PROCESS AND MODELLING STUDIES IN FOREST HYDROLOGY

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DECLARATION

I wish to certify that the work reported in this dissertation is my own original and unaided work except where specific acknowledgement has been made.

Signed: . . . .

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ABSTRACT

The demand for timber products in South Africa, and consequently afforestation, is increasing. There exists, however, abundant experimental evidence that trees utilise more soil water than other dryland crops. Because water is limited in South Africa, decision makers therefore currently face the challenge of determining a socially and economically acceptable afforestation management plan to enable the reconciliation of increased timber demand with scarce water supply. This challenge, and the subsequent decisions that need to be made, may be accomplished by making use of suitable simulation models to predict the impacts of the forest hydrological system on water resources. Currently, these impacts are assessed through an Afforestation Permit System (APS) which is based on a model now acknowledged to have become outdated. In this dissertation an enhanced *ACRU* Forest Decision Support System (FDSS), now called the *ACRU* Forest model, is developed and proposed as a tool for modelling forest hydrological impacts on water resources.

Research for this study included a literature survey, fieldwork at two locations, *viz.* at forest irrigation trials at Mkuze in northern KwaZulu-Natal, and at forest site preparation trials near Ugie in the Eastern Cape, as well as the evaluation, for purposes of model development, of a series of workshops. Results from the fieldwork experiments show that large tree water use potentials are possible if water is not limiting, although a water supply threshold exists at about 1400mm.annum^{-1}, above which diminishing growth returns occur. Furthermore, trees display improved growth on more intensive forest site preparations, but at the expense of higher water usage rates. A series of workshops which had as the main objective the extraction of expert knowledge by stimulating responses to prepared questions and by constructive discussion on relative issues pertaining to forest hydrological modelling, yielded valuable information. This information, together with that gleaned from the literature, the fieldwork and a new Quaternary catchment database for South Africa, was used to develop the *ACRU* Forest model.

The PC-based *ACRU* Forest model has the potential to aid decision makers by providing an initial indication of the impacts of afforestation on water resources, within a matter of minutes. An example of the model's application is used to demonstrate its operation, relative accuracy and its potential benefits in simulating hydrological responses to afforestation.

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LIST OF ABBREVIATIONS

APS = Afforestation Permit System
ARC = Agricultural Research Council
BD = Bulk Density
CCWR = Computing Centre for Water Research
CR = Count Ratio
CV = Coefficient of Variation
DUL = Drained Upper Limit
EIA = Environmental Impact Assessment
FDSS = Forest Decision Support System
FHIS = Forest Hydrology Information System
HPV = Heat Pulse Velocity
ICFR = Institute for Commercial Forestry Research
I_l = Interception Loss
ISCW = Institute for Soil, Climate and Water
K_{cm} = Crop Coefficient
LAI = Leaf Area Index
LL = Lower Limit of Available Water
MAI = Mean Annual Increment
MAP = Mean Annual Precipitation
MAR = Mean Annual Runoff
NEC = Northeast Cape
NMM = Neutron Moisture Meter
PAW = Plant Available Water
Pg = Gross Precipitation
PWP = Permanent Wilting Point
RDP = Reconstruction and Development Programme
RH = Relative Humidity
SAT = Saturation
TDR = Time Domain Reflectometry
VPD = Vapour Pressure Deficit
WUE = Water Use Efficiency

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1. INTRODUCTION

The South African forest and forest products industry has an important role to play in assisting with the Reconstruction and Development Programme's (RDP) objectives. This is especially true if the target of building 300 000 new houses per annum is to be achieved, because this will increase the demand for sawtimber and composite board products (Forest Owners' Association, 1994). In addition to this, the demand for paper products will increase as a result of an increasing population and the RDP's education programme. An expansion of the forest industry is therefore necessary, but conflicting reports exist as to the required magnitude of expansion.

Wessels (1984) suggested that more than 39 000ha of new afforestation per annum were needed in the 30 years from then, while the forest industry is of the opinion that an increase of at most 500 000ha over the next 30 years will occur (Scotcher, 1995). Besides the large forest companies purchasing more land, since 1983 more than 4 000 farmers in KwaZulu-Natal alone have joined small grower commercial timber schemes that are administered by the major timber growing companies (DWAF, 1995).

The inevitable increase in the forest industry to meet future demands will undoubtedly influence water supplies. Trees have the potential to utilise more soil water than other dryland crops. Water use by exotic tree species planted by the commercial forestry sector, is hence a sensitive issue to environmentalists, since most of the afforested areas in South Africa coincide with agriculturally and economically important catchments (Olbrich, Le Roux, Poulter, Bond and Stock, 1993). Furthermore, forest water uptake patterns are complex and simple assumptions cannot be made about the source of soil water extraction (Thorburn, Hatton and Walker, 1993). Therefore, a fundamental water related issue in South Africa at the present time is the conflict between the need for more commercially produced timber versus the increased water usage by trees. This is a contentious and much debated concern, with arguments both for and against commercial afforestation.

Dye and Olbrich (1992) and Görgens and Lee (1992) suggest that commercial forest plantations should be limited to areas with a minimum Mean Annual Precipitation (MAP) of 800mm. This places a challenge on forest and water managers alike since according to Schulze and George (1987):

a) only 20% of South Africa has an average annual rainfall exceeding 800mm,
b) this rainfall is generally highly seasonal and is
c) largely offset by a potential evaporation of 1400-2700mm.annum^{-1}.

These factors are seen to have exacerbated the considerable competition which already exists in South Africa for the limited resource which water is, since most currently unafforested areas are considered climatically and/or physiographically marginal for afforestation. Most of the viable afforestation areas have already been utilised. Commercial forests in South Africa are situated mainly in Mpumalanga (formerly eastern Transvaal), KwaZulu-Natal (Midlands, northern areas and Zululand coast), the Western Cape and, of late, parts of the Eastern Cape provinces. The largest areas of plantations occur in Mpumalanga (571 000ha) and KwaZulu-Natal (529 000ha) provinces. Of all planted areas in South Africa, 53% are planted to pines, 39% to eucalypts and 8% to wattle (DWAF, 1995), and consequently most forest hydrology research has been accomplished on pines and eucalypts.

To add to the problem, the controversial Afforestation Permit System (APS) which has been used to control new afforestation in South Africa, has lost approval in the forest industry. Researchers in the South African timber and water industries are therefore currently faced with the need to:

a) determine the impacts of afforestation on water supplies, in order to
b) supply an increasing need for timber in a region with a limited supply of water, and
c) find an acceptable alternative to the outdated APS.

Satisfying these criteria requires the prediction of impacts of afforestation on hydrological responses and water resources with suitable modelling systems. In order for models to perform accurately, up-to-date information, derived using state-of-the-art techniques, should be included in the modelling system to be used.

In the development of such a model a series of tasks was undertaken as part of the research reported in this dissertation, the first of which was a literature review (Chapter 2) on tree water use information. The Chapter includes a review of the main factors influencing tree water use as well as methods of measuring tree water use and results depicting how much water trees actually use.

Chapter 3 focuses on the fieldwork component of this research and details the determination of soil moisture trends obtained in the field at two experiment sites, *viz*. the forest irrigation trials at Mkuze in northern KwaZulu-Natal, and the forest site preparation trials near Ugie in the Eastern Cape. The aim of the fieldwork component was to use *in situ* soil moisture observations to determine the relationship between tree water use and:

a) varying degrees of site preparation, as well as
b) varying precipitation regimes as indicated by a range of irrigation schedules.

The primary aim of this dissertation entails an assessment into the regionalisation and characterisation of water use by commercial tree species in order to improve on the existing *ACRU* Forest Decision Support System (FDSS) described by Schulze, Jewitt and Leenhardt (1995). Chapter 4 therefore introduces the concept of modelling and the APS and outlines the revision of the *ACRU* FDSS using information obtained from Chapters 2 and 3, and from a series of workshops. The workshop system was regarded as a "thought experiment", which yielded a wealth of expert knowledge. Values of Leaf Area Index (LAI), interception loss (I_l), root distribution with soil depth and root colonisation have been derived for different afforestation scenarios for use in the FDSS. These results have been used together with a Quaternary catchment database of South Africa (Meier, 1996) to develop the revised FDSS as a stand-alone PC-based forest impact assessment tool called the *ACRU* Forest model. This model is intended to be used by the forest and water research fraternities to obtain objective initial estimates, within a matter of minutes, of the impact of trees on hydrological responses. Chapter 5 presents a case study application of the new *ACRU* Forest model to demonstrate its operation, relative accuracy and its potential benefits in simulating hydrological responses to afforestation.

The methodologies used in this dissertation have been intentionally broad based. The forest hydrological system is a complex one and not enough is known about this system as yet to enable the development of sophisticated models that meticulously account for all the processes involved. The development of the *ACRU* Forest model as an objective and process based forest hydrology impact assessment tool will hopefully aid decision makers in determining a socially and economically acceptable afforestation regime to reconcile timber demand with water supply.

2. WATER USE BY TREES: A LITERATURE REVIEW

Historically, commercial afforestation has attracted negative publicity as a result of the increased impact that forests have on a catchment's water yield. Little doubt exists that commercial forest plantations use more water than vegetation in virgin condition (Versfeld, Van Wilgen, Bosch and Kruger, 1994; Versfeld, 1995). Commercial forest plantations are currently estimated to be reducing the available surface water of South Africa by *ca.* 3.5%, which equates to about 7.6% of the country's total current water demand (DWAF, 1995). Since water use by plantations is a contentious issue, this Chapter aims at placing water use aspects into a perspective. The main factors influencing, and some methods of measurement of water use by trees are reviewed, whereafter some typical values of water use by different genera and species are presented.

2.1 Factors Affecting Water Use by Trees

To enable modelling of water use by trees, factors influencing patterns of tree water use, and the quantities involved, must be characterised. The main factors influencing soil water use by trees include total evaporation, LAI, root distribution and rooting depth, all of which vary with genera and species. Some of the factors discussed here also formed the basis of questions asked at a series of workshops on forest hydrological characteristics, detailed further in Chapter 4. For a general review of the soil-plant-atmosphere system in a forest the reader is referred to Zartmann (1992). In summary, commercial forests in South Africa use more water than natural vegetation and dryland crops as a result of:

a) larger canopy surface areas, resulting in greater interception and hence less water reaching the soil,

b) rooting systems being able to extract water from greater soil depths, and

c) evergreen foliage which can transpire throughout the year, as opposed to grassveld which, over most of the summer rainfall areas of South Africa, scenesces during the dry winter months.

Other factors affecting a catchment's hydrological response to afforestation include:

a) the proportion of the catchment afforested,
b) rotation length, and
c) the catchment's climatic potential, often expressed by its MAP.

2.1.1 Total evaporation

Soil water utilisation by trees is expressed through total evaporation, which depends, *inter alia*, on atmospheric evaporative demand. Total evaporation (formerly termed "actual evapotranspiration") consists of three separate processes, *viz.* canopy interception loss, I_l (the physical process involving evaporation of water from the wet outer surfaces of leaves), transpiration (involving uptake of water by roots and transfer through the leaves) and evaporation from the soil surface (usually of lesser importance in forests owing to litter cover).

Some controversy exists as to which of these processes is dominant in plantations. For example, Honeysett and Beadle (1987) regard canopy I_l as the probable major component of total evaporation, while Roberts, Rosier and Srinivasa Murthy (1992) and Zartmann (1992) maintain transpiration to be the dominant component. Dolman and Nonhebel (1988) suggest that differences in hydrological responses of catchments have been found to be primarily a result of differences in canopy I_l. Honeysett, Beadle and Turnbull (1992) confirm this by advising that canopy I_l is probably the major component of total evaporation. However, Chapman and Malan (1994) conclude that canopy interception is not a dominant process in the water balance under forested canopies. Nevertheless, little doubt exists that tree water use is affected by rapid evaporation of intercepted precipitation from tree canopies.

Transpiration as a physical process is subject to more complex physiological control mechanisms than canopy interception, and according to Calder (1992a) is determined mainly by:

a) climatic demand, related to solar radiation, atmospheric Vapour Pressure Deficit (VPD), temperature and windspeed,
b) canopy structure, particularly LAI,
c) the physiological response mechanisms controlling stomatal apertures in response to environmental conditions, the most important being those mechanisms which close stomata in response to increasing water stress and increasing atmospheric humidity deficits, and
d) the availability of soil water to the roots.

An appreciation of these controlling mechanisms is important to understanding water use by trees (Calder, 1992a). A prerequisite to the development of predictive models of total evaporation is a knowledge of the quantity of soil water available to the trees. It is necessary to be able to predict potential tree water use and the point at which transpiration rates will be reduced as the soil water is depleted (Dye and Poulter, 1992). In order to achieve this, Dye (1994) is researching the relationship between transpiration rate and soil water content for *Eucalyptus grandis*, in which the main aims are to:

a) assess the potential maximum quantity of soil water available to the trees,
b) identify the point at which the transpiration rate starts declining from a potential to a lower actual rate, and
c) establish the manner in which transpiration declines in response to further decreases in soil water, as soil water becomes limiting.

Besides being influenced by evaporative demand and soil water content, total evaporation will also be influenced by the LAI of the trees.

2.1.2 Leaf area indices

LAI has been defined in the literature in several different, and sometimes apparently inconsistent ways. An integrated definition is that it represents the planimetric area of leaves relative to the soil surface area. By implication, LAI is thus also an indication of the biomass produced and hence of the potential water use by the tree/plantation

(Honeysett and Beadle, 1987; Dye, Olbrich and Everson, 1995). LAI is regarded as a critical integrator of water availability and productivity (Gholz, Ewel and Teskey, 1990), and a change in LAI may have marked effects on both, since plants with greater leaf areas (such as trees), generally require more water than those with smaller leaf areas (APPC Working Group, 1995).

LAI is primarily a function of genus, tree age, available water, temperature, soil and management practices and, according to Olbrich, Dye, Christie and Poulter (1992) varies not only between genera and species, but also between clones. Cromer, Tompkins, Barr, Williams and Stewart (1984) report that soil moisture stress is a major factor decreasing LAI. This is backed up by Dye *et al.* (1995) who found that the LAI of *E. grandis* decreased in response to severe droughts, associated with decreased transpiration. Gholz *et al.* (1990) echo these ideas by stating that foliage development is reduced during soil water stress. A link between LAI and tree water use, the latter being expressed as an evaporation loss index, is depicted in results from Leuning, Kriedemann and McMurtrie (1991) in Table 1. These results were simulated using a model developed from Australian fieldwork.

Table 1. An LAI: evaporation loss relationship(after Leuning *et al.*, 1991).

LAI	**Evaporation loss (as a % of annual precipitation)**	**Annual evaporation loss (mm)**
1	5.8	42.8
2	10.0	73.8
3	13.6	100.4

Another factor to be taken into account in modelling is that when the LAI>3, tree water use on a certain day is assumed to have an upper limit (Schulze, 1995a) equivalent to that day's maximum evaporation, formerly termed "potential evapotranspiration". Leuning *et al.* (1991) suggest that this limit is a function of the initial Plant Available Water (PAW) content of the day. In their experiments, transpiration soon became limited at PAWs of 200mm, especially for LAIs of 2-3, while values of LAI>3 did not increase transpiration rates because no additional soil water became available to the plant. At PAWs of 800mm, sustained transpiration occurred for longer, at higher levels. Transpiration still displayed an upper limit at LAI=3, while transpiration at LAIs of 1-2 continued, but at a decreasing rate.

Root distribution and rooting depth are important factors in soil water modelling since they determine from where within the soil profile, and in what quantities, the tree obtains its soil water. These factors are discussed in Section 2.1.3 below.

2.1.3 Root distribution and rooting depth

A major problem in forest hydrology modelling remains in that information on rooting patterns, distributions and depths, and the influence of roots on tree water use patterns has generally been poorly researched (Jewitt, 1991). This paucity of information derives from the difficulties involved in characterising the spatial extent of roots and measuring soil water uptake in deep soil horizons (Eastham, Rose, Cameron, Rance, Talsma and Charles-Edwards, 1990). Rooting information is restrained further by the time and effort required in performing root studies being outweighed by the relative ease of obtaining other information that may be as relevant to the researcher. Ong and Khan (1993) indicate that when measurements of root structure, density and water content are made, they must be related to water use by the tree, otherwise they are meaningless.

Nevertheless, for modelling purposes it remains essential to determine where the roots occur in the soil profile and even more importantly, which of these roots have access to and are using the available soil moisture. Thorburn *et al.* (1993) highlight the need for this information by stating that even if roots occur near the groundwater table, they may not be able to extract that water if the root-zone conditions are unfavourable. Roots tend to "search" for water (Schulze *et al.*, 1995), and it is the fine roots (as opposed to tap roots) that extract most of the soil moisture (*ACRU* FDSS Workshop No3, 1995). Therefore, in areas where large amounts of water enter the soil from the surface, one can expect roots to occur mainly in the surface horizons, especially if deeper soil layers are impermeable. In the latter regard, however, Nänni (1971) mentions that in shallow soil it is possible for bedrock to be semi-weathered and permeable to roots, as in the Mokobulaan catchments in Mpumalanga.

In forest hydrology, much importance is placed on the roots in the topsoil horizon (usually to *ca.* 300mm depth) since this is where most of the water-using roots occur. However, Eastham *et al.* (1990) argue that the rate of water uptake per unit root length is lowest in the surface soil horizons and that water uptake per unit root length tends to increase with increasing soil depth. Also, the rate of water uptake per unit root length tends to increase with time in deeper, wetter soil horizons and decrease with time in surface soil horizons as soil water content decreases.

Dye and Poulter (1992) sunk boreholes in the Mokobulaan catchments to determine that moist material occurs to depths of 45m, and suggest that this soil water may be an important source of water to *Eucalyptus* trees during dry periods, providing that roots are deep enough to extract the water. Studies in India confirm that tree roots "mine" for water (Calder, Swaminath, Kariyappa, Srinivasalu, Srinivasa Murthy and Mumtaz, 1992a). If soil water is not limiting, roots may not have to "mine" for water. This is the case at Mkuze in northern KwaZulu-Natal where, as a result of irrigation, roots colonise in the top 1m of the soil profile (Zartmann, 1992). Tree roots have no difficulty in penetrating to below 5m given a suitable soil environment (Boden, 1991a), although *Pinus patula* is generally considered to extract water only to 5m, even if soils are 20m deep (Dye, 1994). Dye (1993a) supports the possibility of deep rooting depths by suggesting that nine year old unstressed, normally growing *E. grandis* trees are able to obtain almost their entire water requirements from depths below 8m. Dye (1993a) also found roots at depths of 28m under three year old *E. grandis* trees.

Soil water extraction patterns generally mirror respective root systems (Boden, 1991a), and consequently root systems may help to explain trends in soil water regimes. For example, on a site preparation experiment at Glendale in KwaZulu-Natal, roots on a pitted plot were not able to extract water from as deep as from ploughed and ripped plots. Also, sparse root systems on the pitted plot were not able to make any impact on the soil water closest to the tree while soil water nearest the tree on the ripped and ploughed sites was depleted (Boden, 1991a). Carbon, Roberts, Farrington and Beresford (1982) used the Neutron Moisture Meter (NMM) technique (*cf.* Section 2.2.2) to study comparative water use by *P. pinaster* plantations and annual and perennial pastures in Western Australia. The *P. pinaster* trees use the most water as a result of a relatively deeper rooting depth of 10m, followed by the annual pasture and natural forest with similar water uses, followed by the perennial pasture with the lowest water use (roots <1m). Water tables are 15-20m deep at the study area, which suggests that this water is unavailable to the trees.

Water uptake by individual roots of a five year old *Croton melagocarpus* tree measured using a technique similar to the sap flow technique (*cf.* Section 2.2.4) is detailed by Ong and Khan (1993). They found maximum flow rates to vary between 400-500g.h^{-1} to 1000-1500g.h^{-1} during the day, but by nightfall, rates reached only 20g.h^{-1}. This suggests that water uptake by the roots matches the daytime demand for water by the canopy, implying that once the demand has been reduced, the tree will use water at a lower rate or wilt.

Ultimately, information on the water use patterns of different tree species is needed, and not just the differences with respect to genera. The current state of knowledge of water use by different genera and species is summarised in Section 2.1.4 below.

2.1.4 Genera and species

E. grandis and *P. patula* account for 52% of all commercial plantations in South Africa (APPC Working Group, 1995). Hence most forest hydrological experimentation has been completed on sites planted to these two species. Water use by *Acacia mearnsii* has not been quantified with any certainty (Versfeld *et al.*, 1994). Also, there have been no catchment based studies of water use by poplar trees in South Africa, although provisional guidelines for estimating the water use by poplars have been provided by Scott and Le Maitre (1994).

Pereira, Tenhunen, Lange, Beyschlag, Meyer, and David (1986) confirm that different eucalypts have different stomatal response mechanisms and that rooting patterns can vary between species, causing water use and Water Use Efficiency (WUE) to vary (*cf.* Section 2.2.1). Despite this, inadequate information is available on total evaporation rates under different species. Therefore, it is often assumed that total evaporation rates from vegetation with similar heights are broadly similar (Calder, 1992a). Olbrich *et al.* (1993) conclude from fieldwork that inter-clonal differences with respect to growth and tree water use are not significant, despite the occurrence of mean differences of up to 100%. They found differences in the clonal mean WUE to also be very marked, resulting in 86% more stem-wood produced in the most efficient of the clones they assessed, per volume of water consumed. Greenwood and Beresford (1979) used a ventilated chamber technique to show that at different sites, the same species displayed higher water use rates. This suggests that particular species have affinities for certain site conditions.

Dye, MacDevette and Olbrich (1994) analysed sap flow and growth data from the irrigation trial at Mkuze, with the aim of identifying water use efficient clones. Of all clones in the study, TAG5 clones generally had the highest WUE and GT529 the lowest, as depicted in Figure 1. This results from different water usages of 2768ℓ (49ℓ.tree^{-1}.d^{-1}) and 1280ℓ (22ℓ.tree^{-1}.d^{-1}) by the GT529 and TAG5 clones respectively, since their mean volumetric growth increments were found to be the same. There is evidence that under water limiting conditions an overall better performance of clones with *E. camaldulensis* in their genetic background exists, and that TAG5 clones do not perform well in drought conditions. The main conclusions from the study by Dye *et al.* (1994) are that:

a) large differences in mean WUE exist among clones, and
b) large variations in WUE exist between replicates of the same clones, caused mainly by volume increments, not correlated to tree size.

Intensive plantation management should include the selection of species and silvicultural practices which increase the WUE of trees. Growth rates and water use by trees may be enhanced by selecting improved genotypes and by improving plantation management. In particular, the improvement of soil water conservation through ripping (where appropriate), weed control and mulching are recommended (Dye, 1993b).

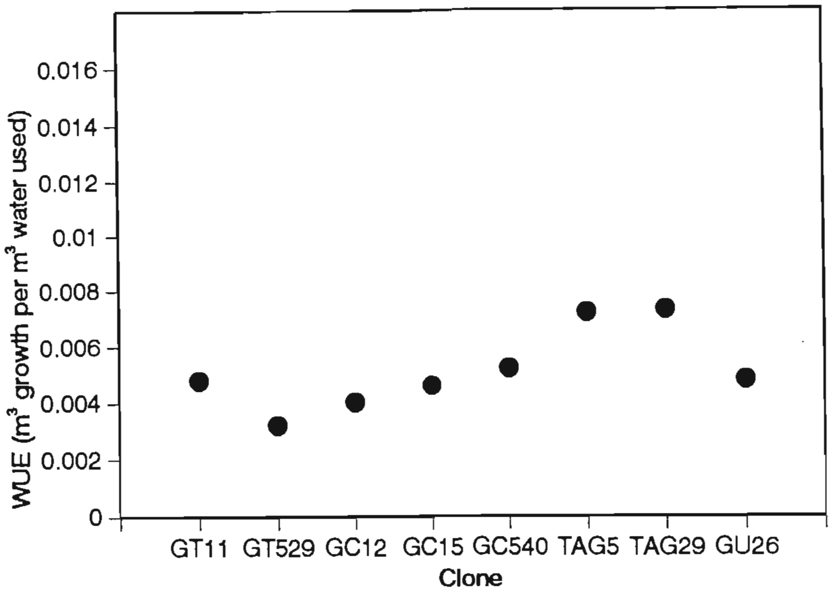

Figure 1. WUE of different clones recorded between 1 December 1993 and 26 January 1994 for all the sample trees at Mkuze in northern KwaZulu-Natal (after Dye *et al.*, 1994).

In order to characterise the factors affecting tree water use, it is necessary to make use of one or more methods of water use measurement. These methods are detailed in Section 2.2 below.

2.2 Methods of Measuring Water Use by Trees

The dilemma of not being able to characterise tree water use accurately is mainly a result of the difficulties involved in measuring complex natural processes with indirect methods. However, the emphasis is moving away from the conventional methods of solving the hydrological water balance, *viz.* by soil water content determination and water budgeting, toward "direct" methods of determining transpiration from the tree. Greenwood (1992) implies that a direct measurement of water use by trees is necessary since previous methods used to estimate tree water use are both impracticable and inaccurate. One of the more common methods of determining utilisation of water by trees, is by direct measurement of changes in water table heights in comparison to total evaporation rates (Thorburn *et al.*, 1993). Nevertheless, as a result of the difficulties of measuring soil water content at depth using direct methods, Dye and Poulter (1992) suggest that studies to predict water use by trees be conducted by comparing transpiration to soil water uptake from the soil profile. Water use by trees has been traditionally determined by utilising one or more of the following techniques which are discussed in detail later in this Section, *viz.* by:

a) measuring soil moisture content, for example by NMM or Time Domain Reflectometry (TDR),
b) making use of total evaporation or techniques providing an indication of total evaporation, for example the Heat Pulse Velocity (HPV) and tracing methods, or
c) measuring streamflows (*i.e.* the paired catchment approach).

Different tree water use measurement methods operate at different, but complementary, space and time scales (Calder, Hall and Prasanna, 1993). This enables a wider understanding of the water use control mechanisms (Roberts *et al.*, 1992). The different scales include, *inter alia*:

a) physiological methods at the leaf and shoot scale: accurate over minutes to hours,
b) tracing studies at the individual tree scale: accurate over days, and
c) the NMM at the plot scale: accurate over weeks.

Depending on the method used for the determination of soil water content, it is often necessary to calibrate results against gravimetrically obtained volumetric water contents and water retention characteristics. The main disadvantage of the gravimetric method is the time required, and the inconvenience of collecting and analysing soil samples. Other less restraining techniques have therefore been developed (Dye and Poulter, 1992).

In some circumstances it is necessary to provide a measure of water use per volume of timber produced, and hence the need to differentiate between tree water use and WUE, as explained in Section 2.2.1 below.

2.2.1 Water use and water use efficiency

WUE is a measure relating biomass production to the consumptive use of water (Olbrich *et al.*, 1993). WUE has also been defined as the ratio of net photosynthetic rate to transpiration rate (Calder, 1992b) and is influenced by the variables outlined in Section 2.1. WUE may be based on stemwood production and not necessarily on whole plant production (Olbrich *et al.*, 1993). WUE may therefore change markedly for the same total biomass as a result of a change in the ratio between canopy biomass and stemwood biomass. Although the definition of WUE implies that the objective on any commercial plantation should be to achieve the most growth for the least amount of water used by the tree, water use may be maximised intentionally as in effluent-irrigated plantations (Myers and Talsma, 1992).

Pereira *et al.* (1986) detail the study of WUE of *E. globulus* trees in Portugal and found that under drought conditions, WUE is highest in spring, less in winter and is lowest in summer. Also, maximum transpiration occurs at maximum VPD in winter, but before maximum VPD in summer. From these results it can be concluded that *E. globulus* trees are effective in controlling water loss when evaporative demand is high.

Olbrich *et al.* (1993) used $\delta^{13}C$ levels in leaves to determine the WUE of four year old *E. grandis* clones representing poor to good growth at the Frankfort State Forest in Mpumalanga. Growth during the first half of the study period (December/January) was less than that during the second half (January/February) during which peak growth rates were experienced, coinciding with peaks in transpiration, VPD, radiation and temperature. As the relatively drier winter approached (*i.e.* as water became limiting), an increase in WUE was apparent. It appears that growth is influenced strongly by climatic variation and not by season alone. These results indicate that two factors influence WUE, *viz.*

a) during the wet season, conservation of water is not a priority, and high WUEs are therefore only achieved during periods of rapid growth, and

b) once the dry season approaches, conservation of water becomes important and the tree reduces transpiration, but still produces stemwood, resulting in a higher WUE.

No exact values are available for South Africa of how much water is required for the production of a unit quantity of wood (Olbrich *et al.*, 1993). Therefore, Olbrich *et al.* (1993) propose WUE as a future basis to help resolve issues regarding the allocation of limited resources. WUE may be improved through correct species selection, the removal of nutrient and water stress and improved silviculture (Calder *et al.*, 1993). It is therefore important to conduct research into tree water use and growth of commercial tree species.

One of the most widely used methods of measuring tree water use is the NMM technique, as reviewed in Section 2.2.2 below.

2.2.2 Neutron moisture meter

In the forest industry alone, about 500 000 NMM readings are taken in South Africa annually (Schulze, 1995a). This illustrates that the NMM technique has become an accepted technique of measuring soil water content, and thus indirectly, tree water use in South Africa. Hensley (1994) suggests that rooting patterns may be determined from moisture patterns using the NMM technique, since root studies are not viable. The main advantage of the NMM technique is that numerous readings can be taken in a relatively short time period.

When fast neutrons are introduced into the soil from a probe containing a radioactive source, the neutrons are slowed by collisions with the nuclei of hydrogen atoms (Gardner, 1987). Hence, slowed neutrons are a function of the soil water content. The NMM technique uses this neutron emission principle and a slow neutron counter to measure neutrons that are reflected. The probe is lowered to pre-determined depths in the ground via aluminium, steel or plastic tubing. Aluminium is usually used because it is more transparent to neutrons than steel and plastic tubing (Hauser, 1984). Plastic tubes have also been used, since they are considerably cheaper. The use of different tubing however, causes a problem, since the type of tubing used has a marked effect on the accuracy of the meter. Higher count rates are obtained in aluminium tubes than in plastic tubes (Hanson and Dickey, 1993). There are, however, some other disadvantages and points that a prospective user of the NMM technique must be aware of.

Precise soil moisture measurement requires the determination of a calibration equation which enables the conversion of the count ratio to volumetric soil moisture content. Soils of varying physical, biological and chemical characteristics require different calibration curves to take into account factors such as different bulk densities, neutron absorbing elements and soil texture. The standard procedure for calibration is the gravimetric method whereby the difference between the weight of a sample before and after oven drying, together with bulk density data are used to determine the soil moisture content.

The notion that absolute values of soil moisture can be determined using the NMM technique must be treated with great caution, owing to the effects of soil heterogeneity, hydrogen occurring in forms other than free water and poor depth resolution of the instrument. Schudel (1983) cites a mean deviation of 25% between soil moisture measurements made using a NMM and a lysimeter. This deviation may be as a result of different bulk densities, the chemical composition of the soil, soil texture, spatial heterogeneity of the soil, instrument sensitivities, the sphere of influence of the probe and cropping practices (Everett, 1988). These effects are explained as follows:

a) NMM counting rates increase with increasing bulk density, despite soil moisture by volume remaining constant (Lal, 1974),

b) bulk density may be affected by materials containing large quantities of hydrogen in forms other than free water, which would be registered by the NMM,

c) sometimes bound water may not be driven off by oven drying and will cause a parallel shift of the calibration curve (Hauser, 1984),

d) coarse textured soils have greater calibration curve slopes compared with those of finer textured soils (Lal, 1974), and

e) sensitivity of the instrument will cause deviations. Field observations have indicated that using the same NMM instrument and field conditions for two readings in succession will not necessarily yield the same count ratio.

The paired catchment technique is widely used in South Africa to determine water use by trees, by assessing streamflow reductions caused by the landuse change. This technique is briefly mentioned in Section 2.2.3 below.

2.2.3 Paired catchments

The first paired catchment experiment was in 1909 at Wagon Wheel Gap in Colarado, USA, and has since been widely used as a method for the determination of the effects of forest management practices on water yield (Bosch and Hewlett, 1982). The method is most commonly used in South Africa by the CSIR (Forestek) on catchments at Jonkershoek in the Western Cape, Cathedral Peak in KwaZulu-Natal and at Westfalia and Mokobulaan in Mpumalanga. The method is suitable for time scales of greater than a year.

The paired catchment approach requires two catchments (one control and the other treated) and two time periods (calibration and treated), the calibration period being prior to the landuse change and the treated period after. During the calibration period, the relationship is determined between (say) monthly streamflow totals from the treated and control catchments using regression analysis. Any "after treatment" effect is illustrated by deviations in streamflow between the expected flow based on the calibration relationship estimates and the observed flow. The paired catchment technique is based on the assumption that the relationship between streamflows of physiographically similar catchments will remain the same, should the vegetation of these catchments either remain the same or change concurrently in a similar manner (Smith, 1991a).

Like the paired catchment approach (*cf.* Section 2.3.3 for a summary of results obtained with the technique), the HPV technique is widely used in South Africa, and is detailed in Section 2.2.4 below.

2.2.4 Heat pulse velocity technique

The HPV technique makes use of a heat pulse as a tracer to determine sap flow in plants and trees, calculated from the convection flux, which may then be related to water use by trees (Thorburn *et al.*, 1993). Dye and Olbrich (1992) and Olbrich (1991) describe the HPV method in which three aligned holes are drilled at three measurement positions in the tree, as depicted in Figure 2. A heater probe is placed in the centre hole and temperature sensing probes are placed in holes 10 and 5mm above and below the heater respectively.

Each probe contains one or two thermistors providing point measurements of temperature after a short heating time of less than a second. The thermistor is placed near the outside of the tree where sap flux is greater and measurement is representative of a larger proportion of the sapwood area (Thorburn *et al.*, 1993). It is important to replicate the samples on different trees since the distance between the heartwood and the sapwood is not even on any one tree (Jayasuriya, Dunn, Benyon and O'Shaughnessy, 1993). Once the equipment is set up, the sap flux is determined by calculating the HPV using Equation 1. A correction for the wound is then applied according to Equation 2. Correction coefficients are appropriate for the measured wound size, the diameter of the probes (1.75mm) and probe separation distances. The corrected HPV is then converted to a sap flux using Equation 3 (Marshall, 1958). Sap flux is then scaled from the individual tree to plantation size by summing the sap fluxes for each tree and expressing the total sap flux on a per unit plot area basis.

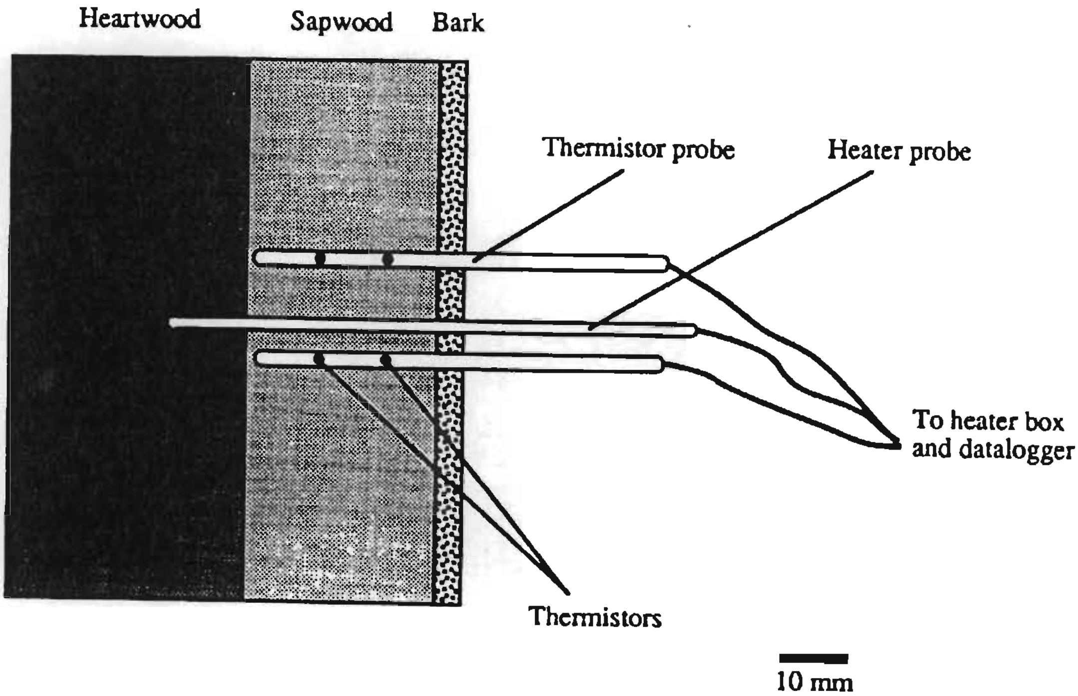

Figure 2. The deployment of heat pulse probes in a tree (after Jayasuriya *et al.*, 1993).

The HPV is calculated using

$$\mathbf{u} = \frac{(\mathbf{X_u}+\mathbf{X_d})}{\mathbf{2t}} \qquad .....(1)$$

where:
u = HPV ($m.s^{-1}$),
X_u = distance upstream from heater (m),
X_d = distance downstream from heater (m), and
t = time delay (s) for temperatures at X_u and X_d to become equal.

The wound correction equation is

$$\mathbf{u' = p+qu+ru^2} \qquad .....(2)$$

where:
u' = corrected HPV ($m.s^{-1}$), and
p, q, r = correction coefficients.

The HPV conversion to sap flux is given as

$$\mathbf{v = \rho_b(M_c+C_{dw})u'} \qquad .....(3)$$

where:
v = sap flux ($kg.m^{-2}.s^{-1}$),
ρ_b = dry wood density ($kg.m^{-3}$),
M_c = moisture fraction of the sapwood, and
C_{dw} = specific heat of dry wood, assumed constant at 0.33.

Hatton and Vertessy (1990) compared plantation transpiration rates using the HPV and Bowen ratio methods on a *P. radiata* plantation. In this experiment, the HPV method over-estimated transpiration by 20-30%, this factor possibly being attributable to the variability in the mean tree flux in this plantation and/or the HPV technique itself. Thorburn *et al.* (1993) therefore used another method in which the weighted average approach of Hatton and Vertessy (1990) was used to integrate the sap velocity in the sapwood. HPV sap flow estimation has been found to be highly sensitive to errors in wound size measurement and probe separation distances (Dye and Olbrich, 1992).

Jayasuriya *et al.* (1993) suggest that in forests in complex topography with trees reaching heights of up to 80m and where roots occur to a depth of 10m and more, the only feasible technique for the determination of tree water use is that of sap flow measurement. The sap flow technique should, however, be used in conjunction with the NMM (Ong and Khan, 1993). Dye *et al.* (1995), however suggest that using the NMM technique to verify sap flow results may be of limited use if the entire rooting zone is not sampled.

The HPV technique provides accurate estimates of single tree sap flux in *Eucalyptus* trees when compared to direct measurements of water uptake (Olbrich, 1991) and tracing sap movement with enriched deuterium (Dye, Olbrich and Calder, 1992). Dye and Olbrich (1992) show that the HPV technique is suitable for the study of sap flow in *E. grandis* by comparing tree water use measurements obtained using the HPV method to those obtained using the cut tree method. The cut tree method involves severing a tree at its base, placing the tree in a bucket of water, and measuring the water uptake rates directly. Measurements compared well for three year old trees, and for 16 year old trees the cumulative uptake from the bucket was 238.8ℓ compared to 266.5ℓ for the HPV, a difference of only 11.6% (Figure 3). Smith, Moses and Versfeld (1992) cite a marginal 2.2% difference in tree water use in wattle calculated using the HPV and cut tree methods.

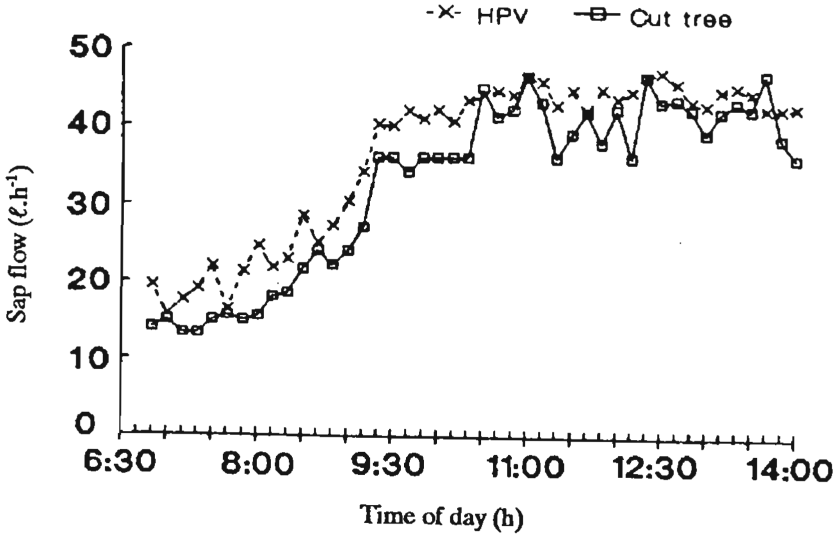

Figure 3. Comparison of HPV and cut tree estimates of sap flow on a 16 year old *E. grandis* tree (after Dye and Olbrich, 1992).

Sap flow work on single trees has been criticised mainly because the method involves too many assumptions (*ACRU* FDSS Workshop No3, 1995). However, Dye and Olbrich (1992) list some advantages of the sap flow technique, *viz.*

a) minimal disturbance to the tree,
b) relative reliability and low cost,
c) good time resolution of sap flow,
d) amenability to automatic data collection and storage,
e) access to the canopy is not necessary, and
f) the apparatus is portable and therefore estimates for the whole plantation are possible.

Dye *et al.* (1995) depict a relationship between VPD and sap flow (Figure 4) for *E. grandis*. This relationship holds potential for forest hydrology modelling since water use by trees could then be related to easily measurable climatic variables such as temperature and Relative Humidity (RH), from which VPD estimates can be derived.

As indicated in this Section, the sap flow technique provides reasonably accurate single tree water use measurements. A similar method involves the tracing of the sap flow in trees, as detailed in Section 2.2.5 below.

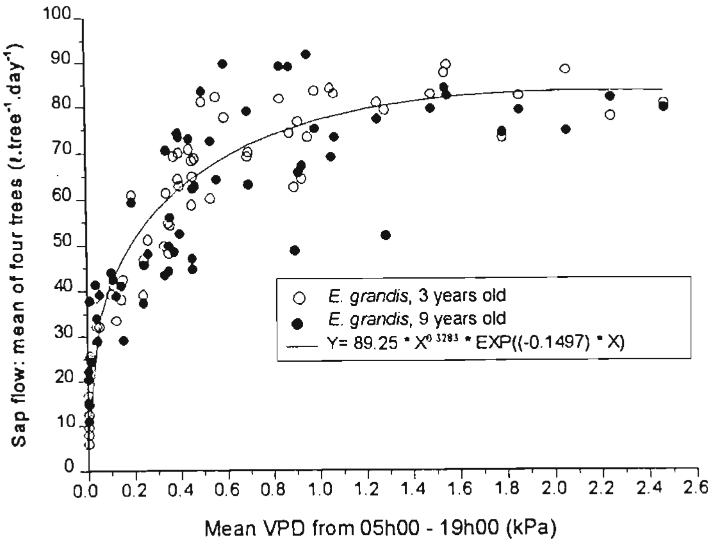

Figure 4. The relationship between mean daytime VPD and daily sap flow in three and nine year old *E. grandis* stands in the Sabie area in Mpumalanga (after Dye *et al.*, 1995).

2.2.5 Tracing methods

The stable isotopes of deuterium (^2H) and oxygen-18 (^{18}O) have been used as tracers to indicate soil- and groundwater usage by trees by several authors, including Calder, Hall and Adlard (1992b) and Thorburn *et al.* (1993). The use of stable isotopes of carbon (^{13}C and ^{12}C) and nitrogen to differentiate between root biomasses of species has also been used, but is a more costly approach than sap flow techniques (Ong and Khan, 1993).

The main advantage of tracing methods is that the tree water source may be determined by comparing concentrations of stable isotopes in tree twigs with those from soil profiles and from groundwater (Thorburn *et al.*, 1993). Another advantage is that clones with high WUEs can be identified at an early age without having to wait for sizeable trees to make costly direct measurements (Vogel and Dye, 1994). Calder (1992b) suggests that the advantages of deuterium tracing are that the method:

a) gives correct transpiration estimates in situations where trees are abstracting directly from the groundwater table, unlike soil water depletion methods,

b) does not require flat topography as ideally needed by some micrometeorological methods,
c) provides an estimate of water use for a single tree, and
d) is considered "absolute" provided that complete mixing occurs before the flow splits to separate branches and that all the tracer moves through the tree during the experiment.

Tracing methods involve injecting a known concentration of tracer into holes drilled in the tree trunk or in the roots (Figure 5). However, if assumptions are to be made about the point in the soil profile from which water is drawn by the roots, then the tracer should be injected into the soil surrounding the roots. The tracer concentration is compared either to the concentration in dried, ground and combusted representative leaf sample analysed by mass spectometry according to Olbrich *et al.* (1993), or to samples of transpired water obtained by attaching bags around the leaves (Calder, 1992b). Aspect and branch length influence carbon isotope ratios in leaves, therefore standardised sampling positions are needed (Dye *et al.*, 1994). The main assumption is that if the isotopic composition of the injected water taken up by the roots is the same as that in the leaves, then the water is from the point it was injected in. Deuterium tracing is based on the "total counts" method using Equation 4 (Calder *et al.*, 1992a). For operational use the equation is adapted to the finite difference form as in Equation 5.

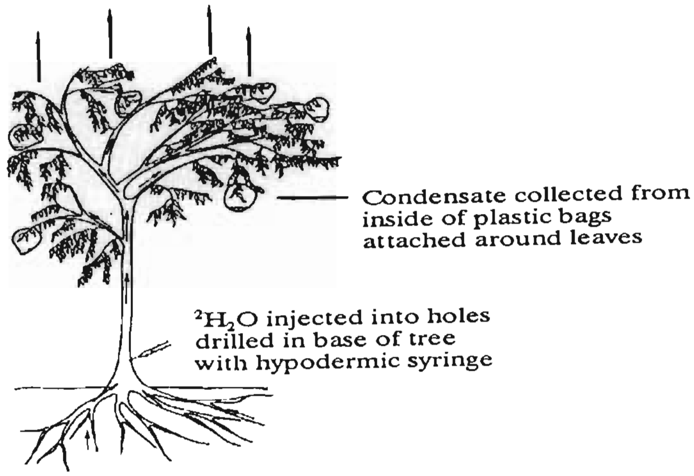

Figure 5. Schematic of the deuterium tracer method for measuring transpiration rates of a tree (after Calder, 1992b).

The total counts method is depicted as

$$\mathbf{m} = \mathbf{F} \int_0^\infty \mathbf{C}\ \mathbf{dt} \qquad .....(4)$$

where:
m = total mass of tracer (g),
F = flow rate ($m^3.d^{-1}$),
C = tracer concentration ($kg.m^{-3}$), and
t = time (s).

In finite difference form

$$\mathbf{F} = \frac{\mathbf{m}}{\sum_{i=1}^{i=T} \mathbf{C}_i\ \Delta \mathbf{t}_i} \qquad .....(5)$$

where:
T = last time increment in which the tracer is present,
C_i = concentration in the i^{th} time increment ($kg.m^{-3}$), and
Δt_i = duration of the i^{th} time increment (d^{-1}).

The $^{13}C/^{12}C$ ratio ($\delta^{13}C$) in plants differs from that of carbon in atmospheric carbon dioxide which plants absorb during photosynthesis. The degree to which this isotope fractionation takes place is determined by the resistance the CO_2 experiences while diffusing through the stomata of leaves. If the photosynthetic process is efficient, the plant will keep the opening of its stomata small, thereby minimising the amount of water lost to total evaporation (Vogel and Dye, 1994). Trees with the lower WUEs should have relatively less ^{13}C, *i.e.* have significantly more negative $\delta^{13}C$ values (Olbrich *et al.*, 1993). Conversely, trees with higher WUEs should have a relatively large ^{13}C, *i.e.* less negative $\delta^{13}C$. For C3 plants a $\delta^{13}C$ value of between -25.22 and -29.66‰ is typical (O'Leary, 1981).

Vogel and Dye (1994) compare results obtained using the carbon isotope ratio of sapwood from eight different *Eucalyptus* clones to a direct measurement of WUE. The correlation coefficient of 84% is considered excellent, considering the variability between the trees. Dye *et al.* (1994) used the $\delta^{13}C$ relationship at Mkuze in northern KwaZulu-Natal, where only 66% of observed variation in WUE was accounted for. Results from stepwise regression were used to improve predictive capability by 15% to 80%, by the addition of a physiological parameter, *viz.* LAI. They concluded that with respect to determining WUE rankings, carbon isotope ratios measured in sapwood samples show the most promise, and that mean clonal WUE can be predicted with greater degrees of accuracy from $\delta^{13}C$ of sapwood and leaf area. Honeysett and Beadle (1987) suggest that the relationship between $\delta^{13}C$ and WUE in *Eucalyptus* trees requires further research to determine the source of variations.

TDR is one of the latest techniques available for the measurement of soil water and has only been in use for the past decade (Zegelin, White and Russell, 1992). This technique is reviewed in Section 2.2.6 below.

2.2.6 Time domain reflectometry

Current techniques for the measurement of soil water frequently involve destructive sampling, are time consuming and are therefore considered impractical for large scale determination of soil water content (Topp, Davis and Annan, 1980), as are needed in tree plantations. TDR is proposed as a solution to these disadvantages. TDR gives water balances to within ±10% of those using weighing lysimeters on a daily basis (Zegelin *et al.*, 1992) and to within 3% without soil calibration (Environmental Sensors, 1994).

TDR involves the transmission of a pulse through guide rods into the soil and monitoring of the delay of the pulse as it interacts with the soil medium (Savo, 1994). The travel time of the pulse is dependent on the dielectric constant of the soil as depicted in Equation 6 (Zegelin *et al.*, 1992), although the relationship between travel time and the dielectric constant is approximate (Topp *et al.*, 1980).

The dielectric constant is expressed as

$$\mathbf{K_a = (ct/2L)^2} \qquad .....(6)$$

where:
K_a = dielectric constant,
c = velocity of light in vacuum ($3*10^8 m.s^{-1}$),
t = travel time (s), and
L = transmission line length (m).

Attempts have been made at characterising soil water content by using individual dielectric constants of the three soil components *viz.* water, soil and air. At zero frequency, the dielectric constant of water at 20°C, K_{water} (80.36) is much greater than that of air, K_{air} (1) or soil material ($3 \leq K_{soil} \leq 7$). These large differences make the use of the three dielectric constants attractive (Zegelin *et al.*, 1992), as depicted in Equation 7.

Hence, the dielectric constant may be given as

$$\mathbf{K_a = [\ \theta K^{\alpha}_{water} + (1-\o)K^{\alpha}_{soil} + (\o-\theta)K^{\alpha}_{air}\ ]^{1/\alpha}} \qquad .....(7)$$

where:
θ = volumetric water content ($m.m^{-1}$),
ø = soil porosity ($m.m^{-1}$), and
α = geometric factor (usually ±0.5).

Topp *et al.* (1980) uses a "universal" empirical third order polynomial relationship (Equation 8) to calculate the water content from the dielectric constant, providing that $\theta \leq 0.6$.

The soil water content may be calculated as

$$\theta = -5.3*10^{-2} + 2.92*10^{-2}K_a - 5.5*10^{-4}K_a^2 + 4.3*10^{-6}K_a^3 \qquad .....(8)$$

TDR is best suited for use in light soils with low electrical conductivities. Measurements are very sensitive to the soil closest to the probe wires and therefore care needs to be taken when inserting the probe wires (Zegelin *et al.*, 1992). The main advantage of TDR is the ability to monitor soil water contents at many sites continuously (Zegelin *et al.*, 1992).

Zegelin *et al.* (1992) provide results from comparative tests of changes in soil water determined using TDR, a weighing lysimeter and the Bowen ratio technique in a wheat field in New South Wales. Figure 6 depicts the comparison of measured changes in total water volume from a 0.8m deep soil for the lysimeter and TDR over a six day period. Trends between these two measuring techniques are similar, with the deviation being in the order of less than 10%. This small difference occurs despite diurnal differences in soil water content of up to 25% occurring over a day.

Section 2.2 has highlighted the more widely used water use measurement methods and some of their advantages and disadvantages. Some of these methods have been utilised in research reviewed in Section 2.3 to determine how much additional water trees use, than the vegetation that they replace.

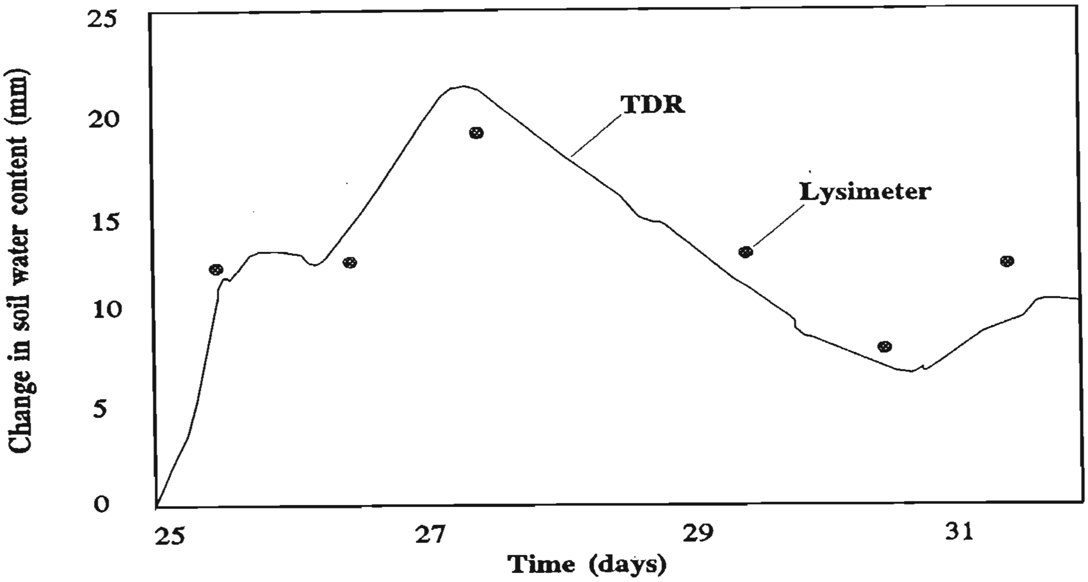

Figure 6. Comparison of the change in stored soil water (to 0.8m depth) between that measured by TDR and that found from a weighing lysimeter for a six day cycle (after Zegelin *et al.*, 1992).

2.3 Water Use by Different Genera and Species

The main reasons for water use differences between genera and species are believed to be related to physiological differences, *i.e.* canopy and root structure. Since biomass production for eucalypts is relatively greater than for the other genera found in South Africa's commercial forest plantations, they will tend to use more water, and in a shorter time period (*ACRU* FDSS Workshop No3, 1995). Water use by eucalypts is therefore hypothesised to be greater than that of pines in the first stages of growth, owing to faster growth and earlier canopy closure. Dye (1994) suggests that even in a deep soil environment, pines have a relatively shallow rooting system and therefore "run out of water" earlier than deep rooted eucalypts. Eucalypts are therefore able to access more soil water from a deeper rooting zone until this water is depleted, whence the tree will die back. A distinct period of water stress and lower transpiration is experienced by the pines during dry periods, indicating that the pines are able to control their soil water usage and become semi-dormant until rainfall occurs (Dye, 1994).

Less is known about water use by wattle. Water use by wattle is estimated to be between that of eucalypts and pines, although wattle are capable of extracting soil water at the same rates as eucalypts (*ACRU* FDSS Workshop No3, 1995). Evidence for this is provided anecdotally by farmers in the KwaZulu-Natal Midlands, who mention that wattle trees dry out the soil faster than pines.

Results indicate that poplars have a high water use (Smith, 1992), possibly equalling that of other species in summer, but having little influence on soil water in winter (in summer rainfall zones) since the trees are leafless (Scott and Le Maitre, 1994). Transpiration rates of poplars also peak at a later age than eucalypts.

Despite these relative water use differences, indications are that water use by different genera tend to be more or less equal over the entire rotation period (*ACRU* FDSS Workshop No2, 1995). For instance, on a short rotation, pines may use only a fraction (say half) the amount of water eucalypts use, but then pines are typically grown on (say) double the rotation period of eucalypts. This suggests that over a period of 20 years, both species probably consume the same quantities of water (Versfeld *et al.*, 1994). Smith (1991b) provides some evidence for this by suggesting that for some catchments in her study, the water use difference between species disappears and the final outcome of afforestation on low flows is the same in that streams dry up completely.

Water use by trees is characterised largely by the extent and the time span that trees are subjected to water stress. The impact of soil water stress on water use is discussed in Section 2.3.1 below.

2.3.1 Influence of soil water stress on water use by trees

Water use by trees is often determined by the degree to which the tree has access to sources of water, *i.e.* whether soil water is a limiting factor or not. Generally, trees grow better if they have access to additional water (over and above rainfall), although it is possible for some tree species to grow well on sites that are water limiting for part of the rotation.

Since South Africa is generally a water scarce country, more information on the importance of alternative water sources to forest plantations is needed, especially at sites susceptible to drought. This is necessary to enable the prediction of annual tree water use and periods of water deficit and reduced growth (Dye and Poulter, 1992). Thorburn *et al.* (1993) suggest that what is needed when determining tree water status is the depth in the soil profile from which the water may be extracted, and whether water at this level originates from the water table or from recent precipitation. For small rainfall events (<10mm), it is unlikely that rainfall will be the origin of water below 300-500mm (Thorburn *et al.*, 1993). It is also possible that tree roots penetrate deeper soil layers and use soil water stored from previous rainfall recharge events (Dye, 1993a).

2.3.1.1 Non water limiting conditions

Low water content usually limits total evaporation and the growth of trees, unless the stand has access to other sources of water. Shallow groundwater, aquifers and irrigation can provide trees with additional water.

Greenwood and Beresford (1979) give an example from Australia of water not being a limiting factor. In this study, eucalypts are shown to use 3600mm of water when the MAP is only 800mm. Additional water is obtained from groundwater, confirmed by root studies where roots were found at a depth of 6m, 1m below the water table depth. Transpiration per unit leaf area increases three fold for all species studied at a different site, Popanyinning, during relatively wet summer periods, this being due to the roots of the two year old trees reaching the water table at a depth of 3-5m (Greenwood and Beresford, 1979). Thorburn *et al.* (1993) study the effect of transpiration from soil water and saline groundwater on the water use of two *Eucalyptus* species. They found that groundwater was used at all sites at all times (despite being highly saline) making up 100% of transpiration in more than half the measurements. Transpiration rates are low for *E. largiflorens* (0.3mm.d^{-1}) and *E. camaldulensis* (up to 2mm.d^{-1}) with the large difference possibly being due to a three times higher LAI for *E. camaldulensis*, although other factors (soil salinity and different root patterns) could also influence transpiration (Thorburn *et al.*, 1993).

Dye and Poulter (1992) substantiate the argument for at least partial water use by *Eucalyptus* plantations at Mokobulaan from sub-soil layers by stating that:

a) the water balance during dry winter months at Mokobulaan indicates that soil water use by trees is greater than the available water capacity of the soil profile, and

b) the occurrence of deep rooting systems influences extraction patterns and depths to which extraction takes place. They cite rooting depths at 28m reported by Nulsen, Bligh, Baxter, Solin and Imrie (1986) and at 18m reported by Carbon, Bartle, Murray and Macpherson (1980).

At sites where roots are able to extract water directly from the water table, high transpiration rates can result (Pereira *et al.*, 1986). Carbon, Bartle and Murray (1981) found little difference in transpiration responses between *E. marginata* and *E. calophylla* except in the late summer rainfall period when transpiration rates are higher as a result of permanently high water tables.

Irrigation of trees will undoubtedly increase total evaporation, but by decreasing soil water stress, WUE may be increased because the same unit of water consumed would lead to higher yields (Calder, 1992a). Where trees are irrigated, high transpiration rates are enhanced by the "oasis effect" which becomes an important additional water use factor due to increased advective energy. Calder *et al.* (1993) investigated the possibility of increasing WUE through improved silvicultural management in Karnataka, India. Different soil water and nutrient stress levels were applied on three different species (*E. camaldulensis*, *E. grandis* and an indigenous species, *Dalbergia sissoo*). Different irrigation regimes (2.5, 5.0 and 7.5mm.d^{-1}) were applied regardless of rainfall, using a drip irrigation system. Results indicated that growth rates could be increased by a factor of five between the control plot and those receiving water plus fertilisers, as seen in Figure 7. After the first year of growth, once soil water reserves had been used up on the control plot, and thus even greater soil water stresses were expected, even greater differences in growth rates were expected, possibly up to 10 times difference (Calder *et al.*, 1993). Water use was determined using deuterium tracing methods and stomatal conductance measurements when the trees were of an adequate size. Preliminary ^{13}C stable isotope studies indicated $\delta^{13}C$ values in the range of -27 to -30%, indicating a relatively low WUE. No trend between species or treatments was evident (Calder *et al.*, 1993).

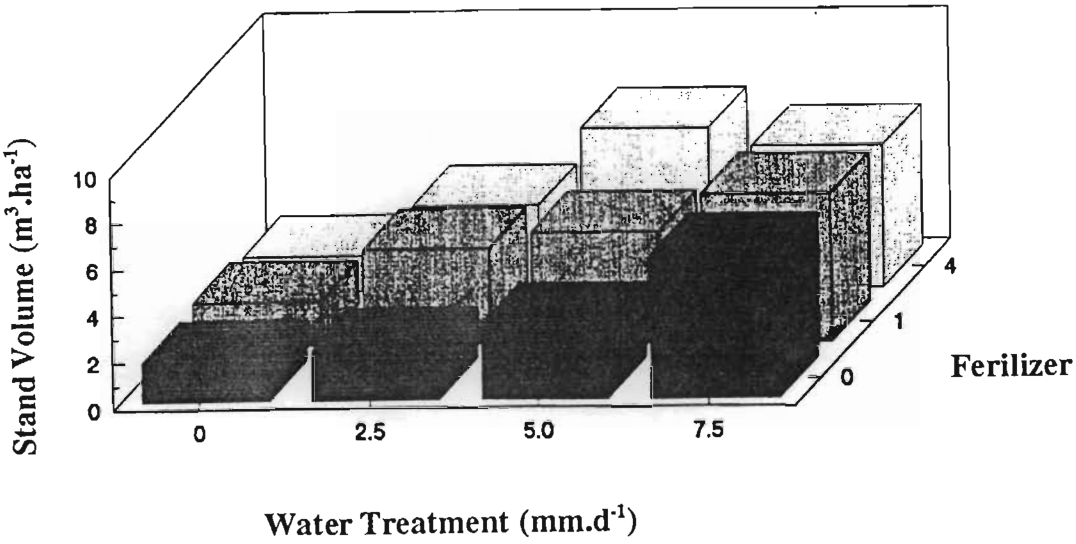

Figure 7. Stand volume as recorded on 20 August 1992 for *E. camaldulensis* grown in India (after Calder *et al.*, 1993).

Myers and Talsma (1992) suggest that on irrigated stands near Canberra in Australia, under conditions where growth is not limited by water, that annual tree water use increases at a rate of about $43mm.t^{-1}$ of foliage as shown in Figure 8. They report that peak rates of tree water use in January (mid summer, wet season) on irrigated stands were relatively high at $7\text{-}8mm.d^{-1}$, although Zartmann (1992) cites transpiration rates of up to $11mm.d^{-1}$ on irrigated plots at Mkuze in KwaZulu-Natal. This is probably the reason why at Mkuze, irrigation applied at 0.8 times A-pan evaporation only sufficed the trees' demand for the first two years, whereafter soil water content gradually decreased, even on the plot with maximum irrigation (Zartmann, 1992). Myers and Talsma (1992) suggest that during October-November (spring, wet season), water use by irrigated stands averaged $3.5\text{-}5.5mm.d^{-1}$. These values correspond to the $4\text{-}5mm.d^{-1}$ measured in *P. radiata* in October (Hatton and Vertessy, 1990) and to an average evaporation of 3.8 and $3.4mm.d^{-1}$ for *E. nitens* and *E. delegatensis* respectively (Honeysett and Beadle, 1987).

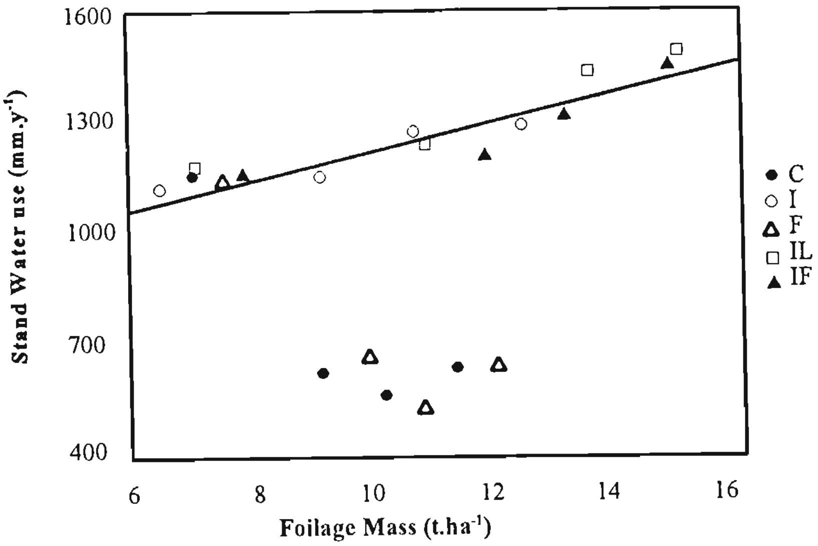

Figure 8. Annual stand water use as a function of average foliage mass for different treatments over three years, where C = control, I = irrigation, F = fertiliser, and L = liquid fertiliser (after Myers and Talsma, 1992).

2.3.1.2 Water limiting conditions

Calder *et al.* (1992a) conducted intensive research into the water use and growth rates of fast growing plantation forests in Karnataka, south-central India. Growth rates in this particular area are relatively low, attributable to soil water limitations, partly as a result of deep water tables of at least 30m (Harding, Hall, Swaminath and Srinivasa Murthy, 1992). Variations in water use and growth patterns at this site are mainly as a result of differing rainfall amounts, concentrated in a short monsoon season (June-September) in large intense storms. Pre monsoon evaporation rates drop to less than 1mm.d^{-1} as a result of dry soils limiting soil water availability (Roberts *et al.*, 1992). During the monsoon, Relative Humidity (RH) and wind speed are high, but radiation is low, resulting in an evaporative demand of only 2-3mm.d^{-1}. After the monsoon period, soil water is depleted at a rate of 3-5mm.d^{-1}, decreasing as the soil dries. During December to February, temperatures remain low, RH and wind speed drops, resulting in potential evaporation increasing slowly. After February, the temperature increases and RH drops, resulting in high potential evaporations of 5-6mm.d^{-1} during March-May (Harding *et al.*, 1992), while soil water is limiting.

Transpiration rates (mainly from dry canopies) have been obtained from soil water abstraction patterns and leaf physiological studies in India (Calder *et al.*, 1992a). These studies indicate that tree water use is not as high as was previously thought. At Puradal in India, tree water use was slightly less than that from adjacent indigenous dry deciduous forest, with both being about approximately equal to the MAP of 980mm. This water use is much less than water use values quoted, for example, by Greenwood (1992), who found that in Australia, annual evaporation from three different eucalypt species ranges from 2330 to 2690mm.annum^{-1}, as a result of the trees having access to ground water. In the experiment in India, no trees are able to use ground water, although on one of the sites tree water use exceeds rainfall (Calder *et al.*, 1992a). This is probably as a result of the tree roots penetrating deeper soil layers every year (at about 1m.annum^{-1}) and using soil water stored from previous high rainfall years (Dye, 1993a).

Calder *et al.* (1992b) show that the growth rate of above ground timber volume is proportional to the volume of water transpired. This relationship is attributable to the fact that water use and growth of trees at those specific sites in India are limited by water. The deuterium tracing method revealed a relationship between individual tree transpiration and cross sectional area, for conditions when trees were not experiencing soil water stress (Calder *et al.*, 1993). The daily transpiration rate for an individual tree is represented by Equation 9, which may also be expanded to plantation size, *viz.*

$$\mathbf{q = (6.6 \pm 0.3) g} \qquad \text{.....(9)}$$

where: q = daily transpiration rate (m^3.d^{-1}), and
g = basal area (m^2).

This relationship has been used in a model which is based on the relationships between transpiration, soil water and growth. The model is applicable in those areas of India with a MAP of less than 1000mm (Calder, 1992a). The assumptions of the model are firstly, that growth is limited primarily by soil water availability and secondly, that transpiration is limited by soil water availability and basal cross sectional area. The model has been found to be particularly useful for assessing growth responses due to different water conservation practices (Dye, 1993b). Calder (1992a) and Calder *et al.* (1993) conclude from this study that:

a) water use by young eucalypts on medium depth soils (3m) is not greater than that by dry deciduous forests in the dry zone,

b) annual water use by eucalypts and indigenous forests is equal to annual rainfall,

c) forest water use is greater than agricultural crops at all sites,

d) in the dry zone on deep soils (>8m) indications are that water use over three dry years of measurement is greater than rainfall,

e) no evidence exists for the abstraction of water by roots from the water table,

f) large variations in canopy I_l between different eucalypt species can be expected, but that it is likely that the variations are less than for other tree species with similar height and density,

g) canopy I_l from eucalypts and other tree species is likely to be greater than from shorter vegetation, and that

h) transpiration rates from eucalypts are likely to be similar to those of other tree species, except where *Eucalyptus* species which do not show stomatal regulation are growing in areas where atmospheric demand is high and soil water is non limiting. Eucalypts may transpire at rates determined by atmospheric demand alone.

Because of similarities with respect to climate and soils between India and some of South Africa's summer rainfall forestry areas, these results may give local hydrologists and foresters some indications of water use patterns of commercial tree species in South Africa (Dye, 1993b).

Having summarised water use values, the remainder of Chapter 2 contains general values of daily and annual tree water use, as well as a summary of water uses by vegetation other than trees. Most of these values are contained in South African literature.

2.3.2 Daily water use by individual trees

Currently, the upper limits of total evaporation and hence water use by forests are a contentious issue, with inflated tree water use values of up to 1500ℓ.tree^{-1}.d^{-1} (SABC, 1995) being used to build the case against afforestation. This Section contains a summary of daily tree water use values, determined mainly using the sap flow technique (*cf.* Section 2.2.4), in order to dispel these misrepresentations.

Theoretically, a tree free from competition (*e.g.* planted at a density of say 25trees.ha^{-1}) can transpire in excess of 500ℓ.tree^{-1}.d^{-1}. For example, Dye *et al.* (1995) cite water uses of 722ℓ.tree^{-1}.d^{-1} on a warm, dry day by a large *E. grandis* tree on a warm aspect where the tree has a particularly high LAI. However, in commercial plantations with common stand densities of 500 to 2500trees.ha^{-1}, considerably lower individual tree water uses will occur, due to competition by neighbouring trees for the same water. Therefore, tree water use values presented here are not strictly comparable unless the tree density is given. Comparisons of water use by stands with different densities are best made by expressing individual tree sap flows in terms of the equivalent depth of water (Dye *et al.*, 1995). To do this, the average water use per tree is multiplied by the number of trees in a given area, and divided by the area.

There is little agreement as to the maximum rates at which a tree is capable of using water. From the literature it is evident that natural vegetation, including trees, are not generally capable of sustained evaporation of more than 6mm.d^{-1} unless irrigated. Under irrigation, tree water uses of up to 18mm.d^{-1} are possible (*ACRU* FDSS Workshop No3, 1995), although Dye *et al.* (1995) suggest that peak tree water uses greater than 9mm.d^{-1} should be treated with caution. Smith (1992) predicts maximum daily transpiration in rainfall equivalents of 10.5mm.d^{-1} for trees with LAIs of 4.5, as a result of high VPDs in summer. Dye (1987) estimates maximum water use by *E. grandis*, thinned to 725trees.ha^{-1}, to be 135.7ℓ.tree^{-1}.d^{-1} (≡ ~~8.9~~mm.d^{-1}).

SHOULD BE 9.8mm.d^{-1} (SEE OPPOSITE)

On thinned 15 year old *P. taeda* plantations (395 trees.ha^{-1}, LAI of 4), McCarthy, Skaggs and Farnum (1991) determined average evapotranspiration rates of 1.4mm.d^{-1} (during dry winter periods) and 4.1mm.d^{-1} (during wet summer periods). At the Mkuze irrigation trial in northern KwaZulu-Natal, Olbrich *et al.* (1992) determined transpiration rates ranging from 2.8 to 10.4mm.d^{-1} by trees in the highest irrigation treatment (equivalent to *ca.* 1300mm annual precipitation) and from 0.3 to 0.8mm.d^{-1} for trees in the control plot (*ca.* 550mm annual precipitation). Myers and Talsma (1992) determined that for 10-14 year old irrigated *P. radiata* in Australia, tree water uses ranged from 7.0-8.0 and 3.5-5.5mm.tree.d^{-1} during summer (high atmospheric demand) and winter (relatively lower atmospheric demand) respectively. Roberts (1995) uses sites of extreme rainfall conditions to simulate that water use by *E. grandis* can be expected to be between 8 and 21ℓ.tree^{-1}.d^{-1}. Dye *et al.* (1994) suggest that for six year old TAG5 and GT529 clones growing at Kwambonambi on the north coast of KwaZulu-Natal, the water uses are 22.5 and 48.5ℓ.tree^{-1}.d^{-1} respectively. Average water use over a six day period by 12 year old *Acacia mearnsii* growing near Stellenbosch in the Western Cape (MAP 1000mm), was calculated as 30ℓ.tree.d^{-1} (Smith *et al.*, 1992). Actual water uses ranged from 14ℓ.tree^{-1}.d^{-1} (overcast, cool conditions) to 44ℓ.tree.d^{-1} (hot, clear conditions).

In addition to these values, Lima (1984) in Adlard (1987) gives values summarised in Table 2, for tree water uses of different *Eucalyptus* species. Despite being for different species, these values are generally comparable with South African results.

Figure 9 depicts typical seasonal water use rates given by Dye *et al.* (1995) with values corresponding to water uses cited in this Chapter. A gradual decline in sap flow over the dry winter months is evident. However, sap flow never reaches zero, indicating that although the tree is dormant, it is still transpiring.

Table 2. Tree water use by *Eucalyptus* species in Australia (after Lima, 1984 in Adlard, 1987).

Species	**Age (years)**	**Tree Water Use**	**Season**
E. saligna	2.5-3.5	23ℓ.tree^{-1}.d^{-1}	summer
E. globulus	2.5-3.5	37ℓ.tree^{-1}.d^{-1}	summer
E. cladocalyx	2.5-3.5	30ℓ.tree^{-1}.d^{-1}	summer
E. regnans	mature	1.9mm.d^{-1}	summer
E. regnans	dense regrowth	2.7mm.d^{-1}	summer
E. regnans	light dense regrowth	3.5mm.d^{-1}	summer
E. camaldulensis	1-2	29ℓ.tree^{-1}.d^{-1}	summer
E. globulus	1-2	37ℓ.tree^{-1}.d^{-1}	summer
E. leucoxylon	1-2	23ℓ.tree^{-1}.d^{-1}	summer
E. robusta	1-2	19ℓ.tree^{-1}.d^{-1}	summer
E. sargentii	1-2	28ℓ.tree^{-1}.d^{-1}	summer
E. wandoo	1-2	23ℓ.tree^{-1}.d^{-1}	summer
E. cladocalyx	1-2	30ℓ.tree^{-1}.d^{-1}	summer
Mixed dry sclerophyll	Mixed	4.5-6.0mm.d^{-1}	summer
Mixed dry sclerophyll	Mixed	1.5mm.d^{-1}	winter
E. regnans/ E. obliqua	70	4.6mm.d^{-1}	winter

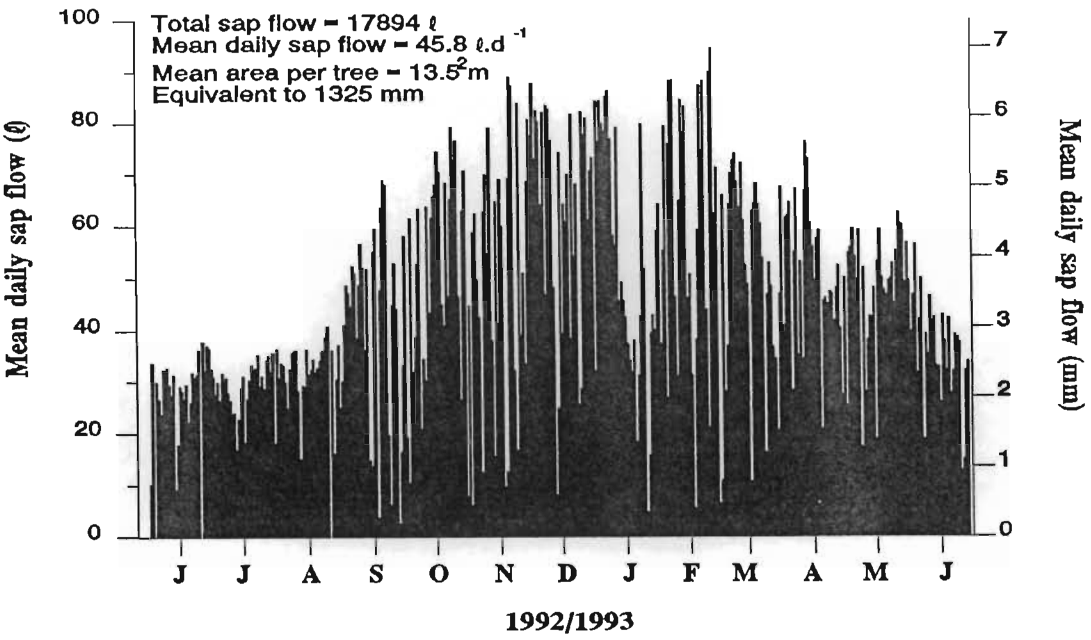

Figure 9. Average daily sapflow of four three year old *E. grandis* trees in the Sabie area in Mpumalanga (after Dye *et al.*, 1995).

To conclude this Section, Versfeld *et al.* (1994) are summarised. They suggest that measured single tree water uses from mature trees vary between 5 and 500ℓ.tree^{-1}.d^{-1}, depending on prevailing site, species and climatic conditions. Nevertheless, for an average plantation of 1000 to 1500trees.ha^{-1}, the water use by a single tree will probably not exceed *ca.* 150ℓ.tree^{-1}.d^{-1} and average 20 to 30ℓ.tree^{-1}.d^{-1}.

Besides determination of water use by single trees, annual water use has been predicted from streamflow measurements, as detailed in Section 2.3.3 below.

2.3.3 Tree water use determined by streamflow monitoring

Information on streamflow generation is needed to link afforestation practices to altered streamflow regimes (Dye and Poulter, 1992). Monitoring of streamflow to determine the impacts of commercial plantation forestry on water yield requires a landuse change, *i.e.* either afforestation or deforestation (clearfelling), with results usually compared to streamflows from a control catchment.

According to studies by, *inter alia*, Nänni (1970); Van Lill, Kruger and Van Wyk (1980); Bosch and Hewlett (1982); Van Wyk (1987); Schulze and George (1987); Bosch and Smith (1989); Smith (1991a), afforestation usually results in a decrease in water yield both of total and low flows. The impacts may differ in terms of size and timing of streamflows (Smith and Scott, 1992). Under certain circumstances it is however possible for afforestation to result in an increase in water yield from a catchment. This could occur, for example as a result of clearing vegetation with a relatively high water use (*e.g.* mature indigenous forest) and replacing it with seedlings with a lower water use (Smith, 1991b).

Eucalypts and pines have been found to differ substantially with respect to the effect they have on streamflow reductions. According to experimental evidence, the general consensus is that:

a) streamflow reductions occur earlier and in larger quantities for eucalypts than pines (*e.g.* Van Lill *et al.*, 1980; Bosch and Smith, 1989; Smith and Scott, 1992),

b) the effect of afforestation on low flows is more marked and is manifest much sooner for eucalypts than for pines (Smith, 1991b; Smith and Scott, 1992), although

c) none of the catchments in a study by Smith (1991b) showed significant signs of decreases in annual low flows during the first two years after the landuse change.

Water use by eucalypts is therefore considered to be greater than pines in the early years of a rotation as a result of faster early growth and earlier canopy closure. If tree water use is averaged over a short rotation, eucalypts may use 50% more water than pines (Versfeld *et al.*, 1994). Pines, however are grown on longer rotations, suggesting that tree water use may be about the same over entire rotation periods (Versfeld *et al.*, 1994).

According to Bosch and Hewlett (1982), the decrease in water yield following afforestation is directly proportional to the growth rate. This would explain the difference in timing of the effects on low flow between pines and eucalypts, which would tend to decrease as eucalypts develop beyond their peak growth periods. Smith (1991b) suggests that catchments planted to eucalypts show the effects on streamflow from the third year onwards while pines respond from the fifth year onwards. After eight years, differences decrease as the pine stands become well established. This also confirms that the effect of afforestation to eucalypts (90-100% streamflow reductions) is far greater than that of pines (40-60%) in the first eight years after changing the landuse (Smith, 1991b).

Lesch and Scott (1993) describe an experiment at Mokobulaan in Mpumalanga (MAP 1167mm) where afforestation to pines of Catchment B with a Mean Annual Runoff (MAR) of 217mm from grassveld produced significant decreases in streamflow from the fourth year. The stream dried up completely in the 12th year after planting. They also cite that afforestation to *E. grandis* of Mokobulaan Catchment A with a MAR of 236mm under grassveld caused significant decreases in streamflow from the third year after planting and that the stream dried up in the ninth year. At 16 years of age, the eucalypts were felled but perennial streamflow only returned five years later. This delay was surprising, but was attributable to eucalypts desiccating deep unsaturated soil-water stores, which had to be replenished before the streams started flowing again. Some of the effect of afforestation on streamflow may of course be ascribed to drought conditions caused by seasonal and annual rainfall variability.

Van Wyk (1987) determined that for 98% afforestation with *P. radiata* at Jonkershoek in the Western Cape, streamflow decreased by 313mm.annum^{-1} from an initial 663mm.annum^{-1} to an average of 350mm.annum^{-1} over a period of 12-32 years after afforestation. In a catchment with 57% afforestation, streamflow declined by 200mm.annum^{-1} from an initial 593mm.annum^{-1} over a period of 16-40 years after afforestation. Rainfall and total biomass appear to have influenced streamflow.

Streamflow changes as a result of clearfelling have also been determined, and for the purpose of model development it may be assumed that the hydrological effects of afforestation and deforestation on streamflow are comparable. Smith (1991a) suggests that clearfelling of 20 to 40 year old pines at Witklip in Mpumalanga initiated a streamflow increase of 280mm.annum^{-1} during the first 4 years after clearfelling. Values from outside South Africa show increases of up to 457mm.annum^{-1} following clearfelling of natural forest (Nänni, 1970). Van Wyk (1993) determined highly significant annual streamflow increases of 182mm and 249mm respectively at Bosboukloof and Biesiesvlei, both at Jonkershoek in the Western Cape, as a result of clearfelling pines. Similar quick streamflow responses are cited by Van Wyk and Scott (1993), where clearfelling *P. radiata* plantations in the Western Cape induced an increase in streamflow that was noticeable after the first third of the catchment had been clearfelled.

Bosch and Smith (1989) suggest that indigenous riparian forests use water relatively conservatively when compared with exotic species. They cite that clearing 83% of a catchment of indigenous scrub forest induced a yield increase of only 20mm, compared to responses of more than 300mm through clearfelling of other forest types. After clearfelling, re-afforestation with eucalypts induced a reduction in annual streamflow of 200mm (48% of mean annual streamflow before treatment) per year within three years after afforestation (Bosch and Smith, 1989).

Van Lill *et al.* (1980) suggest that the maximum reduction in annual flow due to afforestation with *E. grandis* is between 300-380mm.annum^{-1}, while stands of mature pines use about 300-600mm.annum^{-1} of rainfall equivalent more than the vegetation they replace. Maximum streamflow reductions are commonly in the region of 300-400mm.annum^{-1}, while mean losses of 200-300mm.annum^{-1} are common (Versfeld *et al.*, 1994). Bosch and Hewlett (1982) review 94 catchment experiments and conclude that conifers and eucalypts cause an average change of 40mm in annual water yield per 10% change in cover, while Smith (1991a) concludes that pines cause an increase of 54mm per 10% catchment cleared. In areas with annual runoffs of less than 300mm, afforestation of a headwater catchment is expected to cause streamflow to cease (Scott and Le Maitre, 1994).

Smith and Scott (1992) present generalised curves for predicting the percentage reduction in annual and low flows for eucalypts (Figure 10) and pines (Figure 11), based on results reviewed in this sub Section. These curves have been developed as an extension to the Nänni (1970) curves and use data from five paired catchment experiments. Smith (1991b) compares streamflows at Westfalia and Mokobulaan in Mpumalanga, Cathedral Peak in KwaZulu-Natal and Jonkershoek in the Western Cape, from sites planted to pines and eucalypts. Smith (1991b) suggests that for pines, the largest decrease in flow due to afforestation occurs at Mokobulaan, as a result of deep fertile soils, high rainfalls of 1450-1600mm.annum^{-1} and a sub tropical climate (Smith and Scott, 1992), while Cathedral Peak's decreases are the lowest, probably as a result of poorer growing conditions (thinner soils and cooler climate). Soils in the fynbos catchments (Jonkershoek) are usually shallow, contain rocks and are nutrient deficient when compared to those in the sub-tropical Mpumalanga regimes (Mokobulaan and Westfalia), leading to comparatively poor tree growth (Smith, 1991b). Hence, Smith (1991b) assumes that Westfalia and Mokobulaan are optimal areas, and Cathedral Peak and Jonkershoek sub optimal for the development of the streamflow reduction curves shown in Figures 10 and 11. In addition to these results, Dye (1995) provides a summary of post afforestation evapotranspiration results from seven paired catchment experiments (Figure 12).

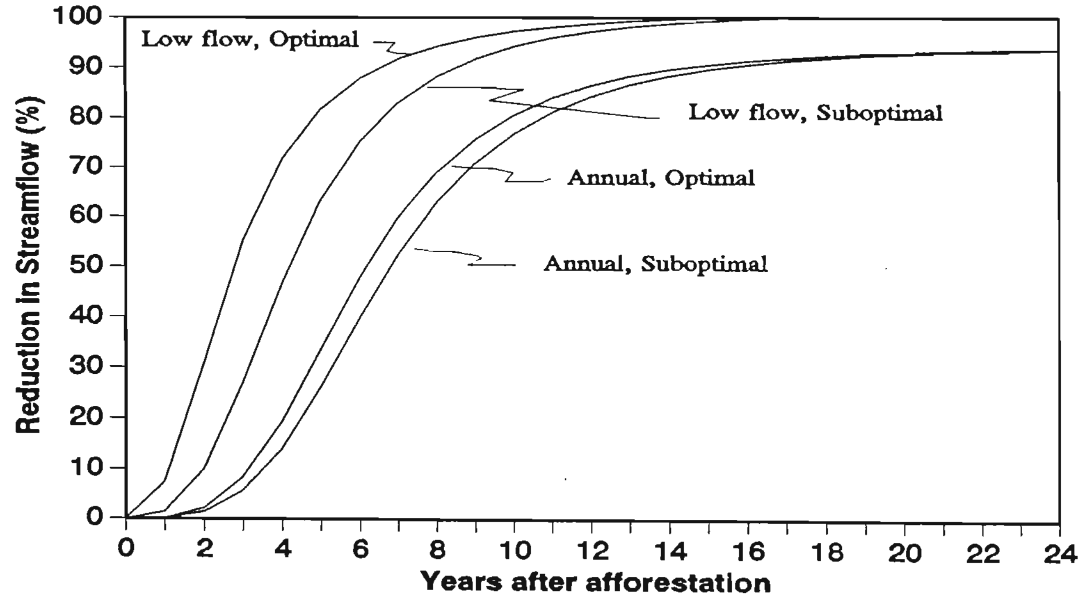

Figure 10. Generalised curves for predicting the percentage reduction in annual flows and low flows at increasing ages for 100% afforestation to eucalypts in optimal and sub-optimal growth areas (after Smith and Scott, 1992).

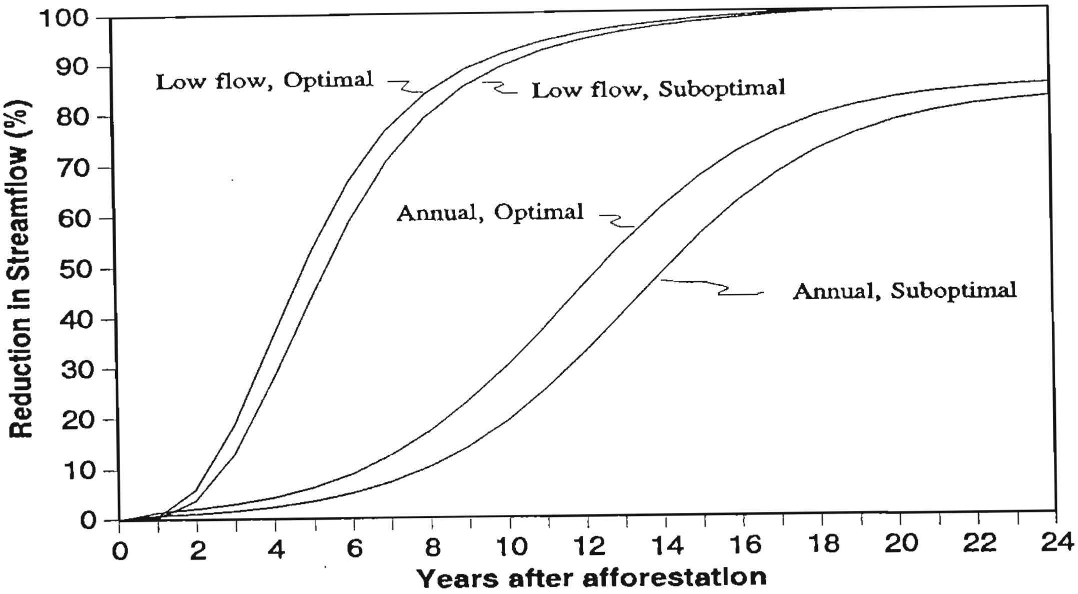

Figure 11. Generalised curves for predicting the percentage reduction in annual flows and low flows at increasing ages for 100% afforestation to pines in optimal and sub-optimal growth areas (after Smith and Scott, 1992).

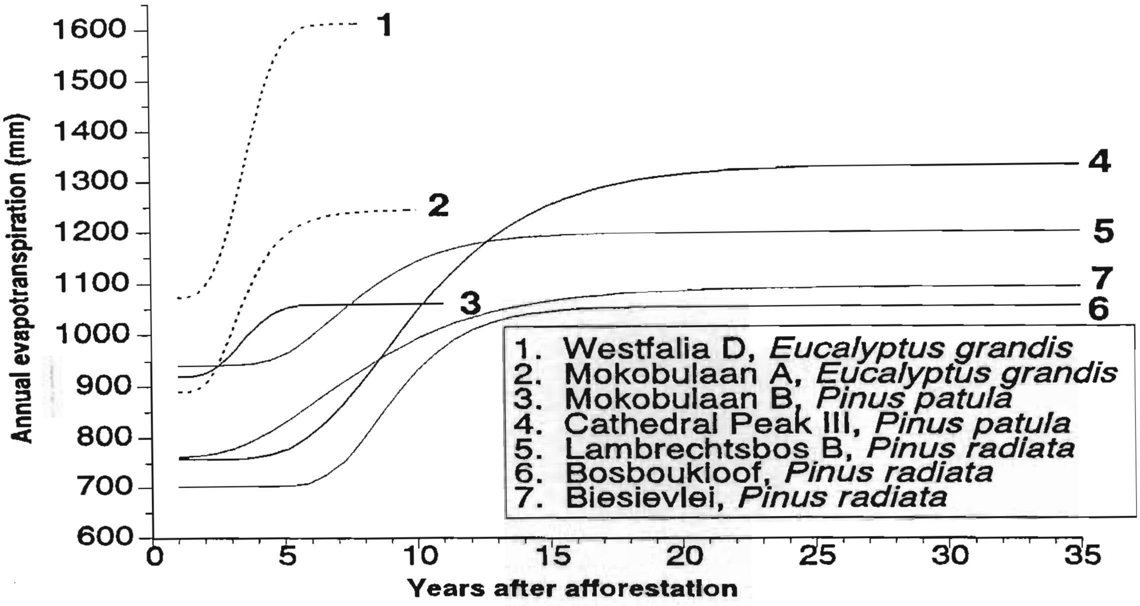

Figure 12. Post afforestation trends in evapotranspiration (after Dye, 1995).

In response to perceived unfair prejudice imposed by the APS against the forestry industry, a need to study water use by trees relative to some other landuses, for example agriculture or virgin conditions, has been suggested, *inter alia* by *ACRU* FDSS Workshop No3 (1995) and Asmal (1995a). Section 2.3.4 of this Chapter introduces the idea of comparing water use by commercial trees and other vegetation.

2.3.4 Comparison of water use by trees and other landuses

Landuses other than commercial afforestation may, under certain circumstances, use more water than afforested areas or may be worth less economically, thereby opening many valid points of discussion on the impact of afforestation on water regimes. For example, Dye and Poulter (1995) are (at the time of writing) comparing the WUEs of different farming and forestry operations, which may well show that forestry is a relatively efficient user of water. One can argue that all uses of land and water in a catchment should be assessed and regulated in a consistent manner, because other uses may use more water and/or be less economically efficient than commercial afforestation.

Irrigated agriculture, as a whole, is highly consumptive of water (DWAF, 1995) and according to Heron (1995) may use seven times as much water as forestry. Irrigated sugar cane, for example uses more water than commercial forests according to Versfeld *et al.* (1994), and is capable of using twice as much water as trees (Asmal, 1995a). On a South African national scale, the estimated water demand for irrigation is 51.0%, 7.5% for forestry, 19.6% for municipal and industrial use and 15.4% for the environment (Scotcher, 1995). Scotcher (1995) suggests that a study by the Kruger National Park Rivers Programme revealed that afforestation in these catchment areas reduced the MAR by 10%, while irrigation used 24% of streamflow. Irrigation, which occupies only 25% of the area covered by forests, thus uses 10 times as much water on a per hectare basis, in that particular area. One hectare of maize uses enough water to supply 1200 people for a year (Asmal, 1995a). If all of the land currently permitted for new afforestation in Mpumalanga were afforested, an additional 2% of streamflow would be "lost", but the total amount would still be about half the current consumption for irrigation (DWAF, 1995). Also, Schulze and Pike (1995) have shown by simulation that in the Franklin area of KwaZulu-Natal the conversion from current landuse to proposed forest may have a smaller impact on water resources than the original conversion from pristine conditions to the present landuse.

Recent results indicate that there may be little difference in daily water use between trees, maize and grassland during the active growing season. However, trees continue to transpire in what is the dormant season for many crops/grasses as a result of their deep rooting systems and evergreen perennial canopies (Versfeld *et al.*, 1994). During wet summer periods, evaporation rates of montane grasslands are as high as from forest plantations at Cathedral Peak, but evaporation from grasslands decreases by mid to late winter (dry period), which is believed to be the principal reason for a reduction in streamflow following afforestation of grasslands (Dye *et al.*, 1995).

* * *

Chapter 2 has emphasised the factors which influence water use by commercially grown tree species and some of the methods used to measure tree water use. From this review, each method has distinct advantages and disadvantages and it is therefore important to compare tree water use results as has been done in Chapter 2. This enables results from different experiments to be compared with each other. Since water use by trees is a controversial and much discussed issue, daily and annual water use values were presented to enable the reader to develop a perception of how much water trees use. One of the methods described in Chapter 2 *viz.* the NMM technique is used in Chapter 3 to determine soil moisture trends and infer water use trends from these data.

3. FIELD EXPERIMENTATION AND RESULTS

3.1 Objectives

Fieldwork forms an integral part of the development of modelling systems since it enables:

a) the development of information and understanding of complex natural processes, that researchers may
b) develop general trends based on these processes, so that
c) predictions of future events may be made with the highest possible degree of certainty.

The objective of the fieldwork component of this dissertation, is to add to findings by researchers in other parts of the world (Chapter 2) in order to update the *ACRU* FDSS (Chapter 4). The NMM technique (Section 2.2.2) is used to analyse soil moisture contents and determine general soil moisture trends under different climatic and field conditions. Hence, soil moisture values measured at a point have sometimes been averaged. The aim was to determine relationships between tree water use and:

a) varying degrees of site preparation, and
b) MAP as indicated by irrigation.

Fieldwork was performed at three experiment sites owned by Mondi Forests, *viz.* Tree Fern Pool and Funeray in the Mondi Northeast Cape (NEC) region of the Eastern Cape province, and Mkuze in northern KwaZulu-Natal. A locational map and photographs of these sites are included as Figures 13, 14 and 15 respectively. Soil moisture data obtained at these sites are used in this Chapter to determine the effects of site preparation and water regime, by way of differences in rainfall as well as in different irrigation schedules, on soil water use by a selection of commercially grown tree species under the respective field conditions.

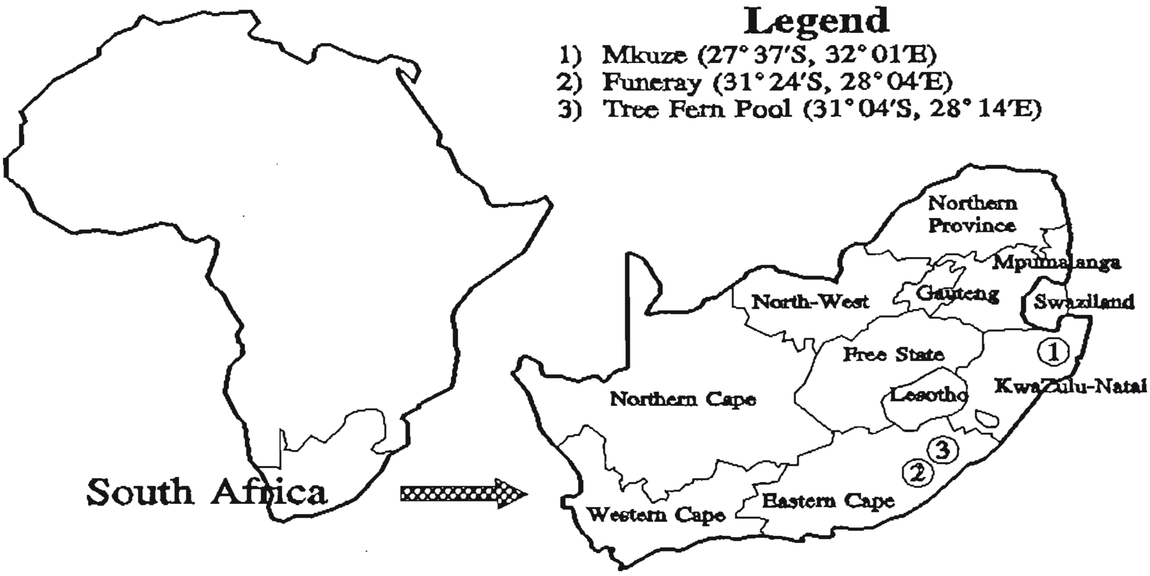

Figure 13. Location of fieldwork sites (Provincial boundaries and names were correct at the time of writing in December 1995, but may change at a future date).

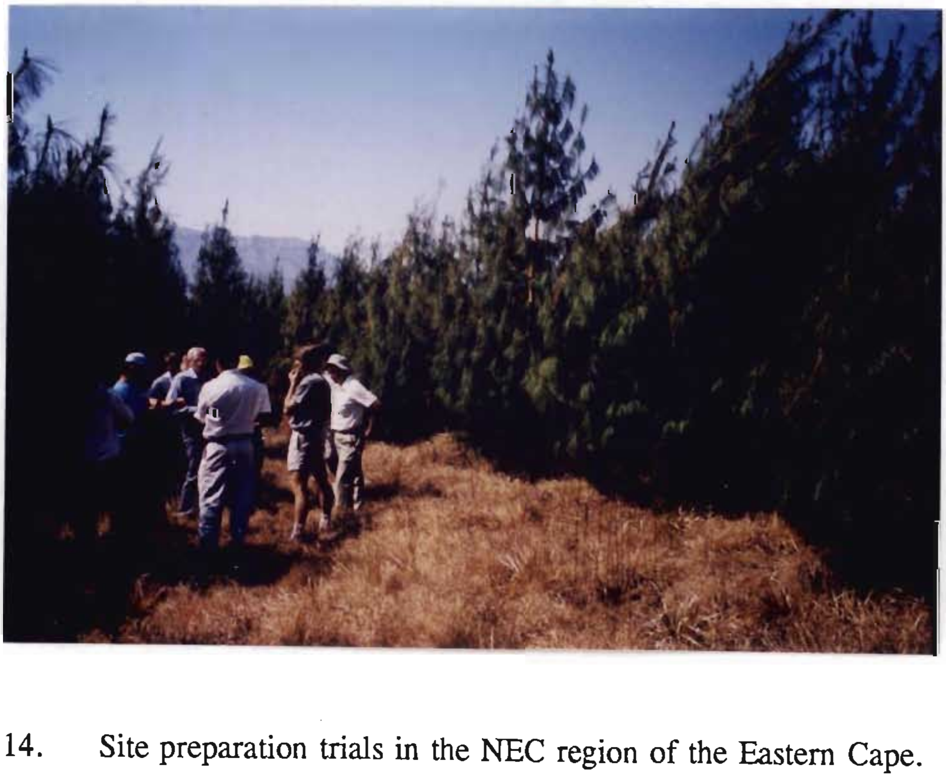

Figure 14. Site preparation trials in the NEC region of the Eastern Cape.

Figure 15. Irrigation trials at Mkuze in northern KwaZulu-Natal.

3.2 The Effect of Site Preparation on Soil Moisture Content

South Africa as a whole is classified as a water scarce country (DWAF, 1986) with resulting limitations on a sustained soil moisture supply to trees, particularly in climatically marginal areas. It is therefore advantageous for foresters to maximise the quantity of water entering the soil profile for potential use by the trees. One method of attaining this is by making use of effective site preparation techniques. With enhanced site preparation, the possibility of increased timber yields therefore also exists. These ideas were backed up by Boden (1991b) who suggests that site preparation is the most important operation when preparing natural grasslands for afforestation.

3.2.1 Background

In the past decade, Mondi Forests has acquired *ca.* 80 000ha of land in the Eastern Cape, of which about 20 000ha has subsequently been afforested, mainly to *P. patula*. During October 1990 a site preparation experiment planted to *P. patula* was established at Tree Fern Pool and at Funeray in the Eastern Cape (*cf.* Section 3.2.2 for details). The initial purpose of the experiment, as documented by Norris and Stuart (1994), was to determine the relationship between different site preparations and tree growth.

Despite its potential importance, particularly in climatically marginal areas, very little work has been conducted into the effects of site preparation on catchment hydrology (Smith and Scott, 1991). Site preparation research at the plot scale that has been reported has been mainly on *E. grandis* (Boden, 1991c; Moerdyk, 1991) and *A. mearnsii* (Herbert, 1984). However, Jewitt (1991) provides the most comprehensive study by researching the effects of site preparation on soil moisture content on sites planted to all three of the main genera, *viz. E. grandis*, *P. patula* and *A. mearnsii.*

Hydrologically related studies were initiated on the Tree Fern Pool and Funeray trials during September 1994. In this dissertation, soil moisture pattern results are presented for the period 1 September 1994 to 31 October 1995. Rainfall over this period was 626 and 673mm at Tree Fern Pool and Funeray respectively, with the largest daily event of 57mm occurring on the 26 December 1994 at both sites. For the purpose of this dissertation, the aims of these soil moisture studies were to:

a) quantify the relationships between site preparation and the water use regimes of *P. patula* on relatively "high" and "low" potential sites in the NEC region, and
b) use these findings to enhance the forest water use module in the *ACRU* FDSS.

3.2.2 Site and experiment details

Funeray is located at latitude 31°24'S and longitude 28°04'E at an altitude of 1400m. The site is 25km southwest of Ugie and is considered by foresters and researchers to be a marginal site for commercial afforestation. This is due to a relatively low MAP of *ca.* 850mm coupled with shallow soils of the Pinedene form and Ceres family (according to Hensley, Van Staden, Anderson and Smith-Baillie, 1995). An impermeable bedrock layer is found at about 1100mm. Consequently, the potential rooting depth is relatively shallow and the trees will therefore be exposed to felling by wind, especially given the long rotation periods, typically up to 30 years for pines in this region. Although Funeray is relatively drier than Tree Fern Pool, the possibility exists that the site receives additional supplies of precipitation from fog, although this has not been measured. Funeray is cooler and has lower evaporation rates than Tree Fern Pool as depicted in Figure 16. The Drained Upper Limit (DUL) for Funeray has been calculated as 28.6% volumetric water content.

The Tree Fern Pool site is located 10km west of Maclear in the Eastern Cape at latitude 31°04'S and longitude 28°14'E, and at an altitude of 1360m. The site is considered by foresters and researchers to be an "ideal" site for afforestation owing to a relatively high MAP (>1000mm) and (according to Hensley *et al.*, 1995) deep, well drained soils of the Bloemdal form and Rietpoort family. This high rainfall is offset partially by relatively high evaporation rates and temperatures (Figure 16).

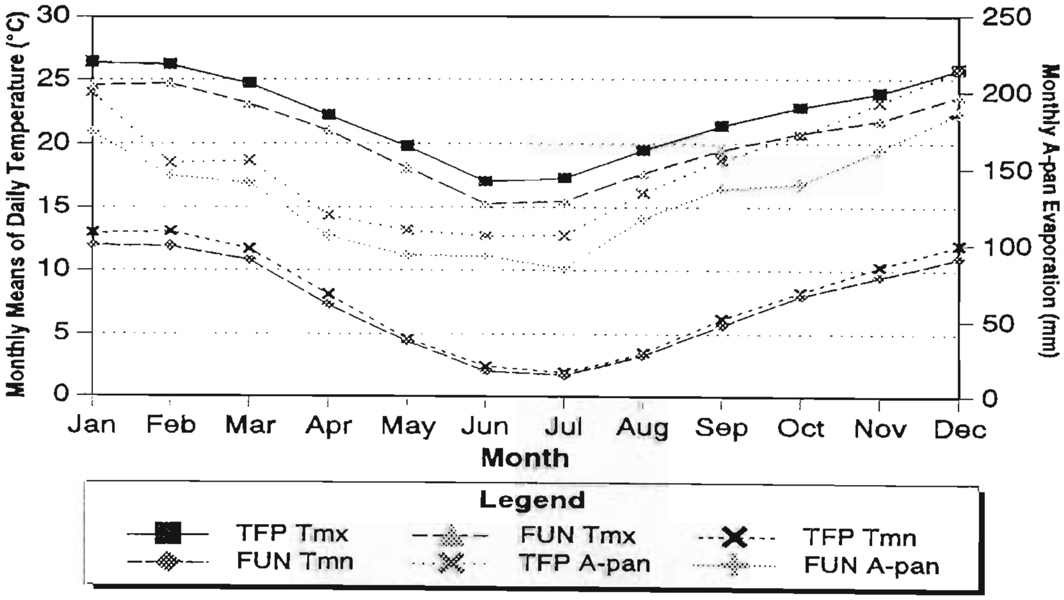

Figure 16. Simulated monthly values of A-pan equivalent reference potential evaporation as well as maximum and minimum temperatures (T_{mx}, T_{mn}) for Funeray (FUN) and Tree Fern Pool (TFP) Source: Schulze and Maharaj (1995).

Soil moisture investigations at Tree Fern Pool are complicated by the existence of a fluctuating water table indicated by a quartz layer at a depth of 1650mm (Hensley, 1995). The DUL for Tree Fern Pool has been calculated as 30% volumetric water content, although this will vary according to the location of the water table, represented by a soil moisture content of 32.7% or greater. From initial soil moisture readings, Hensley *et al.* (1995) suggest that the water table remains relatively constant at a depth of 1050mm under natural grassland, while under five year old *P. patula* the water table is at a depth of *ca.* 1950mm for the cultivation and pitting, and at 2550mm for the rip and ridging preparations respectively. As a consequence of the varying water table depths causing inconclusive results, a decision was made by the author not to present time trend results for soil depths exceeding 1050mm at Tree Fern Pool. Subsequent to advice given by Hensley (1995), soil moisture readings for depths shallower than 1050mm were adjusted to account for the possibility of the water table occurring at these depths by enforcing a maximum Count Ratio (CR) of 2.0 in the calibration equations (*cf.* Tables 4 and 5). As a result of the relatively shallow water table, rooting depths are considered by Hensley (1994) to be limited to a maximum of 800mm.

The NMM technique was used at Tree Fern Pool and Funeray to obtain weekly soil moisture measurements on a control plot (*viz.* grassland) and plots with three different site preparations, *viz.* pitting, cultivation and rip and ridging. The rip and ridging technique is commonly used by Mondi Forests in the NEC region. Comprehensive site preparation details are contained in Norris (1991a), and only a summary has been included as Table 3. It is generally accepted that the order of increasing intensity of site preparation would be pitting followed by rip and ridge and then cultivation respectively. Fertiliser was originally included in the experiment as a treatment but no effects on tree growth have been evident up to a tree age of three years (Norris and Stuart, 1994).

Table 3. Site preparation details for the Tree Fern Pool and Funeray sites in the NEC region.

Site Preparation	**Details**
Pitting	Pits 500mm wide and 250mm deep
Rip and Ridging	Rip to 500mm depth, ridges at 1000mm intervals and 500mm high
Cultivation	Complete surface ploughing to 150-200mm depth

The two sites are typical of the range of sites used for commercial afforestation in the NEC region. Both trials were established on virgin veld. This could present problems of representativeness, since 50% of afforestation in the NEC region is on so called "old lands" (Droomer, 1994). A major constraint to successful commercial afforestation incurred by Mondi Forests in the NEC region is that of "J-root" and "ball and socket" rooting problems. These are caused either by the seedlings remaining in trays for too long a period prior to planting, or by poor planting techniques whereby the tap root becomes restricted, thereby causing a "J-shaped" root to develop. As the root grows, it "strangles" itself to form a "ball and socket" (Figure 17).

Figure 17. The "ball and socket" rooting problem: An example from the NEC region.

On each site preparation and the grassland plot, three access tubes were positioned within four trees selected as being representative of the site (Figure 18). The first tube has been placed at the centre of the trees *i.e.* on the diagonal. Given the 2000 by 3000mm tree spacement at both sites, the second and third access tubes were placed along the former distance at intervals of 500 and 1000mm from the corner tree respectively. This design has previously been found (Zartmann, 1992) to maximise data quantity obtained with a minimum number of tubes, thereby reducing the time required for measurements.

This design was replicated on each of the three site preparations but not on the grassland site for which only a single site was selected. This strategy was used at Tree Fern Pool and at Funeray, totalling 42 tubes. Subsequent to this design having been implemented, three additional tubes have been inserted in the cultivation and pitting treatments at Funeray. These tubes extend to greater depths than the original tubes on these two treatments, but owing to a short data period these data are not included in this dissertation. The relevant plot and tube numbers are detailed in Appendix A.

Soil moisture data are transmitted weekly by modem from the Mondi Forest office in Ugie to the Computing Centre for Water Research (CCWR) in Pietermaritzburg. Automatic weather station data from the two locations are stored at the Agricultural Research Council (ARC) in Pretoria. Problems with the automatic weather stations were experienced until January 1996. Rainfall data presented here are therefore from manual raingauges recorded daily at the two locations *viz.* Tree Fern Pool and Funeray offices.

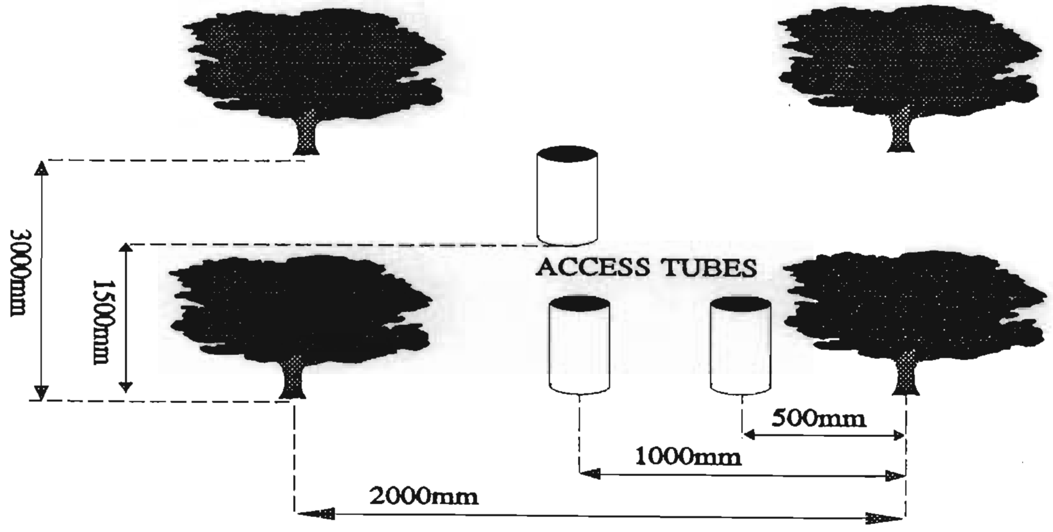

Figure 18. Access tube placement at the NEC site preparation trials.

3.2.3 Neutron moisture meter calibration

A comprehensive calibration of the NMM was performed by the Institute for Soil Climate and Water (ISCW), by analysing soil samples taken during augering. To date, it has been necessary to use two different NMMs in the NEC experiment due to equipment malfunction. NMM No 8550 was used from September 1994 to 23 August 1995, NMM No 9141 from 24 August 1995 to 5 September 1995, and NMM No 8550 from 6 September 1995 onwards. Hensley (1995) expressed concern that NMM counts obtained using NMM No 8550 from the 6 September 1995 onwards may be slightly higher than counts obtained during its initial period of use, and will therefore have to be recalibrated. Data from the 6 September 1995 onwards have hence been excluded from this analysis.

Given the possible inaccuracies of the NMM (Section 2.2.2) and the inconsistent site conditions at these trials, the use of several soil moisture calibration equations for different soil horizons was considered necessary. Relevant equations for the two NMMs are contained in Tables 4 and 5.

Table 4. Calibration equations for NMM No 8550, where $\theta_{\%}$ is the volumetric soil moisture content and CR is the NMM Count Ratio.

Site	**Soil layer (mm depth)**	**Equation**
Tree Fern Pool	0-300	$\theta_{\%}=17.836*CR-0.182$
	300-600	$\theta_{\%}=19.042*CR-3.689$
	600-900	$\theta_{\%}=22.079*CR-3.874$
	>900 (CR<1.8)	$\theta_{\%}=17.124*CR-6.059$
	>900 (CR>1.8)	$\theta_{\%}=60.020*CR-87.37$
Funeray	0-300	$\theta_{\%}=17.456*CR-2.914$
	300-600	$\theta_{\%}=19.804*CR-7.662$
	600-900	$\theta_{\%}=28.635*CR-20.21$
	>900	$\theta_{\%}=15.569*CR-0.915$

Table 5. Calibration equations for NMM No 9141, where $\theta_{\%}$ is the volumetric soil moisture content and CR is the NMM Count Ratio.

Site	Soil layer (mm depth)	Equation
Tree Fern Pool	0-300	$\theta_{\%}=18.426*CR+0.463$
	300-600	$\theta_{\%}=19.672*CR-3.000$
	600-900	$\theta_{\%}=22.809*CR-3.076$
	>900 (CR<1.8)	$\theta_{\%}=17.690*CR-5.440$
	>900 (CR>1.8)	$\theta_{\%}=62.000*CR-85.20$
Funeray	0-300	$\theta_{\%}=18.033*CR-2.283$
	300-600	$\theta_{\%}=20.459*CR-6.946$
	600-900	$\theta_{\%}=29.582*CR-19.175$
	>900	$\theta_{\%}=16.084*CR-0.352$

3.2.4 General hypotheses

In the site preparation component of this research, it was hypothesised that:

a) as a result of differences in MAP, soil moisture observations from Tree Fern Pool should display higher soil moisture contents than those from Funeray,

b) the grassland control plots would exhibit higher, and the complete preparation plots lower soil moisture contents than the others,

c) soil moisture contents should increase in the wetter months, and decrease in the dry winter months as a result of seasonal rainfall patterns, and

d) soil moisture contents should increase with depth as a result of the tree roots not being able to have used this water.

3.2.5 Results from soil moisture observations

In order to ascertain the general effects of site preparation on the soil moisture regime and tree water use, soil moisture content has been plotted against soil depth and time. Results for Tree Fern Pool and Funeray are presented as Figures 19a and 20, and Figures 19b and 21 respectively.

3.2.5.1 Comparison of soil moisture content between sites

Contrary to the hypotheses proposed, the soil moisture contents at Tree Fern Pool (Figure 19a), the wetter site, are generally lower than those at Funeray (Figure 19b), on all site preparations. This is the case despite Tree Fern Pool plots having a higher MAP and soil water holding capacity than the plots at Funeray. Several possible reason for this apparent anomaly are proposed.

The impermeable bedrock layer at Funeray could be prohibiting sub-surface drainage, thereby causing the shallow soil profile to remain relatively wet. This lack of drainage could also reduce transpiration rates if the soils are excessively wet. Tree growth has certainly been constrained at Funeray. Norris and Stuart (1994) reported that at 3.5 years of age, Mean Annual Increment (MAI) at Funeray ($7.78m^3.ha^{-1}$) was less than at Tree Fern Pool ($12.38m^3.ha^{-1}$). These growth differences provide evidence that trees at Tree Fern Pool are certainly utilising more soil water, which would explain their lower soil moisture content when compared with that at Funeray.

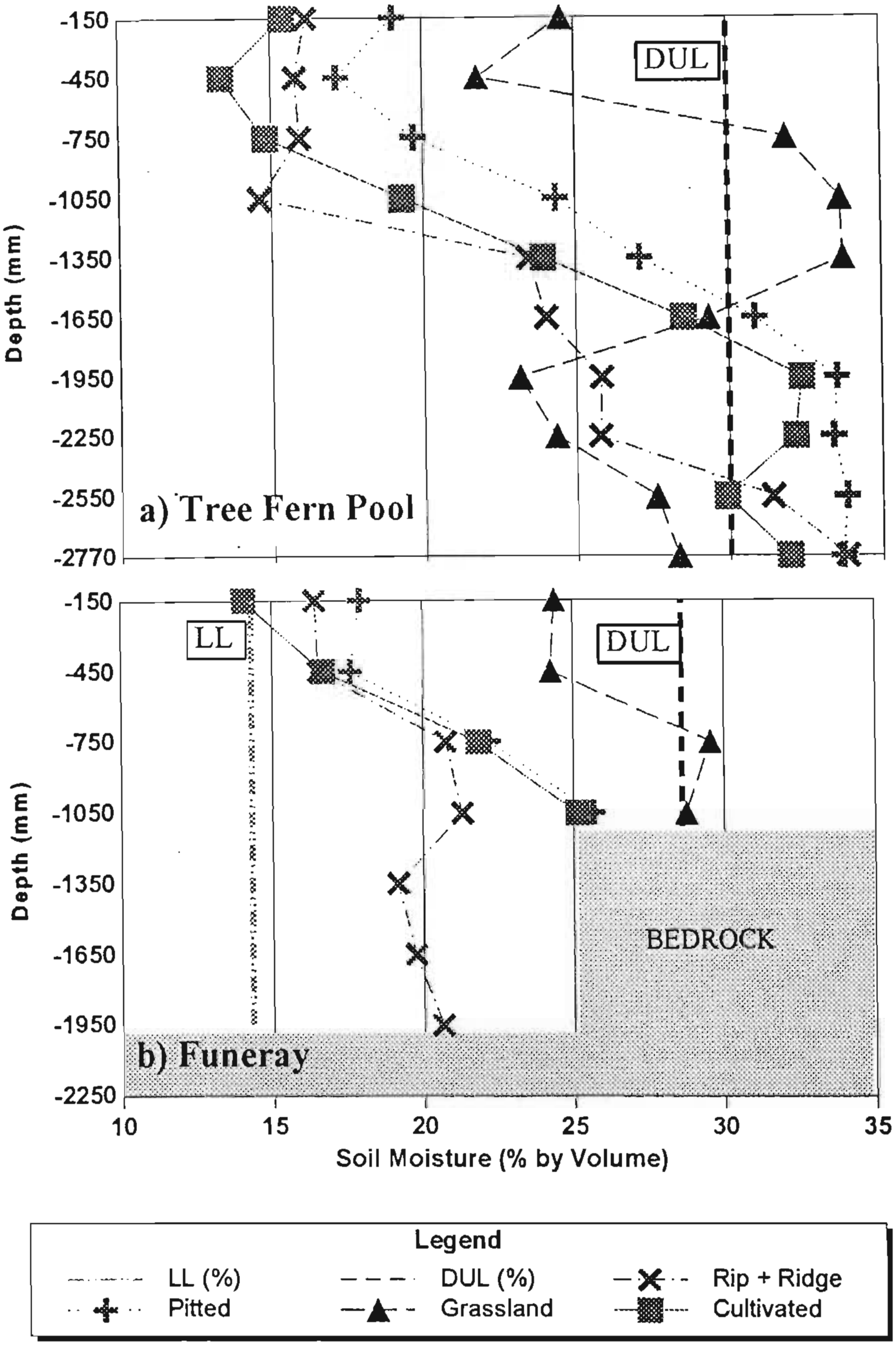

Figure 19. Time integrated trends of soil moisture contents with depth on the different site preparations at Tree Fern Pool (top) and Funeray (bottom) for the period September 1994 to October 1995.

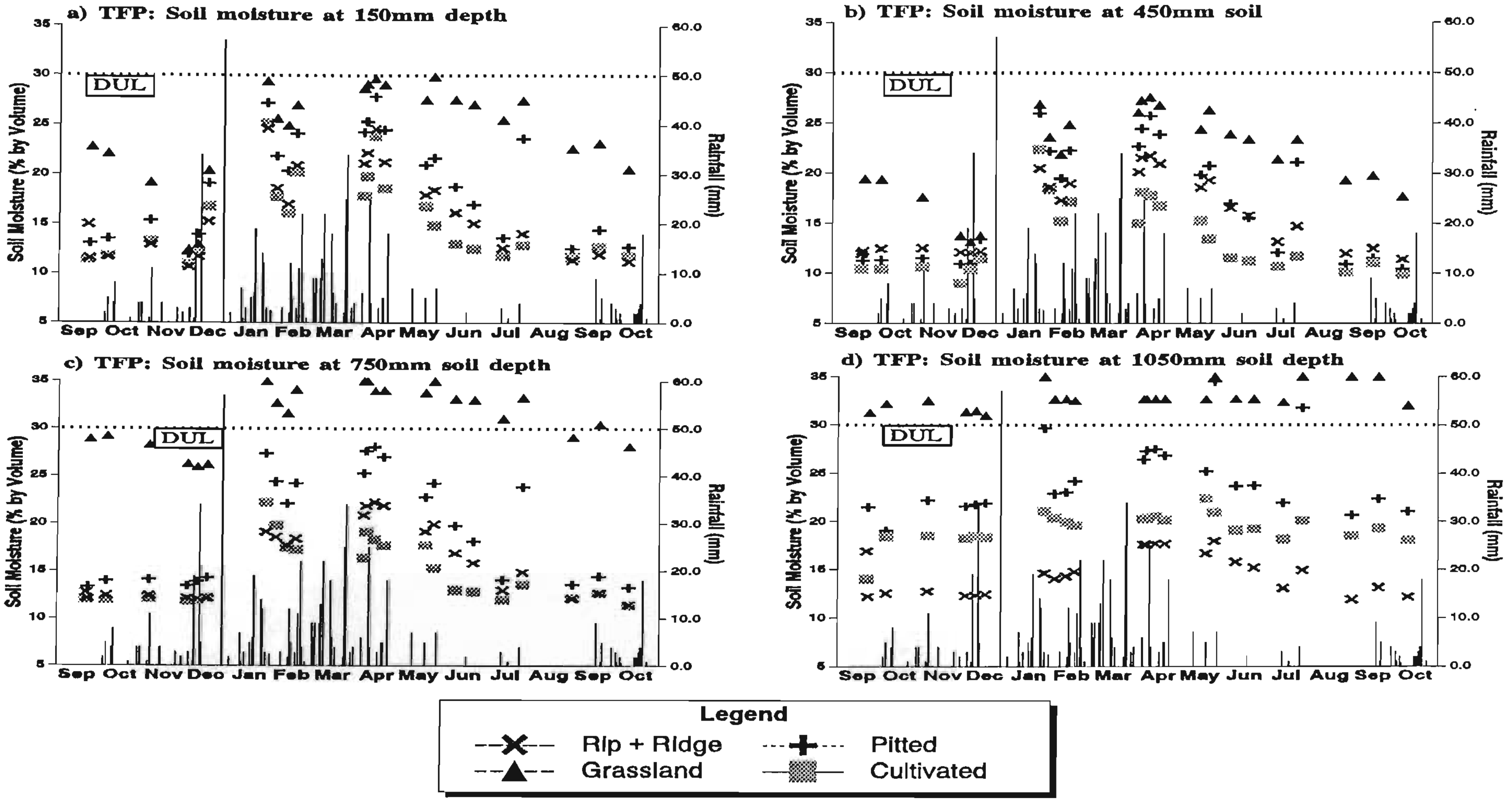

Figure 20. Time trends of soil moisture content for different depths and the different site preparations at Tree Fern Pool for the period September 1994 to October 1995.

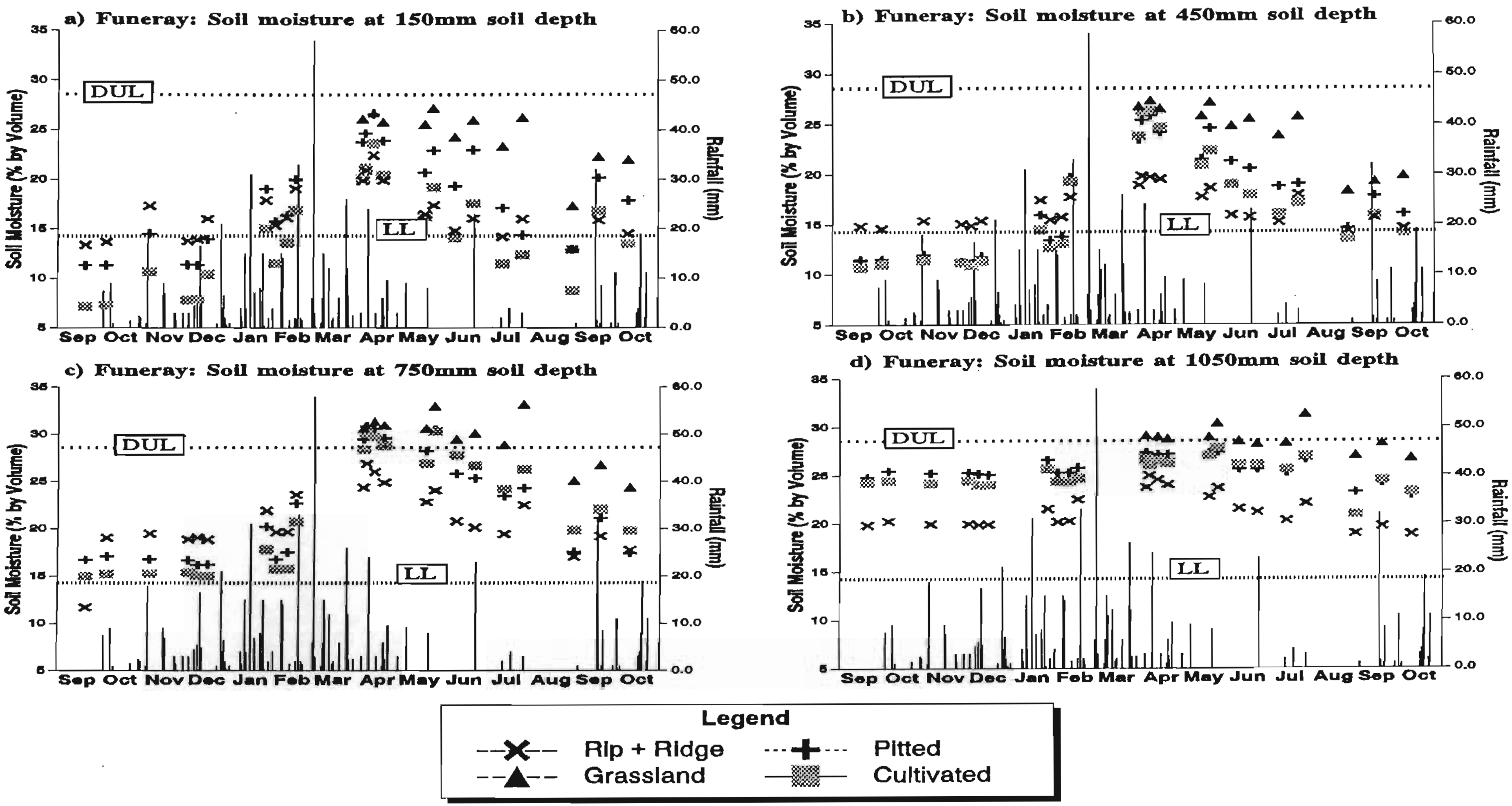

Figure 21. Time trends of soil moisture content for different depths and the different site preparations at Funeray for the period September 1994 to October 1995.

3.2.5.2 Comparison of soil moisture between grassland and site preparation

From Figures 19, 20 and 21 it is evident that in the surface layers at both sites, soil moisture content on the grassland is greater than on the various forest site preparations. Musto (1993) found similar trends while studying soil moisture contents under *E. grandis* trees at Crofton near Ixopo and Beaconhill near Howick. As did Jewitt (1991) in a comparison of soil moisture between grassland and sites planted to *E. grandis*, *P. patula* and *A. mearnsii* at Glendale in the Midlands of KwaZulu-Natal. Lower soil moisture under forest conditions results from trees on the prepared treatments being able to exploit moisture from the soil profile more than on the grassland "control" due to:

a) root development to greater depths for trees than for grassland, and

b) higher overall water use rates from the afforested sites as a result of a larger canopy transpiring throughout the year when soil moisture is available.

3.2.5.3 Comparison of soil moisture content between site preparations

Figures 19, 20 and 21 depict that generally the pitted plots contain more soil moisture than the rip and ridge and cultivation preparations respectively. Soil moisture content differences are clearly a result of the different site preparations. Past work at Bloemendal and Glendale (Jewitt, 1991; Boden, 1992) in KwaZulu-Natal has shown soil moisture differences between different forest site preparations to be a function of the extent to which the soil and existing vegetation had been disturbed. At Bloemendal and Glendale, and now at Tree Fern Pool and Funeray, more intensive site preparations have resulted in lower soil moisture levels. This indicates that soil water use by trees on more complete site preparations is greater than on sites with lower degrees of site preparation. Hensley *et al.* (1995) provided support for this assertion in their soil water extraction results (Table 6). The reasoning behind this conclusion is explained in the following paragraph.

Table 6. Soil water extraction rates at Tree Fern Pool (0-1800mm) from 26 January-10 February 1995, and at Funeray (0-1200mm) from 13 April-20 April 1995 (after Hensley *et al.*, 1995).

Site preparation	**Extraction rate ($mm.d^{-1}$)**	
	Tree Fern Pool	Funeray
Grassland	1.5	not available
Pitting	2.3	2.4
Rip and Ridging	1.3	1.9
Cultivation	4.1	3.6

Ploughing virgin grassland should destroy competing vegetation and break up the dense adventitious root system that tends to clog up pores in the soil surface (Norris and Stuart, 1994). Ploughing is therefore likely to increase infiltrability into the soil, *i.e.* more water becomes available to the roots (Schulze *et al.*, 1995). Hence, with more intensive site preparation at tree establishment, roots are able to develop better (Norris, 1991b) and colonise the topsoil more rapidly (Boden, 1991b). Therefore, more intensive site preparation increases the proliferation of roots, while on pitted plots, poorer root development generally prevails (Metelerkamp, 1995), except for the tap roots. Boden (1992) found at Glendale that *E. grandis* trees on the pitted plots displayed inferior root development when compared to that on the completely prepared plot, which had a dense and vigorous lateral root system in the upper 250mm of the soil profile. Also at Glendale, Jewitt (1991) found that tap roots (rather than the lateral root systems) in the pitted site were still dominant, although they tended to be smaller than on the completely prepared site.

Tree growth therefore appears consistently better under conditions of more complete site preparation, followed by growth on terracing, ripping and pitting (Görgens and Lee, 1992). The enhanced soil moisture availability, however, results in more rapid soil moisture utilisation and hence in drier soils (and lower water yields) under such well prepared site conditions.

While the general trend in Figures 19-21 is for soil moisture content to be lowest near the soil surface and increase with depth, at Funeray (Figure 21), a more uniform soil moisture content over time is apparent on the Rip and Ridging site preparation than on any of the other site preparations. This is summarised to be as a result of:

a) relatively higher soil moisture contents between ridges at the shallower depths, possibly caused by ridging retaining the soil moisture on site, and
b) relatively lower soil moisture contents at greater depths since root development has taken advantage of the rip line, and the roots are able to extract this water from the lower soil horizons.

3.2.5.4 Apparent rooting depths

The apparent depths of the water table at Tree Fern Pool (Figures 19a and 20) concurs with the idea that root development is greater on more completely prepared sites. Relatively shallow rooting concentrations on grassland plots have apparently not had an impact on the water table depth at about 1050mm, while on more completely prepared sites, the water table may have been "drawn down" to depths exceeding 1900mm.

At Funeray (Figure 21), soil moisture levels drop below the Hensley *et al.* (1995) value of Lower Limit of Available Water (LL) only in the top 450mm of the soil profile, while exceeding their DUL only at a depth of 750mm. This is evidence for roots probably not having developed beyond 450mm depth at Funeray, beyond which depth soil moisture content increases rapidly, indicating sources of untapped soil moisture.

3.2.5.5 Seasonal soil moisture trends

Figures 20 and 21 depict seasonal soil moisture trends at the two study sites. Generally, and as expected, the soil is wetter during and immediately following the rainy season

(January-April 1995) and drier during the dry season (August-October 1995). The increase in soil moisture content during the wet season is not as evident on the grassland control plot as on the site preparation plots. This is possibly explained by shading of the soil surface by leaves and litter reducing possible water losses through evaporation.

Jewitt (1991) found similar results at Glendale, where the largest soil moisture differences between site preparations also occurred in the driest months, mainly as a result of high soil moisture extraction by trees on cultivated sites. This indicates that cultivated site preparation allows the roots to make use of this available water during dry periods.

Furthermore, during the dry months, the soil moisture content on the grassland plots is maintained at a relatively high level since grassland scenesces and does not transpire water actively while trees continue to utilise soil moisture. From April 1995 onwards (*i.e.* after the wet period), soil moisture on sites with trees decreased more rapidly than on grassland, indicating greater demand on water resources placed by the trees.

With time, soil moisture contents at depth should decrease as and when the trees utilise more water to grow. It is apparent that this trend is not yet evident at either of these sites. Two possible reasons for this are that:

a) high rainfall in this area replenishes soil moisture, and
b) at five years of age, the pines are still using relatively less soil moisture than they would be at maturity, when deeper root systems are fully established.

To conclude this Section, field results have shown that high MAPs do not necessarily yield higher soil moisture contents, that grassland plots are relatively wetter than adjacent tree plots, that soil moisture contents follow seasonal rainfall patterns and that soil moisture contents under trees decline in the first half meter of soil, but increase beyond that depth.

3.3 The Effect of Irrigation on Soil Moisture Content

Irrigation of commercial timber plantations is yet to be considered an economically viable solution to the timber supply problem, especially in South Africa. This is so despite the obvious growth advantages that are possible when irrigating trees. This sub-Chapter details post 1993 results from the only commercial tree irrigation experiment in southern Africa, situated at Mkuze in north-eastern KwaZulu-Natal. Olbrich *et al.* (1992) and Zartmann (1992) have previously found "profound" differences in the soil water status, LAI, root density, water use and tree growth indices at the Mkuze irrigation trial. Figure 22 depicts the differences in growth that are possible due to irrigation.

The intention of presenting these research results is not only to continue tree water use analyses undertaken previously at Mkuze by Zartmann (1992). These results also form part of a broader study into the regionalisation and characterisation of water use by commercial tree species for purposes of applying findings in forest hydrological models. The reader is referred to Zartmann (1992) for detailed site information for the irrigation trial; Section 3.3.1 merely summarises the research being undertaken at Mkuze.

Figure 22. Growth differences resulting from irrigation on the same soil and clone at the irrigation trials at Mkuze.

3.3.1 Site and experiment details

In May 1990 an irrigation trial consisting of *Eucalyptus* and *Eucalyptus* hybrid clones was planted by Mondi Forests at Mkuze. The MAP of 608mm at Mkuze is considerably lower than the 800mm generally required for afforestation (Görgens and Lee, 1992). This Section of Chapter 3 assesses soil moisture content patterns from observations on plots containing two *Eucalyptus* clones, *viz.* GC540 and TAG5, each grown on two distinct soil forms, *viz.* Bonheim and Shortlands, and each subjected to four irrigation application regimes in addition to there being a rainfed (control) treatment. Tree growth is influenced by the irrigation, and by the end of 1995 after five years of growth, the trees on the higher irrigation treatments were ready for harvesting, effectively halving rotation periods for eucalypts in this area of KwaZulu-Natal characterised by high temperatures. This experiment at Mkuze provides a unique opportunity to study tree water use (and growth) under different water application scenarios. In the specific study reported in this dissertation, soil moisture was monitored weekly from March 1994 to August 1995 by Mondi Forests' staff using the NMM technique. This period included intensive daily monitoring with the assistance of a vacation student during July 1994 and January 1995 to enable comparisons of soil moisture content and tree water use to be made during relatively dry and wet periods respectively. Relevant plot and tube numbers for the irrigation trials are given in Appendix B.

3.3.2 Selection of clones for soil moisture studies

Ultimately, information on water use patterns of individual tree species is needed for modelling purposes, and not only the broad differences with respect to genus. Of 20 different *Eucalyptus* clones in the Mkuze irrigation trial two, *viz.* TAG5 and GC540, were selected for this study, since these clones were considered to be of greater importance to the commercial forest industry. Important properties of these clones that influenced their selection are summarised as follows. The TAG5 clone may be described as:

a) being similar to the standard *E. grandis* species, thereby facilitating a comparison with results from other research concentrating on *E. grandis*,

b) being an excellent grower in areas where *E. grandis* can be grown,
c) being relatively disease resistant except in drought conditions, but
d) having relatively poor pulping properties.

On the other hand, the GC540 clone is described as:

a) being a *E. grandis x camaldulensis* hybrid clone,
b) having relatively favourable growth properties,
c) possessing the ability to continue growing even in drought conditions,
d) being relatively resistant to disease, and
e) having excellent pulping properties.

3.3.3 General hypotheses of the effect of irrigation on soil moisture

In this research it was hypothesised that:

a) different irrigation treatments would result in different soil moisture regimes, with the rainfed treatment displaying the lowest and the highest irrigation treatment the highest soil moisture content,
b) different clones would have different soil water use patterns, with TAG5 (better growth) postulated to utilise more soil water than GC540,
c) with respect to the soil profile, most of the soil moisture would occur near the surface where irrigation is applied (with the exception of the rainfed treatment), or below the rooting zone, while lower soil moisture contents would be expected in that part of the soil horizon where most roots occur, and that
d) under conditions of insufficient moisture supply, total profile soil moisture should decrease over time from the planting date due to greater water usage as trees grow to maturity.

3.3.4 Results

Results from the irrigation trial are presented by way of graphs depicting changes in soil moisture with soil depth and over time.

3.3.4.1 Total water received

Values of total, average daily and fraction of A-pan water received are contained in Table 7 and Figure 23 summarises the irrigation and rainfall inputs, and trends for the first year of analysis. Although the total water received by the different treatments is in the required sequence, the Shortlands soils Treatment 2 and the Bonheim soils Treatment 3 have received relatively too much water as illustrated in Figure 23. This is a result of ongoing problems with the irrigation system caused mainly by poor irrigation water quality as identified previously by Zartmann (1992). This could have repercussions on respective soil moisture contents and results thus may have to be regarded with circumspection. For this reason and for the sake of analytical simplicity, results for the rainfed (control), "lowest" (Treatment 1) and "highest" (Treatment 4) irrigation treatments only will be presented.

Table 7. Total water received by all treatments at the Mkuze irrigation trial for the first year of analysis (February 1994 - January 1995).

	Total (mm)	**Average Daily (mm)**	**% of A-pan equivalent evaporation**
Rainfed	490	1.34	0.27
Treatment 1	843	2.31	0.46
Treatment 2	1208	3.31	0.66
Treatment 3	1367	3.75	0.75
Treatment 4	1461	4.00	0.80

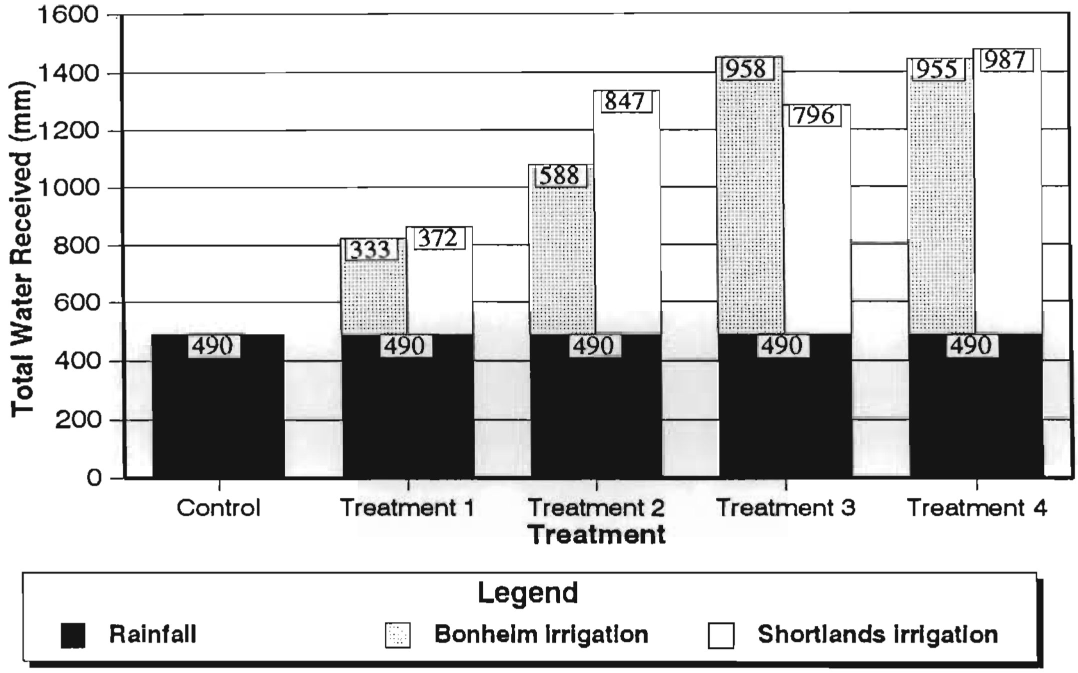

Figure 23. Total annual water received on different treatments at Mkuze for the period February 1994 to January 1995.

3.3.4.2 Soil moisture variation with depth

Figure 24 summarises time averaged soil moisture patterns with soil depth of the three selected water supply regimes and for the four soil/clone combinations. The most noticeable trend gleaned from Figure 24 is that Bonheim soils generally display higher water contents than Shortlands soils, irrespective of clone. This is so despite the Shortlands plot receiving marginally more irrigation during the study period as illustrated in Figure 23. One viable reason for this is that Bonheim soils have higher water retention capabilities than Shortlands soils because of their higher clay contents (Zartmann, 1992). Another possible reason is that roots may not have been able to penetrate the Bonheim soils (as a result of their higher bulk densities) to the same degree as on the Shortlands soils, and hence have not been able to utilise the soil moisture store to the extent that the trees on the Shortlands plot have. Evidence for this exists in the apparent depths of the active rooting systems on the irrigated treatments. Roots seem to be concentrated at a depth of 1200 to 1600mm on the Shortlands plot and at about 800mm (shallower) on the Bonheim plot, as indicated by relatively low soil moisture contents (Figures 24b and c). A site inspection revealed that on rainfed treatments the trees on the Bonheim soils have survived, while on the Shortlands control treatment the mortality rate is high, supporting evidence for lower soil moisture contents on the Shortlands treatments.

Table 8. Characteristics of Shortlands and Bonheim soils, where SAT is saturation, BD is Bulk Density, PWP is the Permanent Wilting Point, DUL is the Drained Upper Limit and PAW is the Plant Available Water (after SASEX, 1995).

Soil	**Characteristic**	**Depth (m)**		
		0.05	**0.15**	**0.60**
Shortlands	SAT (vol %)	42.6	42.2	41.4
	BD (Mg/m^3)	1240	1287	1250
	PWP (vol %)	17.5	21.1	24.1
	DUL (vol %)	32.0	33.0	30.0
	PAW (vol %)	14.5	11.9	5.9
Bonheim	SAT (vol %)	34.9	34.9	36.0
	BD (Mg/m^3)	1760	1760	1720
	PWP (vol %)	15.8	15.8	24.1
	DUL (vol %)	34.7	34.7	35.5
	PAW (vol %)	18.9	18.9	11.4

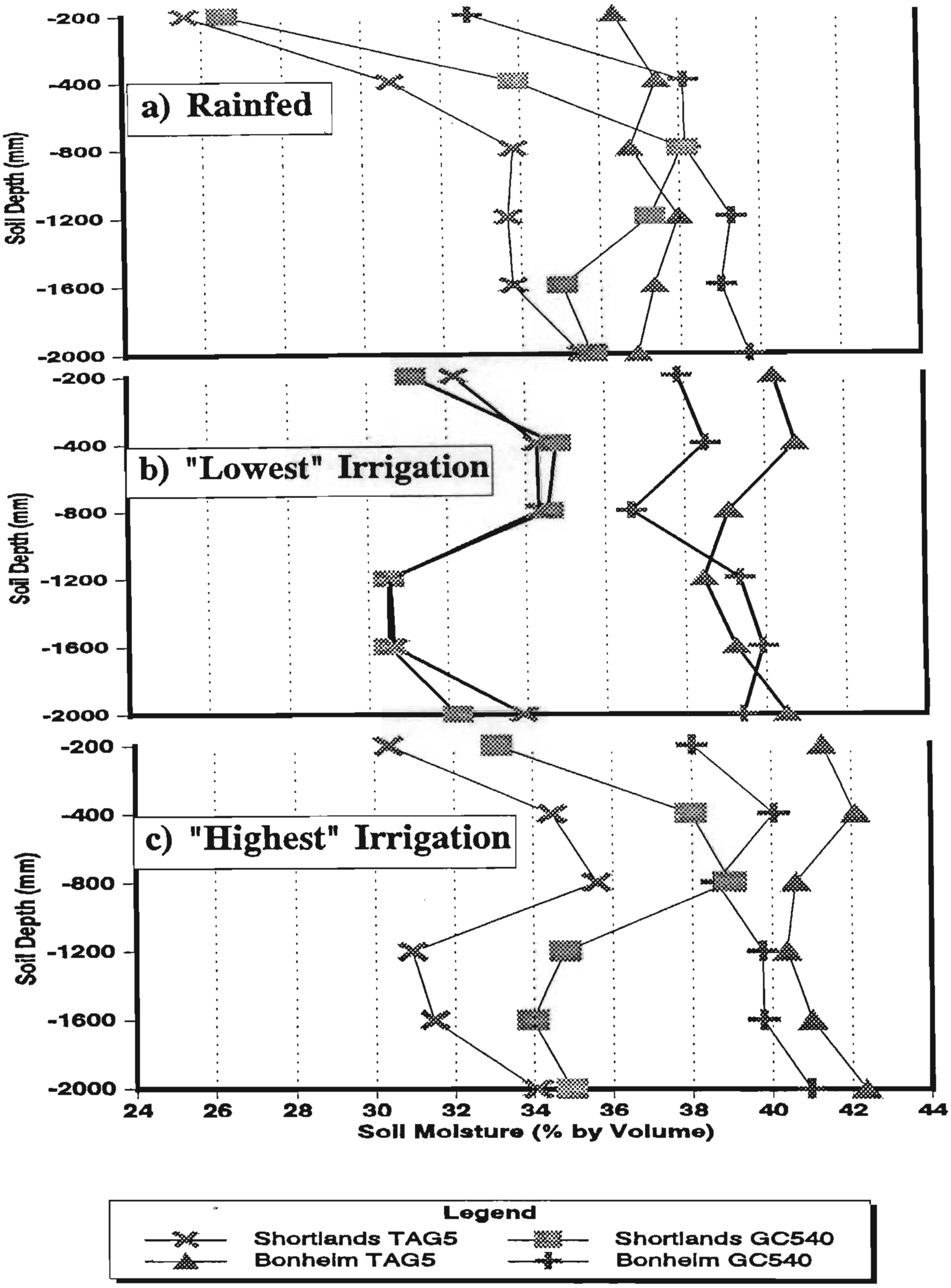

Figure 24. Time averaged soil moisture contents with depth for different soil/clone and treatment combinations at Mkuze from February 1994 to August 1995.

As expected, the rainfed treatment is relatively dry at the surface, since minimal canopy and litter cover exist (particularly on the Shortlands soil) to protect surface layers from soil water evaporation. Also, those trees that have survived on the rainfed treatment would not have received sufficient water to develop deep rooting systems and hence would only be able to use soil moisture from near the surface. Olbrich *et al.* (1992) concluded from studies at Mkuze that on the rainfed treatments, roots tended to have higher densities near the surface than on irrigated treatments, thereby concentrating water usage near the surface. The rainfed treatment also displays large volumes of unexploited water at depths greater than 600mm. This indicates that recharge from the surface is able to reach 2000mm, but appears not to be exploited by roots to any significant degree.

Dye *et al.* (1994) found on the Nyalazi hybrid trial in KwaZulu-Natal that the mean daily sap flow of the GC540 clone was greater than that of the TAG5 clone, and that the WUE of the GC540 clone was less than that of the TAG5 clone. Also, in Olbrich *et al.* (1992) it was concluded that at Mkuze on the Shortlands soils, the GC540 clone is consistently the fastest transpiring of all clones on the irrigated treatments, despite GC540 consistently having the lowest LAI. The above-mentioned results imply that water usage by GC540 clones is greater than that by TAG5 clones. For the current study, this hypothesis holds on the Bonheim soil, but not on the Shortlands soil, as indicated by the graphical summaries of irrigated treatment responses (Figures 24b and c). To explain further, on the Bonheim soils the TAG5 clone generally displays higher water contents than the GC540 clone (implying higher water usage by GC540, as in the above-mentioned conclusions), whereas on the Shortlands soil this trend is reversed (contrary to the above-mentioned conclusions). This anomaly between moisture contents on the two soils may indicate that certain clones have "affinities" for certain soil (and possibly other) conditions. The importance of the soil in species/site matching has been indicated by Ellis, Donald, Theron and Jacobs (1993) and emphasises the need for the inclusion of these trends in a multi-faceted, fully integrated decision making tool such as the *ACRU* FDSS.

3.3.4.3 Soil moisture use over time

For an analysis of soil water use over time, the Bonheim GC540 combination is presented in Figure 25. Figures depicting similar trends (subject to the relative differences depicted in Figure 24) for the other three clone/soil combinations are included in Appendices C, D and E. The A horizon (*i.e.* topsoil) is defined for this analysis as 0 to 500mm depth, while the B horizon (*i.e.* subsoil) extends from 500 to 2000mm, the latter also the maximum NMM monitoring depth. Over time, a general increase in soil moisture in both horizons is evident, especially in the A horizon, as a result of additional supplies of moisture (rainfall). The B horizon soil moisture increases to a lesser extent than that of the A horizon (as a result of less redistribution of rainfall and since most of the active roots occur in the B horizon, according to Figure 24). As a result, the A horizon becomes wetter in summer than the B horizon on the irrigated treatments. This general increase in soil moisture in both horizons over the study period suggests that the steady downward trend of soil moisture over time depicted by Zartmann (1992) may have been a result of young trees' initially using relatively more soil moisture in their establishment phase than at their current age of five years. After five years of growth, soil moisture patterns appear to be influenced largely by seasonal differences in precipitation supply.

The B horizon soil moisture content on the rainfed treatment decreases marginally over time, with maximum soil moisture contents occurring during July 1994, despite no precipitation occurring during this month. This is probably due to those rainfed trees that have survived, decreasing their water usage as a result of a lower evaporative demand in the winter months. Schulze (1994) has suggested that trees often decrease their transpiration rate during winter months and only use enough water to "tick over" until the next wet season.

To conclude this Section, field results have shown that higher irrigation water application quantities yield higher soil moisture contents, that clones with better growth rates do not necessarily deplete soil moisture contents to a greater degree, that the bulk of the soil moisture content is concentrated either near the irrigated surface or below the rooting zone, and that trees may in fact use less water as they mature.

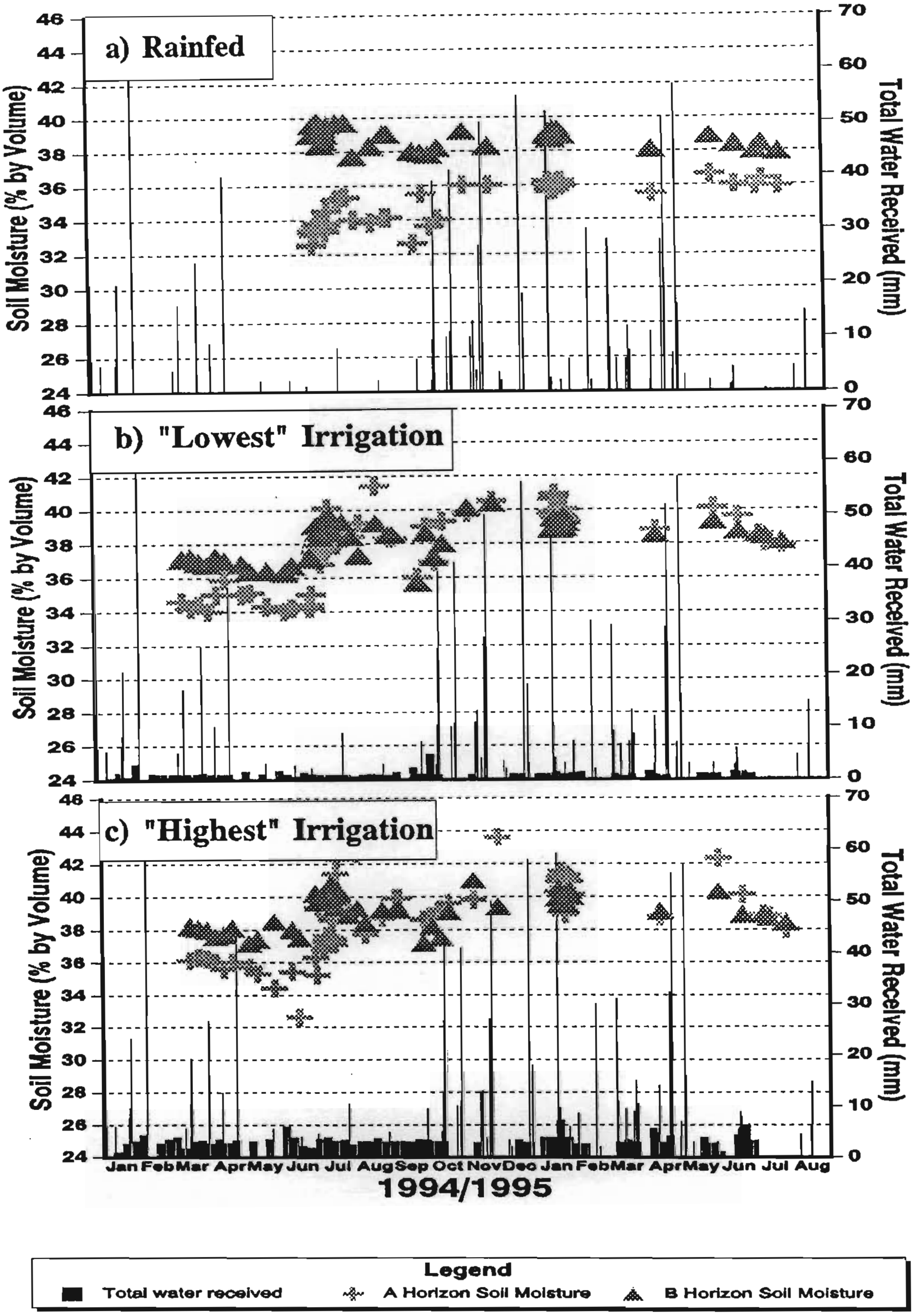

Figure 25. Depth integrated soil moisture trends over time for the Bonheim GC540 combination for the three selected water application regimes at Mkuze for the period March 1994 to August 1995.

3.4 General Conclusions Regarding Application of Results to Modelling

Possibly the largest challenge faced by forest hydrology modellers is that of spatial and temporal heterogeneity of natural processes. Results presented in this Chapter confirm the heterogenous nature of forest hydrology processes. Nevertheless, important relationships (including their magnitudes) between site preparation and tree water use as well as between irrigation and tree water use, have been identified. These and other results support the progress that is currently being made toward a better understanding of forest hydrological processes and the prediction capabilities of forest hydrology modelling.

The *ACRU* FDSS developed by Jewitt (1991) contained three varying degrees of site preparation. Site preparation results presented in this Chapter show that besides a grassland control, it may be sufficient to distinguish only between a "good" (cultivated) and a "poor" (pitted) site preparation for forest hydrology modelling. The complex tree water use and movement mechanisms caused by different site preparation techniques have yet to be fully understood.

Results from the NEC site preparation experiment work show that more intensive site preparation enhances root and canopy growth by allowing roots to access more water. Hence, with more complete site preparation, catchment water yields should decrease relatively more than with lesser degrees of site preparation.

Results from previous studies (Zartmann, 1992) and field observations at the Mkuze irrigation trials show that under conditions of non-limiting water, very rapid tree growth is possible. Evidence does, however, exist for an upper threshold quantity of water that is necessary for potential economically viable tree growth. At Mkuze, this threshold occurs at about 1400mm.annum^{-1} (Treatment 3), whereafter additional water supplies result in diminishing additional yield returns.

The clearly decreasing trend over time of soil moisture content at these irrigation trials, as depicted by Zartmann (1992) for then one to two year old trees, is no longer evident in results presented in this Chapter. Soil moisture content appears, in fact, to be steadily increasing. From these results it may be concluded that young trees use large quantities of water to establish themselves, whereafter, despite the trees being more mature, soil water use declines.

The extent to which additional supplies of water through irrigation are utilised by trees depends on not only the genus, but also the species. However, it is at the present stage still premature to include water use differences between different species in a forest hydrology model for South Africa. The reasons for this conclusion are that:

a) the study of the growth and water use aspects of new clonal varieties is still in its infancy, partly because

b) rapid development of the numerous different clonal varieties has outstripped the capability to undertake water use research on them, and subsequently

c) many of these new clones have, as yet, not been accepted by the forest industry for commercial planting.

* * *

In this Chapter the effects of site preparation and irrigation of commercial plantations on soil water content and tree development were evaluated, with results having been obtained through fieldwork in the NEC region of the Eastern Cape and at Mkuze in KwaZulu-Natal. This knowledge is included in the development of an upgraded *ACRU* FDSS module, which is discussed in Chapter 4.

4. REFINEMENT OF THE *ACRU* FOREST DECISION SUPPORT SYSTEM

This Chapter describes the development of a refined *ACRU* FDSS and a stand-alone PC-based forest hydrology impact assessment model called *ACRU* Forest. This interactive model, developed specifically for application in South Africa, Lesotho and Swaziland, enables objective forest hydrology response related decisions to be made with relative ease and in a short time. The *ACRU* Forest model is dynamic and multifunctional, and is capable of replacing certain current techniques used as aids in forest permit allocations. The model has been developed using information from Chapters 2 and 3, from a series of workshops, and a Quaternary catchment database for southern Africa produced by Meier (1996). The first version of the *ACRU* FDSS developed by Jewitt (1991) has been used as a foundation on which to make refinements as well as major conceptual and practical changes.

4.1 The Need to Model

The natural environment is a complex system. Modelling of the environment is necessary, in order to *inter alia*, enable prediction of future events and responses with some degree of certainty. Much of the problem in prediction of forest hydrological responses occurs because the mechanisms by which soil water exerts its control of the evaporation and transpiration processes at the stand level are not entirely clear (Gholz *et al.*, 1990). Deterministically based models such as the *ACRU* system have been suggested as being suitable for the prediction of impacts of forest management (Görgens and Lee, 1992). The reason for this is that structurally, the potential exists to change any process module of the modelling system as and when improvements are made and then to predict responses within a relatively short period of time. Since forest water use and the associated reduction of streamflows are contentious issues, a future system for the allocation of afforestation permits (or other landuse changes), based on sound process orientated models, is required to enable effective decision making. Currently, these decisions are being made using the socalled APS.

4.2 The Afforestation Permit System

The APS (Van der Zel, 1995) determines where, when and in what quantities catchments may be afforested to commercial tree species, by the allocation of planting permits. Its basis is a series of curves developed by Nänni (1970) which depict streamflow reductions with afforestation. Since its inception in 1972, the APS has been widely criticised, *inter alia* by Bosch and Von Gadow (1990), Jewitt (1991) and Görgens and Lee (1992), and according to Asmal (1995b), has become inadequate to address environmental issues and other demands related to water and forestry of a South Africa of the future. Despite the APS having been periodically updated, the process of permit allocation has not been transparent (*ACRU* FDSS Workshop No2, 1995) and the process has therefore lost the confidence of the forest industry. Edwards (1995) suggests that the forest industry has not been treated impartially with regards to water use aspects when compared with other water users. Ferguson (1995) has even suggested that the APS is possibly unconstitutional in that it takes away landowners' rights without compensation.

The main reason for the forest industry's despondence about the APS is that it believes that it has been unfairly discriminated against since most other landuses may develop unhindered and thus potentially use more water than forests (Chapter 2). For example, of the total surface area of South Africa, 1.05% and 1.2% respectively is under irrigation and under afforestation. However, irrigation in South Africa uses seven times as much water as forestry (Edwards, 1995), while he states it is not being subjected to the same degree of control in its expansion as forestry. It may therefore be argued that utilisation of all natural resources should be subject to some form of Environmental Impact Assessment (EIA), and not only the forest industry. Policy in future will have to acknowledge that forestry has earned "the right to the water it requires" (Versfeld, 1995). At the time of writing (December 1995), procedures for granting new afforestation permits may include an EIA of the effects of the proposed afforestation on, *inter alia*, water resources.

When calculating the hydrological impacts of afforestation, the impacts of the current landuse on hydrological responses is often compared to that of the anticipated afforestation.

This practice is essentially unfair since the conversion of land from virgin conditions to the present landuse may have had a larger impact on water resources than the additional impact of the proposed afforestation (Schulze, 1995a). Currently, the APS does not take this into account, although this is a scenario that a future afforestation impacts system should be able to simulate.

Restrictions on forestry have in the past been based on expected impacts on mean annual flows, rather than on low season flows (Versfeld, 1995). It is often these low flows that are critical to downstream users in regard to both quantity and quality, and the impact of afforestation on low flows are generally relatively larger than on annual flows.

In addition to the APS, there are several other models that have potential to assess the impacts of planting of commercial forests in South Africa. These include, *inter alia* Bosch and Von Gadow's (1990) linear programming model, the Forest Hydrology Information System (FHIS) described by Le Maitre and Scott (1995) and the *ACRU* FDSS (Schulze *et al.*, 1995). Whichever approach is adopted for forest permit allocation, the need for objective, accurate and process-based forest hydrological modelling is now without doubt. The remainder of this Chapter describes the refinement of the *ACRU* FDSS as a model that could fulfil this need.

4.3 Infrastructure of the *ACRU* FDSS

The *ACRU* FDSS uses the *ACRU* agrohydrological modelling system as its computational "driver". *ACRU* is a physical conceptual, multi-layer soil water budgeting model that operates at a daily time step (Schulze, 1995b). *ACRU* is generally regarded as an accurate multi-purpose tool for the evaluation of process responses in the hydrological system.

The structure of the first version of the *ACRU* FDSS was based on a series of options regarding tree genus, tree age and intensity of site preparation. This information was supported by a large interactive information base regarding vegetation and soil characteristics relating to the various options. There were, however, shortcomings in this initial version, some of which are addressed in this Chapter, which sets out to produce an updated version of the FDSS. These shortcomings, presented by Jewitt (1991) and Görgens and Lee (1992) as future research needs include the need to:

a) represent potential tree water use and canopy storage more accurately by using the LAI concept,
b) account for root extraction patterns and root distribution adequately, including the introduction of the concept of root colonisation,
c) represent soil moisture extraction patterns at different sites at species level, and not only for different genera,
d) perform more research to confirm that eucalypts use more water than other commercially grown genera (Chapter 2),
e) develop an automated forest dynamic landuse file to account for forest growth and management changes over time,
f) improve model representation of litter interception since this process is currently based on simple litter drying curves derived from empirical results, and hence may not be universally applicable,
g) "drive" the evapotranspiration process by the Penman (1948) equation, although insufficient data prohibits this,
h) research comparative water use patterns in cool temperate regions and warm humid areas, and
i) verify and publish results.

The aim of this dissertation's research was therefore to improve as many of these shortcomings as possible for inclusion in an upgraded FDSS. In order to achieve this, information and data were obtained primarily from *ACRU* FDSS Workshop No's 1, 2 and 3 (1995), from subsequent communication with some of the participants, from a detailed literature search (Chapters 2 and 4), and from fieldwork studies (Chapter 3). The results presented in this Chapter are thus a synopsis of information gleaned from these sources.

4.4 Concepts and Methodology of the *ACRU* FDSS Workshops

A series of workshops on forest hydrological processes was held, based on informal discussions in small select groups of some of South Africa's foremost forest hydrologists. The objective of this workshop series was to:

a) stimulate constructive discussion on relative issues pertaining to forest hydrological modelling, prompted by a series of structured questions and guidelines (an example is given in Appendix F), in order to
b) extract expert knowledge consisting of commonly agreed upon trends regarding forest hydrological parameters, for purposes of
c) improving forest hydrological modelling by the *ACRU* system.

Fieldwork and literature searches have historically been the domain of scientific research. The workshop concept, however, has a significant additional contribution to make towards research. In this study, the use of workshops proved to be an invaluable source of information. The main advantages of using workshops (in addition to fieldwork and a literature search) is that they are:

a) time efficient,
b) reactive and interactive,
c) a means of collecting and collating up-to-date information often not yet published, and
d) a platform for co-operation and constructive criticism.

Data and information from different workshop participants were often not directly comparable. In such circumstances, hydrological judgement had to prevail in order to determine scientifically correct trends. When direct information was not available from the workshop participants, trends were interpolated or extrapolated. This provides an element of subjectivity to some of the results. Questions as to whether enough field data exist to be able to perform a parameter assessment objectively were raised at the workshops. It was, however, suggested that in addition to collating currently available information, the workshops would assist in indicating areas for future research (*ACRU* FDSS Workshop No1, 1995). For example, a paucity of information on Crop Coefficients (K_{cm}) and rooting patterns emerged from the workshops. K_{cm} is not reviewed in this dissertation since it was proposed that for the revised FDSS water use by trees be "driven" by the LAI rather than the K_{cm} concept (Schulze, 1995a). Nevertheless, relationships between LAI and K_{cm} do exist in *ACRU*, should they be required.

4.5 Results from the Workshops

This Section describes part of the *ACRU* FDSS modification process whereby LAI, I_l and rooting components are considered for different:

a) forestry regions in South Africa,
b) rotation periods,
c) rainfall regimes,
d) genera, and
e) management practices, including site preparation and thinning.

Results from different species are assumed to be representative of the three main genera, *viz*. eucalypts, wattle and pines, since not enough is, as yet, known about the comparative water use aspects of different species. This decision was confirmed at the *ACRU* FDSS Workshop No2 (1995) where it was suggested that although forest companies are opting for hardier species, for example *E. dunnii* and *E. macarthurii* over *E. grandis*, researchers should only be studying generalised water use patterns by different genera and not yet those of different species.

4.5.1 Leaf area indices

General relationships between LAI and tree water use have been reviewed in Chapter 2. Sufficient research has been completed on LAIs in South Africa and abroad to begin using general LAI trends in forest hydrology modelling. Problems were, however, encountered in the determination of LAI trends. These include that:

a) LAIs have often been determined in other countries (for example Anderson, 1981) for species other than locally grown ones and for rotation periods very much longer than would be representative of those in South Africa,

b) LAI studies in South Africa have focused on eucalypts, causing a paucity of data on other genera, and

c) LAIs have, historically, been measured using several different methods, resulting in uncertainty as to whether the values are comparable with each other or not.

For the new FDSS, LAI at planting is assumed to be that of grassland under fair hydrological condition, *viz.* 0.7. Thereafter, LAIs are assumed to increase with age, the magnitude of which is dependent on the genus, regional climatic conditions, the timing and degree of thinning, and to a lesser degree, the competition by tree roots for water as they become more developed (*ACRU* FDSS Workshop No1, 1995). Generally, during the first eight years of a rotation, the LAI of eucalypts is greater than that of wattle and pines respectively, whereafter LAI for pines is greater than that of wattle and eucalypts respectively. This is as a result of pines growing at relatively slower rates (with consequent longer rotations) than the other genera.

LAI varies within an annual climatic cycle (Gholz *et al.*, 1990), and in the dry season, LAI is estimated to decrease by about 1.0 in response to soil water stress (*ACRU* FDSS Workshop No1, 1995). However, a decision was made not to vary LAIs intra-seasonally, since LAI measurements are rarely made for periods longer than a week at a time.

Peak LAIs for pines are generally higher, and occur later in the rotation period, than those of eucalypts and wattle respectively (*ACRU* FDSS Workshop No2, 1995). From the literature studied, the maximum LAI obtained for pines was 8.3 on a 15 year old *P. taeda* stand in North Carolina, USA (McCarthy *et al.*, 1991), while for eucalypts, Honeysett and Beadle (1987) determined a LAI of 6.0 on four year old *E. delegatensis* in Australia. These extreme LAI values were considered too high for South Africa, based on local research into LAI. Dye (1987) obtained a peak LAI for eucalypts of 4.2 in a 5.5 year old *E. grandis* plantation at the Frankfort State Forest in Mpumalanga. For the development of the FDSS, maximum values of 5.5 and 4.5 were therefore assumed to be representative of pines and eucalypts respectively. From information supplied during the various workshops and in the literature, peak LAIs are assumed to occur at 10, 7 and 6 years of age for pines, wattle and eucalypts respectively. One exception to this occurs under optimum growing conditions in Zululand where full canopy closure can already occur at 1.8 years (*ACRU* FDSS Workshop No1, 1995), and LAIs were assumed to peak at three years.

After peak LAIs have been attained, LAI tends to decrease, and according to Roberts (1995), will eventually become more or less equivalent for the different genera toward the latter part of a rotation. The LAI decline is due to increasing competition by roots for available soil water and due to thinning (*ACRU* FDSS Workshop No1, 1995). Dye (1993c) confirms this by stating that *E. grandis* LAIs of 3.0 at two years of age dropped to 1.5 at an age of nine years on a site near Sabie in Mpumalanga.

Values of LAI were also inferred indirectly from other studies for the development of LAI trends for the FDSS. For example, since a relationship exists between growth and LAI, the WUE curves (Figure 26) developed by Roberts (1994) were used to infer values of LAI. Figure 26 shows that warm, wet areas (exemplified by Kwambonambi in Zululand) would be expected to reach a higher LAI, and sooner, than at relatively drier, cooler areas such as Clan Syndicate near Cramond and Kiaora near Ixopo, both in KwaZulu-Natal. These results of Roberts (1994) provide support for assuming in the development of the new FDSS that LAIs in Zululand should generally be higher than those in Mpumalanga, followed by LAIs in KwaZulu-Natal and the Eastern Cape respectively.

Olbrich *et al.* (1992) used data from 1.5 year old *E. grandis* trees at the Mkuze irrigation trial (*cf.* Chapter 3.3) to suggest the LAIs given in Table 9. Corresponding effective MAPs for the various irrigation regimes were obtained from Summerton and Schulze (1995). These Mkuze results indicate the relative increases in LAI that could be expected as MAP increases. This trend was used to distinguish between LAIs for high and low rainfall areas (>1000 and <1000mm.annum^{-1}) respectively.

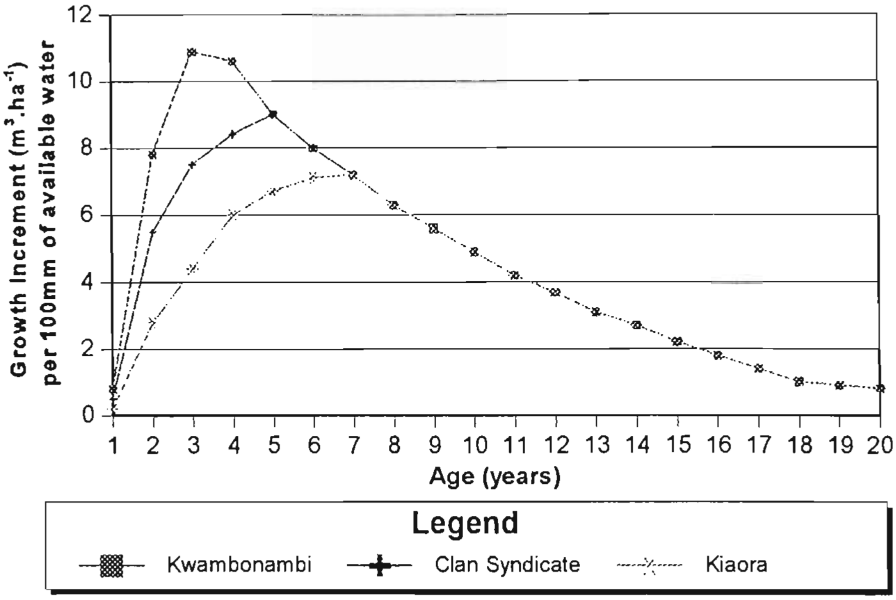

Figure 26. Idealised Water Use Efficiency curves (after Roberts, 1994).

Table 9. LAI and effective MAP (*i.e.* rainfall plus irrigation) for 1.5 year old *E. grandis* trees at the Mkuze irrigation trial in northern KwaZulu-Natal (after Olbrich *et al.*, 1992; Summerton and Schulze, 1995).

MAP (mm.annum^{-1})	**LAI**
600	1.2
900	3.1
1400	3.7

Honeysett and Beadle (1987) measured LAIs of 3.0 and 6.0 for four year old *E. nitens* and *E. delegatensis* respectively while in an area in Australia with deep ripped soils with an MAP of 916-1132mm, Honeysett *et al.* (1992) determined LAIs ranging from 1.6 to 4.4 (Table 10).

Table 10. LAIs for *E. nitens* and *E. delegatensis* in Australia (after Honeysett *et al.*, 1992).

Age (years)	***E. nitens***	***E. delegatensis***
3.5	3.0	1.6
5.0	4.4	2.2

LAI data for pines are relatively scarce as indicated by Dye (1993c), who suggested that there were no data to show how LAI changes with age for *P. patula*. Consequently, results from studies from outside of South Africa have been used to assess the LAI trends of pines. Waterloo (1994) determined LAIs for *P. caribaea* (Table 11) on an island in Fiji with typical MAPs of 2000-2800mm. Natural thinning by monsoons is a common occurrence in this region. Table 11 substantiates the previously mentioned trend of LAI generally increasing, and then decreasing toward the latter part of a rotation. Kelliher, Whitehead and Pollock (1992) determined a LAI of 1.7 on seven year old *P. radiata* planted to a density of 450 stems.ha^{-1}.

From the workshops and literature search, no data on LAI for wattle were found. LAI trends for wattle were therefore developed using hydrological intuition.

Table 11. LAI and stand density for *P. caribaea* in Fiji (after Waterloo, 1994).

Site	**Age (years)**	**LAI (Pre monsoon)**	**LAI (Post monsoon)**
Tulasewa	6	3.7 (825 stems.ha^{-1})	1.5 (491 stems.ha^{-1})
Korokula	11	4.4 (822 stems.ha^{-1})	3.2 (789 stems.ha^{-1})
Koromani	16	4.0 (621 stems.ha^{-1})	3.1 (not available)

LAI may be altered by management practices. The most important of these considered in this dissertation are the effects of thinning, fertilisation and site preparation on LAI values.

4.5.1.1 The effect of thinning on LAI

Dye *et al.* (1995) indicate that LAI may be altered by management options which include:

a) thinning,
b) rotation lengths, and
c) planting density.

Dye suggested at the *ACRU* FDSS Workshop No1 (1995) that another decision be included in the FDSS, *viz.* whether the plantation is managed for pulpwood or for sawtimber. The rationale behind this is that trees planted for pulpwood are not thinned (unless thinned to waste at 15-20 years), whereas sawtimber plantations are. The main reason for thinning is that better quality timber is produced. The process of thinning involves either removing branches (*i.e.* pruning) or entire trees to reduce the initial stocking density, and hence the LAI. This LAI reduction is more evident toward the end of a rotation period. When thinning takes place, the smaller trees are usually removed, and hence the relationship between the reduction of the number of stems.ha^{-1} and LAI may not be proportional. Within two to three years after thinning, the LAI should attain the value of LAI had no thinning occurred (*ACRU* FDSS Workshop No3, 1995). Pine and wattle plantations are usually thinned (Tables 12 and 13), but occasionally eucalypts are also thinned as depicted in Figure 27. Alternative thinning regimes are contained in Van der Sijde (1994). Some notes regarding Tables 12 and 13 are that:

a) in marginal sites on pine plantations the 18 year thinning is omitted, and
b) on wattle plantations the two year old thinning is usually omitted.

Table 12. Typical stocking densities during a rotation, resulting from thinning of pine plantations managed for sawtimber (after *ACRU* FDSS Workshop No3, 1995).

Age (years)	0	5-8	13	18
Density (stems.ha^{-1})	1200	650	400	250

Table 13. Typical stocking densities during a rotation, resulting from thinning of wattle plantations managed for sawtimber (after *ACRU* FDSS Workshop No3, 1995).

Age (years)	0	2	3-4	5
Density (stems.ha^{-1})	2200	2000	1800	1500

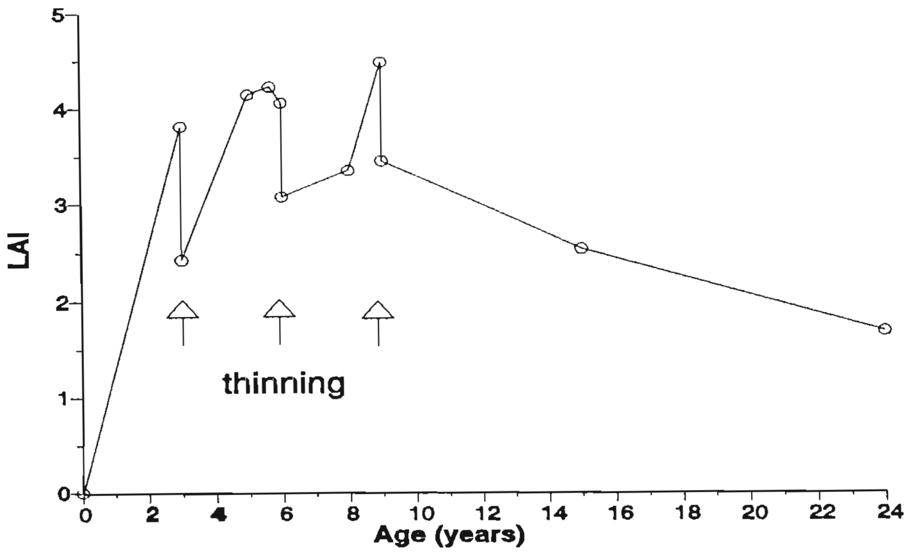

Figure 27. Trend in LAI recorded in different age classes of *E. grandis* in the Sabie area in Mpumalanga (after Dye *et al.*, 1995).

It is evident from Tables 12 and 13 and from Figure 27 that thinning commonly ranges from about 10-50%, with larger thinnings early in the rotation getting progressively smaller toward the end of the rotation. McCarthy *et al.* (1991) indicate a thinning of 40% on *P. taeda* plantations by suggesting that canopy closure was reduced from 85 to 50% as a result of thinning.

The possibility therefore exists that plantations managed for sawtimber use less water over the long term than those managed for pulpwood (Dye *et al.*, 1995). Most studies attribute the increase in soil moisture after thinning to a decrease in the water utilisation of the tree. Stogsdill, Wittwer, Hennessey and Dougherty (1992) found that water use on heavily thinned *P. taeda* plots decreased due to greater effective rainfall (throughfall) resulting from decreased canopy I_l. Myers and Talsma (1992) suggest that heavy thinning could increase throughfall by as much as 15% for *P. pinaster*.

Roberts (1995) suggested that trees planted with a closer spacing had less leaf biomass, situated at the top of a tall trunk. Thinning may, therefore, induce the remaining canopy to grow more vigorously, thereby increasing the LAI. Consequently, the remaining trees may use as much water as all the trees would have had they not been thinned. Waterloo (1994) found that total water use was about the same for plantations of different densities, since spacing affects the canopy structure. It is therefore possible for tree water use to remain unaltered by thinning.

4.5.1.2 The effect of fertilisation on LAI

According to the *ACRU* FDSS Workshop No2 (1995), the effect of fertilisation on WUE is important and is currently being researched by *inter alia*, the Institute for Commercial Forestry Research (ICFR). Fertilisation affects the site potential and aids tree development, especially in the initial stages of growth. During the first year of growth, a 220-400% growth increase is possible (*ACRU* FDSS Workshop No3, 1995), giving the tree a growth advantage for the entire rotation. Time to canopy closure may be decreased by about six months by using fertiliser (*ACRU* FDSS Workshop No3, 1995).

If water is not limited, fertilised trees may start utilising water earlier than non fertilised trees (*ACRU* FDSS Workshop No3, 1995). Although the possibility exists for the absolute increase in yield (as a result of fertilisation) to be greater on good sites, relatively marginal sites may respond relatively better than superior sites when fertilised (*ACRU* FDSS Workshop No3, 1995). A possible reason for this is that marginal sites usually allocate more resources to development of a larger root biomass (than above ground biomass), and are therefore able to take greater advantage of fertilisation than superior sites (*ACRU* FDSS Workshop No3, 1995). The potential impact of fertilisation on LAI is illustrated in Figure 28.

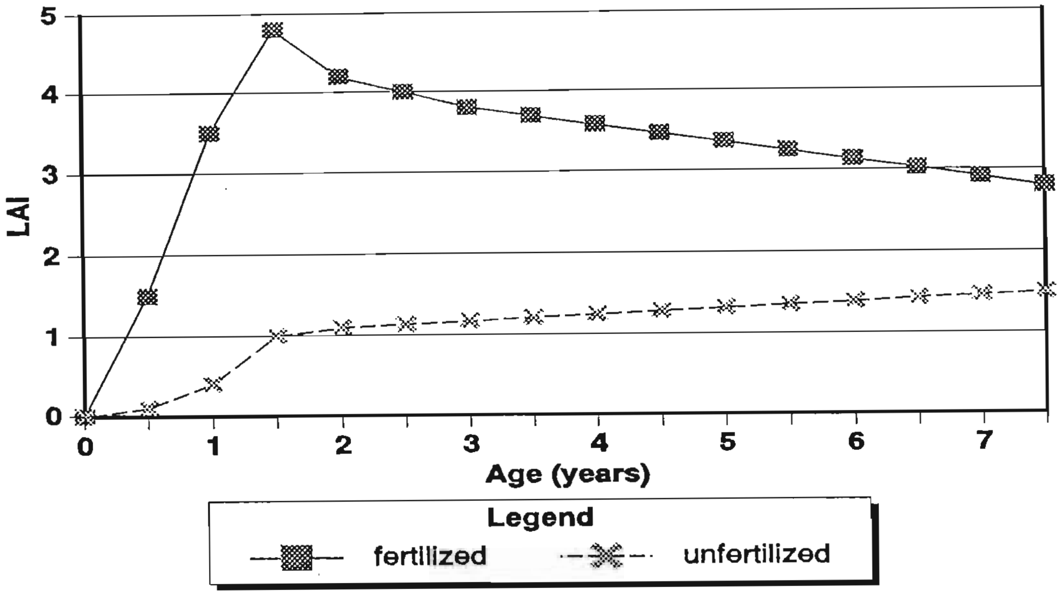

Figure 28. LAI with and without fertilisation as assumed for modelling purposes (after Leuning *et al.*, 1991).

Although fertilisation does have an effect on LAI, this has not been included in the new FDSS, since the magnitude of the relationship is not yet entirely clear.

4.5.1.3 The effect of site preparation on LAI

For the development of the new *ACRU* FDSS it was assumed that more complete site preparations will induce higher LAIs. The rationale behind this is that on intensively prepared sites, the tree has access to more soil moisture and hence would grow more rapidly as illustrated by Moerdyk (1991) for *E. grandis* at Bloemendal and by Jewitt (1991) for *P. patula* and *A. mearnsii* at Glendale. There does, however, exist a different school of thought that maintains that more complete site preparations will induce the tree to develop more root biomass at the expense of canopy biomass or LAI (*ACRU* FDSS Workshop No3, 1995).

4.5.1.4 LAI values and time trends for use in the *ACRU* FDSS

Results from the above discussion on LAI have been used to develop a matrix of LAI values for use in the new *ACRU* FDSS (Table 14). Results are summarised graphically in Figures 29-34. These values are by no means conclusive or absolute since they were developed from a limited database and both interpolation and extrapolation were required to obtain smoothed continuous curves.

Table 14. Values of LAI in the *ACRU* FDSS for a typical rotation period for different genera, major forest areas in South Africa, site preparation intensities and rainfall regimes.

	Age (years)													
	0	1	2	3	4	5	6	7	8	10	15	20	25	30
engh	0.7	1.8	3.1	3.7	4.2	4.6	4.8	4.7	4.1	3.6	2.4			
enmh	0.7	1.7	2.9	3.4	3.9	4.3	4.6	4.5	3.9	3.4	2.4			
enph	0.7	1.5	2.4	3.0	3.5	4.0	4.3	4.2	3.7	3.2	2.4			
ezgh	0.7	3.1	4.3	5.0	4.9	4.6	4.3	4.0	3.7	3.5	3.1			
ezmh	0.7	2.9	4.0	4.8	4.7	4.4	4.1	3.9	3.6	3.4	3.0			
ezph	0.7	2.7	3.6	4.5	4.4	4.2	4.0	3.8	3.5	3.3	2.9			
etgh	0.7	2.0	3.5	4.3	4.7	4.9	5.0	4.9	4.5	3.9	2.4			
etmh	0.7	1.9	3.1	3.9	4.5	4.7	4.9	4.8	4.3	3.7	2.4			
etph	0.7	1.7	2.9	3.5	4.1	4.4	4.7	4.6	4.1	3.5	2.4			
ecgh	0.7	1.7	2.9	3.5	4.0	4.4	4.6	4.5	3.9	3.4	2.6			
ecmh	0.7	1.5	2.5	3.2	3.7	4.1	4.5	4.3	3.7	3.3	2.6			
ecph	0.7	1.3	2.0	2.6	3.2	3.7	4.1	4.0	3.4	2.9	2.6			
pngh	0.7	0.8	1.0	1.5	2.0	2.7	3.4	4.2	4.8	5.2	5.3	4.9	4.3	3.7
pnmh	0.7	0.8	1.0	1.4	1.9	2.6	3.3	4.1	4.7	5.1	5.2	4.8	4.2	3.6
pnph	0.7	0.8	0.9	1.1	1.6	2.3	3.0	3.8	4.4	4.8	4.9	4.5	3.9	3.3
ptgh	0.7	1.0	1.3	1.8	2.3	3.0	3.7	4.5	5.1	5.5	5.6	5.2	4.6	3.8
ptmh	0.7	0.9	1.1	1.6	2.1	2.8	3.5	4.3	4.9	5.3	5.4	5.0	4.4	3.8
ptph	0.7	0.9	1.0	1.4	1.9	2.6	3.3	4.1	4.7	5.1	5.2	4.8	4.2	3.4
pcgh	0.7	0.8	1.0	1.4	1.9	2.6	3.3	4.1	4.7	5.1	5.2	4.8	4.2	3.6
pcmh	0.7	0.9	1.0	1.3	1.8	2.5	3.2	4.0	4.6	5.0	5.1	4.7	4.1	3.5
pcph	0.7	0.8	0.9	1.0	1.5	2.2	2.9	3.7	4.3	4.7	4.8	4.4	3.8	3.2
wngh	0.7	1.6	2.3	2.9	3.6	4.0	4.2	4.0	3.6	3.2	2.8			
wnmh	0.7	1.4	2.1	2.7	3.3	3.7	4.0	3.8	3.4	3.0	2.8			
wnph	0.7	1.2	1.8	2.3	2.8	3.4	3.8	3.6	3.2	2.9	2.8			
wtgh	0.7	1.7	2.4	3.0	3.7	4.1	4.3	4.1	3.7	3.3	2.9			
wtmh	0.7	1.5	2.2	2.8	3.4	3.8	4.1	3.9	3.5	3.1	2.9			
wtph	0.7	1.3	1.9	2.4	2.9	3.5	3.9	3.7	3.3	3.0	2.9			
wcgh	0.7	1.5	2.2	2.8	3.5	3.9	4.1	3.9	3.5	3.1	2.7			
wcmh	0.7	1.3	2.0	2.6	3.2	3.6	3.9	3.7	3.3	2.9	2.7			
wcph	0.7	1.1	1.7	2.2	2.7	3.3	3.7	3.5	3.1	2.8	2.7			

(Continued)

Table 14. (Continued).

	Age (years)													
	0	1	2	3	4	5	6	7	8	10	15	20	25	30
engl	0.7	1.5	2.6	3.1	3.6	3.9	4.1	4.0	3.5	3.1	2.0			
enml	0.7	1.4	2.5	2.9	3.3	3.7	3.9	3.8	3.3	2.9	2.0			
enpl	0.7	1.3	2.0	2.6	3.0	3.4	3.7	3.6	3.1	2.7	2.0			
ezgl	0.7	2.6	3.7	4.3	4.2	3.9	3.7	3.4	3.1	3.0	2.6			
ezml	0.7	2.5	3.4	4.1	4.0	3.7	3.5	3.3	3.1	2.9	2.6			
ezpl	0.7	2.3	3.1	3.8	3.7	3.6	3.4	3.2	3.0	2.8	2.5			
etgl	0.7	1.7	3.0	3.7	4.0	4.2	4.3	4.2	3.8	3.3	2.0			
etml	0.7	1.6	2.6	3.3	3.8	4.0	4.2	4.1	3.7	3.1	2.0			
etpl	0.7	1.4	2.5	3.0	3.5	3.7	4.0	3.9	3.5	3.0	2.0			
ecgl	0.7	1.4	2.5	3.0	3.4	3.7	3.9	3.8	3.3	2.9	2.2			
ecml	0.7	1.3	2.1	2.7	3.1	3.5	3.8	3.7	3.1	2.8	2.2			
ecpl	0.7	1.1	1.7	2.2	2.7	3.1	3.5	3.4	2.9	2.5	2.2			
pngl	0.7	0.8	0.9	1.3	1.7	2.3	2.9	3.6	4.1	4.4	4.5	4.2	3.7	3.1
pnml	0.7	0.7	0.9	1.2	1.6	2.2	2.8	3.5	4.0	4.3	4.4	4.1	3.6	3.1
pnpl	0.7	0.8	0.8	0.9	1.4	2.0	2.6	3.2	3.7	4.1	4.2	3.8	3.3	2.8
ptgl	0.7	0.9	1.1	1.5	2.0	2.6	3.1	3.8	4.3	4.7	4.8	4.4	3.9	3.2
ptml	0.7	0.8	0.9	1.4	1.8	2.4	3.0	3.7	4.2	4.5	4.6	4.3	3.7	3.2
ptpl	0.7	0.8	0.9	1.2	1.6	2.2	2.8	3.5	4.0	4.3	4.4	4.1	3.6	2.9
pcgl	0.7	0.8	0.9	1.2	1.6	2.2	2.8	3.5	4.0	4.3	4.4	4.1	3.6	3.1
pcml	0.7	0.8	0.9	1.1	1.5	2.1	2.7	3.4	3.9	4.3	4.3	4.0	3.5	3.0
pcpl	0.7	0.8	0.9	1.0	1.3	1.9	2.5	3.1	3.7	4.0	4.1	3.7	3.2	2.7
wngl	0.7	1.4	2.0	2.5	3.1	3.4	3.6	3.4	3.1	2.7	2.4			
wnml	0.7	1.2	1.8	2.3	2.8	3.1	3.4	3.2	2.9	2.6	2.4			
wnpl	0.7	1.0	1.5	2.0	2.4	2.9	3.2	3.1	2.7	2.5	2.4			
wtgl	0.7	1.4	2.0	2.6	3.1	3.5	3.7	3.5	3.1	2.8	2.5			
wtml	0.7	1.3	1.9	2.4	2.9	3.2	3.5	3.3	3.0	2.6	2.5			
wtpl	0.7	1.1	1.6	2.0	2.5	3.0	3.3	3.1	2.8	2.6	2.5			
wcgl	0.7	1.3	1.9	2.4	3.0	3.3	3.5	3.3	3.0	2.6	2.3			
wcml	0.7	1.1	1.7	2.2	2.7	3.1	3.3	3.1	2.8	2.5	2.3			
wcpl	0.7	0.9	1.4	1.9	2.3	2.8	3.1	3.0	2.6	2.4	2.3			

Legend:

Genera:	e=eucalypts, p=pines and w=wattle.
Forestry regions:	n=KwaZulu-Natal, z=Zululand, t=Mpumalanga and c=Eastern Cape.
Site preparations:	g=good ("intensive"), m=medium ("intermediate") and p=poor ("pitting").
Rainfall regimes:	h=high (MAP>1000mm) and l=lower (MAP<1000mm).

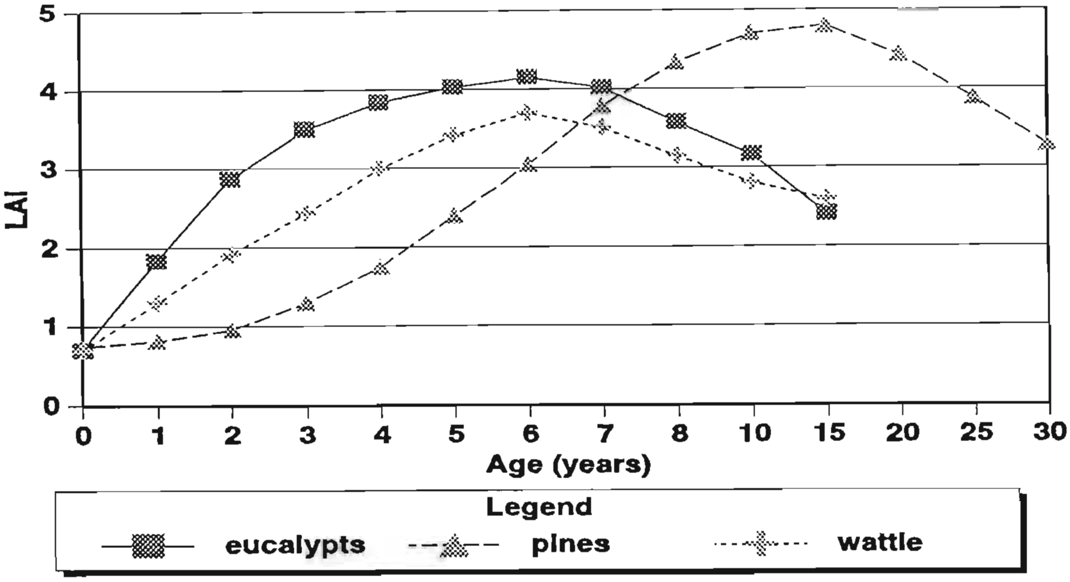

Figure 29. LAI values used in the *ACRU* FDSS for the three main genera grown commercially, averaged for four major forestry areas in South Africa, three levels of site preparation and two rainfall regimes.

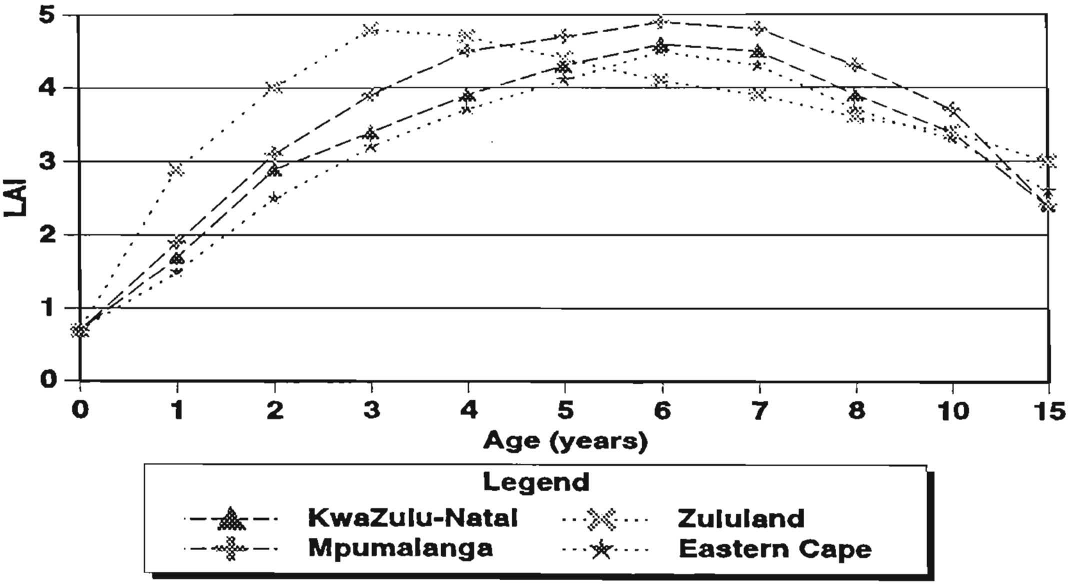

Figure 30. LAI values used in the *ACRU* FDSS for four major forestry areas in South Africa. The example used here is for eucalypts planted in a zone of relatively high rainfall (MAP > 1000mm) on intermediate site preparation.

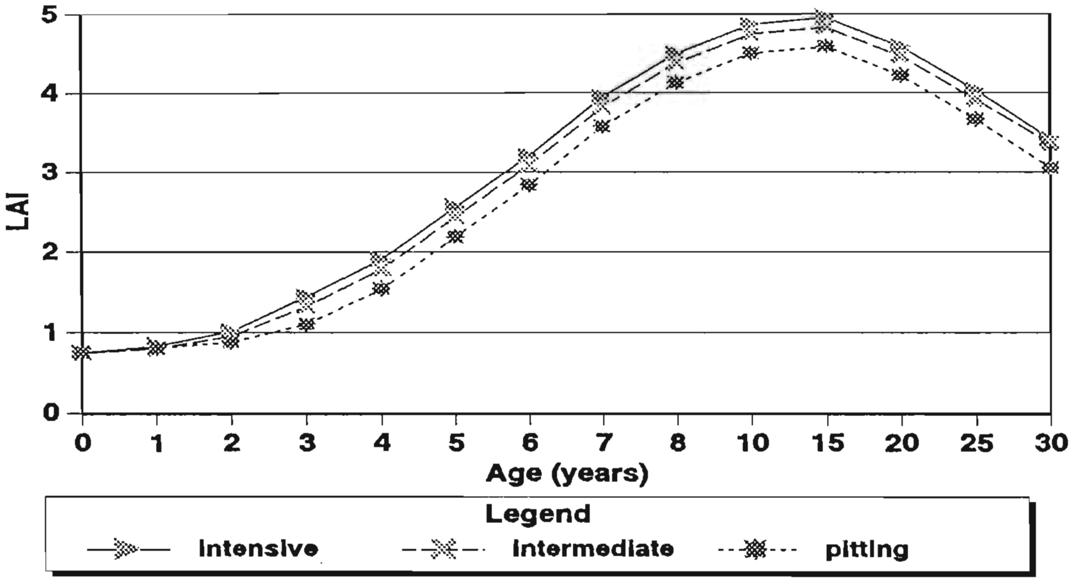

Figure 31. LAI values used in the *ACRU* FDSS for three levels of site preparation. The example used here is for pines, averaged for both high and low rainfall regions and for four major forestry areas in South Africa.

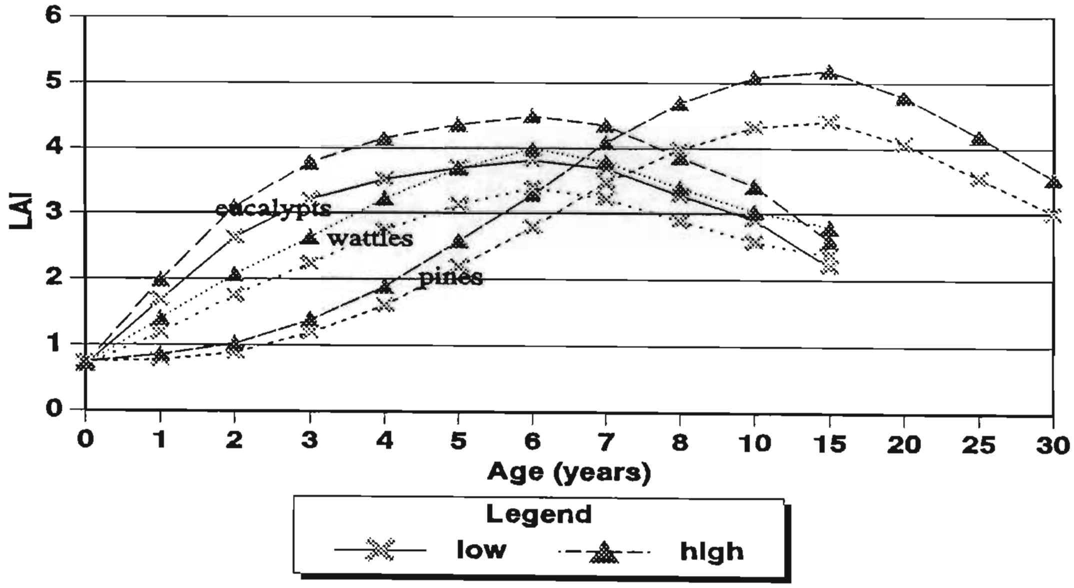

Figure 32. LAI values used in the *ACRU* FDSS for relatively high (MAP > 1000mm) and lower (MAP < 1000mm) rainfall regimes, averaged for four major forestry areas in South Africa and three levels of site preparation.

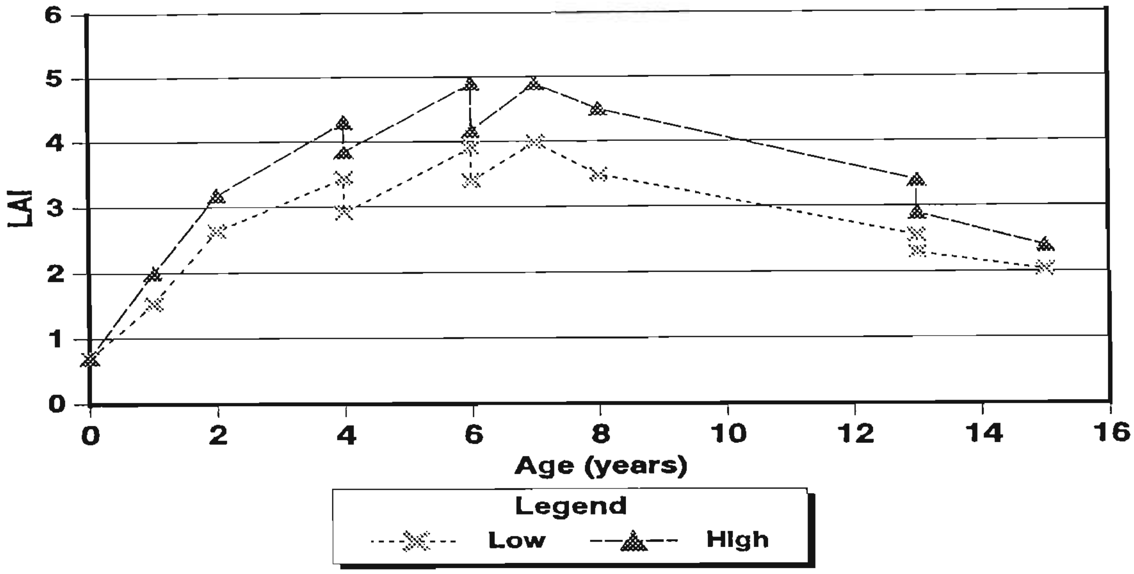

Figure 33. An example of the effects of thinning on the LAI of eucalypts in the Midlands of KwaZulu-Natal on a site with intensive site preparation.

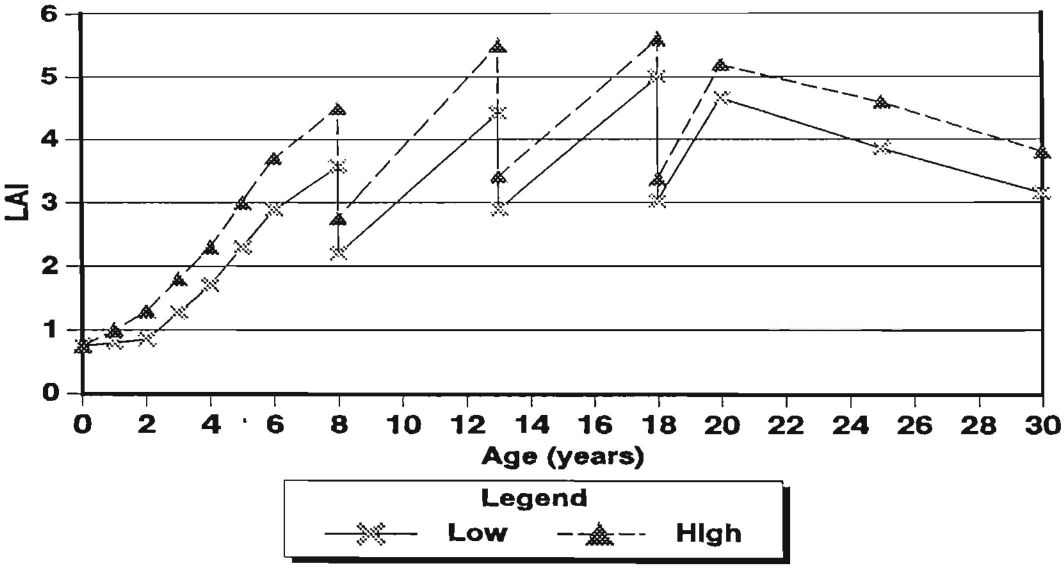

Figure 34. An example of the effects of thinning on the LAI of pines in the Midlands of KwaZulu-Natal on a site with intensive site preparation.

In addition to estimates of LAI, values of I_l were also derived for inclusion in the new *ACRU* FDSS. These are detailed in the following Section of this Chapter.

4.5.2 Interception losses

Interception loss includes losses from the canopy and from the litter layer.

4.5.2.1 Canopy interception losses

More recent studies of canopy I_l by trees in South Africa include those by Schulze, Scott-Shaw and Nänni (1978), Dye and Versfeld (1992a and b), Versfeld and Dye (1992) and Dye (1993c). According to Dye (1993c) the problem of using overseas values of I_l for modelling purposes is that data from elsewhere in the world are difficult to assess and adapt to South African needs because:

a) I_l depends on the relative frequency of different rainfall classes, with frequent occurrences of small rainfall events resulting in larger total values of I_l,
b) evaporation during rainfall is an important component of I_l, and
c) comparisons of I_l between sites where climate differs are difficult.

Furthermore, differences between species renders it difficult to use I_l studies from other parts of the world to estimate I_l in South Africa (Dye and Versfeld, 1992b). Given a limited I_l database from South Africa, extrapolation to age classes other than those studied is best based on the assumption that I_l is directly related to LAI, as suggested by Dye (1993c). It was therefore assumed for the revised *ACRU* FDSS that canopy I_l curves should follow previously derived LAI trends.

In the revised FDSS, canopy I_l at planting is assumed to be 1.0 mm.rainday^{-1}, *i.e.* a typical value of short natural grassland. It was accepted at the *ACRU* FDSS Workshop No3 (1995) that in general, I_l by pines is greater than that of eucalypts, wattle and short vegetation (*e.g.* grassland), in that sequence. Pine canopies intercept more water than eucalypt canopies due to their larger LAIs and the fact that water clings to the pine needles while being repelled by eucalypt leaves (APPC Working group, 1995). Large variations in I_l do however exist under different climatic conditions (Calder, 1986).

I_l has frequently been cited in the literature as a percentage of Gross Precipitation (Pg). For modelling purposes, a canopy I_l in mm.rainday^{-1} is, however required. In South Africa, canopy I_l ranges from 0.5 to 3.5mm per rainfall event in pines (Schulze *et al.*, 1978; Dye and Versfeld, 1992b; Versfeld and Dye, 1992). Some examples of canopy I_l values are summarised in Table 15.

Table 15. Values of canopy I_l as a percentage of gross precipitation gleaned from the literature.

I_l (% Pg)	**Site details**	**Reference**
20-40%	Pines	Rutter, Kershaw, Robbins and Morton (1971)
14%	*E. radiata*, *E. dalrympleana*, *E. pauciflora*	Talsma and Gardner (1986)
42%	*Abies grandis*	Gholz *et al.* (1990)
10-35%	*P. taeda*, 15 years old, unthinned, with 85% canopy closure	McCarthy *et al.* (1991)
5-25%	*P. taeda*, 15 years old, thinned, with 50% canopy closure	McCarthy *et al.* (1991)
19%	*P. radiata*, seven years old	Kelliher *et al.* (1992)
20-40%	Temperate forests	Dye *et al.* (1995)

Canopy I_l of nine year old *P. patula* and four year old *E. grandis* grown near Sabie in Mpumalanga, were about 13% and only 4.1% of Pg respectively, which is also similar to canopy I_l values for grassland (Dye, 1993c). These South African values are lower than those from temperate regions, but reflect the canopy I_l in areas of frequent, intense rainfall in the summer rainfall regions of South Africa.

Schulze *et al.* (1978) studied canopy I_l of *P. patula* at Cathedral Peak in KwaZulu-Natal. Dye (1993c) concluded that canopy I_l at Cathedral Peak was greater than at Sabie in Mpumalanga; however, he was not certain whether this was a result of climate or canopy differences. Therefore, in the development of regional I_l trends for the *ACRU* FDSS, the relative differences for LAI were used as an index to compare I_l estimates. Hence, canopy I_l in Zululand would generally be assigned a larger value than at Mpumalanga, KwaZulu-Natal and the Eastern Cape in that order.

4.5.2.2 Litter interception loss

Litter is an important factor to take into account when considering the water balance of a forest, since it will:

a) prevent a certain fraction of rainfall from entering the soil by intercepting it, and simultaneously will

b) reduce soil water evaporation losses.

Besides being a function of the magnitude of the rainfall event and of tree species, litter I_l is also indirectly dependent on ambient temperature, and is hence influenced by altitude. More litter tends to build up at higher altitudes as a result of slower litter decomposition rates (*ACRU* FDSS Workshop No3, 1995). In addition, pines tend to develop thicker litter layers. For example, a mature pine plantation at an altitude of 1500m frequently has a litter layer of 250-300mm thickness, while at the same altitude eucalypts and wattle have a litter layer of about only 100 and 50mm depth respectively (*ACRU* FDSS Workshop No3, 1995). Generally, at low altitudes, less litter accumulates and litter interception is thus also less as a result of lower decomposition rates at higher temperatures. At Cedara in KwaZulu-Natal, for example, litter I_l values of 1-2mm for a 120mm pine litter layer have been determined (Jewitt, 1991). Jewitt (1991) also studied litter interception on four and eight year old *E. grandis* and *P. patula* near New Hanover in the KwaZulu-Natal Midlands. Jewitt (1991) found that litter interception by *E. grandis* was less than *P. patula* for both age classes.

For modelling purposes it was decided that litter I_l in eucalypts and wattle was small enough to be omitted. Therefore, litter I_l is only considered for pines (*ACRU* FDSS Workshop No3, 1995), even though some (*ACRU* FDSS Workshop No1, 1995) consider litter I_l to be almost negligible. Typical pine litter thicknesses in KwaZulu-Natal are depicted in Table 16.

Table 16. Typical pine litter thicknesses for mature forests in KwaZulu-Natal as a function of altitude (after *ACRU* FDSS Workshop No3, 1995).

Altitude (m)	**Maximum litter thickness (mm)**
up to 1000	100
up to 1500	200-250
up to 2000	300-350

A factor that complicates the litter I_l modelling process is that pine roots may grow back up towards the soil surface (*ACRU* FDSS Workshop No2, 1995). These roots may form a dense mat (*ACRU* FDSS Workshop No3, 1995), and consequently utilise soil moisture near the litter layer.

4.5.2.3 Canopy interception loss values for use in the *ACRU* FDSS

Results from the I_l discussion have been used to develop a matrix of canopy I_l values (Table 17) for use in the new *ACRU* FDSS. These results are summarised as Figures 35-37. These values are by no means conclusive or absolute since they were developed from a limited database of observations, were related to LAI and interpolation and extrapolation were required to obtain smooth curves.

Table 17. Values of canopy I_l (mm.rainday^{-1}) in the *ACRU* FDSS for a typical rotation for different genera, major forest areas in South Africa and levels of site preparation.

	Age (years)													
	0	1	2	3	4	5	6	7	8	10	15	20	25	30
eng	1.0	1.4	1.8	2.3	2.5	3.0	3.1	3.0	2.4	2.1	1.5			
enm	1.0	1.3	1.7	2.0	2.3	2.6	3.0	2.9	2.3	2.0	1.5			
enp	1.0	1.2	1.5	1.7	2.0	2.4	2.7	2.5	2.3	1.7	1.5			
ezg	1.0	1.7	2.6	3.4	3.2	3.0	2.9	2.4	2.3	2.1	1.7			
ezm	1.0	1.6	2.4	3.0	2.9	2.6	2.4	2.3	2.1	2.0	1.6			
ezp	1.0	1.5	2.2	2.6	2.6	2.5	2.1	2.2	1.9	1.7	1.5			
etg	1.0	1.6	2.0	2.5	2.7	3.2	3.3	3.2	2.6	2.3	1.7			
etm	1.0	1.5	1.9	2.2	2.5	2.8	3.2	3.1	2.5	2.2	1.6			
etp	1.0	1.4	1.7	1.9	2.2	2.6	2.9	2.7	2.5	1.9	1.5			
ecg	1.0	1.2	1.6	2.1	2.3	2.8	2.9	2.8	2.2	1.9	1.3			
ecm	1.0	1.1	1.5	1.8	2.1	2.4	2.8	2.7	2.1	1.8	1.3			
ecp	1.0	1.0	1.3	1.5	1.8	2.2	2.5	2.3	2.1	1.5	1.3			
png	1.0	1.2	1.5	2.0	2.4	2.7	3.3	3.5	3.8	4.3	4.3	4.0	3.7	3.4
pnm	1.0	1.1	1.4	1.9	2.3	2.6	3.2	3.4	3.7	4.2	4.2	3.9	3.6	3.3
pnp	1.0	1.0	1.3	1.8	2.2	2.5	3.1	3.3	3.6	4.1	4.1	3.8	3.5	3.2
ptg	1.0	1.3	1.6	2.1	2.5	2.8	3.4	3.6	3.9	4.4	4.4	4.1	3.8	3.5
ptm	1.0	1.2	1.5	2.0	2.4	2.7	3.3	3.5	3.8	4.3	4.3	4.0	3.7	3.4
ptp	1.0	1.1	1.4	1.9	2.3	2.6	3.2	3.4	3.7	4.2	4.2	3.9	3.6	3.3
pcg	1.0	1.1	1.4	1.9	2.3	2.6	3.2	3.4	3.7	4.2	4.2	3.9	3.6	3.3
pcm	1.0	1.0	1.3	1.8	2.2	2.5	3.1	3.3	3.6	4.1	4.1	3.8	3.5	3.2
pcp	1.0	1.0	1.2	1.7	2.1	2.4	3.0	3.2	3.5	4.0	4.0	3.7	3.4	3.1
wng	1.0	1.2	1.4	1.5	2.0	2.5	2.7	2.5	2.0	1.7	1.4			
wnm	1.0	1.1	1.3	1.4	1.9	2.4	2.6	2.4	1.9	1.6	1.3			
wnp	1.0	1.0	1.2	1.3	1.8	2.3	2.5	2.3	1.8	1.5	1.2			
wtg	1.0	1.3	1.5	1.6	2.1	2.6	2.8	2.6	2.1	1.8	1.5			
wtm	1.0	1.2	1.4	1.5	2.0	2.5	2.7	2.5	2.0	1.7	1.4			
wtp	1.0	1.1	1.3	1.4	1.9	2.4	2.6	2.4	1.9	1.6	1.3			
wcg	1.0	1.1	1.3	1.4	1.9	2.4	2.6	2.4	1.9	1.6	1.3			
wcm	1.0	1.0	1.2	1.3	1.8	2.3	2.5	2.3	1.8	1.5	1.2			
wcp	1.0	1.0	1.1	1.2	1.7	2.2	2.4	2.2	1.7	1.4	1.1			

Legend:

Genera:	e=eucalypts, p=pines and w=wattle.
Forestry regions:	n=KwaZulu-Natal, z=Zululand, t=Mpumalanga and c=Eastern Cape.
Site preparations:	g=good ("intensive"), m=medium ("intermediate") and p=poor ("pitting").

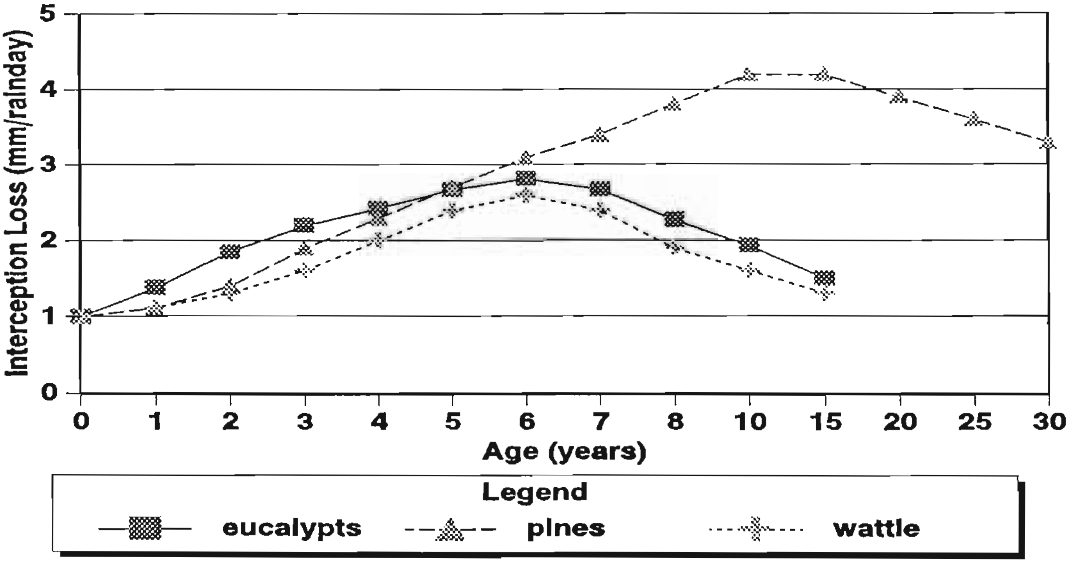

Figure 35. Canopy I_l values used in the *ACRU* FDSS for the three main genera, averaged for four major forestry areas in South Africa and the three levels of site preparation.

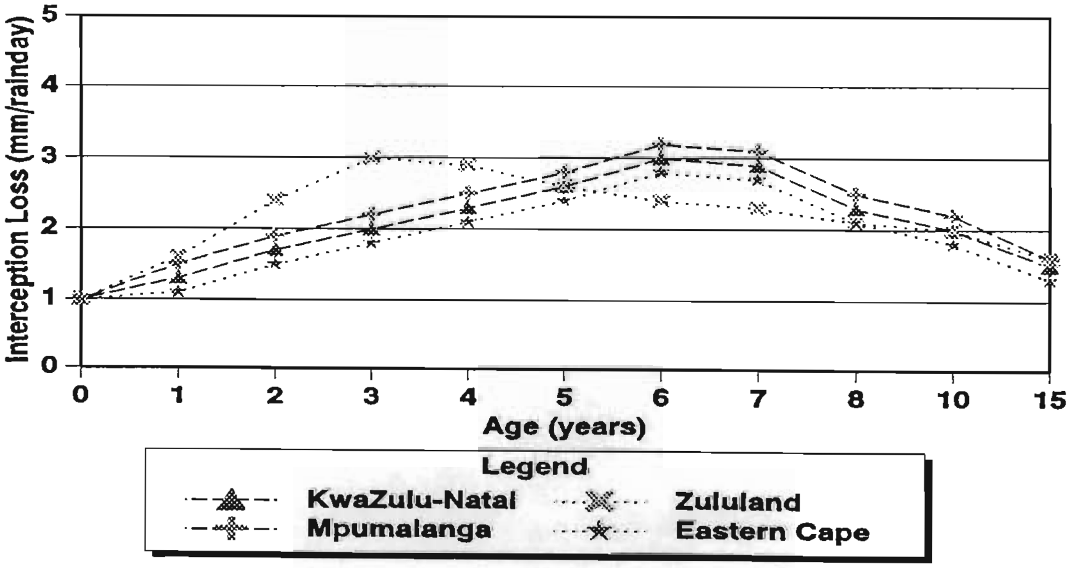

Figure 36. Canopy I_l values used in the *ACRU* FDSS for four major forestry areas in South Africa for eucalypts planted on a site with intermediate preparation.

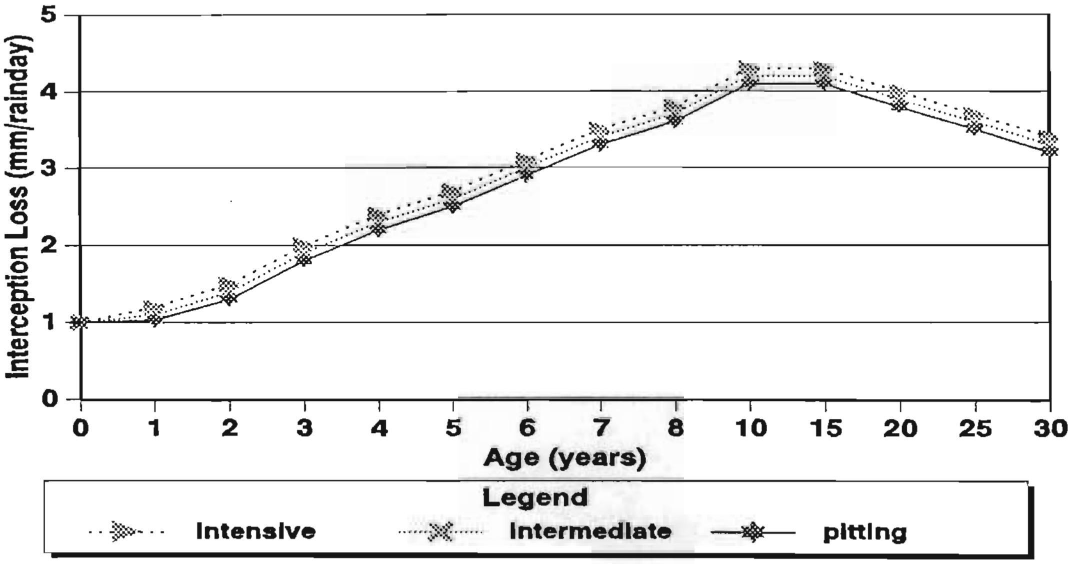

Figure 37. Canopy I_l values used in the *ACRU* FDSS for the three levels of site preparation for pines, averaged for four major forestry regions in South Africa.

Further important characteristics to consider and incorporate into forest hydrological modelling is that of the tree rooting patterns. This theme is discussed in the following Section of this Chapter.

4.5.3 Rooting patterns

The proportion of active roots in the topsoil (assumed for hydrological response modelling to be the top 300mm of the soil profile) and the degree of colonisation of roots in a soil horizon are variables commonly used to describe rooting patterns and from where, within the soil profile, the tree is able to extract its soil moisture. However, as mentioned in Chapter 2 (Section 2.1.3), rooting information from afforestation situations in South Africa is scarce.

4.5.3.1 Fraction of active roots in the topsoil

Even under afforested conditions, a high percentage of roots may reside in the topsoil portion of the soil profile. This is also that section of the soil profile where most hydrologically related activity takes place. Hence, the importance of the proportion of roots in the topsoil to forest hydrological modelling. Some examples of topsoil rooting proportions from the literature are given in Table 18. These results reflect rooting proportions in the depth of soil sampled. The likelihood exists that roots may exist beyond this depth.

Table 18. Proportion of roots in the topsoil.

Roots in topsoil (%)	**Site details**	**Reference**
60%	1.5 year old *E. grandis*	Olbrich *et al.* (1992)
85%	10-14 year old *P. radiata*	Myers and Talsma (1992)
77%	not available	Baldwin and Stewart (1987)

For the development of routines depicting the fraction of roots in the topsoil, trends were developed using information gleaned from the *ACRU* FDSS Workshops (1995). It was assumed that the fraction of roots in the top 300mm of soil would generally:

a) decrease with age as roots develop from the topsoil into the subsoil,
b) be lower for more intensive site preparations since under these conditions, roots may develop to depths beyond the topsoil horizon at a faster rate,
c) be larger for wattle, followed by eucalypts and pines respectively,
d) be dependent on the depth of the soil profile, and hence would be larger in the Eastern Cape, followed by KwaZulu-Natal, Mpumalanga and Zululand respectively, and
e) range between 0.95 for trees at planting to 0.50 at maturity.

Besides being dependent on genus and soil properties (including site preparation), root distributions may be dependent on moisture supply. Rooting patterns are, in fact, often dictated to a larger extent by site conditions (for example, the need for roots to reach water) than by the genera (*ACRU* FDSS Workshop No2, 1995), as has been found at the Mkuze irrigation trial. Results from Mkuze indicate that trees on the rainfed control plots allocate more resources to root growth and colonisation in order to enable extraction of as much of the limited available water as possible (Olbrich *et al.*, 1992). Roots on the irrigated plots have access to water and therefore do not depend on the development of very deep rooting systems for survival. They are therefore expected to concentrate their development near the soil surface, where the moisture supply is maintained. In a generic sense, this was confirmed at the *ACRU* FDSS Workshop No3 (1995), where it was stated that not as many roots develop at depth on wetter as on drier afforestation sites. Root distributions generally tend to be more uniform in the surface soil layers and follow increasingly less predictable patterns with depth (*ACRU* FDSS Workshop No1, 1995).

Besides being influenced by soil moisture content, the majority of nutrients that are to be found in the topsoil may cause the fine root system to concentrate in the topsoil horizon. Hence, root development may also depend on the level of fertilisation. Fertilisation enhances the development of roots at an early age, with this effect generally being observed throughout the entire rotation (*ACRU* FDSS Workshop No3, 1995). Metelerkamp (1995) suggested that fertilised plots show higher levels of growth and consequently, water use. Metelerkamp (1995) also suggested that roots are able to extract water more effectively from the upper soil levels, where the fertiliser is, due probably to better root colonisation.

It is not only the proportion of roots in any horizon that is important, but also what proportion of these roots have access to and are using soil moisture. This is represented by the concept of root colonisation, as outlined below.

4.5.3.2 Root colonisation

Root colonisation may be defined as the fraction of the soil matrix under consideration to which roots have ready access to any soil moisture available in that horizon. For example, if a particular soil layer is 100% colonised then, if there is water in the soil, the roots can utilise/extract water from 100% of that layer. Root colonisation is indirectly related to canopy development and, given enough time, the roots will eventually fully colonise the soil profile (*ACRU* FDSS Workshop No1, 1995). Eucalypt and wattle roots tend to colonise the soil profile relatively quicker than pines as a result of faster growth rates. At the *ACRU* FDSS Workshop No3 (1995) there were some differences in opinion as to the age at which the topsoil under pines would be fully colonised, with 5-8 years and three years (more likely) being stated. Values of colonisation of the topsoil have been collated from the *ACRU* FDSS workshops and are illustrated in Figure 39. For development of the *ACRU* FDSS, however, it has been assumed that the topsoil is always fully colonised with roots, be they from the original vegetation which dominates colonisation in the early years, or from the tree roots which dominate the root system of the topsoil in time. Hence, only the subsoil colonisation was assumed to change over time in the new *ACRU* FDSS.

Colonisation of the subsoil is difficult to characterise given a paucity of root data under forest conditions in South Africa. Within the first few months of growth, pines tap roots rapidly attain considerable depths and anchor the tree (*ACRU* FDSS Workshop No3, 1995). This indicates that colonisation of the subsoil may begin at an early age. Experienced forest hydrologists maintain that in 7-8 year old *E. grandis* trees it is difficult to find moist subsoils (*ACRU* FDSS Workshop No3, 1995), indicating that by that age the subsoil is potentially fully colonised. For the development of the *ACRU* FDSS, colonisation of the subsoil was eventually assumed linear over time, owing to a lack of quantitative information being available.

4.5.3.3 Rooting characteristics for use in the *ACRU* FDSS

Results from the above discussion on rooting have been used to develop a matrix of the fraction of roots in the topsoil and percentages of root colonisation of the subsoil for use in the new *ACRU* FDSS (Tables 19 and 20 respectively). These results are summarised graphically in Figures 38-40 for rooting fractions and as Figures 41-42 for colonisation. The values given are by no means conclusive or absolute since they were developed from a limited database and both interpolation and extrapolation were required to obtain smoothed continuous curves. In addition it must be realised that it is important to distinguish between fine and macro root systems that have different efficiencies and functions. Even in mature trees the fraction of fine roots in the topsoil may exceed 0.75 due to the soil moisture/nutrient/aeration relationships (Dye, 1996).

Table 19. Fractions of roots in the topsoil in the *ACRU* FDSS for a typical rotation period for different genera, major forest areas in South Africa and levels of site preparation.

	1	2	3	4	5	6	7	8	10	15	20	25
eng	0.82	0.79	0.75	0.72	0.69	0.65	0.62	0.58	0.55			
enm	0.82	0.79	0.77	0.74	0.72	0.69	0.66	0.64	0.61			
enp	0.82	0.80	0.78	0.76	0.75	0.73	0.71	0.69	0.67			
ezg	0.70	0.68	0.65	0.63	0.60	0.58	0.55	0.53	0.50			
ezm	0.70	0.68	0.66	0.64	0.63	0.61	0.59	0.57	0.55			
ezp	0.70	0.69	0.68	0.66	0.65	0.64	0.63	0.61	0.60			
etg	0.77	0.74	0.70	0.67	0.64	0.60	0.57	0.53	0.50			
etm	0.77	0.74	0.72	0.69	0.67	0.64	0.61	0.59	0.56			
etp	0.77	0.75	0.73	0.71	0.70	0.68	0.66	0.64	0.62			
ecg	0.87	0.84	0.80	0.77	0.74	0.70	0.67	0.63	0.60			
ecm	0.87	0.84	0.82	0.79	0.77	0.74	0.71	0.69	0.66			
ecp	0.87	0.85	0.83	0.81	0.80	0.78	0.76	0.74	0.72			
png	0.80	0.77	0.75	0.72	0.70	0.67	0.65	0.62	0.60	0.57	0.55	0.52
pnm	0.80	0.78	0.75	0.73	0.71	0.69	0.66	0.64	0.62	0.60	0.57	0.55
pnp	0.80	0.78	0.76	0.74	0.72	0.70	0.68	0.66	0.64	0.62	0.60	0.58
ptg	0.78	0.76	0.74	0.71	0.69	0.67	0.65	0.63	0.61	0.58	0.56	0.54
ptm	0.78	0.76	0.74	0.72	0.70	0.68	0.67	0.65	0.63	0.61	0.59	0.57
ptp	0.78	0.76	0.75	0.73	0.71	0.70	0.68	0.67	0.65	0.63	0.62	0.60
pcg	0.83	0.80	0.77	0.74	0.71	0.68	0.65	0.62	0.59	0.56	0.53	0.50
pcm	0.83	0.80	0.78	0.75	0.72	0.69	0.67	0.64	0.61	0.58	0.56	0.53
pcp	0.83	0.81	0.78	0.76	0.73	0.71	0.68	0.66	0.63	0.61	0.58	0.56
wng	0.90	0.87	0.83	0.80	0.77	0.73	0.70	0.66	0.63			
wnm	0.90	0.87	0.85	0.82	0.80	0.77	0.74	0.72	0.69			
wnp	0.90	0.88	0.86	0.84	0.83	0.81	0.79	0.77	0.75			
wtg	0.85	0.82	0.78	0.75	0.72	0.68	0.65	0.61	0.58			
wtm	0.85	0.82	0.80	0.77	0.75	0.72	0.69	0.67	0.64			
wtp	0.85	0.83	0.81	0.79	0.78	0.76	0.74	0.72	0.70			
wcg	0.95	0.92	0.88	0.85	0.82	0.78	0.75	0.71	0.68			
wcm	0.95	0.92	0.90	0.87	0.85	0.82	0.79	0.77	0.74			
wcp	0.95	0.93	0.91	0.89	0.88	0.86	0.84	0.82	0.80			

Legend:

Genera:	e=eucalypts, p=pines and w=wattle.
Forestry regions:	n=KwaZulu-Natal, z=Zululand, t=Mpumalanga and c=Eastern Cape.
Site preparations:	g=good ("intensive"), m=medium ("intermediate") and p=poor ("pitting").

Table 20. Percentages of root colonisation in the subsoil in the *ACRU* FDSS during a typical rotation period for different genera, major forest areas in South Africa, different levels of site preparation and rainfall regimes.

	Age (years)											
	0	1	2	3	4	5	6	7	8	9	10	11
engh	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
enmh	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
enph	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
ezgh	0.0	20.0	40.0	60.0	80.0	100.0						
ezmh	0.0	16.7	33.3	50.0	66.7	83.3	100.0					
ezph	0.0	14.3	28.6	42.9	57.1	71.4	85.7	100.0				
etgh	0.0	14.3	28.6	42.9	57.1	71.4	85.7	100.0				
etmh	0.0	14.3	28.6	42.9	57.1	71.4	85.7	100.0				
etph	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
ecgh	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
ecmh	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
ecph	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0
pngh	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
pnmh	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
pnph	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0
ptgh	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
ptmh	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
ptph	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
pcgh	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
pcmh	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
pcph	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0
wngh	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
wnmh	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
wnph	0.0	8.3	16.7	25.0	33.3	41.7	50.0	58.3	66.7	75.0	83.3	91.7
wtgh	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
wtmh	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
wtph	0.0	7.7	15.4	23.1	30.8	38.5	46.2	53.8	61.5	69.2	76.9	84.6
wcgh	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
wcmh	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0
wcph	0.0	7.7	15.4	23.1	30.8	38.5	46.2	53.8	61.5	69.2	76.9	84.6

(Continued)

Table 20. (Continued).

	Age (years)											
	0	1	2	3	4	5	6	7	8	9	10	11
engl	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
enml	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
enpl	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
ezgl	0.0	20.0	40.0	60.0	80.0	100.0						
ezml	0.0	20.0	40.0	60.0	80.0	100.0						
ezpl	0.0	16.7	33.3	50.0	66.7	83.3	100.0					
etgl	0.0	16.7	33.3	50.0	66.7	83.3	100.0					
etml	0.0	14.3	28.6	42.9	57.1	71.4	85.7	100.0				
etpl	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
ecgl	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
ecml	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
ecpl	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0
pngl	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
pnml	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
pnpl	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
ptgl	0.0	14.3	28.6	42.9	57.1	71.4	85.7	100.0				
ptml	0.0	14.3	28.6	42.9	57.1	71.4	85.7	100.0				
ptpl	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
pcgl	0.0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0			
pcml	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
pcpl	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0
wngl	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
wnml	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
wnpl	0.0	8.3	16.7	25.0	33.3	41.7	50.0	58.3	66.7	75.0	83.3	91.7
wtgl	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
wtml	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
wtpl	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	
wcgl	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
wcml	0.0	11.1	22.2	33.3	44.4	55.6	66.7	77.8	88.9	100.0		
wcpl	0.0	9.1	18.2	27.3	36.4	45.5	54.5	63.6	72.7	81.8	90.9	100.0

Legend:

Genera:	e=eucalypts, p=pines and w=wattle.
Forestry regions:	n=KwaZulu-Natal, z=Zululand, t=Mpumalanga and c=Eastern Cape.
Site preparations:	g=good ("intensive"), m=medium ("intermediate") and p=poor ("pitting").
Rainfall regimes:	h=high (MAP> 1000mm) and l=lower (MAP< 1000mm).

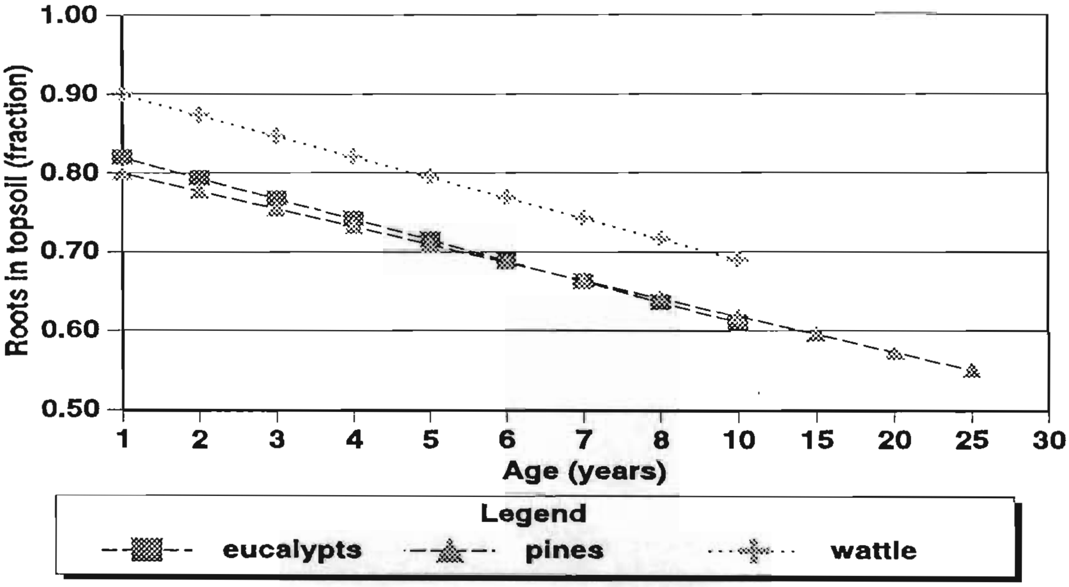

Figure 38. An example of the fraction of roots in the topsoil in the *ACRU* FDSS for different genera grown in KwaZulu-Natal on a site with intermediate preparation.

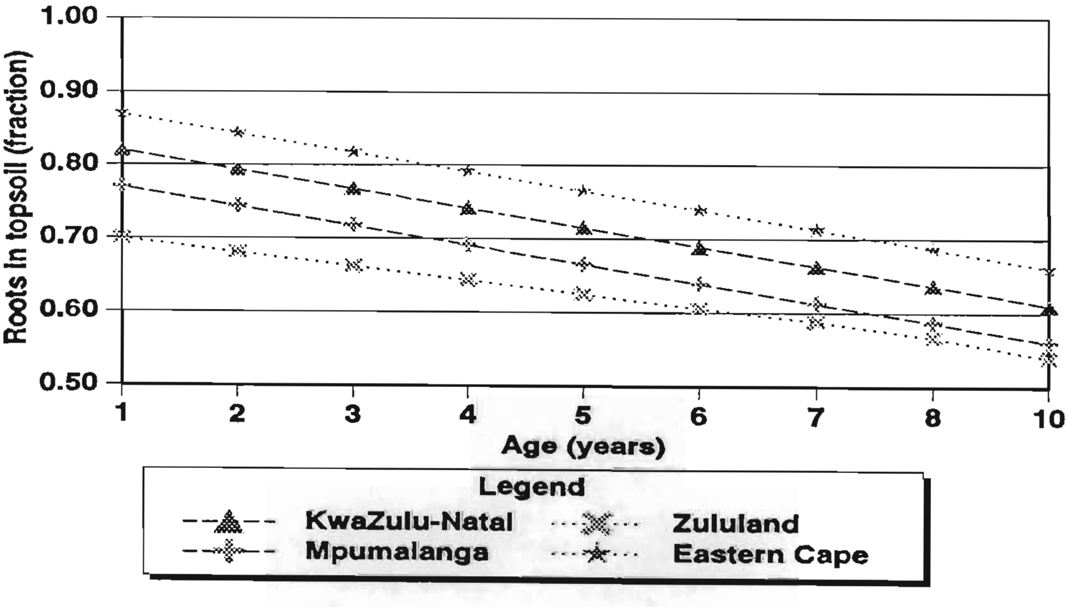

Figure 39. An example of the fraction of roots in the topsoil in the *ACRU* FDSS for four major forestry regions in South Africa for eucalypts on a site with intermediate preparation.

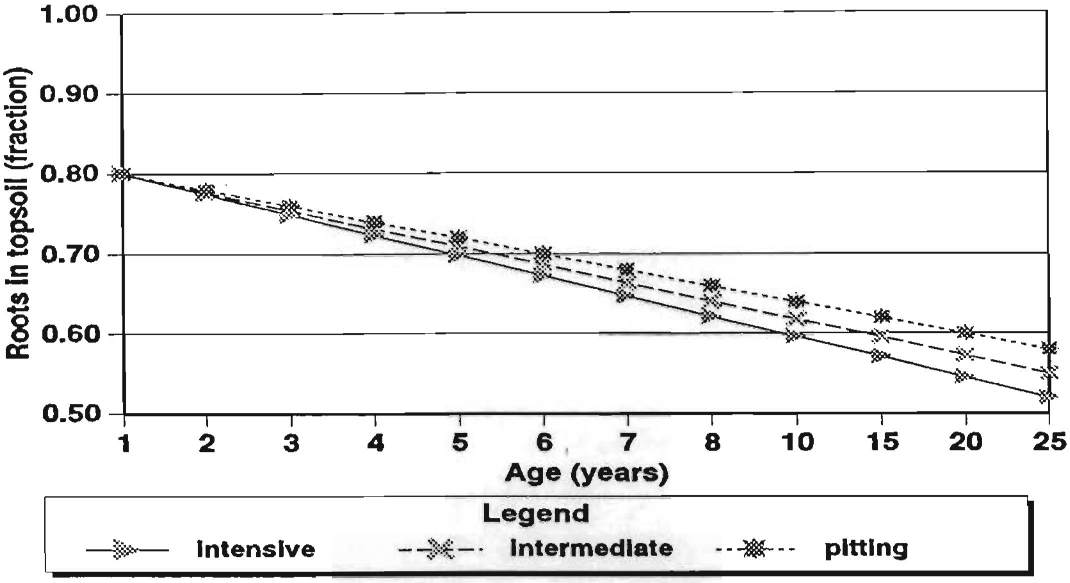

Figure 40. An example of the fraction of roots in the topsoil in the *ACRU* FDSS for pines in KwaZulu-Natal grown under different levels of site preparations.

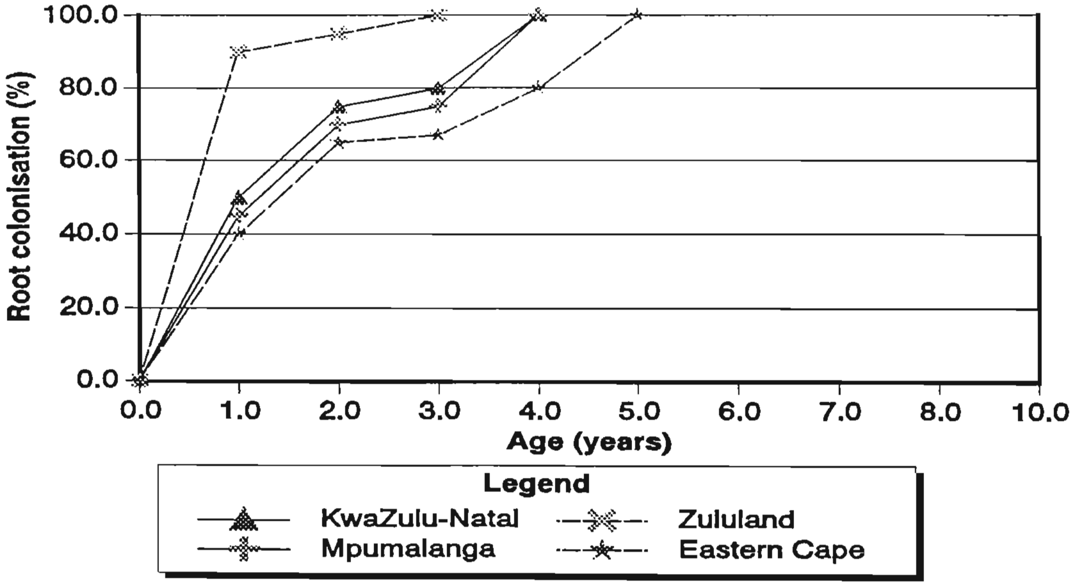

Figure 41. An example of tree root colonisation of the topsoil in four major forest regions in South Africa for eucalypts grown on a site with intensive preparation.

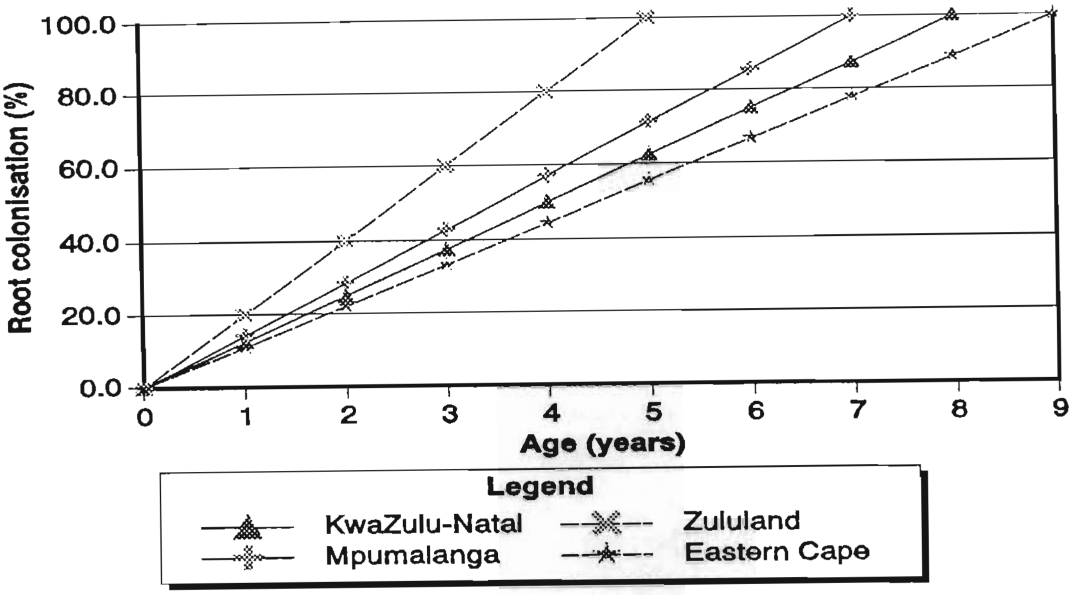

Figure 42. An example of tree root colonisation of the subsoil in the *ACRU* FDSS for eucalypts in four major forest areas in South Africa, grown on a site with intensive preparation in a high rainfall area.

The trends developed in this Section have been incorporated into a new *ACRU* FDSS, the operation of which is described in the Section which follows.

4.6 Incorporating the New FDSS into *ACRU*

Section 4.6 of this dissertation has been developed in conjunction with Meier (1996), whose input has been on the computational linkage of the FDSS into the *ACRU* model.

The new FDSS has been designed to be imbedded within the *ACRU* modelling system or to operate as a stand-alone PC-based model called the *ACRU* Forest model. The systems layout of *ACRU* Forest is depicted in Figure 43.

This model enables the user to obtain an initial assessment of the impact of afforestation on catchment hydrological responses in a short period of time (minutes). Interpretation of these initial results will indicate whether an in-depth regional/local assessment of afforestation impacts would have to be performed or not. Should this be necessary, the complete version of the *ACRU* modelling system (Schulze, 1995b; Smithers and Schulze,.

1995) with all its utilities and options for the inclusion of *inter alia* irrigation supply and demand, reservoirs and operation in semi-distributed mode can be used. Possibly the biggest advantage of the *ACRU* Forest model is that the user does not need to possess any detailed knowledge of the *ACRU* system, nor of forest water use, nor of the other processes involved. The *ACRU* Forest model owes its computational speed to:

a) the user being prompted by a series of easy-to-answer questions, which facilitate
b) automation of data selection, from
c) databases containing canopy and rooting characteristics, and from
d) the Quaternary catchment database for South Africa developed by Meier (1996).

The simple inputs the user is prompted with and has to answer interactively include:

a) either a user specified latitude and longitude, or alternatively the Quaternary catchment number (if known),
b) either a user specified altitude and soils information, or opting for the pre-programmed default altitude and soils information from the Quaternary catchment database,
c) an initial landuse (from a selection of six), representing the landcover from which the conversion to afforestation is taking place,
d) the genus to be planted (*i.e.* replacing the initial landcover),
e) the forestry region,
f) the rotation period,
g) whether or not thinning is practised, and if so, how often, at what tree ages and the percentages thinned,
h) a level of site preparation, and
i) the percentage of the catchment, or area of concern, that will be afforested.

This input determines the selection within the model, of relevant variables from the forest database (as developed in this dissertation), the landcover database (Schulze, 1995b) and the Quaternary catchment database (Meier, 1996). The Quaternary catchment database includes 45 years of pre-determined daily rainfall (for the period 1950 to 1994) from over

1200 stations, that are representative of the rainfall of each of 1946 Quaternary catchments in South Africa. The database furthermore consists of:

a) monthly means of daily maximum and minimum temperatures,
b) monthly totals of A-pan equivalent reference potential evaporation, and
c) hydrological soils information, in each case for each Quaternary catchment, as well as
d) month-by-month values of LAI, root fractions in the topsoil, K_{cm} and I_l.

As mentioned previously, LAI is used as the driving force of tree water use in the new FDSS. A series of either "high" or "lower" rainfall zone values of LAI for each year after planting are chosen within the model from Table 14, depending on the MAP for the Quaternary catchment being used. These LAIs are then linearly interpolated to convert the annual to monthly values, and then decreased by a percentage for thinning if required.

The model will determine internally the maximum number of rotations that may be run, given the 45 years of daily rainfall data for each Quaternary catchment. For example, if the user inputs a rotation of 20 years, the model will be run for 20 years, twice, always with simulations ending in December 1994.

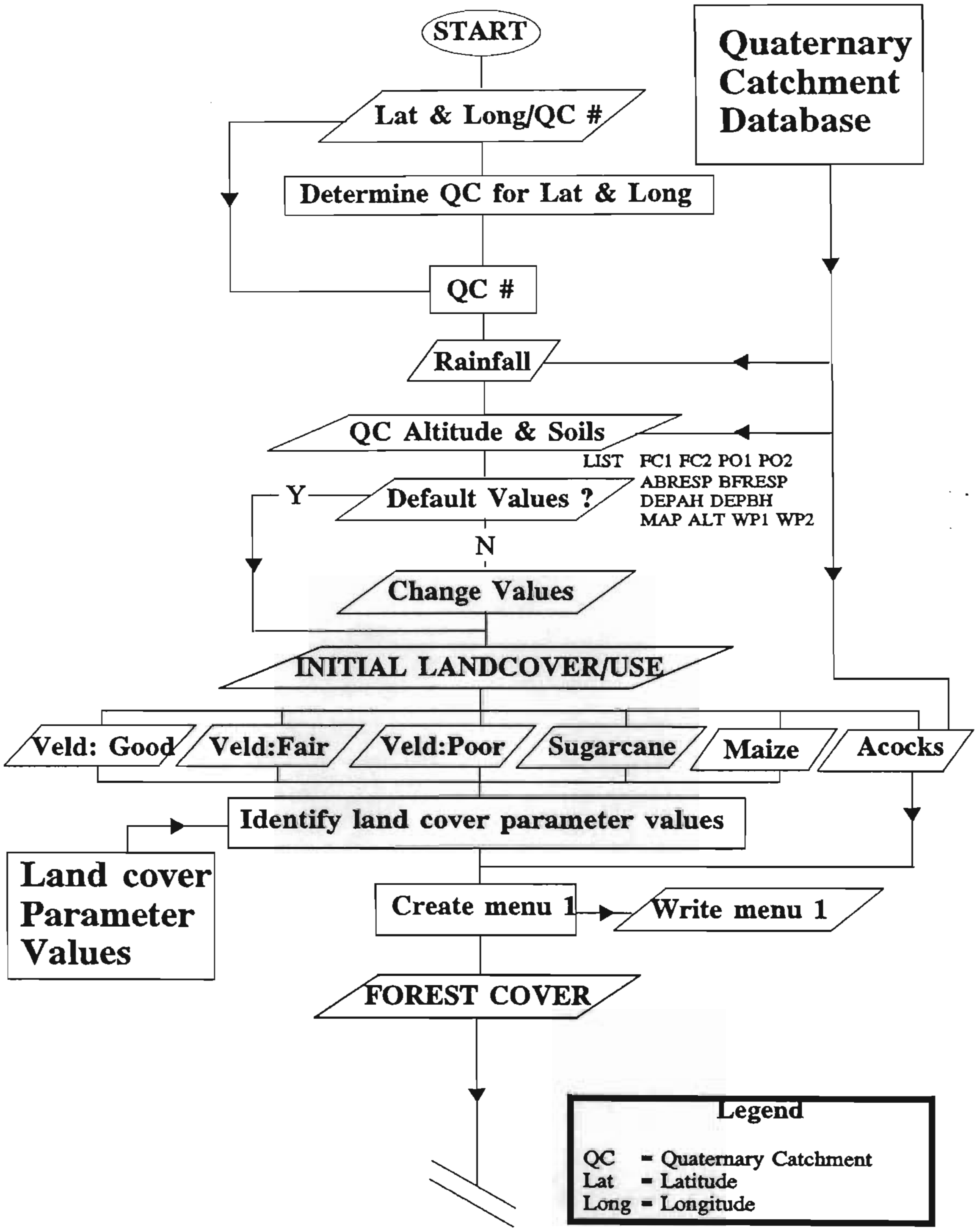

Figure 43. The system layout of the *ACRU* Forest model for assessing the impact of afforestation on streamflows.

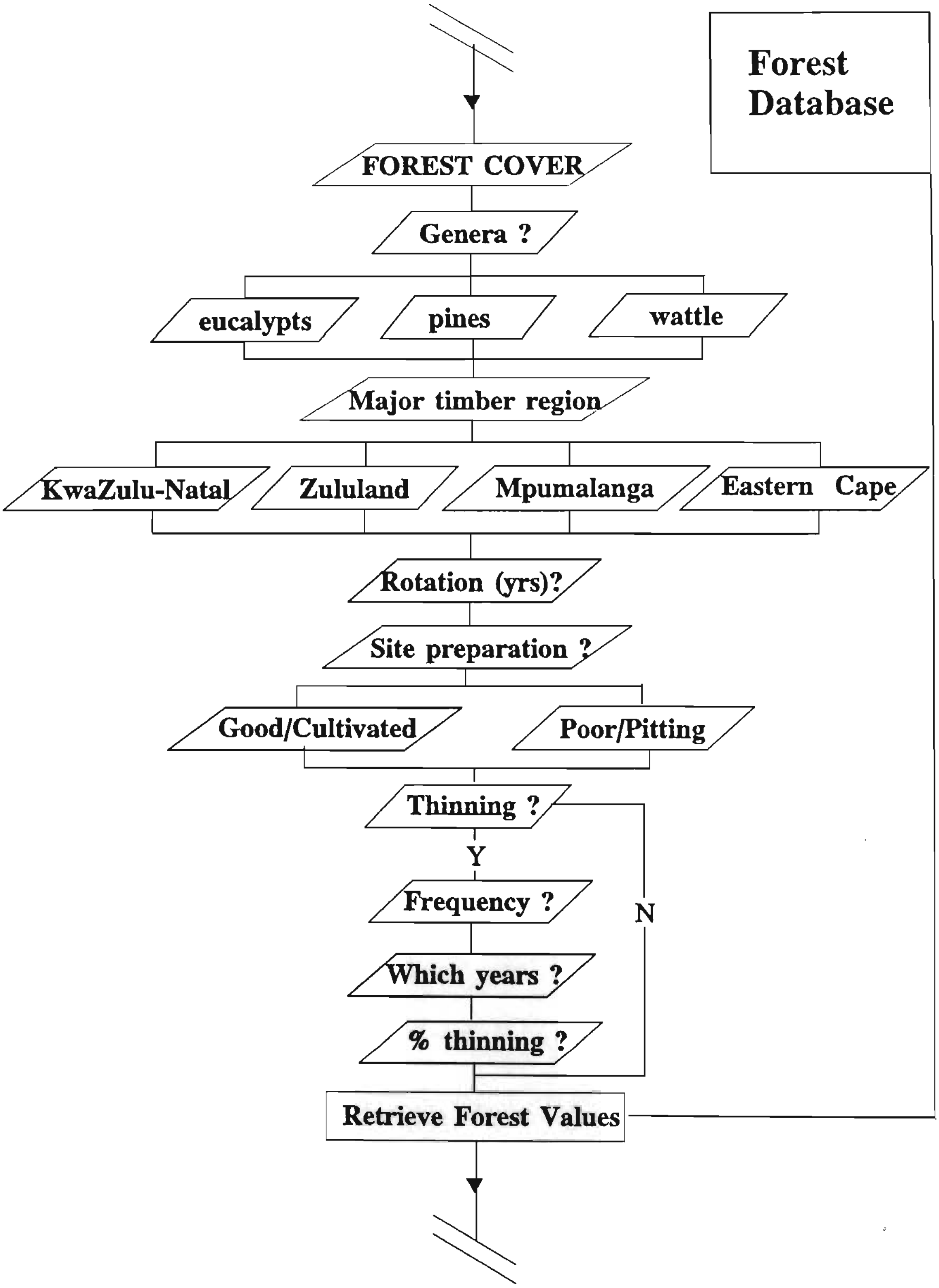

Figure 43. (Continued).

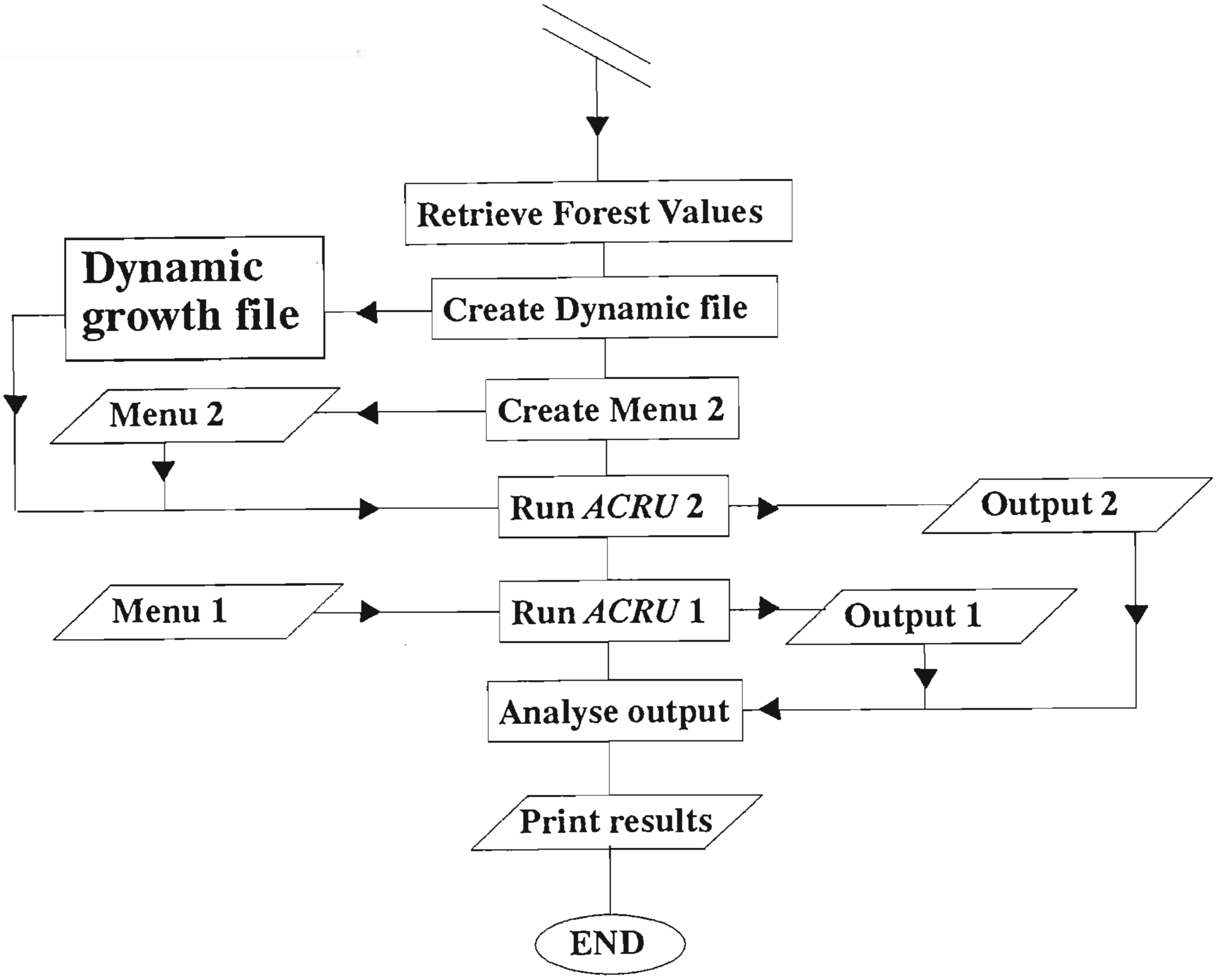

Figure 43. (Continued).

The input information is used in the model to automatically develop a menu for initial landcover conditions, and a menu and a dynamic file for the afforested conditions. In the dynamic file the values of LAI, I_1, rooting fractions and colonisation change over time according to genus, region, MAP, site preparation and thinning practices, according to the information in Tables 14, 17, 19 and 20. Together, these files contain the relevant site attributes and parameters needed to run the model. An updated version of *ACRU* 3.00, accounting now also for root colonisation and with a more sophisticated tree water stress routine (Schulze, 1995a), is then automatically run for each landuse. In this manner, simulations may be performed on a PC for a range of possible afforestation options, all within minutes (Initial runs indicate that output may be obtained within the order of two minutes of inputting the initial data on a 486 PC).

Output consists of a comparison of simulated streamflow, made up of stormflow and baseflow, a cumulative frequency distribution and the Coefficient of Variation (CV) for the initial and proposed vegetation.

* * *

Any natural process is very complex. The processes associated with afforestation and water use are no exception, and hence it becomes difficult to "mimic" such hydrological processes and their responses objectively and realistically. The new FDSS will hopefully go a long way toward addressing this problem, and with new data and knowledge further development will be possible. The module has been developed using data files that are easily replaced with improved data sets as and when they become available.

The need to model a complex forest hydrological system using a more deterministic approach than that used for the present APS has been outlined. This Chapter has detailed the development of a revised *ACRU* FDSS, driven by LAI. The *ACRU* FDSS has been refined and has been developed into the *ACRU* Forest model, which is capable of simulating the impacts of afforestation on streamflows in a short period of time. This model is hopefully capable of contributing to a future afforestation permit allocation system.

5. A SIMULATION OF AFFORESTATION IMPACTS

Chapter 5 describes results from a simulation using the *ACRU* Forest model to illustrate its potential application in assessing the impacts of afforestation on streamflow.

5.1 Model Input

A typical afforestation scenario has been used for this hypothetical example. Input information for this simulation is given in Table 21.

Table 21. Input details for the example simulation.

Location	23°43'S, 30°04'E
Region	Mpumalanga
Topography, Climate and Soils	Default Quaternary catchment values
Initial Landcover	Veld in fair hydrological condition
Final Forest Cover	*E. grandis*
Management Input	10 year rotation
	30% thinned at seven years
	Intensive site preparation

5.2 Simulation Results

Figure 44 depicts a comparison of the simulated accumulated streamflows of the two landcovers, while Figure 45 shows the difference of the simulated streamflows (grassland - afforested) for a 10 year rotation period. Figures 44 and 45 illustrate that the effects of afforestation on streamflow become increasingly larger as the plantation grows. Figure 45 illustrates clearly that the modelled impact of afforestation only really starts manifesting itself three seasons after planting. The first three years' slightly lower accumulated streamflow for the afforested simulation, results from enhanced infiltration (and hence reduced streamflow responses) associated with intensive site preparation. Seasonal streamflow patterns are also evident, with a flattening off of the accumulated streamflows during the dry winter periods (Mpumalanga being in the summer rainfall region).

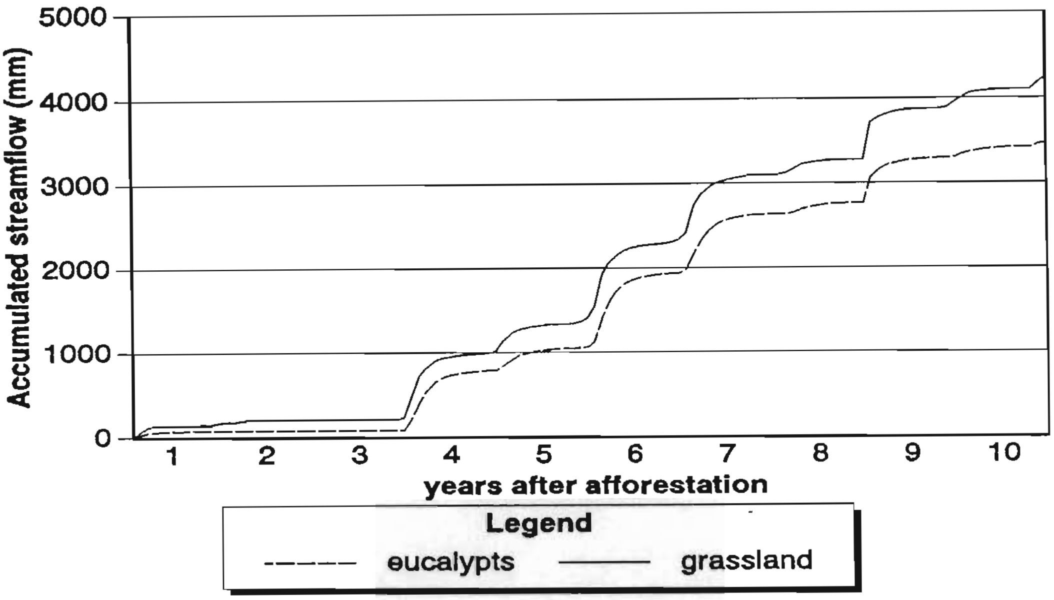

Figure 44. Simulated accumulated streamflows for eucalypts and grassland at a specific location in the Mpumalanga region.

Figure 45, in particular, depicts a definite annual cyclical trend in streamflow response. During the wet seasons, streamflows from the grassland are simulated to be greater than from the afforested area, while in the dry seasons following heavy summer rainfalls, more streamflow is evident from the afforested area. This may be explained by the infiltrability of the forest soils being greater than that of grassland as a result of higher initial abstractions associated with litter cover, a deeper critical soil depth from which less stormflow is generated and faster saturated soil water redistribution rates in the forest, all parameterised in the original *ACRU* FDSS by Jewitt (1991) and Schulze *et al.* (1995). Streamflows during wet seasons are thus considerably higher from grassland than from forest areas. During the dry season following a very wet summer, infiltrated water from the afforested area, which meanwhile would have drained to below the root zone, is released as delayed baseflow. Hence the negative streamflow difference *i.e.* higher baseflows from the afforested areas as shown in Figure 45.

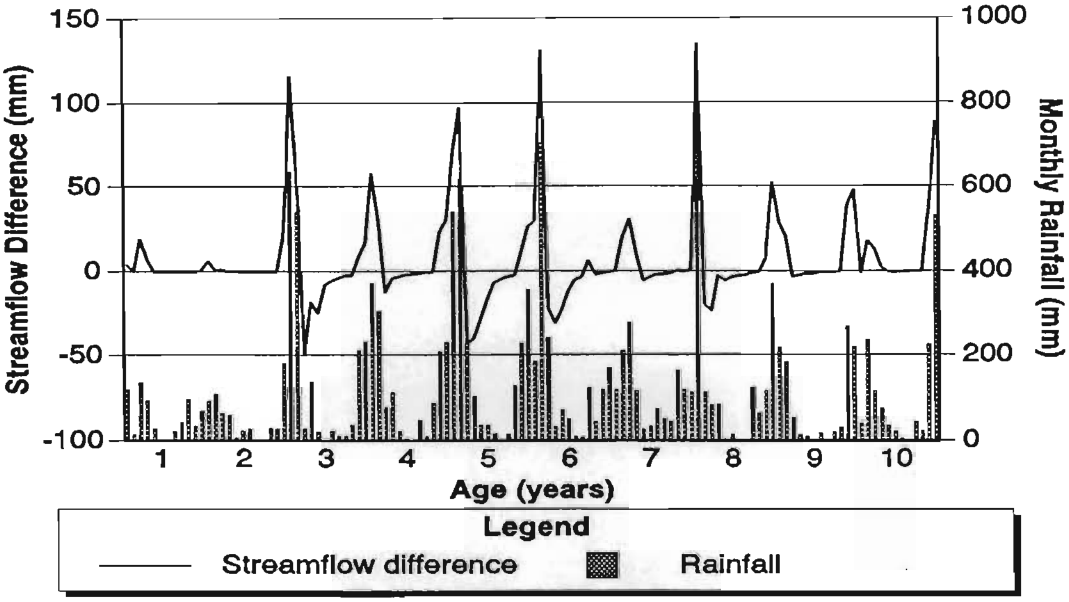

Figure 45. Simulated streamflow differences between grassland and *E. grandis* at a specific location in Mpumalanga.

Streamflows also tend to decrease later in the simulation for both the grassland and afforested runs as indicated by the streamflow difference diminishing (Figure 45), as a result of decreasing rainfall. This streamflow reduction is more pronounced for the afforested simulation since during the latter part of the simulation, the streamflow difference tends to be slightly positive as a result of the grassland landcover generally having larger streamflows than the afforested simulation. This is probably as a result of the afforested catchment's ability to intercept more rainfall and extract larger quantities of soil moisture than grassland in order to satisfy larger transpirational demands.

The cumulative frequency distribution (Figure 46) depicts a range of percentiles. The 50th percentile denotes median annual streamflows of 145.3 and 56.5mm for grassland and afforested conditions respectively. Therefore, for this simulation, a median streamflow decrease of 88.8mm, or 61.1%, is simulated. The 10th percentile (driest year in ten) simulation depicts a reduction of 36.7mm (88.0%) from 41.7 to 5.0mm.

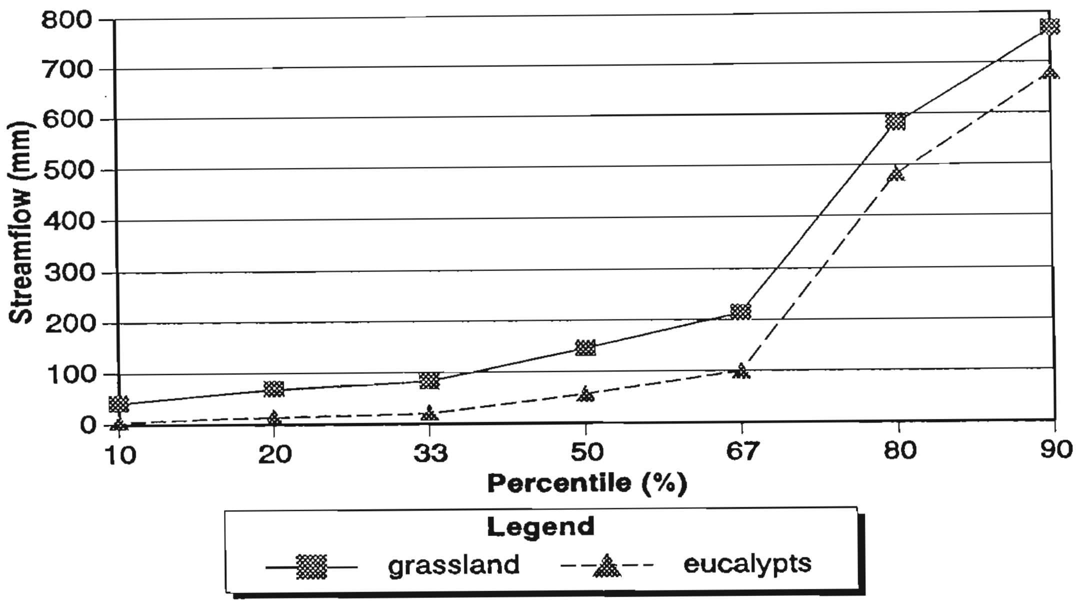

Figure 46. Cumulative frequency distributions of simulated annual streamflows from grassland and *E. grandis* for a range of hydrological conditions from the driest year in 10 to the wettest year in 10.

When a catchment is afforested, drastic streamflow reductions are therefore possible. The impact is particularly severe during low flow periods and in this example, streamflow response from grassland is almost double that for an afforested area during periods of median flow periods.

These results of course denote the impact of afforestation assuming that 100% of the area under review is being afforested. This is never the case in practice because of riparian zone restrictions. An "allowable" area of afforestation may be calculated if a streamflow reduction limit is set. Using the above simulation results by way of example, if a 10% reduction in median annual streamflow were to be acceptable, then the maximum area of a catchment to be afforested upstream of some critical point of conflict would be 16.4% [(10/61.1)*100].

The CV statistic gives a measure of the variability of the simulated streamflow for a given time period. The inter-annual CV from the simulations was higher for the afforested area (142.8%) than for the grassland area (110.8%). Schulze and Pike (1995) attribute the increased inter-annual variability under afforested conditions to the relatively bigger impacts of afforestation in dry years than in wet years.

The trends of the above results concur with those reported in other studies (*e.g.* Schulze, Stacey and Summerton, 1993; Schulze and Pike, 1995) for similar catchments. Within the forested zones of South Africa, the new *ACRU* Forest model is a more realistic simulator of afforestation impacts because the forest now "grows" dynamically, accounting for broad regional differences, more specific day-to-day conditions, management practices, root colonisation and improved soil water relations under stressed conditions, all in addition to processes previously catered for in the original *ACRU* FDSS (Jewitt, 1991; Schulze *et al.*, 1995).

* * *

In Chapter 5 the results of a hypothetical simulation of the impacts of afforestation on streamflow were presented. The example has illustrated the ease of input into the *ACRU* Forest model and the potential for interpretation of output. The original *ACRU* FDSS underwent extensive and successful verifications on gauged catchments (Jewitt, 1991; Jewitt and Schulze, 1993). It is considered that:

a) the various revised process representations (based on new fieldwork),
b) the new information which was provided by experts during the workshops, and
c) particularly the new modelling procedure accounting for the dynamics of tree growth and hence water use over time, the concept of which had previously been demonstrated successfully with *ACRU* on a research catchment by Schulze and George (1987),

will all result in the new FDSS imbedded in the *ACRU* Forest model to be applied with confidence in the timber and water industry.

6. DISCUSSION AND CONCLUSIONS

The process of forest permit allocation in South Africa has attracted much discussion and controversy, *inter alia* as to whether the Afforestation Permit System in its present form has a valid mandate, and whether the system should continue to be utilised or not. The likelihood is high of another system based on the use of hydrological simulation models with better process representations, shorter modelling time steps, greater versatility and a more objective risk assessment being used in future to predict the impact of commercial afforestation on water resources. Calls have even been made for the replacement of the APS with a more generic and unbiased system whereby all land/water users are judged according to the same criteria. One system that holds promise in this regard is the deterministic *ACRU* agrohydrological modelling system with its new FDSS.

The existing *ACRU* FDSS (Jewitt, 1991; Schulze *et al.*, 1995), together with new results presented in this dissertation and a Quaternary catchment database for South Africa (Meier, 1996) have been used to develop a revised FDSS as a stand-alone PC-based model called *ACRU* Forest. This model is capable of predicting not only the impacts of afforestation, but also the impacts of other landuses on water yield, including *inter alia* various crops and natural vegetation conditions. The *ACRU* Forest model has been developed to provide the potential user with an initial indication of the impact of afforestation on streamflows within a matter of minutes. The *ACRU* Forest model owes its computational speed to the automated selection of the relevant variables for use in the model, prompted by unambiguous questions requiring minimal user input. The model may be easily upgraded as new data become available. The potential of the model has been depicted in Chapter 5, where *ACRU* Forest predicted that eucalypts grown in Mpumalanga would decrease streamflows under median conditions and those prevailing in the driest year in ten by 61.1% and 88.0% respectively.

The revision process involved the collation of data and information from a literature survey (Chapter 2), fieldwork (Chapter 3) and a series of workshops (Chapter 4). A large portion of this research involved the determination of parameters for rooting characteristics, I_l and LAI. The *ACRU* Forest model is "driven" by LAI in its soil water use routines since adequate LAI information is available. Parameters representing different scenarios have been included for:

a) four major forest areas in South Africa *viz.* the Midlands and northern areas of KwaZulu-Natal, the sandy plains of Zululand, Mpumalanga, and the NEC part of the Eastern Cape,
b) the entire rotation period,
c) two different rainfall regimes, and
d) management practises, including the effects of site preparation, rotation period lengths and thinning.

Factors affecting water use by trees have been reviewed in this dissertation. Ultimately, however, tree water use is limited by soil water availability and that is therefore the main factor influencing growth of commercial plantations. Studies are required particularly to determine the comparative water use by different species and the mechanisms which control the use of water in regions of different climate. The growth and water use by forests is predominantly dependent on two climatic variables, *viz.* temperature and precipitation, with commercial trees generally occurring in areas of relatively higher temperatures and precipitation.

The most widely used methods for tree water use determination in South Africa are the Neutron Moisture Meter, paired catchment and Heat Pulse Velocity techniques. These techniques have been used to determine that trees grown in a plantation use between 20-40ℓ.tree.d^{-1}. Maximum streamflow reductions have been cited at 300-400mm.annum^{-1}. The possibility for trees using more water than vegetation in pristine condition is therefore high, although other landuses may use more water than commercial trees. For example, irrigation may use up to seven times more water than trees (Edwards, 1995).

Since water availability for commercial forestry is often a limiting factor in South Africa, experimentation sites which allow the study of the potential for increasing water supply to trees were chosen. Fieldwork was undertaken at two sites, *viz.* the irrigation trials at Mkuze in northern KwaZulu-Natal, and the site preparation trials near Ugie in the Eastern

Cape. Results from these trials provide evidence that differences in water use do exist in terms of different water application regimes, site preparations, soil characteristics and clones. Large growth potentials are possible if water is not limiting, although a water supply threshold exists at about 1400mm.annum^{-1} above which diminishing growth returns occur.

Trees in the Mkuze environment are likely to experience severe soil water stress if rainfall is not supplemented by irrigation. High mortality rates on rainfed treatments and excellent growth on irrigated treatments testify to this and to the accuracy of the generally stated 800mm Mean Annual Precipitation prerequisite for successful afforestation. After five years of growth, trees on the higher irrigation treatments at Mkuze are ready for harvesting, effectively halving rotation periods for eucalypts as a result of irrigation in this area of high temperatures. This provides exciting potential for the forest industry, should enough water be available for irrigation.

Results from the site preparation experiments near Ugie in the Eastern Cape support findings at other similar trials in South Africa (*e.g.* at Glendale in KwaZulu-Natal), *viz.* that grassland sites generally contain more soil moisture than tree sites under pitted, rip and ridge and cultivation preparations, in that order. Trees tend to initially grow better on "complete" site preparations, but at the expense of higher water use rates.

A disturbing finding during this research was the paucity of field observations of parameters depicting tree water use, especially rooting properties. For effective forest hydrological modelling, accurate input of these variables is required. From personal communications, it was found that occasionally fieldwork had, in fact, been undertaken or researchers had observed processes, but the findings had not been satisfactorily documented. The workshop system afforded the opportunity of extracting this expert knowledge from managers, researchers and technicians working in the field of forest hydrology. As a result of the paucity of data, trends were often extrapolated or interpolated from the results obtained at the workshops, thereby providing a subjective element to the results.

The main finding of this research has been that tree water use characteristics are intricate and incorporate many complex physiological processes that are difficult to characterise quantitatively, as required for modelling purposes. Nevertheless, future research will provide some of the answers required and, undoubtedly pose further questions concerning the processes involved in tree water use modelling.

7. RECOMMENDATIONS FOR FUTURE RESEARCH

The experience gained while researching and writing this dissertation indicated that researchers do not yet fully understand the dynamics of the forest hydrological system. The reason for this is that the system is highly complex and involves numerous interrelated processes. The need therefore exists to use contemporary methodologies to determine understandable relationships that may be used in simulations. Particular areas requiring research include:

a) the effect of rooting patterns and colonisation on tree water use,
b) tree water use as affected by the onset of stress,
c) competition by roots for available soil moisture,
d) the impacts of litter with respect to interception, evaporation and mulch protection,
e) impacts of management, *i.e.* thinning, weeding and fertilisation on soil moisture availability to the tree,
f) distinguishing between photosynthetically active and passive LAI, as well as impacts of soil water stress on LAI and consequently water use,
g) maximum transpiration rates,since the upper limits of tree water use have not yet been defined,
h) the influence of second and subsequent rotations on soil moisture extraction patterns, and
i) modelling soil evaporation and plant transpiration under plantation conditions separately and not as an entity as has been done in the past.

Continuation of soil moisture monitoring at the Mkuze irrigation trial and at the site preparation experiments in the Eastern Cape would greatly benefit the South African forest industry, especially if continued beyond the first harvest. Invaluable information on the effects of landuse change as well as of second and subsequent rotations on water use by commercial tree species would be gained. The determination of a water balance at these sites would also enhance understanding of tree water use regimes of commercial tree species.

In order to determine the real benefit of irrigating trees in South Africa, an economic analysis including the would-be cost of water and the quality of timber produced, needs to be performed. At Mkuze, for example, transpiration and growth rates on the low irrigation treatment were only slightly lower than those on the high irrigation treatment. Therefore, low level irrigation may be cost beneficial in terms of increased returns, while irrigating at higher magnitudes may provide diminishing economic returns for the amount of water applied. This indicates that the low irrigation treatment may be the most cost effective and water use efficient treatment.

Like any modelling system, *ACRU* Forest requires continual updating as more and improved data and information become available. A re-verification of the model is also required to ensure that the model output has remained acceptably accurate.

An exceptionally high level of collaborative research and cooperation was experienced during this research and the preparation of this dissertation. Maintaining this standard of cooperative research is a recommendation that researchers in many other fields of study can take cognizance of. Cooperative research not only stimulates lateral thinking and the formulation of new concepts and ideas, but eliminates much duplication of work that has already been concluded.

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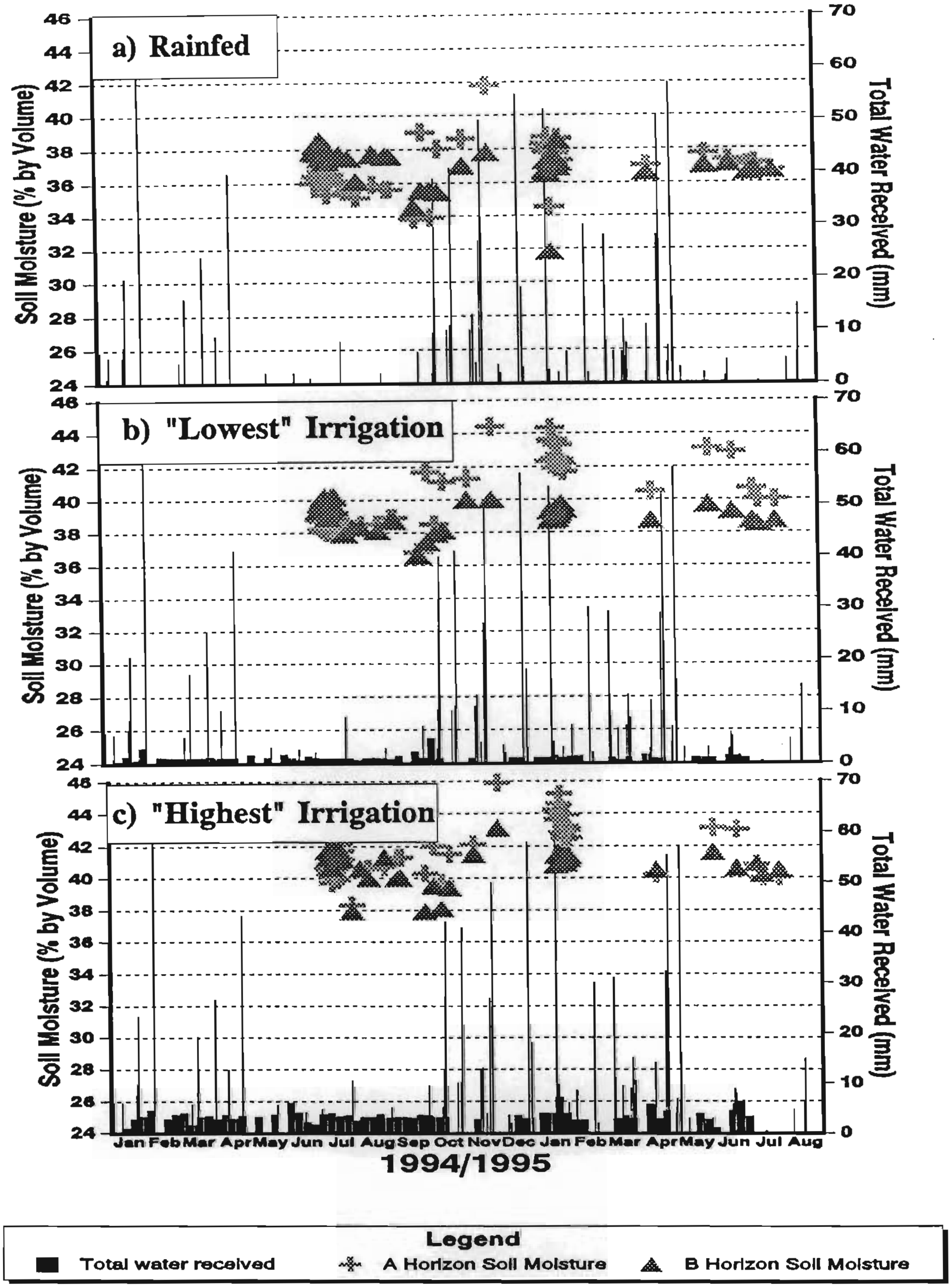
9. APPENDICES

APPENDIX A. Plot and NMM access tube numbers for the site preparation experiments at Tree Fern Pool and Funeray in the Eastern Cape.

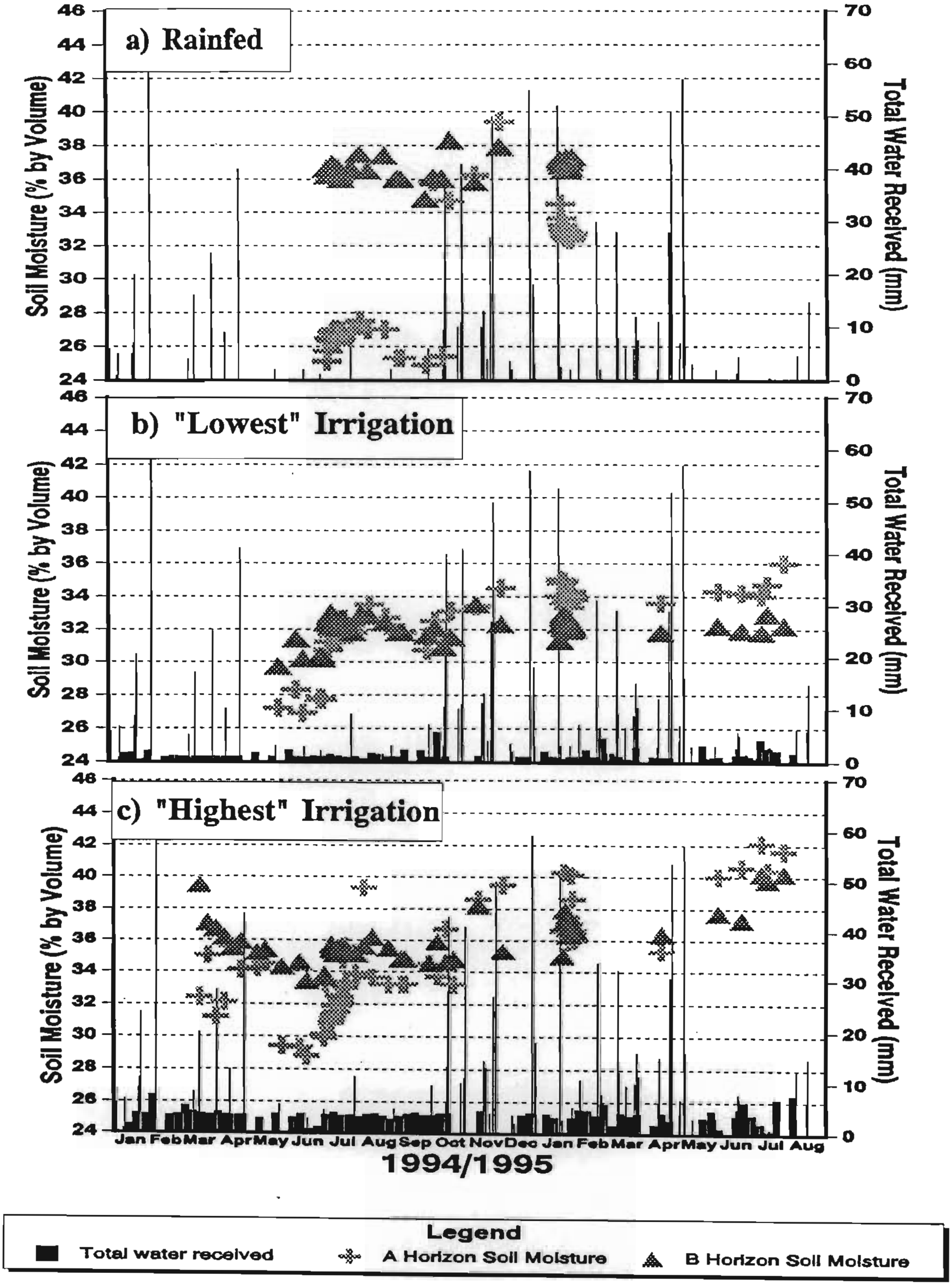
Site	**Preparation**	**Plot numbers**	**NMM access tube numbers**
Tree Fern Pool	Cultivation	47	1-6
	Pitting	40	7-12
	Rip and Ridging	39	13-18
	Grassland	-	19-21
Funeray	Cultivation	39	51-56 (shallow); 72-74 (deep)
	Pitting	38	57-62 (shallow); 75-77 (deep)
	Rip and Ridging	48	63-68
	Grassland	-	69-71

APPENDIX B. Plot and NMM access tube numbers for the Mkuze irrigation trials in KwaZulu-Natal.

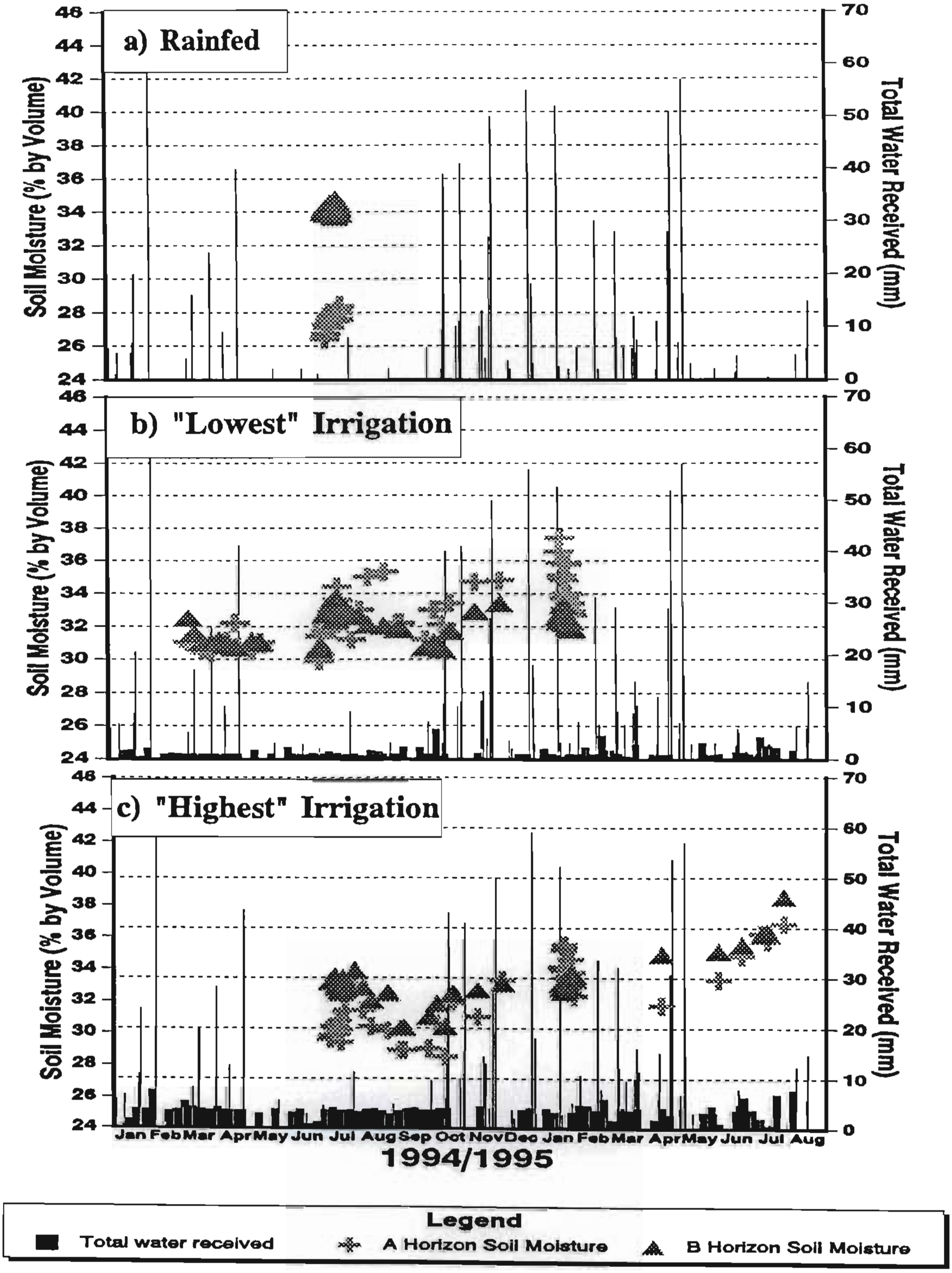
Treatment	**Plot numbers**	**NMM access tube**
	Shortlands TAG5	
Control	276	70-72
1	81	46-48
2	33	16-18
3	148	10-12
4	54	34-36
	Shortlands GC540	
Control	265	501-503
1	70	201-203
2	35	119-121
3	147	122-124
4	55	116-118
	Bonheim TAG5	
Control	254	516-517
1	62	513-515
2	28	507-509
3	154	504-506
4	51	510-512
	Bonheim GC540	
Control	268	110-112
1	83	97-99
2	185	104-106
3	168	107-109
4	102	101-103



APPENDIX C. Depth integrated soil moisture trends over time for the Bonheim TAG5 combination for the three selected water application regimes at Mkuze for the period March 1994 to August 1995.



APPENDIX D. Depth integrated soil moisture trends over time for the Shortlands GC540 combination for the three selected water application regimes at Mkuze for the period March 1994 to August 1995.



APPENDIX E. Depth integrated soil moisture trends over time for the Shortlands TAG5 combination for the three selected water application regimes at Mkuze for the period March 1994 to August 1995.

APPENDIX F. An example page of the 12-page questionnaire used at the *ACRU* FDSS Workshops.

LAI for eucalypts on a completely prepared site.

Age (y)	**Zululand Coast**		**Natal Midlands**		**N Natal/SE Tvl**		**NE Cape**		**NE Tvl**		**E Tvl**	
	Sandy soils	Other soils	Shallow soils	Deep soils	Shallow soils	Deep soils	Shallow soils	Deep soils	Shallow soils	Deep soils	Shallow soils	Deep soils
2												
4												
6												
10												

Definitions:

a) Shallow soils <0.7m, PAW <60mm

b) Deep soils >1.2m, PAW >100mm

c) Sandy soils >2.0m