et al. (2013), WRC Project K5/2275//4.

Continuous constant heat is applied to the whole circumference of the stem and the mass of sap flow is obtained from the balance of the fluxes of heat into and out of the heated section of the stem (Baker and van Bavel 1987) by accounting for conduction both vertically upwards and downwards (axially) through and radially from the stem and heat stored in the plant limb. The theory is presented according to Savage et al. (2000). The heat component convected in sap can then be determined as follows:

$$E_{sap} = E_{heater} - E_{axial} - E_{radial} - E_{storage} \tag{11}$$

Sap flow (kg s^{-1}) can then be determined from sap convection energy (J s^{-1}), the sap specific heat capacity (J kg^{-1} K^{-1}) and the temperature difference between the above and below heater, as follows:

$$M_{sap} = \frac{E_{heater} - E_{axial} - E_{radial} - E_{storage}}{C_w \times dT_{stem}} \tag{12}$$

where

$$E_{sap} = C_w \times dT_{stem} \times M_{sap} \tag{13}$$

and where C_w is the specific heat capacity of sap, assumed to be the same as that for water (4186 J kg^{-1} K^{-1}), dT_{stem} (K) is the mean sap temperature difference (frequently assumed from measurements on the stem surface) between the two pairs of vertical point, each upstream and downstream of the heater and M_{sap} is the sap flow (kg s^{-1})

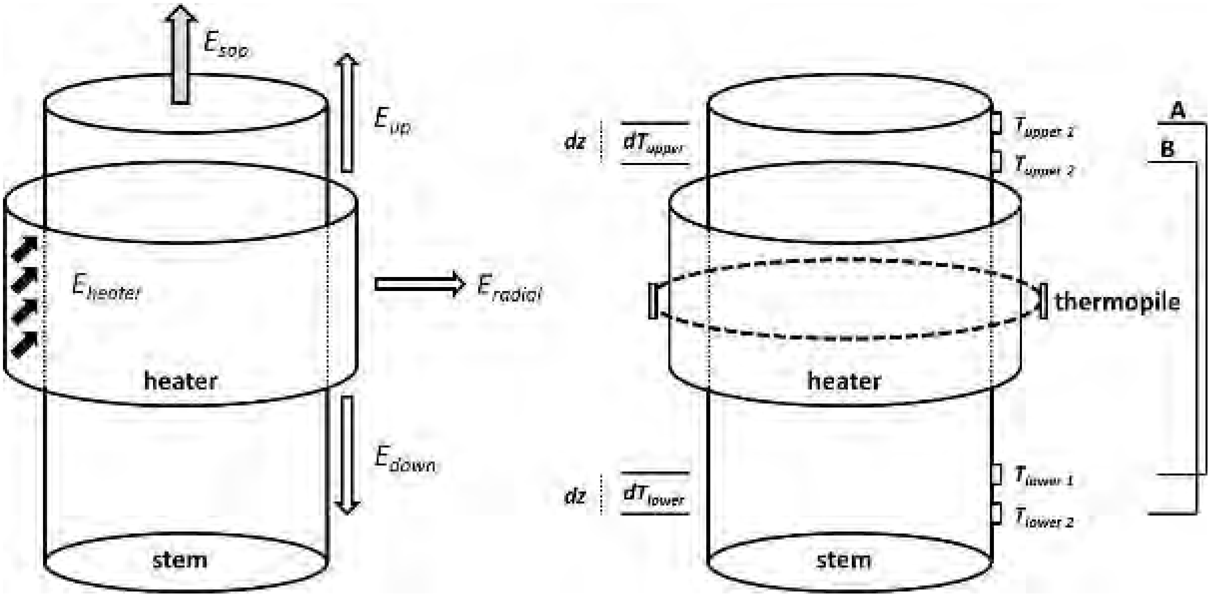


Figure 1: Schematic representation of the stem heat balance method (Savage et al., 2000). The figure of the left illustrates the components of the heat energy balance, with arrows representing the heat flux components. The figure on the right illustrates the conceptual and sensing components of the technique.

The heat energy supplied by the heater is calculated from the potential difference (V_{heater}) and electrical resistance (R_{heater}) across the heater

$$E_{heater} = \frac{V_{heater}^2}{R_{heater}} \tag{14}$$

The radial component (E_{radial}) can be calculated from the thermopile measured voltage difference ($V_{thermopile}$) between the inner and outer surfaces of the cork layer surrounding the heater using a proportionality constant which is usually the effective thermal conductance of the sheath materials making up the gauge (K_{gauge})

$$E_{radial} = K_{gauge} \times V_{thermopile} \tag{15}$$

K_{gauge} can be calculated from heat transport theory under conditions of zero sap flow (Baker and van Bavel 1987). Zero flow conditions are assumed to occur before dawn (Steinberg et al. 1989), but sap flow can occur at night and therefore care must be taken when calculating this term.

The heat energy balance term to describe heat storage is described by:

$$E_{storage} = V\rho C_p \frac{\Delta T}{\Delta t} \tag{16}$$

where V is the heated segment volume (m^3), ρ is the density of the stem (kg m^{-3}), C_p is the stem specific heat capacity (J kg^{-1} K^{-1}) and $\Delta T/\Delta t$ is the rate of temperature change in the stem (K s^{-1}).

The vertically conducted (axial) energy flux can be determined using the potential difference between two thermocouples (A and B), such that:

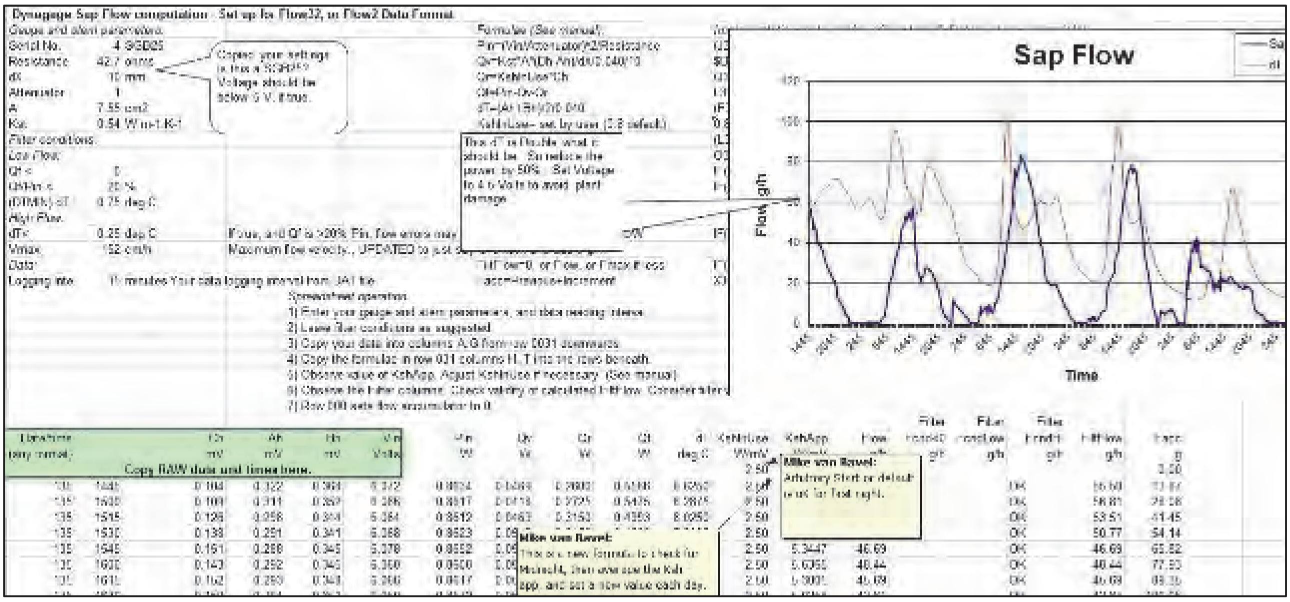
$$E_{axial} = \left(\frac{V_{thermocouple\,A} - V_{thermocouple\,B}}{S \times dz}\right) \times A_{stem} \times K_{stem} \tag{17}$$

where S (μV K^{-1}) is the Seebeck coefficient for copper-constantan thermocouples, dz (m) is the distance between the thermocouples (**Error! Reference source not found.**), A_{stem} is the stem area (m^2) and K_{stem} is the stem thermal conductivity (W m^{-1} K^{-1}).

Practically dT_{stem} is measured by the same thermocouples (A and B) used to measure E_{axial} as follows:

$$dT_{stem} = \frac{\left(\frac{V_{thermocouple\,A} + V_{thermocouple\,B}}{2}\right)}{S} \tag{18}$$

It is critical to ensure good thermal contact between gauge and the stem and therefore the stem where the heater collar is installed needs to be as straight as possible, without swelling or lumps (Smith and Allen 1996). In addition, silicone-grease should be placed on the stem prior to installation to ensure good contact, to allow slippage of the gauge during installation, to prevent water and condensation from accumulating between the stem and gauge and to allow movement of the gauge with expansion and contraction of the stem. Careful monitoring of the stem for any constrictions is required if the gauges are left on stems for long periods of time. It is important that water is prevented from entering the set-up as it can cause considerable damage to the electrical components. Due to the convoluted nature of citrus stems this technique will not be suitable and will not be evaluated in this study.



Dynagage Sap Flow computation - Set up for Flow32, or Flow2 Data Format

Gauge and alert parameters:

Serial No.	4 SGB25
Resistance	42.7 ohms
dX	10 mm
Attenuator	1
A	7.55 cm2
Ksl	0.54 W m-1 K-1

Copied your settings – is this a SGB25? Voltage should be below 5 V if true.

Spreadsheet operation:

1) Enter your gauge and alert parameters, and data reading interval
2) Leave filter conditions as suggested
3) Copy your data into columns A-G from row 0031 downwards
4) Copy the formulas in row 031 columns H..T into the rows beneath
5) Observe value of KshApp. Adjust KshUse if necessary (See manual)
6) Observe the filter columns. Check validity of calculated HiFlow.
7) Row 000 sets flow accumulator to 0

Figure 2: **Example of the correction table used for SSS flow correction and zero flow calculation**

9.4 Appendix 4 Biomass and ecological data

9.4.1 Equations for pioneer indigenous trees

Estimation of biomass equation at the sample level for *Celtis africana*

Table 1: Different selected models on the relationship of branch diameter and logarithm transformed of branch, wood and foliage Model for *Celtis africana*. BM is given in kg and diameter in mm.

Models	Functions	R^2
Model 1	ln BMbranch= 1.623-2.0968	0.64
Model 2	ln BMwood = 0.9872-2.4544	0.78
Model 3	ln BMfoliage = 0.7598-2.5018	0.31

Table 2: Parameters and model statistic of branch, wood and foliage *Celtis africana*. Ln branch diameter is the logarithmically transformed branch diameter data.

Components	Independent variables	Estimate	Std. Error	t-stat	Pr(>|t|)	p-value	R2
Branch (kg)	Intercept	-2.0968	0.3181	-6.591	1.00e-06***	1.15E-06	0.6345
	Ln branch diameter cm	1.6223	0.2484	6.531	1.15e-06 ***		
Wood (kg)	Intercept	-2.0968	0.3181	-6.591	1.00e-06 ***	9.24E-08	0.7735
	Ln branch diameter cm	1.6223	0.2484	6.531	1.15e-06 ***		
Leaves (kg)	Intercept	-2.6669	0.3841	-6.943	3.52e-07 ***	0.07303	0.281
	Ln branch diameter(cm	0.7106	0.2329	3.052	0.00549 **		

Significance levels * $p < 0.05$ ** $p< 0.01$ *** $P < 0.001$

Estimation of biomass equation at the sample level *Rapanea melanophloeos*

Table 3: Relationship between logarithms transformed branch diameter and dry mass of branch, wood and foliage of *Rapanea melanophloeos*

Models	Functions	R2
Model 4	lnBMbranch = 2.374 x – 3.1308	0.76
Model 5	lnBMwood = 2.4188x – 3.3593	0.77
Model 6	lnBMfoliage= 2.110 x – 4.3633	0.80

Table 4: Parameters and model statistics of branch for *Rapanea melanophloeos*

Components	Independent variables	Estimate	Std. Error	t-stat	Pr(>|t|	p-value	R2
Branch (kg)	Intercept	-3.1308	0.3739	-8.373	1.40e-08 ***	6.14E-09	0.752
	Ln(branch diameter)	2.374	0.2711	8.757	6.14e-09 ***		
Wood	Intercept	-3.3593	0.379	-8.863	7.08e-09 ***	7.221e -09	0.76
(kg)	Ln (branch diameter)	2.4188	0.2732	8.853	7.22e-09 ***		
Leaves	Intercept	-4.3633	0.2989 - 14.600	4.03e-13 ***		9.532e -10	0.801
(kg)	Ln(branch diameter)	2.1101	0.2135 9.883	9.53e-10 ***			

Significance levels (* p < 0.05 ** p< 0.01 *** P < 0.001

Estimation of biomass equation at the sample level *Vepris lanceolata*

Table 5: Relationship between logarithms transformed branch diameter with branch, wood and foliage of dry mass of *Vepris lanceolata.*

Models	Functions	R2
Model 2.7	lnBMbranch = 002266x – 2.302	0.81
Model 2.8	lnBMwood = 2.0331x – 2.4893	0.76
Model 2.9	lnBMfoliage = 1.5624x – 3.3506	0.62

Table 6: Parameters and model statistic of branch wood and foliage *Vepris lanceolata*

Component	Independent variables	Estimate	Std. Error	t-stat	Pr(>|t|)	Fisher-stat	p-value	R 2
Branch (kg)	Intercept	-2.302	0.2629	-8.76	4.36e-09 ***	106.4	1.711e - 10	0.8021
	ln (branch diameter) (cm)	2.0266	0.1965	10.3	1.71e-10 ***			
Wood (kg)	Intercept	-2.4893	0.3251	-7.658	9.01e-08 ***	73.71	1.25e - 08	0.7518
	ln (branch diameter)(cm)	2.0331	0.2368	8.586	1.25e-08 ***			
Leaves (kg)	Intercept	-3.3506	0.3708	-9.037	1.69e-08 ***	32.15	1.504e -05	0.5973
	ln (branch diameter)(cm)	1.5624	0.2756	5.67	1.50e-05 ***			

Significance levels (* p < 0.05 ** p< 0.01 *** P < 0.001

9.4.2 Methods of Upscaling for Tree Biomass

Stem volume biomass

Smalian's formula was used to calculate the volume of stem section between measuring point. Seifert and Seifert (2014) proposed the geometric approach to estimate oven dry biomass as a function of stem volume and basic density as: $BM = V \cdot R$

1. BM is the oven dry biomass (kg).
2. V is the stem volume (m^3).
3. R is the basic density defined as dry weight divided by green volume (kg/m^3).

The density average was multiplied by stem volume. Total stem biomass (BM)was the summation of stem section biomass values. The results are shown in a box plot in Figure 7.

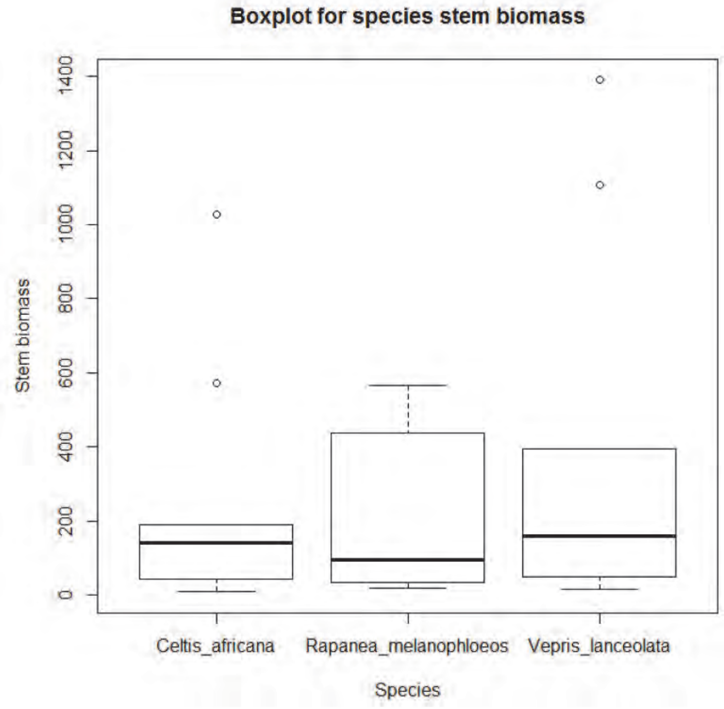


Figure 7: Stem biomass of three indigenous species (*Celtis africana, Rapanea melanophloeos* and *Vepris lanceolata*)

Developed allometric equations of tree components

Estimation of aboveground biomass of tree components was modelled with ln transformed linear regression based on branch diameter as independent variable. Table 8 shows the functions of tree components for three indigenous species *Celtis africana Vepris lanceolata* and *Rapanea melanophloeos*.

Table 8: Allometric function of tree components

Allometric equation of species	Branch	Wood	Foliage
Celtis africana	ln BMbranch = - 2.0968 + 1.6223*ln (D)	ln wood =- 2.6929 + 1.9745 * ln (D)	lnfoliage == - 2.6669 + 0.7106 *ln (D)
Vepris lanceolata	lnBMbranch = - 2.302 + 2.0266* ln (D)	ln wood =- 2.4893 + 2.0331 * ln (D)	ln foliage =- 3.3506 + 1.5624 * ln (D)
Rapanea melanophloeos	ln BMbranch =-3.1308 + 2.374 *ln (D)	ln wood =- 3.3593 + 2.4188)* ln (D)	ln foliage = - 4.3633 + 2.1101 * ln (D)

Upscaling form biomass sample to tree level

At the first stage of upscaling, the allometric equation that relate to biomass of components (wood, foliage, and branch) was developed. The models obtained from the tree component were applied to scale up the individual tree biomass. The tree total biomass was found to add up the biomass of wood plus biomass of foliage and biomass of stem volume such as:
BM (total) = BM (branch wood) + BM (Foliage) + BM (stem)

Table 9: Parameters and model statistics total biomass of *Celtis africana*

	Estimate	Std. Error	t value	Pr(>|t|)	F- statistic	p-value	R^2
Intercept	-1.2858	0.5096	-2.523	0.0356 *	157.3	1.529e - 06	0.91
lndbh	2.0313	0.1619	12.543	1.53e-06 ***			

Significance levels * p < 0.05 ** p< 0.01 *** P < 0.001

Table 10: Parameters and model statistic of tree total biomass of *Vepris lanceolata*

Variables		Estimate	Std. Error	t value	Pr(>|t|)	F - statistic	p - value	R^2
Intercept		-1.0361	0.5338	-1.941	0.0882.	147	1.98e - 06	0.94
ln.DBH.		2.0418	0.1684	12.124	1.98e-06 ***			

Significance levels * p < 0.05 ** p< 0.01 *** P < 0.001

Table 11: Parameters and model statistics total biomass of *Rapanea melanophloeos*

Variables	Estimate	Std. Error	t value	Pr(>|t|)	F -statistic	p-value	R^2
Intercept	-0.3559	0.8268	-0.43	0.678226	43.33	0.000173	0.86
ln.dbh.	1.8077	0.2746	6.583	0.000172 ***			

Significance levels * p < 0.05 ** p< 0.01 *** P < 0.001

9.4.3 Forest Ecology at New Forest

Table 12: IV values for mature forest and Mixed re-growth forest. IV with at least one species >10 in mature forest and at least one species >5 in mixed re-growth forest.

Species ***(Sub canopy species in tall forest and canopy species in low forest)**	**Species groups (Canopy trees measure ≥15 cm DBH; sub-canopy are trees <15 cm DBH)**			
	Mature forest Canopy	**Mature forest sub-canopy**	**Native species of mixed re-growth Forest canopy**	**Native species in mixed re-growth forest sub-canopy**
Buddleja auriculata	-	-	-	15
Buddleja salicifolia	-	-	12	6
Canthium ciliatum	-	15	7	-
Canthium obovatum	-	15	-	-
Carissa bi-spinosa	-	24	-	-
Celtis africana	21	-	16	-
*Clausena anisata **	25	-	-	-
Diospyros whyteana	-	50	-	-
Chionanthus foveolatus	12	-	-	-
*Euclea natalensis **	22	-	7	-
Eugenia zuluensis	-	30	-	-
*Gymnosporia buxifolia**	10	-	22	9
*Gymnosporia harveyana**	22	-	-	-
*Halleria lucida**	10	-	-	5
Kiggelaria africana	25	-	-	-
Leucosidea sericea	-	-	65	20
Maytenus peduncularis	21	-	-	-
Podocarpus latifolius	15	13	7	-
Ptaeroxylon obliquum	41	17	-	-
Scolopia mundii	33	-	23	5
Scutia myrtina	-	22	-	-
Searsia pyroides	-	-	-	5
Trimeria grandifolia	12	-	-	-

Table 13: Mature forest communities at New Forest showing species with IVs >18 from at least one community.

Species (* indicates regenerating canopy species)	Steep Riparian community		Slope community		Flood plain community	
	Upper canopy (≥ 15 cm DBH)	Sub-canopy (5-15 cm DBH)	Upper canopy (≥ 15 cm DBH)	Sub-canopy (5-15 cm DBH)	Upper canopy (≥ 15 cm DBH)	Sub-canopy (5-15 cm DBH)
Calpurnia aurea	-	-	-	-	-	27
Canthium obovatum	-	-	-	-	-	24
Canthium ciliatum	-	-	-	-	-	24
Carissa bispinosa	-	29	-	37	-	-
Celtis africana	29	26*	39			18*
Clausena anisata	-	-	26	19	26	39
Chionanthus foveolatus	29	-	25	-	-	-
Combretum edwardii	24	-	-	20	-	-
Diospyros whyteana	-	27	-	46		53
Dombeya tiliacea	-	-	-	-	-	20
Eugenia zuluensis	-	25	-	41	-	-
Euclea natalensis	-	-	-	-	38	36
Gymnosporia harveyana	40	57	-	34		29
Gymnosporia buxifolia	-	-	-	-	26	24
Halleria lucida	26	57	-	-	-	-
Kiggelaria africana	-	-	21	-	38	-
Maytenus albata	-	-	-	-	24	20
Maytenus peduncularis	42	-	25	-	-	-
Podocarpus latifolius	39	-	-	19	-	18*
Ptaeroxylon obliquum	30	-	41	31*	48	-
Rapanea melanophloeos	-	-	-	-	-	-
Scolopia mundii	39	29*	41	-	-	-
Scutia myrtina	-	-	-	19	-	-
Trimeria grandifolia	-	24	-	31	-	-

Table 14: Ecological roles of key regenerating species at New Forest

Species	Species groups*					
	Upper Canopy	Forest sub-canopy	Forest understory	Forest edge or Re-growth forest	Re-growth Canopy	Liana
Buddleja auriculata	-	-	-	x	x	-
Canthium ciliatum	-	-	x	x	-	-
Carissa bispinosa	-	-	x	x	-	-
Celtis africana	x	-	-	-	x	-
Clausena anisata	-	x	-	x	x	-
Diospyros whyteana	-	x	x	-	-	-
Dombeya tiliacea	-	-	-	-	x	-
Dovyalis rhamnoides	-	-	x	-	-	-
Eugenia zuluensis	-	x	x	-	-	-
Grewia occidentalis	-	-	x	x	-	x
Gymnosporia harveyana	-	x	x	x	x	-
Gymnosporia buxifolia	-	x	-	x	x	-
Halleria lucida	x	x	-	x	x	-
Leucosidea sericea	-	-	-	x	x	-
Podocarpus latifolius	x	-	-	-	-	-
Ptaeroxylon obliquum	x	-	-	-	x	-
Scolopia mundii	x	-	-	-	x	-
Scutia myrtina	-	-	x	x	-	x
Searsia dentata	-	-	-	x	x	-
Searsia pyroides	-	-	-	x	x	-
Strophanthus speciosa	-	-	-	-	-	x
Trimeria grandifolia	-	x	-	-	x	-

* Species groups: Upper Canopy - Species forming part of the closed upper canopy of climax forest; Forest sub-canopy – Species growing above the understory layer in tall climax forest but do not form part of the upper canopy; Forest understory - Low growing shade-tolerant woody species; Forest edge or Re-growth forest – Small -demanding, fast-growing, disturbance-driven species; Re-growth canopy - Fast-growing pioneer canopy species; Liana - Understory shrub when small and large creeper when older, which uses surrounding species as support to grow.

Table 15: IndVal scores for significant species in regeneration communities at New Forest

Species	Community	indval	P=value	Relative Frequency
Diospyros whyteana	1	0.78	≤0.001	24
Strophanthus speciosus	1	0.69	≤0.001	9
Eugenia zuluensis	1	0.69	≤0.001	13
Dovyalis rhamnoides	1	0.68	≤0.001	10
Clausena anisata	1	0.62	≤0.004	28
Scutia myrtina	1	0.62	≤0.001	8
Calpurnia aurea	1	0.58	≤0.004	28
Dombeya tiliacea	1	0.52	≤0.002	14
Gymnosporia harveyana	1	0.51	≤0.011	31
Allophylus dregeana	1	0.46	≤0.005	6
Apodytes dimidiata	1	0.38	≤0.012	5
Scolopia zeyheri	2	0.69	≤0.001	12
Carissa bispinosa	2	0.54	≤0.003	23
Buddleja auriculata	2	0.49	≤0.005	21
Scolopia mundii	2	0.47	≤0.004	31
Grewia occidentalis	2	0.46	≤0.006	32
Lauridia tetragona	2	0.43	≤0.009	8
Euclea natalensis	3	0.53	≤0.019	32
Canthium ciliatum	3	0.49	≤0.01	40
Searsia pyroides	3	0.41	≤0.026	25
Halleria lucida	4	0.44	≤0.012	23

Table 16*:* IVs for species in regeneration communities, showing species with IVs >20 from at least one species in each community.

Species (* indicates small understory specialist shrub, # indicates liana, x= present in community but no IV)	**Regeneration Community's**				
	R1 Mature Forest	**R2 Mature Re-growth forest**	**R3 Young Re-growth**	**R4 Pioneer – stands**	**R5 Young pioneer**
Buddleja auriculata	-	53.08	36.30	17.98	-
Buddleja sericea	-	31.58	16.54	12.97	-
Canthium ciliatum	48.63	52.90	57.65	21.16	-
Carissa bi-spinosa	50.77	54.83	15.88	-	-
Celtis africana	45.03	44.48	42.57	31.99	-
Clausena anisata	49.74	53.25	29.00	4.21	-
Diospyros whyteana	51.11	50.97	12.68	8.47	-
Dombeya tiliacea	29.37	10.09	12.66	-	-
Dovyalis rhamnoides	33.65	-	3.15	-	-
Euclea natalensis	25.87	31.67	53.24	16.95	x
Eugenia zuluensis	43.50	20.88	-	-	-
Grewia occidentalis	45.97	56.24	37.93	12.88	-
Gymnosporia buxifolia	3.64	20.26	39.08	21.63	-
Gymnosporia harveyana	53.08	45.18	35.25	12.64	-
Halleria lucida	-	40.97	25.92	44.73	x
Kiggelaria africana	7.21	20.35	15.92	17.14	-
Lauridia tetragona	10.95	31.05	6.41	-	-
Pittosporum viridifolium	-	20.26	15.81	8.57	-
*Podocarpus latifolius **	7.21	10.09	13.03	8.47	-
Ptaeroxylon obliquum	10.91	21.23	32.81	17.33	-
Putterlickia verrucosa	22.00	10.53	3.26	-	-
Rapanea melanophloeos	7.24	20.26	16.13	-	-
Scolopia mundii	33.18	52.46	45.06	12.83	-
Scolopia zeyheri	3.64	51.67	16.18	4.26	-
Scutia myrtina	49.27	41.23	28.79	8.43	-
Searsia dentata	-	-	26.08	21.73	x
Searsia pyroides	3.71	20.70	48.55	26.65	x
Strophanthus speciosus	33.58	-	-	-	-
Trimeria grandifolia	15.29	40.97	39.15	17.00	-