THE USE OF VEGETATION IN THE AMELIORATION OF THE IMPACTS OF MINING ON WATER QUALITY - AN ASSESSMENT OF SPECIES AND WATER USE

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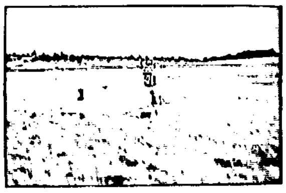

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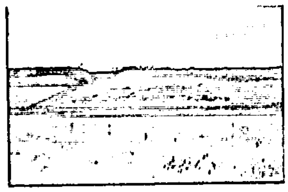

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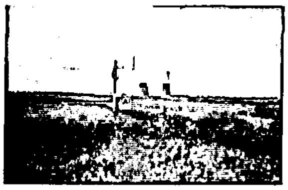

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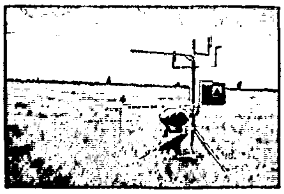

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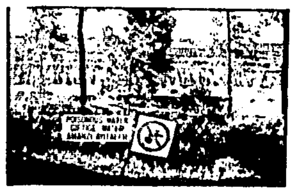

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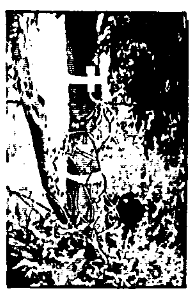

n) ***HPV instrumentation***

Frontispiece : Water use by trees in mining environments : images of sites and instrumentation.

EXECUTIVE SUMMARY

BACKGROUND

OBJECTIVES

The aims of the project were originally defined as follows:

To assess the degree to which vegetation can be effective in utilizing rain and surface water, thus preventing its movement through, and leaching of, mining waste piles, replaced or fractured profiles, resulting in acidified or otherwise polluted ground and surface waters. This comprised four areas of focus (as expressed in the project document):

- Evaluation of sites, growing conditions, and the success in establishment of species already found either colonizing mining sites or planted within the landscape for commercial, woodlot, ornamental or other purposes. The role of indigenous grasses and woody species, and that of established pastures, will also be considered. Sites and species will be selected for further research.

- Determination through field measurement of how much water could be utilized by those different species and vegetation types which have potential for establishment on mining waste piles, replaced soil profiles, and land surfaces disturbed by sub-surface mining activity (eg. coal longwall mining).

- Development of modelling and predictive methods to extrapolate water use estimates by species over scales of space, time and climate variation.

- Assessment of species for establishment, and how effective measures are likely to be, in achieving the management objectives of minimizing throughflow to the sub-surface and groundwater.

RESEARCH APPROACH

Trees are recognized as being potentially major consumer of water, with the genus *Eucalyptus* targeted as a consequence of both South African and international experience. The hypothesis is that consumptive water use is likely to be higher where trees are established on sites which would otherwise be carrying grass or other low biomass vegetation. To prove this requires measurements of water use both by trees growing in mining environments and the vegetation which such trees might replace.

An examination of the potential role of trees as water users required water use measurements in both trees and grass across a range of sites and species, and for different seasons of the year. Sites were required to include the most important mining types in terms of hydrological management problems. Trees for which water use was measured had to be typical of those which might be used in the practice of water management.

Research was limited to the eucalypts - recognized water-users and the most successful colonizers of mine sites. There have also been a number of deliberate plantings providing research material. Research was therefore aimed at establishing the principles and potentials of water use by eucalypts, whilst recognizing the potential role of other tree species.

The following mining activities, sites, and species were researched:

- ***Gold slimes dams***

  Robinson Deep, Western Areas, Durban Deep, Withok, and West Extension: *E. sideroxylon, E. camaldulensis* and *E. viminalis.* Two acacias (*A. baileyana and A. melanoxylon)* were included in a pilot study at Robinson Deep.

- ***Coal - Rehabilitated open cast***

  Hendrina: *E. macarthurii*

- ***Coal - High extraction underground***

  Secunda: *E. viminalis*

Evaporation from grassland was monitored concurrently on adjacent sites.

The research methodology entailed two techniques:

(i) Direct uptake and transpiration of water by trees through determination of the sapflow rate using the heat pulse velocity (hpv) method.

(ii) Measurement of evaporation from grassland by means of Bowen ratio energy balance partitioning to determine the latent heat of evaporation.

Water use by trees was estimated on the basis of ground area allocated to the tree if the tree was in a formal planting. The area occupied by the tree canopy was used in those cases where trees were not evenly spread. Tree water use was expressed in terms of area occupied to facilitate comparison with water use by grassland vegetation. Actual water use is heavily dependent on the age and leaf area of the tree and results do not always reflect the potential water use of a well developed canopy.

RESEARCH COMPONENTS

The principal components of this research project comprised:

- An extensive literature review of the role of trees in mining environments, with an emphasis on water use.

- Field measurements of tree and grass evaporation over a range of sites, including seasonal variation. Tree water use measurement was limited almost exclusively to the eucalypts.

- An investigation of the rooting strategies of trees in order to assess their abilities to exploit a greater soil root volume than grass.

- A survey of tree species most suited to Highveld conditions, with notes on establishment and silviculture.

- Recommendations for research and management.

RESULTS AND CONCLUSIONS

Mining environments are adverse both in terms of climate and substrate for growing trees. Although trees have now been successfully established on a number of mine sites, and have been seeded on gold dumps and slimes dams for many years, there remains a paucity of material useful for water use research. If the impact of trees is to be comprehensively determined then more trees will have to be planted.

Trees are found to use more water than grass under most of the circumstances examined. Although different species were measured on different sites, a general pattern for daily water use can be derived.

The expression of water use by trees is very dependent upon the leaf area of the tree and the ground space which it occupies. This results in wide variation in daily water use by single trees, with average values ranging from 0.36 to 1.36 mm in winter, and 1.53 to 7.92 mm in summer. The lowest values have been obtained for older trees growing on gold slimes dams whilst the most consistently high rates are for trees growing within a slimes dam seepage area. Younger trees on gold slimes dams are also very effective.

Grass can, if the cover is exceptional, compete with trees in the summer, as was found at Secunda where both natural grass cover and trees were using in the order of 5 mm per day. It is the evergreen nature of trees which makes them more `efficient' water users, continuing to transpire at 3 mm/day during winter while the value for grass is close to zero. This difference during winter may result in a substantial difference in water use between grass and trees on a annual basis. A 1 mm increase in daily water uptake by the vegetation, for example, will reduce the effective rainfall (after growth) by approximately 50% of the annual rainfall budget.

Tree water use expressed on the basis of evaporation per unit leaf area was generally within the range expected for commercial forestry tree species. Most trees transpired at rates of less than $1\ell/m^2$/day, with rates during winter months being approximately $0.5\ell/m^2$/day. The exceptions were the summer values for trees growing in toe areas at Withok and Western Areas, and at West Extension where values of greater than $1\ell/m^2$/day were often recorded.

Distinct differences in rates of water use were evident among trees. Mature trees with fully developed canopies showed greater rates of water loss than younger trees. The objective is therefore to maximize tree or stand canopy density. A management strategy to achieve this through species selection, age class and regeneration will require further research.

A clear difference in water use with respect to tree genera was also found. Eucalypts maintained relatively high transpiration rates. The acacia species were not able to match these rates. Differences in rates of water use among the various species of the genus *Eucalyptus* were also evident. The highest water use rates were recorded for *E. camaldulensis* trees at West Extension, and for *E. viminalis* trees at the base of Withok slimes dam during summer. However, eucalypt species such *E. sideroxylon* (Western Areas) and *E. macarthurii* (Hendrina) showed higher transpiration rates than *E. viminalis* during autumn and winter respectively. These differences among eucalypt species should be interpreted with caution since measurements were undertaken on trees growing in different physical environments and direct comparisons among species are therefore not entirely valid. It is not yet possible to make any generalizations regarding which eucalypt species will be more efficient at ameliorating the impacts of mining water. The selection of the appropriate tree species for rehabilitating mines should be based on how well that particular species is suited to the site conditions. Values of water use by trees and grass from all research sites, are given in the accompanying table.

Table: Water use (daily evaporation) by trees and grasses at various Highveld mining sites and at different times of the year.

Site	Season	Daily evaporation		
		Grass (mm)	Trees (mm)	Trees (ℓ/m²)
Western Areas	Nov/Dec	2 mm (average)	-	-
		3 mm (18-30 Nov)	7.0 mm	2.5 ℓ
West Extension	Feb	-	1 - 12 mm	0.9 - 2.5 ℓ
Durban Deep	Dec/Jan	-	1.5 mm	1.0 ℓ
Withok	Jan/Feb	2 mm	7.0 mm	2.5 ℓ
Secunda	Feb	3 mm	0.5-4 mm	0.4 ℓ
	Feb/March	-	2.5 mm	0.4 ℓ
Hendrina	Feb/March	1 mm	2.6 mm	0.5 ℓ
Hendrina	May	-	1.5 mm	0.2 ℓ
Withok	May	1 mm	4.0 mm	1.0 ℓ
Durban Deep	May	-	0.5-1 mm	0.5 ℓ
Hendrina	June	0.2 mm	1-2.5 mm	0.4 ℓ
	July	-	1-2.5 mm	0.4 ℓ
Secunda	Aug/Sept	0.1 mm	0.8-3 mm	0.2-1.0 ℓ

PROJECT EVALUATION AGAINST OBJECTIVES

- *Evaluation of sites, species, and growing conditions*

  Tree planting is playing an increasing role in mine water management planning and the research reported on in this document places these efforts into perspective. Suitable species are available for growing under a wide range of seemingly adverse conditions. Research was conducted almost exclusively on *Eucalyptus* species.

- *Measurements of water use*

  Tree water use has been measured over a variety of sites and seasons, also almost exclusively on the eucalypts. The permutations of mining activity (e.g. gold, coal, other), site, soil, water quality, and the hydrology are almost endless. The potential for trees has been demonstrated for a number of these conditions. Grassland evaporation measurements which were undertaken to compare with tree water use values, are the first measurements of their kind on the South African Highveld.

- *The extrapolation of water use estimates*

  Tree water use data for any single site remains very patchy in terms of seasonal variation. Annual estimates of total water use have not been modelled from hourly or daily climate and water uptake data. Such estimates can be done, but at this stage are not likely to be any better or more accurate than the seasonal derivations made from the data. The wide variation in water use between individual trees, as well as substrate differences, are clearly confounding factors for the development of appropriate models.

  Estimates of optimal water use can be made on the basis of established leaf area: water use relationships, and on the basis of the potential which sites may have to maintain additional growth.

- *Assessment of species for establishment and probable effectiveness of tree planting measures*

  Tree species and their establishment are reviewed in detail. The effectiveness of trees is discussed in the light of water use results, along with issues related to tree planting and sustainability.

RECOMMENDATIONS FOR FURTHER RESEARCH

- There is no end to the possible list of permutations for which water use uptake can be measured. The bank of data so far developed will need to be extended if accurate predictions are to be made so as to refine the planting model required to achieve a specific water management goal. A first step would be further analysis of the existing data set.

- To support hydrological research there is a need to set up a series of species and establishment trials across a range of sites, and using a variety of species.

- It is also recommended that plant material from trees growing successfully in the seep areas of fast-disappearing gold slimes dams and sand dumps be collected and propagated in a clonal data bank. This material should then be made available for planting on sites of matching quality.

- The principle that tree planting can be beneficial is generally accepted. However, there are a number of further silvicultural research questions, relating to site preparation, irrigation, espacement, agroforestry, and to the growing of species other than the eucalypts, that still need to be answered.

- Water use by grass pasture should be researched with an emphasis on the possible hydrological benefits of improved pasture management.

- Soil depth and tree rooting strategies need to be explored in more detail, along with ways of increasing rooting depth and the impact which this might have on site hydrology.

- A study should be implemented on a scale whereby the planting of trees can be evaluated in terms of the `bottom line' i.e. how streamflow, mine seepage inflow, or mine seepage outflow are directly affected as result of a tree planting exercise.

- The impacts of reducing water throughflow in mines needs to be evaluated in terms of positive, or possible negative, benefits. Suitable areas for the use of trees should then be identified.

- More research work needs to be prioritized on the tops of slimes dams, on rehabilitated open-cast coal mines, and within the seep or decant areas for all mining activity.

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CHAPTER 1

INTRODUCTION

1.1 RESEARCH OBJECTIVES AND APPROACH

The aims of this project, as described in the CSIR's original proposal to the Water Research Commission, are as follows:

To assess the degree to which vegetation can be effective in utilizing rain and surface water, thus preventing its movement through, and leaching of, mining waste piles, replaced or fractured profiles, resulting in acidified or otherwise polluted ground and surface waters. This comprises four areas of focus :

- Evaluation of sites, growing conditions, and the success in establishment of species already found either colonizing mining sites or planted within the landscape for commercial, woodlot, ornamental or other purposes. The role of indigenous grasses and woody species, and that of established pastures, will also be considered. Sites and species will be selected for further research.

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- Development of modelling and predictive methods to extrapolate water use estimates by species over scales of space, time and climate variation.

- Assessment of species for establishment, and how effective measures are likely to be, in achieving the management objectives of minimizing throughflow to the sub-surface and groundwater.

We investigated the ability of trees growing in mining environments to utilize unwanted water, and compare this to the evaporation measured for adjacent natural and rehabilitated grassland sites. The water use of trees was determined using the heat pulse velocity method (HPV) for measuring sap flow, while grassland evaporation was determined by means of the micrometeorological Bowen ratio technique. Rates of water use have been obtained for individual trees and for grassland on and around gold slimes dams in the Johannesburg area, above total extraction coal mines near Secunda, and growing on a rehabilitated open-cast coal mine near Hendrina. Measurements have been under a range of conditions for both the winter and summer seasons and comparative water use data are presented.

Each mining activity represents a different research environment but with common key questions: Can trees survive and grow in what are often hostile conditions? How much water would trees use? How much water would be utilized by an alternative land-use? These questions have guided this research programme.

1.2 BACKGROUND

Water runoff from gold slimes dams, sand dumps and coal spoil is generally of undesirable quality for direct release into rivers. Rainwater, infiltrating into rehabilitated open-cast coal mines and rock fractured by total extraction methods, also often deteriorates in quality - usually through acidification - to the point where it is unacceptable for release and must be contained or otherwise utilized.

Vast areas of the South African landscape are affected by the mining industry. While there are now stringent guidelines with regard to rehabilitation, and environmental regulations make it very difficult to achieve mine closure, many of the physical changes cannot be undone.

High yield extraction of coal could destabilize at least 410 000 ha of the Highveld, while coal reserves underlie 2,7 million hectares of which 1,0 million ha could potentially be mined. This area contains 49% of South Africa's coal reserves. Major water quality problems are now being experienced in the Vaal and Loskop dam systems and mining activity is perceived as an important contributor (Van Niekerk Report of the Committee on the Investigation into the Long-term Effects of High Recovery Of Coal on Agriculture in the Eastern Highveld, 1990). R4 million is spent annually on neutralizing acidified water in the district of Vryheid alone. It is further expected that changes in the Water Act will place responsibilities on land-owners and industrial users for groundwater quality, and not only the quality of surface water as in the past.

It is argued that the ability of some tree species to transpire high volumes of water can be put to good use in areas where runoff is of unacceptable quality, and trees are now being considered by the mining industry as one of a range of water management options. The manner in which trees are used will depend upon how and where they can be most effective, and what the implications may be for the environment, water supply, sustainability and future land use. Applications may be at the commercial scale, with timber as a valuable by-product, or through the introduction of agroforestry, or the placement of strategically sited ornamental copses.

1.3 USING VEGETATION

The use of vegetation, and particularly fast growing tree species (eg. *Eucalyptus*) is seen as an effective way of reducing leaching to the groundwater table. Its value to the mining industry is as a form of land management for stabilization and rehabilitation. It is believed that trees can play a positive role in controlling seepage from mine waste dumps and dams, and along flow pathways.

The impact of trees on catchment water yield is well researched in South Africa although questions pertaining to deep rooting, groundwater, and the utilization of aquifer storage, are only now receiving attention. The idea of using trees with the primary objective of reducing acid or polluted mine water is new to this country and has generally only been considered as a secondary consequence elsewhere in the world.

The removal of indigenous, deep rooted trees both for agriculture and mining in Western Australia has led to increasing salinity levels in streams, and to reductions in arable land through rising groundwater flushing salts up through the soil profile. In this analogous problem research has concentrated on the establishment of trees to prevent the rise of groundwater tables (Greenwood and Beresford 1979, 1980, Greenwood *et al.* 1981). In West Australia the re-establishment of vegetation is a planning pre-condition for proposals to extensively strip mine for bauxite.

In South Africa forestry is recognized as having negative impacts on water resources, and research is now being directed toward water efficient species. On mining sites water use by trees can be turned to good advantage although any reductions in yield as a result of control of throughflow on limited source areas need to be weighed against the benefits to water quality.

The establishment of woodlots on sites where water quality control is essential could also be used to reduce pressure on undisturbed sites which can be reserved for water yield.

Research into water use by individual species has numerous other benefits to South African hydrology. This research was intended to identify both consumptive and water use efficient species and adds to our predictive knowledge of the effects of woody invasion, woodlot establishment, and afforestation on water resources. Research on the establishment, growth and water relations of species in highly unfavourable environments could prove advantageous to a number of industries other than the mining industry. One example would be disposal of saline or noxious effluent through irrigation.

Rehabilitation could be managed through the production of commercial timber, and/or establishment of ecological preserves. Longer-term objectives may include the rehabilitation of sites to former agricultural potential, or potential for urban development or recreation. Agro-forestry practices may prove ideal as an interim land management measure. The use of trees is not irreversible and should be viewed as a short to medium term option for the management of agricultural land, and through which such land can be brought back into agricultural production. The agricultural nature of small scale forestry operations, and the ability to mix farming and tree planting activities is an advantage.

Several mining houses have already accepted the potential value of trees in water management and have either commenced, or are planning, plantings at an operational - if still experimental - scale. The implications which the extensive introduction of trees for the management of water *quality* may have on water *supply* in the Olifants, Crocodile and Vaal river catchments, and for the economy of the Highveld, must also be considered.

Active mines must be kept free of seepage water. Vegetation established on these areas during, or in advance of, operations could be used to reduce or eliminate drainage into active mines.

1.4 TYPICAL MINING ENVIRONMENTS

Mining activity disturbs surface soils, the regolith, and shatters the underlying bedrock, affecting runoff and infiltration and resulting, particularly, in acid drainage. The acidification and pollution of water resources is an inevitable consequence of the movement of water through mine waste and disturbed soil over areas of mining activity. Fifty percent of the pollution load in the Vaal Barrage is attributed to non-point sources (Jones *et al.* 1989) and the low pH values in the upper Olifants river are attributed to coal mining activity.

Typical examples of such activity are :

- Gold mine sand dumps and slimes dams - acid drainage through the dumps (directly and via 'weeping toes') and consequent pollution of the groundwater reserves.

- Coal waste dumps - acid mine drainage through the heaps of carbonaceous shale and into the groundwater.

- Open cast mines may appear to be fully "rehabilitated" after closure but the profile remains very loose, with rapid infiltration into the carbonaceous layers.

- Infiltration is accelerated in high extraction underground coal mining (shallow subsurface mines often only 30m beneath the surface). Water draining through the fractured rock and subsidence areas develops a high acidity before entering the river systems.

1.5 ISSUES AND IMPLICATIONS

It is recognized that the use of vegetation in manipulating the water balance, and thus alleviating the potential negative effects of mining activity upon the hydrological system, is not an exclusive management option. It is also recognized that the use of trees, particularly of fast growing trees, for the control of water quality, will influence water quantity if applied on a large scale. This project establishes this impact and places the use of vegetation amongst the list of most practical tools available to land managers.

There are different schools of thought with regard to the approach and consequences of water management in ameliorating mining impacts. The first of these has been simply to reduce water throughput - for example by cladding, or through growing trees. More recently it has been argued (Hodgson and Krantz, 1994) that the reduction of water throughput may simply lead to more concentrated outputs, and that the problem is not mitigated. This leads to the argument that one should really be flushing the system rather than 'bottling up' the problem. Another alternative is that containment may be the best option.

These arguments can be added to a number of other issues which arise when considering the long-term implications of extensive tree planting. These include :

- The potential impact of trees on regional water resources; ie water supply vs water quality. Water yield, particularly in the Vaal catchment, is a critical issue and it is likely that afforestation will always be strictly controlled. This may limit tree planting exercises to the most critical areas, allowing only very site specific use of trees for water quality management. Alternatively the combined benefits of wood production and water quality management may shift in favour of the Highveld as a tree planting zone (and away from other regions) despite the silvicultural limitations.

- What is the scope for secondary objectives in the growing of trees? Can tree production be used for purposes other than water management?

- What are the long-term impacts on soils, particularly where trees are irrigated or grown on seepage areas?

- Allied to the questions related to pollutant concentration raised by Hodgson and Krantz (1994), does the reduction in flow simply postpone leaching and thus leave the problem to future generations ?

- Will the planting of trees be used by mine-owners to side-step the responsibility to return the site to its original land capability? Tree planting may be seen as a simple and cheap form of land rehabilitation, not requiring the degree of site restoration which would otherwise be demanded. Alternatively trees may be a sensible and economic land use while natural processes restore an equilibrium to the landscape. It is essential that trees be recognised as a transient land use and that the ultimate objective is either to restore the land to its original form, or at least to leave this option open to any future land manager.

- Can trees be reconciled with entrenched agricultural interests? The Highveld carries a strong agricultural economy. Trees must be seen as additional to this landscape and not as a threat to agricultural land. There is a need to research the combination of these interests through agroforestry options on rehabilitated sites.

- What species should be planted and on what basis - commercial, ornamental, woodlot, agroforestry?

1.6 COMPONENTS OF THIS STUDY

All research has been centred on mining areas in Mpumalanga and Gauteng (previously Eastern Transvaal Highveld) and comprises the following components:

(1) ***Literature review.***
Investigation of previous work on the establishment of vegetation, and its water use, in mining environments.

(2) ***Selection of target species and research sites.***
A variety of mining conditions are covered, with attention given to gold and coal mining sites. There has been very little tree planting by the mine industry for the purpose of water uptake. Research was restricted by the limitations on suitable sites.

(3) ***Field measurement of water use by trees and grasses.***

Verification of sap flow measurement methodology
This technique has been verified for *E. grandis* (Olbrich 1991), *Populus deltoides* (Smith 1991), *Pinus patula* (Dye 1992) and *Acacia mearnsii* (Smith *et al.* 1992). The HPV method has been extensively tested as part of the CSIR's existing research programme and has proved a most efficient way of assessing water use characteristics of single trees. It is necessary to verify the HPV method on all previously untested species where the wood anatomy varies significantly from previously verified species. In this project the only new species verified was *Acacia meamsii* (the black wattle). Research was aimed at quantifying the potential value of vegetation rather than providing an exhaustive catalogue of water use by species. All measurement work, with the exception of one short run on *Acacia* species, was eventually carried out on *Eucalypts.*

Micrometeorological determination of water use by grass species

Trees and woody shrubs are expected to use more water than grasses both because of the expected deeper root systems and because of their evergreen nature, with transpiration throughout the year. Water use by grasses must nevertheless be determined both for purposes of comparison (how much more effective are trees ?) and given that grassland may in many instances prove to be the only successful land management option available. Water use by grassland species was determined at the scale of the grass sward using micrometeorological techniques, in this case the Bowen ratio technique. Eddy correlation was initially favoured, but the use of this technology in South Africa was still in the experimental phase during the study, and successful application could not be guaranteed.

Measurement of water use by trees

Water use by trees was determined through the measurement of sapflow rates using the heat pulse velocity technique. This was completed for a range of species (almost all Eucalypts), on gold slimes, coal open cast, and high extraction coal mines.

(4) ***Establishment of the relationships between water use by vegetation and the prevailing climate, edaphic, and environmental conditions.***

The measurement programme over three years allowed for data capture over a range of seasons and climatic variability. Data capture was planned to include at least one month within each season, although this was not always achieved due to instrument failures and logistics.

Climatic parameters were measured concurrent with these field surveys, using portable micrometeorological stations. Parameters included radiation, temperature, wind, and vapour pressure deficit.

(5) ***The modelling and extrapolation of results.***

The broad scale potential for water balance control using vegetation has been assessed. The Penman-Monteith evaporation model tests well against actual recorded grassland evaporation for summer and winter but the development of water balance models has not yet been explored to full potential.

(6) ***An examination of rooting strategies by trees and grasses.***
Tree and grass roots were excavated on a number of sites in order to answer the question of whether trees effectively occupy a greater soil volume than grass. Representatives of the industry (mining and rehabilitation) were also surveyed for opinions and knowledge of the nature of tree roots on mine soils.

(7) ***Recommendation of species and methods of establishment.***
Tree species suited to Highveld environments are recommended on the basis of site surveys, literature searches, and the experience of the forestry industry. Methods of establishment are the summation of experience in this field, adapted for Highveld conditions.

1.7 SPECIES AND SITE SELECTION FOR RESEARCH

1.7.1 The site selection process

This study was extremely broad in its initial conception, with the field study objectives aimed at covering a range of tree species (for example the eucalypts, *Acacia mearnsii*, and possibly indigenous species), over a range of sites (gold sand dumps, gold slimes dames, rehabilitated open-cast coal mines, and total underground extraction sites for coal). This introduced a set of further conditions including geographic location and climate, position in the landscape both topographically and in terms of the mining activity, soil type, and water quality factors. It would also be necessary to determine evaporation from the grass cover or other vegetation in the vicinity of each tree water use research site.

Species

Of the species which may be employed in mining environments only the genus *Eucalyptus* stands out as being ubiquitous. Although the particular species employed varies from site to site the recognition of eucalypts as both silviculturally suited and as notable water users encouraged the focus accorded to the genus. Black wattle (*Acacia mearnsii*) was initially earmarked as a very important species, particularly in the Witbank area, and the heat pulse velocity method for determining sap flow was verified on this species. No further work was done in measuring actual water use - partly as a result of an obvious reluctance by mining houses to contemplate using the species in planned tree planting exercises, a reluctance ascribed to the invasive nature of both the black and silver wattle. The verification study has been published in the South African Forestry Journal (Smith, Moses and Versfeld, 1992). The verification findings are already proving useful in other fields of water research.

Site

Site selection was determined by a number of factors - both perceptual and circumstantial. It is difficult to accord an importance ranking to each environment, but there did seem to be little need to work on gold sand dumps, given the current rate of reprocessing, despite the extent of pollution loading for which these dumps may still be responsible (Jones *et al.* 1989). Gold slimes dams are extensive and increasing, particularly as sand dumps are being reprocessed and stored as slimes. There are also different generations of slimes, dating from 1890 to currently active slimes. Slimes also provide different research situations - with trees potentially growing either on the tops or slopes of the slimes, or on seepage areas at the base.

The coal industry remains by far the most extensive in terms of its impacts, and potential impacts, on the landscape - although these may be less visible once rehabilitation is complete. Open-cast coal mining is currently the most extensive of the coal extraction methods.

Research on tree water use was also determined by the availability of trees growing on suitable and representative sites. Research was influenced and advantaged by the fact that there have been a number of mine industry plantings in the vicinity of gold slimes, open cast and total extraction coal mines. Work on the tops of slimes dams was disadvantaged by the uneven age, poor survival, and patchy distribution of trees.

It has been necessary to make some assumptions with regard to the strategies which mining companies might eventually want to employ in the establishment of trees. Research was however also intended to assist in guiding these strategies. Would we, for example, be likely to see extensive plantings on slimes dams or only in the vicinity, with plantings on seep areas? Maximizing evaporation on slimes through tree planting would mean the replacement of the grass cover, with possible loss of surface soil stability. Trees were also not expected to be especially effective in utilizing water on slimes, given the shallow root systems due to the growing medium and the nature of the rainfall, with high intensity storms giving rise to ponding and surface runoff. Trees have also proved difficult to establish on slimes dams. One school of thought therefore calls for the concentration on the seepage pathway away from the dam perimeter. But the survival success of some trees, observations on rooting, and results from actual measurements of water use argue, on conclusion of this study, for more work on the establishment of trees on the tops of slimes dams.

1.7.2 Sites selected

In the light of the above arguments and constraints the following sites were chosen for experimental measurements of water use by trees and/or grass. The general position of the research sites is depicted in Figure 1.1. Detailed site maps are to be found in Chapter 3 along with more thorough descriptions.

Gold slimes

Robinson Deep

An old slimes close to Central Johannesburg, previously seeded with various tree species as part of a revegetation programme. Measurements were made on two different *Acacia* species (*A. melanoxylon, A. baileyana*) growing on the top of the slimes dam.

Western Areas

A more recent, but inactive and well grassed slimes dam on the West Rand. This site, with its extensive and uninterrupted grass cover, provided the only suitable opportunity for Bowen ratio measurements of grassland evaporation in the Johannesburg area. Grassland evaporation was measured on this site for comparison with trees on the edge and at the base of this slimes dam, and with trees growing on Durban Deep. Tree water use at Western Areas was measured for *E. sideroxylon* growing in the toe paddocks, and for some opportunistic eucalypts growing around the top perimeter of the slimes. These trees were growing on a site where grasses were still being irrigated as part of a vegetation establishment and maintenance programme.

Durban Deep

An old slimes dam close to Roodepoort. Trees were measured on the top, mid slope and at the base of the slimes dam. Comparative grass measurements are from Western Areas.

Withok slimes

The site is located on the old Heidelberg road to the west of Springs, near Withokspruit. This is a new and still actively growing slimes dam. There is therefore no vegetation on the top of the slimes or on the slopes. Trees (*E. viminalis, E. cinerea*) have however been planted by the tailings management around much of the periphery of the slimes dam, primarily for screening but with some specifically planted for water uptake. Measurements of tree water use were made for a bank of trees planted on the western perimeter of the slimes, on old agricultural land within the seep area. Water use by natural vegetation was measured using the Bowen ratio in an adjacent field of grass and weeds.

West Extension

This is a gold slimes dam situated between Potchefstroom and Klerksdorp, close to Orkney. This dump was built in response to the bursting of the grass dam adjacent to the Western Extension in 1966, from which the slimes dam gets its name. Measurements were undertaken on self sown *Eucalyptus camaldulensis* trees. There were no water use measurements for the grasses growing under the trees, nor for comparative grassland should there have been no trees. Grass and trees together probably reflect an optimum situation.

Rehabilitated open cast coal mines

Hendrina (Optimum Colliery)

On the Highveld near Hendrina. Water use measurements for trees are in stands of *E. macarthurii*. These trees were successfully established in 1990 with a view to their potential water management function. Evaporation from grassland was determined from nearby pastures, and also on a rehabilitated site.

High extraction underground coal mines

Sasol, Secunda (Brandspruit Colliery)

On the Highveld close to Secunda. Water use measurements for trees were in stands of *E. viminalis* established on Brandspruit colliery in 1990 for purposes of water management. Grassland evaporation was measured over a nearby sward of natural grass. Both sites have experienced underground mining resulting in surface subsidence. Evaporation was also measured over a period of one month from a pasture irrigated with Sasol effluent, on the farm Goede Hoop adjacent to the processing plant.

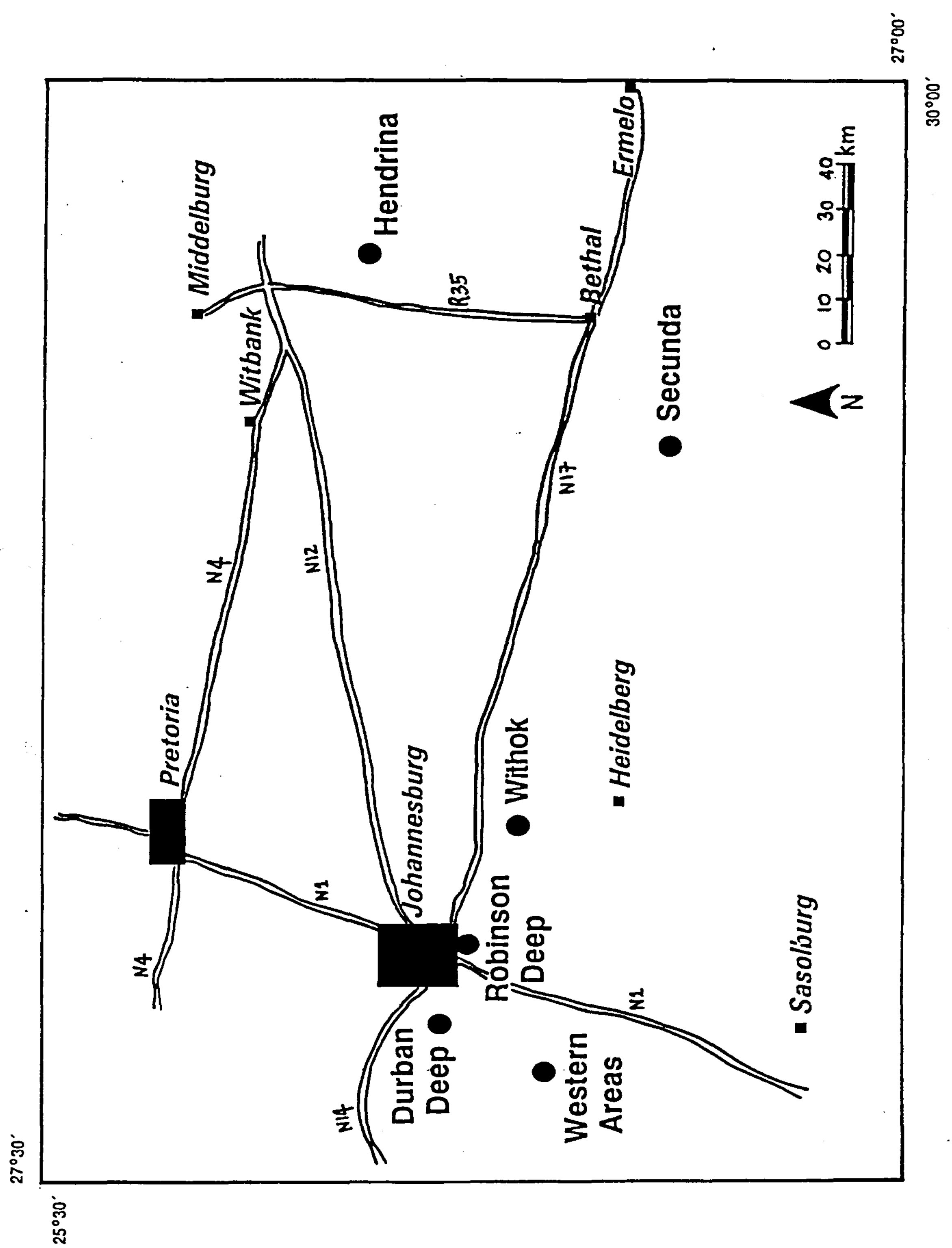

Figure 1.1: The research area. Sites for which tree water use was determined are marked with a ●. The locality of West Extension (27°06'S; 26°43'E) is not shown.

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CHAPTER 2

LITERATURE REVIEW

THE USE OF VEGETATION IN MANAGING THE IMPACTS OF MINING ON WATER QUALITY

2.1 INTRODUCTION

Deterioration in water quality as a result of mining activity is recognized as a major problem requiring long-term solutions. Within South Africa the two most important mining industries, gold and coal, are both recognized as having potentially large negative impacts on groundwater, stream and dam-water quality, both through acidification and through the leaching of heavy metals and noxious waste.

Leaching to groundwater has, in the case of waste dumps, primarily been controlled through dump design, the construction of impermeable layers, and the trapping of runoff water in toe-dams for later evaporation. The rehabilitation of waste dumps using vegetation has always played an important role but with the primary objectives being dust management, erosion control, and aesthetics. Constructed wetlands have also been introduced in order to process water biologically for improved quality.

South Africa is perhaps unique in that much of the mining activity is in a relatively treeless environment, but one in which trees will grow. Trees, and their role in erosion control and in the evaporation process, are recognized as integral to rehabilitation on sites where they form part of the natural environment, but have only recently been recognized in South Africa as having potential to reduce the volume of polluted water derived from mine dumps and spoils, and in reducing acid mine drainage. This recognition has stemmed in large measure from the observed impacts of afforestation (again of relatively treeless environments) on streamflow in South Africa (van Lill *et al.* 1980, Van Wyk 1987, Bosch and Smith 1989) and from the secondary salinity problems experienced in South and Western Australia through the rise in groundwater tables after deforestation (O'Loughlin 1988, Loh 1988, Bell *et al.* 1990).

South African mine dumps and spoils frequently support some tree growth, both as a result of deliberate seeding, and through natural invasion of exotic woody species. Occasional belts of trees have also been planted around toe dams and seepage areas. These efforts have however been sporadic and were not motivated by the potential positive impacts on the hydrology. However, in 1990 Secunda Collieries commenced with experimental afforestation on the Mpumalanga Highveld on lands undermined by total extraction (near Secunda), and Trans Natal Collieries on rehabilitated open cast spoil near Hendrina, also in 1990. Trees were also established by Ergo within toe paddocks adjacent to slimes dams near Springs at about this time. In 1991 Genmin initiated a forest species and establishment trial on a gold slimes dam on the West Rand. In these cases the reduction of acid drainage through an increase in evaporative losses has been a primary objective. Industry awareness can be ascribed, at least in part, to symposium presentations by J. Easton (Vegetation Unit, Chamber of Mines), D. Morrey (Steffen Robertsen and Kirsten Consulting Engineers) and others over the last number of years.

This review seeks to describe the nature of those problems for which trees are seen as having ameliorative potential, and to examine experiences with afforestation and deforestation (particularly in South Africa and Australia), together with conscious efforts to establish or re-establish trees on mining sites for hydrological mitigation. Irrigation with effluent is also considered, along with the use of wetlands for water purification, as alternative or additional techniques to be used in providing an integrated solution.

2.2 MINING IMPACTS IN SOUTH AFRICA

The total annual waste production in South Africa is estimated to be 318 million tons. The mining industry is responsible for the major part of waste generation (75%). A breakdown of the major waste-producing industries is shown in Figure 2.1. Waste from the gold/uranium and platinum mining sectors is estimated to amount to 120 million tons per annum whereas low grade coal discard dumps receive 44 million tons of waste per annum. The largest waste problem in the electricity generating industry is that of pulverised fly ash (PFA). It is estimated that 35 million tons/a of PFA will be produced in 1997. The majority of wastes produced by the agricultural industry are non-toxic biodegradable organic residues. Municipal waste amounts to 15 million tons/a, varying in composition. Municipal wastes are usually disposed of in landfill sites. Wastes from the chemical-process industry are mainly made up of coal ash and phosphogypsum (Korentajer, 1992). The electricity-generating industry, agriculture, municipalities and chemical industries are respectively responsible for roughly 7, 6, 5, and 4 % of national waste production.

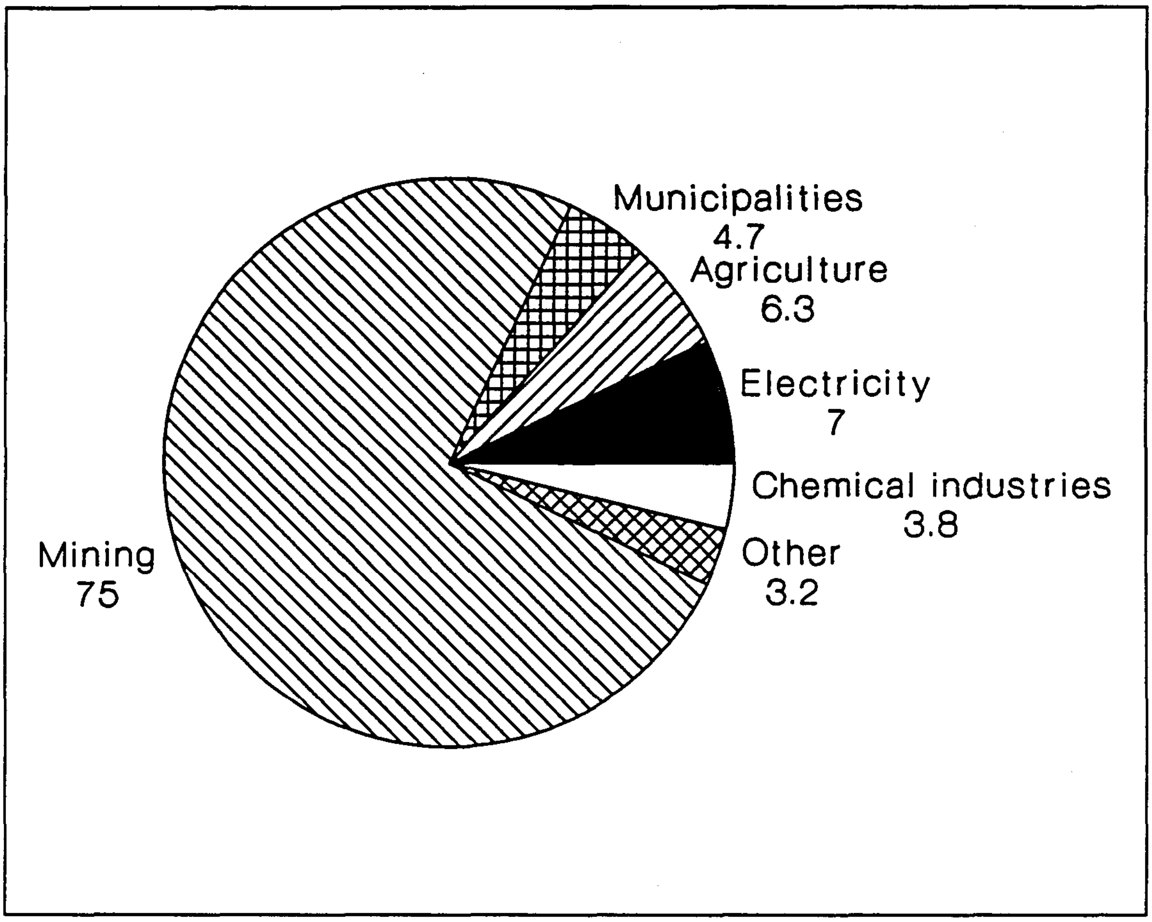

Figure 2.1: Graphic representation of the relative sizes (in percent) of the major waste-producing industries (after Korentajer, 1992).

Only the coal and gold mining industries are discussed in any detail in this review, and these primarily for the Highveld areas of Mpumalanga and Gauteng provinces.

One of the main processes resulting from mining activities impacting on water quality, is the oxidation of iron sulphide minerals (i.e. pyrites, commonly present in mining spoils) resulting in the formation of sulphuric acid which in turn enhances the release of toxic heavy metals to drainage water (Sutton and Dick 1987, Korentajer 1992). Mine drainage water (water percolating slowly through old mining workings) from both coal and gold mining in South Africa, is often found to have low pH values and high concentrations of heavy metals, particularly iron, manganese and lead (Korentajer 1992). High salt loads are also a major problem. Toxic concentrations of other pollutants, notably fluoride, have also been found, while high salinity (Na) levels have been recorded following gold mining activities in the Orange Free State goldfields.

In addition to the milling and processing of fresh gold-bearing ore, 90 million tons of low-grade sand dumps and slimes dams are reprocessed each year (Funke 1990). The reprocessing of sand dumps has meant their gradual disappearance, but an increase in the area occupied by slimes dams - with major new slimes dams of up to 2 500 ha in extent. Sand dumps, the last of which were deposited around 1960, were highly permeable, with oxidation of pyrites to depths exceeding 10 m. Gold slimes dams have a far lower permeability and consequently a low pollution potential, although high pollution is observed from combined gold/uranium plant/pyrite flotation tailings (Funke 1990). Using accumulative values from 40 major gold mines, Pulles (1992) estimated that 400 Ml water passes through the mines per day, 260 Ml into groundwater and 130 Ml into surface waters, with the pH of the discharge varying between 10.7 for gold plant effluent and 2.3 for slimes dam seepage.

The primary catchment area for gold mine pollutants is that of the Vaal river. Jones *et al.* (1989) have quantified the relative contribution to such pollution from sand dumps, and old and new slimes dams, and extrapolated these results to estimate pollution off all mine workings in the Vaal catchment above the Vaal Barrage. Seepage into surface groundwater systems recharging streams was found to be a more significant source of salt load than storm surface runoff. A total annual figure of approximately 50 000 *t* was obtained as an estimate of salt load discharged to the environment. The pH of the water was below pH 3, and sulphate comprised a large proportion of the salts in this acid drainage. Pulles (1992) calculated the annual pollution loads of total dissolved solids (TDS) from 40 major gold mines in South Africa to be 143 360 tons, with sulphates contributing 35% of the load. Total point- and non-point pollution figures of over 170 000 tons per annum TDS have been calculated for the Vaal River Barrage (Best, 1985). On the other hand, outside of the Vaal catchment, Cogho *et al.* (1990) estimate 335 000 tons TDS contributed by the Free State gold mines alone.

The coal mining industry on the Highveld in Mpumalanga province provides a somewhat more complex picture. It is a growth industry, the areas affected are extensive, and mining methods are variable. Currently the total accumulated coal mine waste in South Africa is estimated at 283 million tons, covering an area of about 1020 ha (Korentajer 1992). Areas affected by underground total extraction methods, and by open cast mining, are far greater. It is estimated that surface coal mining operations alone are responsible for the disturbance of more than 1000 ha per year (De Villiers, 1992). The rehabilitation of coal mining land carries a high priority since coal mining areas frequently underlie prime farmland. The van Niekerk report into the long-term effects of high-recovery coal mining on agriculture on the Eastern Transvaal Highveld (Van Niekerk 1990) provides an assessment of the different forms of coal extraction, the area which might be affected, and of problems which might result. Of the 2.7 million ha underlain by coal deposits at least 400 000 ha could, with time be affected by high recovery coal mining, either open cast mining or total extraction underground. Acidification resulting from contact between drainage water and coal or coal-bearing shale is recognized as a major problem both in the Van Niekerk report and by the Department of Water Affairs. Pollution loads in 1979-81 from active and defunct mines were already estimated at 131 600 tons TDS per annum, 44% being contributed by sulphates. Acidification of the Olifants river and Loskop dam has also resulted in strong public protest (Agricultural News 1989).

Pollution sources in coal mining include open-cast pits, coal discard dumps, and underground total extraction workings. The potential for trees to reduce leaching, through the evaporation of rainwater (interception of rainfall and transpiration of soil water) before it reaches the mined surfaces, is considered for both rehabilitated open cast mines and for surfaces above areas of total underground extraction. Trees may also be used, through strategic planting, to intercept and evaporate water seeping off coal discard dumps.

Other activities responsible for major disturbances of surface land are quarrying and mining activities for sand, clay, lime, gravel, gypsum and diamonds.

2.3 WATER USE BY TREES

Forest hydrological research in South Africa was initiated as a result of concern that the increasing afforestation of landscapes which did not previously support trees would lead to a decrease in water yield. In a review of catchment experiments worldwide, Bosch and Hewlett (1982) find a direct relationship between afforestation and water yield, while shrubs and woody vegetation have a lesser, but also significant, effect. South African studies reflect these results very clearly with declines in catchment water yield generally in the order of 25 - 30% for afforestation with pines (Bosch 1979, van Wyk 1987) and up to 100% for *Eucalyptus* species (van Lill *et al.* 1980, Bosch and Smith 1989, Lesch and Scott 1993).

Percentage changes are less indicative of water use than of the actual differences in yield observed. These reflect a decrease in yield of up to 400 mm as a result of afforestation. The catchment experiments at Mokobulaan (van Lill *et al.* 1980, Lesch and Scott 1993) and Westfalia (Bosch and Smith 1989) demonstrate clearly that *Eucalyptus* trees exploit water far more rapidly (at an earlier age) than pines. Direct measurements of transpiration using porometry (Dye 1987) and through the measurement of sap flow (Olbrich 1991) provide measures for total potential water use by *Eucalyptus* in a favourable environment where soil water is not limiting. These data show that actual water use may be even higher than annual rainfall (1 200 mm), and potentially 2 000 mm per annum. But this would only be possible where trees are able to draw water from groundwater or previously untapped soil storage. In an investigation of rooting depth and soil water extraction by *E. grandis,* Dye (1993) have found mature trees to be drawing water from below 8 m soil depth while young trees are still exploiting the upper levels of the profile.

In Australia the clearing and replacement of deep-rooted native vegetation by shallow-rooted annuals has long been recognized as a major cause of increased groundwater recharge (Peck 1983, Dumsday *et al.* 1989, Bell *et al.* 1990, Leuning *et al.* 1991, Morris 1991, Schofield 1991, Ward 1991). Reforestation of pastures where groundwater tables had risen, saw a proportional relationship between water table reduction and proportion of area reforested (Schofield 1990). Rising groundwater tables bring accumulated salts to the surface with degradation in river water quality and extensive losses to arable acreage. The cost to the Australian economy has been alternatively estimated at A$700 million/year (Edwards and Thompson 1987 in Dumsday *et al.* 1989) and at A$2 billion/year (Eckersley 1989). To this must be added health, social, and environmental costs. Various legislative and other measures restricting land clearing are now in place with, for example, the clearing of *Eucalyptus* forest for bauxite strip mining in Western Australia made dependent on the immediate revegetation of these sites with trees **proven** to have an ability to use water equal to, or better than, that of the original vegetation.

Farrington and Bartle (1989), in comparing recharge beneath a Banksia woodland and *Pinus pinaster* plantation on coastal deep sands in south Western Australia, found that substantially less rainwater (114 mm p.a.) infiltrated to the groundwater beneath the pine plantation than beneath the Banksia woodland (173 mm). This difference is attributed to rainfall interception by forest litter, and to higher evaporative losses.

In reviewing reforestation and agroforestry strategies for groundwater control in Australia, Dumsday *et al.* (1989) see trees as an important control measure because of high water use throughout the year. Strategies include the reforestation of large areas of low-productivity land, strip planting along fence lines and in zones of perennially high groundwater recharge, and woodlot or agroforestry (Dumsday *et al.* 1989, National Afforestation Programme 1990). Other possible strategies for groundwater control include the modification of cropping and grazing practices through the introduction of deep-rooted perennial grasses and legumes (Oram 1987) or engineering measures to prevent water reaching the groundwater of already saline areas (Peck 1983).

Australian native tree species are also being established in trials in both Pakistan and Thailand in areas affected by waterlogging and salinity. Trees include both *Acacia* and *Eucalyptus* species (Marcar *et al.* 1991).

2.4 GROWING TREES FOR WATER MANAGEMENT

It is rare for the primary, or even secondary, objective of mine site revegetation to be the control of groundwater pollution or acid mine drainage. The emphasis does however seem to be changing in South Africa. It is now law that all companies submit an Environmental Management Programme Report (EMPR) to the Department of Mineral and Energy Affairs. An *Aide-mémoire* released by this Department, serving as a guide to entrepreneurs and mine owners to compile EMPRs acceptable to all regulating authorities concerned (Department of Mineral and Energy Affairs 1993) has as a major component the estimation of potential impacts of the mining operation on ground- and surface water quantity and quality. This includes long-term impact assessment after closure and how these impacts will be managed (rehabilitation of surfaces) as mining progresses and after closure. They are to use Best (proven) Available Technology Not Entailing Excessive Cost (BATNEEC), and revegetation is encouraged for "optimising surface rehabilitation in order to minimise adverse ground-water impacts". See also the Chamber of Mines rehabilitation guidelines (Chamber of Mines 1990) for information on both rehabilitation standards and methods, and on the BATNEEC concept.

In the USDA's 'User Guide to Hydrology - Mining and Reclamation in the West' (USDA 1980) the role of vegetation is recognized both for its evaporative capacity and for its use in the control of surface runoff. The planting of `woody, deep-rooted vegetation' is suggested for the removal of excess water through transpiration. However, engineering techniques are the only methods suggested for the management of water influx where the objective is limiting throughput and thereby reducing acid mine drainage. Trees are not suggested for the interception of polluted water weeping from mine tailings.

Sinha (1990) recommends `ecological restoration' as a strategy for the maintenance of the soil-water-vegetation balance in monsoonal India. The lack of vegetative cover is directly linked to acid mine drainage and erosion on 0,63 m ha of land strip mined for coal in the humid region of the United States (Sutton and Dick 1987). Data on spoil properties, and information on ameliorative techniques and vegetation re-establishment, are presented in this paper - but the link between vegetation and water use is not quantified.

Tree planting has been part of routine revegetation of coal-mine spoil in New South Wales (Ryan *et al.* 1991). This is no doubt intended in part as a hydrological control measure in view of secondary salinity but is not explicitly for the mitigation of acid mine drainage.

Revegetation is a recurring theme in Ritcey (1989). This is almost exclusively in terms of rehabilitation, and the value of vegetation in reducing or controlling water pollution (other than through erosion control) is given only cursory attention. With regard to the control of acid mine drainage brief reference is made to the value of vegetation in the restriction of oxygen penetration (Ritcey p. 275, p. 414), and to evaporative demand (Leroy 1973, in Ritcey 1989). In Ritcey (1989) engineering strategies are generally preferred for the task of preventing infiltration into mine tailings, but there is also a wealth of information presented on revegetation strategies with regard to species, establishment, and toxicity.

2.5 SOIL FACTORS AFFECTING GROWTH
(with emphasis on opencast coal mines)

A classification system for mine soils in South Africa has been implemented to facilitate the identification of most important minesoil criteria and thus assist in the management of rehabilitated land (De Villiers, 1992).

Good soil physical and chemical properties are of prime importance for the initial establishment and the long term sustainability and productivity of previously mined land. Szafoni *et al*. (1988) researched soil properties on barren mine sites in Illinois where no or little revegetation had taken place. Major factors contributing to unfavourable conditions for plant growth in this area included:

- inadequate soil moisture;
- high soil temperatures;
- low pH;
- nutrient deficiencies;
- high salt levels;
- instability and erodibility of the spoil; and
- heavy metal toxicity.

Torbert *et al.* (1988) studied the properties of minesoils that affect the growth of pines in Virginia, USA. The study included parameters such as particle size fractions, nutrient contents, pH, electrical conductivity (EC), density, organic matter and heavy-metal concentration. The rooting volume index, defined as the depth to a restrictive layer times the soil-size fraction (%) of the surface 10 cm, was found to have the biggest influence on tree growth. It seems logical that early growth of vegetation on rehabilitated land is often largely influenced by non-soil factors, e.g. quality of plants and weed competition, whereas post-establishment growth is more greatly affected by soil properties. Evidence to support this view was also found in Torbert's (1988) study. It can be concluded that the long-term post-establishment growth greatly depends on a good rooting volume.

2.5.1 Rooting volume and compaction

Effective rooting depth is likely to be a critical factor affecting water use by trees, except on saturated sites where water is continuously available. Effective rooting in *Eucalyptus* has been identified by Herbert (1991) as the soil parameter most strongly correlated with productivity. The high and continuous water use observed in *Eucalyptus* trees in the Mpumalanga forestry zone can be ascribed to deep rooting of many metres (Dye and Poulter 1991, Dye 1993). But the rooting depths of two tree species (Douglas Fir and Red Alder) on coal mine spoils about 15 years after afforestation, were found to be only 0.6 and 0.7 to 1 m respectively (Heilman 1990). The capping of mine spoil with compacted impermeable clay layers will inhibit rooting depth (Ritcey 1989). Some concern has however been expressed that tree roots may penetrate impermeable layers and provide conduits for water into otherwise sealed dumps. Trees on gold slimes dams of older vintage in South Africa have been observed rooting to at least 3 metres (personal observation). In South Africa the breaking up of superficial impermeable rock layers through open cast coal mining may increase the potential rooting depth.

In South Africa, legislation dictates that all soft material within 1m of the surface be used when surface-mined land is rehabilitated (Read *et al.*, 1992). In practice the document "Guidelines for the Rehabilitation of Land Disturbed for Surface Coal Mining in South Africa", issued by the Chamber of Mines of South Africa, is adhered to. According to this system, at least 0.6 m of soil is replaced for arable land, 0.25 m for grazing land and 0.15 m for wilderness land.

Soils are often compacted in the surface mining operation, which reduces the effective rooting volume of plants in that soil. Compaction typically leads to a decrease in macropores and an increase in micropores in the topsoil. The saturated hydraulic conductivity of disturbed soils was found to be reduced to between 25% and 10% of their original values after compaction (Potter *et al.*, 1988). Inferior productivity and sensitivity to drought stress are experienced where the soils are excessively compacted during construction. Since soil water acts as a lubricant for the movement of soil particles, most severe compaction occurs at a certain optimum moisture content for each soil (Barnhisel, 1988). Soil gets compacted throughout the profile during surface-mine reclamation operations, due to the fact that each layer of soil is compacted by earth-moving equipment after its deposition. In the USA, regrading of spoils is often prescribed as one of the steps in land reclamation. Grading of each deposited soil layer has been singled out by many authors as being a major contributor to soil compaction. Grading of soil layers and topsoiling is often not warranted if the site is to be replanted with trees since adequate tree growth can be attained on selected non-compacted spoils even without topsoiling (Plass and Powell, 1988). Tanner *et al.* (1986) propose a penetrability index which takes the depth of a layer and its resistance to penetration into account. This index correlates well with plant yield. Some deep-tillage practices have been quite successful in improving the compacted soils, but it is far better to avoid compaction during handling of the soil materials (Jansen and Hooks, 1988). Tanner *et al.* (1986) compared the effect of different ripping implements on soil compaction. It was found that a single-tooth dozer ripper disturbed the soil to a much greater depth than tractor-mounted implements. However, zones of decompaction were restricted in the lateral plane. A winged-tine ripper achieved greatest loosening of the topsoil. The fact that the whole soil profile is compacted and not just a plough pan, necessitates deep ripping of the whole profile

Studying eight Highveld open cast coal mines rehabilitated to grass for up to ten years, de Villiers (1992) found that in most cases the cover-soil layers had compacted, preventing root penetration to any depth and causing heavy root growth in weaker areas, such as cracks. The underlying clastic spoil material did not limit root penetration, although the good weatherability of the spoils resulted in pyrite oxidation, causing the soil water pH to be less than pH 4. Structural amelioration of the soil profile due to root action and accumulated organic matter was limited to the upper 5-10 cm.

2.5.2 Soil surface properties and management

The stabilization of disturbed soils is of paramount importance in achieving improved water infiltration and water retention in the soil so as to encourage plant growth. This involves the creation of an irregular soil surface which can be achieved by primary tillage, micro-imprinting, creation of contour furrows, pitting, trenches or terraces (DePuit, 1988; Plass and Powell, 1988). An irregular soil surface will reduce the surface velocity of wind and water and so minimize erosion. Modification of the soil surface may prove to be beneficial to plant establishment and growth in many circumstances. Large scale (30 m wide and 1.5 m high) ridge and furrow landforms are commonly used in reclamation schemes in Britain, to aid the removal of excess winter rainfall and improve rooting conditions for forest trees (Moffat and Roberts, 1989). The system is effective in wetter areas, but in drier areas it leads to excessive drying out in the topsoil, and therefore may have limited applicability in South Africa. Soils may also be compacted during the construction of these landforms, exacerbating the droughty conditions.

Furthermore, large ridges on the contour may lead to frost-pocket formation. Ridges that are small in amplitude are suggested for dry and frost-prone areas. Scholl (1985) had success at a dry coal-mine site in New Mexico with plant survival in smaller ridges (contour furrows), or ridges formed by the action of dozers. This was due to increased soil moisture content in the furrows. Schuman *et al.* (1987) also found that surface-modification treatments (pitting, furrowing and soil ridges) increased biomass-production of grasses, which can probably be ascribed to trapping and retention of soil moisture. Mulches provide an elegant way to stabilise disturbed land in addition to their value as soil physical ameliorants and nutrient reservoirs.

The preparation of a seedbed that will provide seeds with adequate moisture, aeration and that eliminates weed competition in the early stages of plant growth is achieved by proper soil tillage. Primary tillage operations on mined land usually include one or more of the practices listed in Table 2.1.

Table 2.1: Primary tillage operations

Ripping	Used to reduce compaction in the soil
Ploughing	To turn the sod and allow better water infiltration
Discing	Used to mix amendments with the soil
Chisel ploughing	For use on stony soils
Rotary tiller	To break the surface soil up and to prepare the seedbed

In mine soils where the replacement of topsoil is recent, primary tillage is often not done since the soil is already loose and aerated. Secondary tillage is used to reduce the size of clods and to prepare the seedbed. Single or double-action discing or harrowing is normally employed for this purpose (Lyle, 1986).

2.5.3 Soil chemistry

Many soil chemical reasons exist for poor plant growth on rehabilitated mine soils. For this reason, Askenasy and Severson (1988) compiled a list of the most useful pre-mine chemical analyses to be conducted on all materials above mineable coal seams. These are pH, electrical conductivity (EC), sodium adsorption ratio (SAR), cation exchange capacity (CEC), % base saturation, exchangeable sodium percentage (ESP), exchangeable acidity, total potential acidity, carbon forms, hot water extractable B and total content for Al, As, Cd, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, U, V, and Zn. The results of such tests will indicate where elemental deficiencies or toxicities may arise, so that ameliorative steps can be taken. Soil acidity and salt concentration are probably the two most important factors affecting minesoil suitability, and are discussed in more detail below.

2.5.3.1 Soil pH

Soil pH governs the solubility and hence the availability of most elements in the soil solution, and manipulation of the soil pH has the potential to improve mine soils considerably. Hedin (1987) studied revegetation on 36 strip-mined sites in Pennsylvania. Low soil pH was most commonly associated with poor revegetation. Although pyrite oxidation had virtually ceased at all sites, indicating the abatement of extremely acid conditions, soil chemistry was still dominated by aluminium buffering, indicative of very acid conditions. Excessive soil acidity is usually addressed by liming soil or by applying fly ash. Very large quantities of lime or fly ash may be applied, commonly around 50 t/ha of lime (Hensley and Carpenter, 1986; Taylor and Schuman, 1988) or 800-4500 tons of fly ash per ha (Sutton and Dick, 1987). The amount of lime applied to spoils is usually based on the following calculations (Pietz *et al.*, 1990a after Sukthumrong, 1975):

- Immediate lime requirement is based on the combined acidity of sequentially extracted water-soluble and KCl extracts.
  (Mg/ha lime = $cmol_c$ x 2.24)

- Long term lime requirement is based on the pyritic sulphur contents.
  (Mg/ha lime = g/kg pyritic S x 30 x 2.24)

Pietz *et al.* (1989c) suggests that a safety factor of 1.5 - 2.0 be built into the long term lime requirement techniques to ensure the neutralisation of slowly oxidising pyrite. This may however increase high levels of N in runoff and percolation. Where pyrite oxidation is not a problem i.e. on moderately acidic sites that are earmarked for revegetation with trees, care should be taken to avoid excessive liming since this may only encourage weed growth (Plass and Powell, 1988).

In addition to raising soil pH, fly ash may improve the texture and water-holding capacity of soils (Fail, 1987). The texture of fly ash is a silty loam, and it is said to improve both fine and coarse-textured soils to the condition of a medium-textured soil. Due to its silty nature, it is susceptible to wind erosion. Fly ash may form aggregates or a crust when it is wetted in the presence of a liming material, but this phenomenon does not seem to affect plant growth to a large extent (Sutton and Dick, 1987). The application of fly ash has a potential risk factor to it: high levels of boron may come into solution and cause toxicities in plants (cf section 2.5.3.3).

2.5.3.2 Salinity

The weathering of spoils normally causes high concentrations of soluble salts (Sutton and Dick, 1987). Torbert *et al.* (1988) found that the soluble salt content had a marked effect on pine tree growth - second only to the rooting volume. It was found that pines were adversely affected at an EC of 200 mS m^{-1}, and an EC of 300 mS m^{-1} was found to be toxic. Soils should also be tested to determine their sodicities. This is usually done by comparing the ratio of divalent base cations : sodium ions on the exchange complex. This measurement is termed the Sodium Adsorption Ratio (SAR), and should be interpreted together with the EC value to formulate a land-rehabilitation strategy. Reclamation of saline soils can be done by leaching of salts, whereas sodic soils require the replacement of sodium ions with divalent ions. The latter is usually achieved by the application of gypsum and leaching of the soil profile. Tolerance levels for soil salinity and sodicity (alkalinity) is well documented in many basic soil chemistry texts, e.g. Kamphorst and Bolt (1978).

The success of using trees on highly saline mine spoils will depend initially on the survival rate of seedlings and later on the ability of these trees to ameliorate the spoils to such an extent that salinity is controlled. The way in which seedlings survive in a highly saline environment can be ascribed to a drop in the plant's tugor pressure, leading to decreases in osmotic potential until the correct ratio between the water potential of the cells and that of the embedding solution is restored (Heth and MacRae 1993).

A long term study (10 years) of fuelwood trees on sodic sites in India, showed that the trees reduced the upper soil pH from 9.5 to 7.9 and the exchangeable sodium from 30 to 8% (Garg and Jain 1991).

2.5.3.3 Toxicity

Toxicity is a major barrier to vegetation establishment within any waste water or mining context. The variability in potential toxins deleterious to plant growth is such that `each tailings impoundment area must be independently assessed for the potential of supporting plant growth' (Ritcey 1989). Questions of toxicity, species selection and adaption, and the amelioration of sites through the addition of topsoil, fertilizer, etc., are dominant in the literature.

Boron toxicity is one of the most commonly mentioned problems. A value of 75 mg/kg B in plant tissue is generally regarded as toxic, although plants have been established where the B content in vegetative tissues was 300 ppm. Bester and Fey (1992) tested the growth of five different tree and pasture species in soils with high concentrations of B in a pot experiment. They concluded that eucalypts do not have a high tolerance to B since a concentration of 15 ppm B in the soil solution caused a 50% reduction in dry matter yield of eucalypts. The eucalypts were more sensitive to B than either ryegrass or fescue.

2.5.4 Organic soil amendments

The organic matter content of spoils are normally very low. This results in poor plant nutrition and poor physical properties of the soil. Due to low levels of organic matter in soils, N is most commonly a limiting nutrient in acid spoil materials (Sutton and Dick, 1987). To compensate for the lack of nitrogen in mine spoils, the planting of nitrogen fixing species can be used to encourage N accumulation (Cherfas 1992). Different species, and even varieties within species, can react very differently to different conditions of soil pH and suitable selection is often difficult to predict (Ward 1991).

The rate of biological activity is normally much lower in acidic mined lands than natural soils. This will limit the mineralisation of organic matter and the weathering of spoil materials, resulting in reduced nutrient availability for plants. The incorporation of organic amendments into reconstructed stripmine spoil is recommended by many scientists, especially when the topsoil on the pre-mined land is thin or eroded. Olsen and Jones (1989) found that application of organic additives may provide an alternative to topsoil replacement. Sewage sludge, sawdust, animal manure and bark are commonly used to rehabilitate strip-mined land in the USA.

2.5.5 Fertilisation

Fertilizers (especially for N and P) are commonly applied to rehabilitated lands to enhance early growth and so promote rapid revegetation of the site (Angel and Feagley, 1987a,b; Reeder and McGinnies, 1989). Surface mined lands are commonly deficient in N, but the establishment of N-fixing species seems to be a more efficient way of incorporating N into the ecosystem than fertilization. Palmer and Chadwick (1985) showed that N is accumulated more rapidly in an ecosystem in the presence of a nitrogen fixing species than with mineral N fertilisation. Fertiliser recommendations are normally based on the results of soil tests and known fertiliser norms for different crops.

2.6 WETLANDS

Another biological alternative in the management of acid mine drainage water or waste water effluent is purification by means of wetlands. Wetlands exclude oxygen from the underlying terrain, deterring the oxidation of sulphide minerals and further generating methane which enhances anaerobic conditions, thus deterring the oxidation of sulphide minerals (Brown 1991). Hydrophytic plants have a particular ability to absorb and remove toxins and pollutants from water and in raising the pH. Natural and `constructed' wetlands are now used in South Africa and elsewhere, particularly in the USA, both for the treatment of sewerage effluent (Wood and Hensman 1988, Simpson 1991) and for the purification of mine waste water (Ritcey 1989). Effluents may be treated in biologically active ponds or by passing through reedbeds, or moss and peat, for cation adsorption and acid control. Wetland water treatment seems to be a particularly attractive option in cold temperate environments (Kalin and van Everdigen 1988).

In South Africa there appears to be potential for the use of trees to evaporate excess water either within the wetlands, or in the post-wetland phase when toxicity has been sufficiently reduced.

2.7 IRRIGATION WITH WASTEWATER

Irrigation with wastewater effluent is now widespread practice. Typically irrigation would be with sewage effluent, pulp mill 'black water', industrial effluent, or mine-water. Recognized schemes in South Africa include the irrigation of pasture both at SAPPI's Ngodwana pulp mill, and at the Sasol plant near Secunda. The primary objective in these schemes is to encourage the discharge of water to the atmosphere.

These are a number of effluent irrigation schemes in Australia with the main objective being to dispose of water by evapotranspiration through plantations of trees; revenue is a secondary objective (Cromer 1980, Cromer *et al.* 1984, Hopmans *et al.* 1990, Boardman 1991). This effluent irrigated forestry (EIF) is seen as a long-term, and potentially permanent cropping system. Hazard evaluation is one of the main gaps in knowledge.

Irrigation with saline effluent from power plants has been under trial in Utah since 1976. Several years of irrigation have been necessary in order to predict the long-term effects of salinity on the soil profile and groundwater (Hanks *et al.* 1986). In this study actual evaporation from crops, necessary for the sophisticated irrigation scheduling required, is calculated by means of the Bowen ratio method. Saline power station effluent is an important waste management factor on the Highveld and experience in the establishment and use of trees for controlling toxic and acid mine water is likely to find additional application in this field.

2.8 GUIDELINES FOR SUCCESSFUL REVEGETATION OF LAND

2.8.1 Selection of species

Species should be selected with the geographic and topographic location in mind. The range of geographic adaptability of indigenous species can be derived from their occurrence in the region. But many species can grow well outside their natural range and the geographic adaptability of exotics planted for commercial use have been well researched in many countries (Plass and Powell, 1988). Elevation, slope and aspect should also be considered when selecting species for revegetation. Climatic variables often used in species selection are annual precipitation and its distribution, daily and seasonal maximum and minimum temperature, evaporation and relative humidity (Plass and Powell, 1988).

Soil characteristics required for the growth of annual crops or pastures are usually readily accessible. However soil requirements for establishment of shrub/tree vegetation are poorly documented since species in these categories normally have very low nutrient requirements. Consequently, selection of tree and shrub species will not normally be influenced by soil nutrient status (Plass and Powell, 1988). Soil chemical factors that may limit species choice are most commonly acidity/alkalinity and sodicity. Soil physical parameters should also be considered when selecting species for reclamation. The most important soil physical constraints are probably rooting depth, soil type (specifically the type of clay) and aeration.

Land-use options will also influence species choice. When the aim is to restore natural ecosystems, the most realistic approach is to plant species (adapted to the spoil conditions) representing more than one successional stage. Natural succession forces are then allowed to determine the composition and density of the plant community (Plass and Powell, 1988). The commercial value of species must also be considered.

Differences within one species is an important characteristic to keep in mind, especially when native species are established. Many experiments in the USA and elsewhere have shown that species adaptability to sites can vary between provenances or ecotypes within one species (Plass and Powell, 1988).

2.8.2 Establishment

Successful revegetation of land depends on rapid initial establishment of plants even if some species do not persist. This enhances buildup of soil organic matter, rapid soil stabilisation, nutrient enrichment if N-fixers are used and exclusion of less desirable pioneers (weeds). The presence of herbaceous vegetation on land that will be afforested is desirable to limit erosion until such time as the woody plants become established. However, most woody plants are intolerant of competition by grasses. Most authors recommend hoeing or herbicide treatments around planted trees or in strips to minimise this problem (Powell, 1988). The results of Andersen *et al.* (1989) show that tree seedling height growth and survival are dependent on the control of competing ground-cover vegetation during seedling establishment. In arid regions, ground cover crops should be established much less densely than in high rainfall areas so as to reduce competition between the ground cover and trees as well as save on water use (Plass and Powell, 1988). Competition between herbaceous or grass species and forest trees is a well documented phenomenon and various site preparation techniques are employed primarily to control competition with trees. Iverson and Wali (1987) recommend mowing of pioneer species just before seeding to promote the re-establishment of grasses following surface-mining in grassland regions.

If plants are established by seeding, special seed treatment may be necessary. Scarification or the removal of hulls may improve germination of certain dormant seeds, whereas certain grass seeds germinate quicker when exposed to light (Lyle, 1986; Plass and Powell, 1988). The seed size and the terrain normally dictates which seeding methods can be used. Large seeds are normally sown by hand, whereas smaller seeds lend themselves to mechanical sowing. The distribution of seed is commonly done with a broadcast seeder (cyclone-type seeder). This apparatus can be attached to a tractor or it can be carried by an aircraft. Grass seeders or grain drills are commonly used in agriculture, and can be used where the terrain is smooth and relatively stone-free. Hydraulic seeders are used to spread mulches, fertilizer and seeds on rough terrain (DePuit, 1988; Lyle, 1986; Plass and Powell, 1988). The application rate of seed is normally much higher with broadcast seeding methods than grain drills. Seeding rates should be based on a pure live seed per unit area basis. A common practice in more arid climates is to establish a fast-growing ground-cover crop in the fist year which is subsequently ploughed in to enrich the soil. This also provides a stubble mulch, ideal to sow the preferred species (DePuit, 1988).

Transplanting of vegetation is commonly used, even with grass species. Sod seeding is particularly effective with stoloniferous or rhizomatous types of vegetation (DePuit, 1988). Trees can be transplanted as bare-rooted seedlings or as containerised seedlings. The latter may be a better choice on harsh sites, albeit more expensive. Tree establishment by the use of vegetative cuttings has been proved to be successful for some plants, e.g. willow and poplar species (Plass and Powell, 1988).

When transplanting vegetation, the following steps can be taken to enhance survival (DePuit, 1988):

- hardening off;
- pruning of the aboveground parts;
- transplant during times of plant dormancy;
- protection of plants from animals; and
- reduction of competition from other plants.

Climatic conditions and plant-available moisture are probably the major factors governing the choice of species to be planted in rangelands. The survival rate of many woody species can be enhanced by a once-off irrigation event at planting. This option should seriously be considered in arid areas. The application of mulches around trees and shrubs will also facilitate moisture retention in the early stages of plant establishment which is critical for survival (Powell,1988; DePuit, 1988).

Planting grasses and herbs in-between woody species on rangelands as well as in pastures may form an integral part of the revegetation effort. Comprehensive lists of grass and pasture species as well as legumes suited to the different climatic regions of the USA has been compiled by Powell (1988). Some of the listed species that grow well in the southern great plain states and the south-eastern states may be well adapted to climatic conditions in the interior of South Africa.

2.8.3 Maintenance and monitoring of revegetated land

The proper maintenance of revegetated land is of great importance since conditions are rarely optimal for plant growth. If a vegetation cover on rehabilitated mined land is not maintained properly, considerable soil loss may occur, and subsequent replanting may be necessary. Regular inspection of established vegetation should be made to asses its growth as well as the occurrence of insect pests, disease, or nutrient imbalances/metal toxicities (Lyle, 1986). Analysis of plant material or soil can be used to indicate nutrient imbalances. Acute nutrient deficiencies can usually be identified as visual leaf symptoms. Leaf nutrient deficiency symptoms are well documented in many plant physiology texts, for example that of Kramer and Kozlowski (1979).

The ecological stability of a minesoil should be monitored to detect pollution that may occur, e.g. acidic drainage, eutrophication of waters, metal leaching and the buildup of toxic concentrations of certain elements in plants. Many different approaches exist to monitor ecosystem stability. So, for example, Alberici *et al.* (1989) monitored levels of trace metals in soil, vegetation and rodents from a spoil treated with sewage sludge, while Smedley (1986) used the mineral level in the liver, serum and bile of cattle grazed on pasture from a reclaimed minesite to monitor animal performance.

2.9 CONCLUSIONS

It is apparent that the revegetation of mine spoil is seen as integral to virtually every rehabilitation scheme. Objectives however have been primarily the cost effective reduction in dust and surface erosion, ecological considerations, and aesthetics. The use of vegetation to reduce water flow through mine spoil or soil profiles disturbed by mining has not been a generally recognized management objective. Trees have also not been seen as a means of absorbing waste water seepage, resulting in a dependence on engineering solutions. This picture appears to be changing in South Africa.

Trees are recognized in Australia as essential to groundwater management and it is here that effluent irrigation forestry is also most advanced. The genus *Eucalyptus* offers species with a wide range of environmental tolerances, variable abilities to accumulate nutrients, well suited to cross-breeding for specific tolerances, and which are in the upper range in both transpiration and photosynthetic rates (Boardman 1991). Eucalypts have also been very successful trees on the Transvaal Highveld in ornamantal, agricultural and woodlot applications, and are commonly found in a wide variety of mining environments.

The steps taken in South Africa to establish trees on mining sites, with the expressed primary objective of reducing the occurrence of acid mine drainage, appear from the world literature to be almost unique. Equally so, there appears to have been no international research designed to quantify actual water use by trees, or indeed any type of vegetation, with a view to quantifying the impact of cover on mine site hydrology and acid mine drainage.

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CHAPTER 3

RESEARCH METHODOLOGY AND SITE DESCRIPTION

3.1 INTRODUCTION TO THE RESEARCH APPROACH

The foremost hypothesis tested in this research is that trees can be effective (and therefore useful) in their utilization of unwanted water in mining environments.

This implies that trees must be more effective than the vegetation type replaced. Alternatively it may be found that the establishment of a good and well managed vegetation cover, be it grass, shrubs, or mixed species, differs little from trees in terms of total water use.

All vegetation evaporates water. Determining differences in this study requires an assessment of water use firstly by trees, where these are already growing in mining environments, and secondly by the vegetation and the surrounds which would otherwise be in place in the absence of trees. This study has therefore attempted, wherever possible, to pair evaporation measurements for trees with those for the surrounding grassland.

The mining sites which we have attempted to cover have been described in Chapter 1 and again in more detail in section 3.5. These include gold slimes, rehabilitated open cast coal mines, and high extraction underground coal mining operations.

Water use was measured for each of these sites at different times of the year in an attempt to capture the seasonal variation. The methodologies employed were very different, with tree water use measured through use of the heat pulse velocity (HPV) technique for measuring the sap flow rate in individual tree stems (see also section 3.3.1). This technique has been extensively used in the commercial forestry zone in Mpumalanga, after verification and refinement of the technique for use in *Eucalyptus* species (Olbrich 1991), and in pine species (Dye 1993).

Water use from grass or other low natural cover was measured, wherever possible on adjacent sites, using the Bowen ratio energy balance technique for determining the evaporative flux over the vegetation surface (see also section 3.3.2). These two approaches provide different outputs and it is necessary to develop a picture of total water use by a stand of trees from the sap flow measurements on a few individuals if comparisons are to be made.

There are always risks in scaling up. Where single trees are growing within a stand of other similar single trees, and where several trees are measured, this risk can be assessed through a determination of the potential error. Where, however, trees are growing as individuals without similar neighbours, the competitor relationships for both water and energy are not in play, and extrapolation is more hazardous.

In this study mature trees in occasional dense clumps were found on old slimes dams, but these have at no time been planted and managed for optimal cover. On, and around, new slimes dams, and on coal mining sites, trees are newcomers to the environment and on no site (with the possible exception of the Withok slimes seepage area) are trees yet approaching full site utilization. Actual water use, as measured, can therefore be assumed at some level considerably below potential and it becomes necessary to estimate from these data what this potential water use could be, on the basis of expected further development of the stand - in this case through expected ability to increase leaf area.

Water use measurements by trees are also limited to the determination of the transpiration power of trees only. Rainfall interception by trees can also be expected to be higher than for grass or any other low vegetation cover type. Dye (1993) has however determined that rainfall interception by eucalypts in the Transvaal escarpment region is a low 6.4%. Although a comparative figure for grass is not given, the difference can be assumed at less than 5%. This difference should nevertheless be taken into consideration when considering the merits of trees on sites where they are established for the purposes of reducing the effective rainfall.

One other important consideration which may lead to large underestimates when making site estimates of water use by trees from heat pulse data is the fact that all understorey vegetation is ignored. In the early stages of a tree planting programme this 'understorey' may be very similar in nature to the surrounding vegetation, with the trees as an additional component. Estimates from young stands will therefore most certainly be underestimates, although when extrapolated to mature stands with fully developed leaf area this error should reduce, as most of the understorey will have been shaded out. In fact the competition provided by the understorey in the early years will to some extent counterbalance the competition between mature trees for which we cannot yet account when making stand water use extrapolations.

The Bowen ratio energy balance technique, in contrast to the heat pulse velocity method, measures evaporation off the entire site within the vicinity of the instrumentation. This evaporation includes both transpiration, evaporation off bare ground, and the evaporation of intercepted water. The accuracy of the technique is dependent on a significant fetch distance (eg 100-200m), ie. the instrumentation must be placed within a large area of similar vegetation, without obstructions to disturb the air flow. These requirements may be met on the tops of large slimes dams where no trees are present (as in the centre of the Western Areas slimes dam), within large fields, and even over continuous forest canopy. As the Bowen ratio estimate of evaporation is for the entire surrounding area, rather than being a strictly point measurement, there are fewer problems with scaling up results to represent the field or site within which the instrumentation was placed.

The fetch requirements and need for an extensive canopy surface, did however limit the number of suitable sites available and it was not, for example, possible to measure grass water use at Durban Deep. Western Areas grass water use was therefore also measured for comparison with trees on Durban Deep.

3.2 EXPERIMENTAL DESIGN

Sites:

4 slimes dams
1 underground high extraction coal mine
1 rehabilitated coal mine

Area:

Johannesburg, Secunda, Hendrina. Climatically and silviculturally fairly homogenous.

Soils:

Man-made (slimes), very disturbed (open cast coal), slightly disturbed (high extraction coal), undisturbed (toe paddock sites).

Vegetation types:

Grass - tall Highveld (*Themeda* dominated)
- pasture grasses (*Eragrostis* dominant)
- seeded slimes dam
- irrigated pasture

Trees - *Eucalyptus viminalis, E. macarthurii, E. sideroxylon, E. camaldulensis*
- *Acacia melanoxylon, A. baileyana*

Vegetation age/condition:

Variable for trees and grasses.

Season:

Intermittent measurements - different seasons.
Instrumentation moved from site to site.

The degree of variability which this study has attempted to address allows only for very specific comparisons for specific sites at specific times. It becomes difficult to project accurate annual estimates from the short term blocks of data available for any one site and at best this can be done for single seasons. But the scale of the question, (ie. do trees use more water than grass), also demands the development of a more general picture of water use by trees.

3.3 INSTRUMENTATION AND METHODOLOGY

Water use by trees was determined by means of the heat pulse velocity (hpv) method of determining sap flow through the tree stem. This is considered equivalent to the transpiration rate.

Water use by grass or other low 'natural' vegetation was measured by means of a micrometeorological technique known as the "Bowen ratio" for determining the site energy balance, which includes a term for the latent heat of evaporation. These methods, together with the verification of the technologies used, are described in more detail, although still very briefly.

3.3.1 The Heat Pulse Velocity Method

The heat pulse velocity method was employed on one or more trees at each site, depending on the availability of both suitable trees and of instrumentation. Each instrument comprises a data logger with heat pulse sender (heater), four pairs of thermistor probes for insertion into the trunk at different depths within the sapwood in order to sample sap flow across the sapwood, and a battery. This configuration is depicted schematically in figure 3.1.

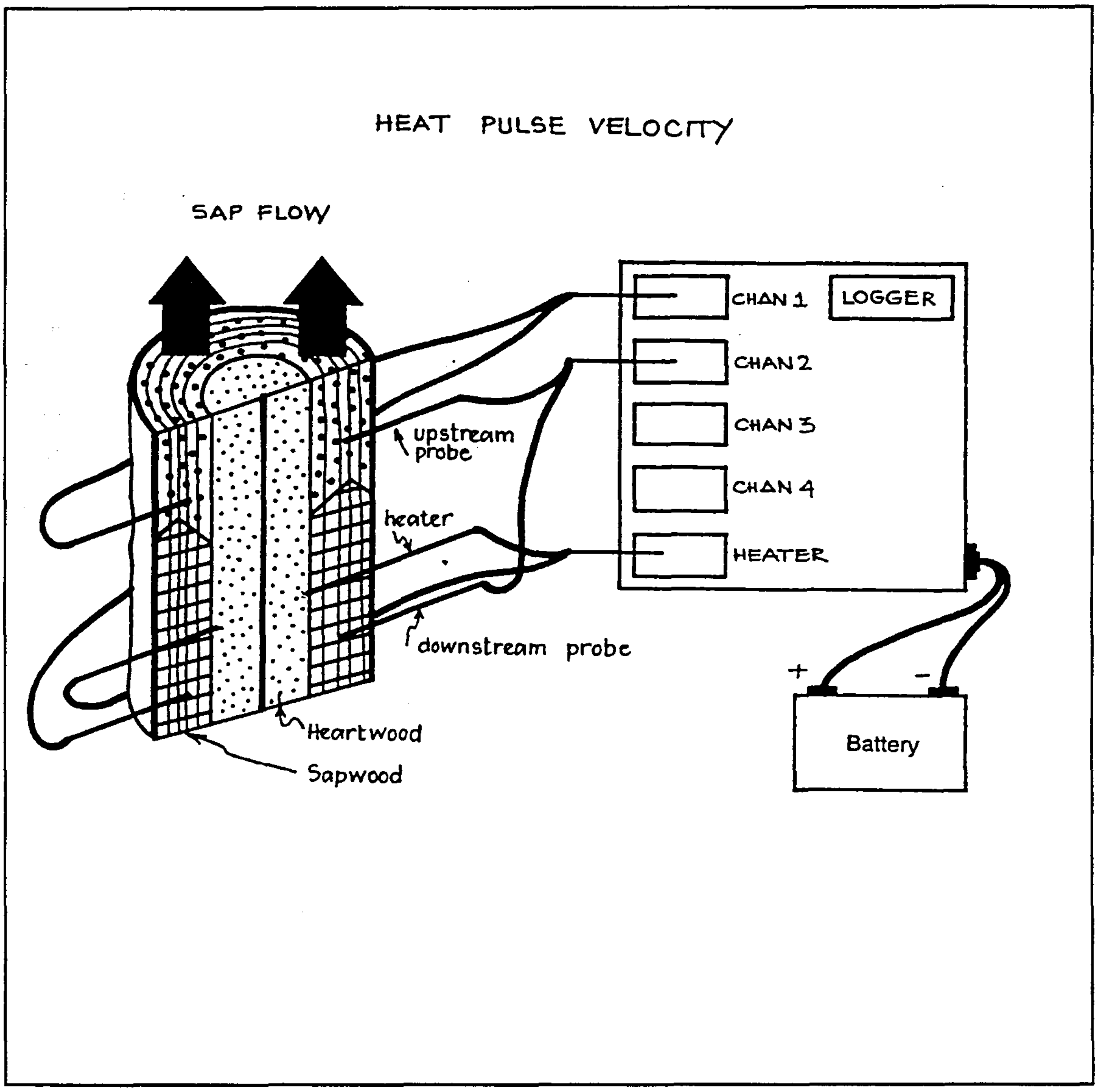


Figure 3.1: Heat pulse velocity instrumentation for the measurement of sap flow in tree stems.

Sensors were pulsed and data recorded on an hourly basis throughout the day in order to establish the diurnal and cumulative water use of each tree.

Once installed, instrumentation could generally be left for one to two weeks, after which memory overflow and battery failure would curtail measurement unless the system was attended to.

The single data logger employed during the first year was a "Custom" heat pulse velocity recorder supplied by the Soil Conservation Centre (Aokautere), Ministry of Works and Development, Private Bag, Palmerston North, New Zealand. In 1993 data loggers of South Africa manufacture (Micro Innovations, P.O. Box 99266, Garsfontein, Pretoria, 0042) became available and a further four loggers were added to the project. Of these one was stolen off the site, and another temporarily disabled by the flooding of a toe paddock. Temperature sensors and heaters of New Zealand manufacture were used throughout the project.

Estimates of total sap flow/transpiration from recorded values of heat pulse velocity have been verified for eucalyptus trees by Olbrich (1991) and for pines by Dye (1993) by means of the cut tree method of water uptake. The technique may now be used with confidence in all species with similar anatomical characteristics to the eucalypts, provided the necessary precautions are obeyed - particularly those related to sampling depth and wound width determination. The sampling procedure for pines is more complex due to its ring porous wood anatomy (Dye, 1993).

The full process of heat pulse measurement and sap flow/transpiration determination is described in detail by Olbrich (1991) and is presented here in summary only.

Four sets of probes were implanted in the trunk of each tree to be measured. For each set three vertically aligned holes were drilled, with the aid of a drill jig, into the sapwood at each position, using a 1.85 mm drill bit. A heating probe was inserted into the middle hole, while a teflon tube containing a single thermistor sensor was inserted in each of the two other holes, 10 mm above and 5 mm below the heating probe. These were connected in a Wheatstone bridge configuration. The thermistor probes were inserted to differing pre-selected sample depths below the cambium, with maximum sampling depth dependent on the thickness of the sapwood (usually in the order of 50 mm for *Eucalyptus*. The data logger triggered a heat pulse once every hour throughout the day for each of the probes.

HPV (u) was measured using the compensation technique (Huber and Schmidt, 1937; Swanson, 1974). The temperature rise was measured at distances X_u upstream and X_d downstream from the heater, and u was calculated as follows:

$$u = (X_u + X_d) / 2t$$

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

Swanson and Whitfield's (1981) wound correction coefficients were used to derive corrected heat pulse velocities (u'). The correction takes the form:

$$u' = p + qu + ru^2$$

where p, q and r are the correction coefficients appropriate to the measured wound size, diameter of teflon probes, and probe separation distances. The size of the wound at each probe set location was measured at the end of the experiment.

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

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

where ρ_b is the density of dry wood, m_c is the moisture content of sapwood, and c_{dw} is the specific heat of dry wood, assumed constant at 0.33 (Dunlap, 1912). In calculating wood density, the volume of a fresh sample of sapwood was determined by immersion in water and the application of Archimedes' principle.

Each of the four sap flux measurements recorded in each tree was taken to be representative of a ring of sapwood centred on the probe depth. Total sap flow was then calculated as the sum of the partial areas multiplied by their associated sap flux.

Sap flux, or transpiration, must be related to the size of the tree or other measure of tree growth. The most useful measure appears to be the leaf area of the tree. This allows transpiration to be expressed per unit area of leaf, and ultimately on the basis of total leaf area, or leaf area index of the stand. Results also showed a strong relationship between leaf area and water use by single trees, suggesting that leaf area would be a satisfactory measure for the extrapolation of potential water use by developing stands.

In order to obtain leaf area measurements each tree was stripped of all leaves at the end of the measurement cycle. Leaves were then weighted and a sub-sample both weighed and measured for total leaf area with a leaf area meter. Using this relationship total leaf area was then estimated from total leaf mass.

Transpiration has been found strongly dependent on the climatic parameters of photosynthetically active radiation (PAR) and vapour pressure deficit (VPD) - at least for *Eucalyptus grandis* growing under non water-limiting conditions (Dye and Olbrich 1993). Climatic data was captured on the nearby Bowen ratio sites in order to provide a basis for the modelling of tree water use, and possible estimates of total annual water use given annual daily (or hourly) climate data. Climate data included air temperature, radiation (solar, net, and/or PAR), VPD, wind and rainfall.

3.3.2 The Bowen ratio

The Bowen ratio system was used to determine surface evaporation. This techniques relies on the partitioning of available energy (net radiation) above the canopy into sensible heat (temperature) and latent heat (evaporation). This is achieved by measuring the small gradients in temperature and vapour pressure above the canopy. Instrumentation used in this study comprised the system supplied by Campbell Scientific Inc. (CSI Bowen Ratio System). A typical installation is depicted in Figure 3.2.

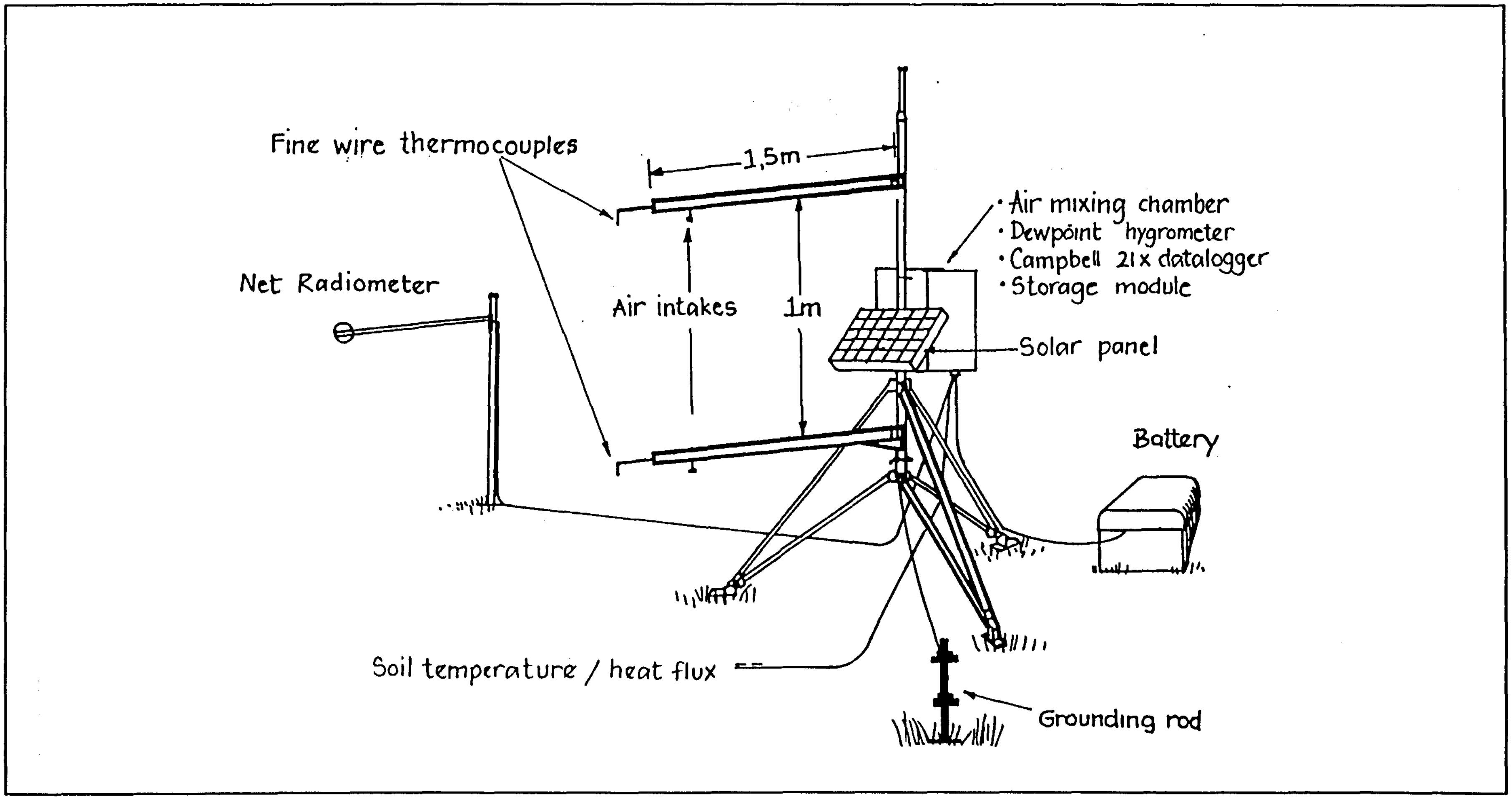


Figure 3.2: A typical Bowen ratio installation as supplied by Campbell Scientific Instruments. A full automatic weather station was added to this mast, with all data recorded at 20 minute intervals on a Campbell 21X data logger.

The temperature and vapour pressure gradients were measured by sampling at two levels above the canopy, with a vertical separation of 1 m. A net radiometer (REBS Q6 (Fritschen)), two soil heat flux plates (REBS type), and four temperature sensors, were used to measure net irradiance I^{net} (Wm^{-2}),soil heat flux density F_s(Wm$_{-2}$) and soil temperature T_{soil}(°C) respectively, and to calculate the Bowen ratio latent heat flux density L_vF_w(Wm^{-2}). In this study L_vF_w values were converted to millimetres of water. The net radiometer was placed 1,0 m above ground on a north-south axis with the radiometer support on the south side to avoid shading of the ground surface by the supports. The soil heat flux plates were buried at a depth of 80 mm, on a north-south axis together with a liberal length of wire to reduce the influence of heat conduction along the surface exposed wires to the sensor. Four soil temperature sensors (type E thermocouples mounted in tubes) were buried at depths of 20 mm and 60 mm below the soil surface. These sensors were connected in parallel to produce a spatially averaged soil temperature measurement for the two depths for the two different positions. Soil water content in the 80 mm layer was gravimetrically measured from six randomly selected samples. Undisturbed bulk density samples were taken, typically, from four sites in the soil surface (0-80 mm).

Within the Bowen ratio system, a single cooled dewpoint hygrometer was employed to measure the dewpoint T_{dp} (°C) of air drawn in from, typically, 0,8 m and 1,8 m above the ground. Air temperature at 0,8 m and the air temperature difference between 0,8 and 1,8 m was measured using two bare type E thermocouples each with a parallel combination of 76 *um* diameter thermocouples.

All sensors were connected to a Campbell 21X datalogger. A frequent measurement period of 1s for dewpoint and air temperatures was employed and 10s for all other sensors. The dewpoint temperature was averaged for a period of 80s (after a mirror stabilization time of 20s first), converted to water vapour pressure and then the datalogger switched a solenoid to sample the other level. Every 20 minutes the datalogger converted an average of the output storage values to final storage. Campbell SM176 storage modules were used to collect the data, which was eventually transferred to a portable micro-computer for data analysis. The data were analysed and corrected following the procedures described by Metelerkamp (1992).

The leaf area index (LAI) of the grass was measured using a Li-Cor 2000 plant canopy analyser. The biomass was determined by hand clipping ten random samples of known area. These were separated into living and dead fractions to give an estimate of the proportion of actively transpiring plant material.

A full weather station was set up in the vicinity of the Bowen ratio apparatus (instrumentation was later added directly to the system). This station monitored relative humidity, temperature, wind speed, wind direction and rainfall at 20 minute intervals.

The method used to calculate the heat storage term and hence soil heat flux, requires site specific inputs for bulk density, mass basis water content, and the specific heat of the dry soil. The soil heat flux at the surface is calculated by adding the measured flux at a fixed depth (in this case 80 mm) to the energy stored in the layer above the heat flux plates. The specific heat of the soil and the change in temperature over the output interval are required to calculate the stored energy.

The heat capacity of the moist soil on a volume basis is calculated as follows:

Heat Capacity $J/(m^3 °C) = BD \times (CS + W \times CW)$

where BD is the bulk density, CS the specific heat of dry soil, W the soil water content and CW the specific heat capacity of water.

3.4 DATA CAPTURE RECORD

The data capture record is summarized in Table 3.1.

Table 3.1: Comparative measurements of water use by trees and grassland on highveld mining sites.

Site	Bowen ratio			Heat Pulse Velocity		
	Vegetation	Date	Ndays	Species	Date	Ndays
Western Areas and Robinson Deep slimes dams	Grass on slimes	920301 - 920305	5	*E. camaldulensis* *Acacia*	920301 - 920305	5
Western Areas slimes dam	Grass on slimes	930119 - 930203 931113 - 931225 940101 - 940118	15 42 17	*E. camaldulensis*	930120 - 930203 931113 - 931128	14 15
Secunda high extraction coal	Natural grass	920818 - 920915	28			
	Irrigated pasture	920915 - 921105	50	*E. viminalis*	920820 - 921016	57
	Natural grass	930204 - 930524	20	*E. viminalis*	930204 - 930304 940222 - 940307	28 13
Ergo Withok slimes toe paddock	Grass	930427 - 930524 940120 - 940223	27 34	*E. viminalis*	930428 - 930603 940119 - 940204 940119 - 940223	35 16 35
Hendrina rehabilitated open-cast coal	Grass	930527 - 930702 940324 - 940329	35 5	*E. macarthurii*	930603 - 930618 930702 - 930723 940301 - 940329 940429 - 940516	15 21 28 17
West Extension	not measured	-	-	*E. camaldulensis*	960207 - 960229	23
Durban Deep	not measured	-	-	*E. viminalis* *E. viminalis*	931205 - 940117 940518 - 940603	42 16

3.5 SITES

The site selection process has been described in section 1.7.1, with a brief description of each site in section 1.7.2. The position of each site, and the sampling points on these sites, are depicted in Figures 3.3 - 3.9.

Regional overviews of climate and geology, are provided in sections 3.6 and 3.7. Each site is now described in more detail.

3.5.1 Robinson Deep

Site description:

Gold slimes dam. Trees on top of slimes.

Location:

26° 14′S 28° 02′E. Close to central Johannesburg, north-east of Robertsham.

Altitude:

1756 m

Vegetation:

Mixed trees and grasses. This is an old slimes dam, long revegetated. Trees include both *Eucalyptus* and *Acacia* species, growing singly and in clumps with large gaps. HPV measurements were carried out only on the Acacias. Trees are variable in age and size. Most have attained an average height of 6 m to 6.5 m. Leaf area is very variable between trees, with the four *Acacia melanoxylon* trees measured carrying an average of 6.5 m^2 of leaf, and the *A. baileyana* 14,5 m^2. These leaf area data cannot be applied to the whole slimes dam due to the clumped nature of the established trees. Grasses were sparse with large gaps.

Soils:

The slimes comprise between eighty-five to ninety-five per cent silica in the form of quartz, while pyrite comprises between 1.5 to 2.5 percent. Seventy-five per cent of the slime particles fall within the silt-clay size fractions (Clausen 1973).

Rooting depth:

No root sampling was carried out on the trees measured. Most of the Acacias are shallow rooted species. Probable maximum rooting depth 80 cm.

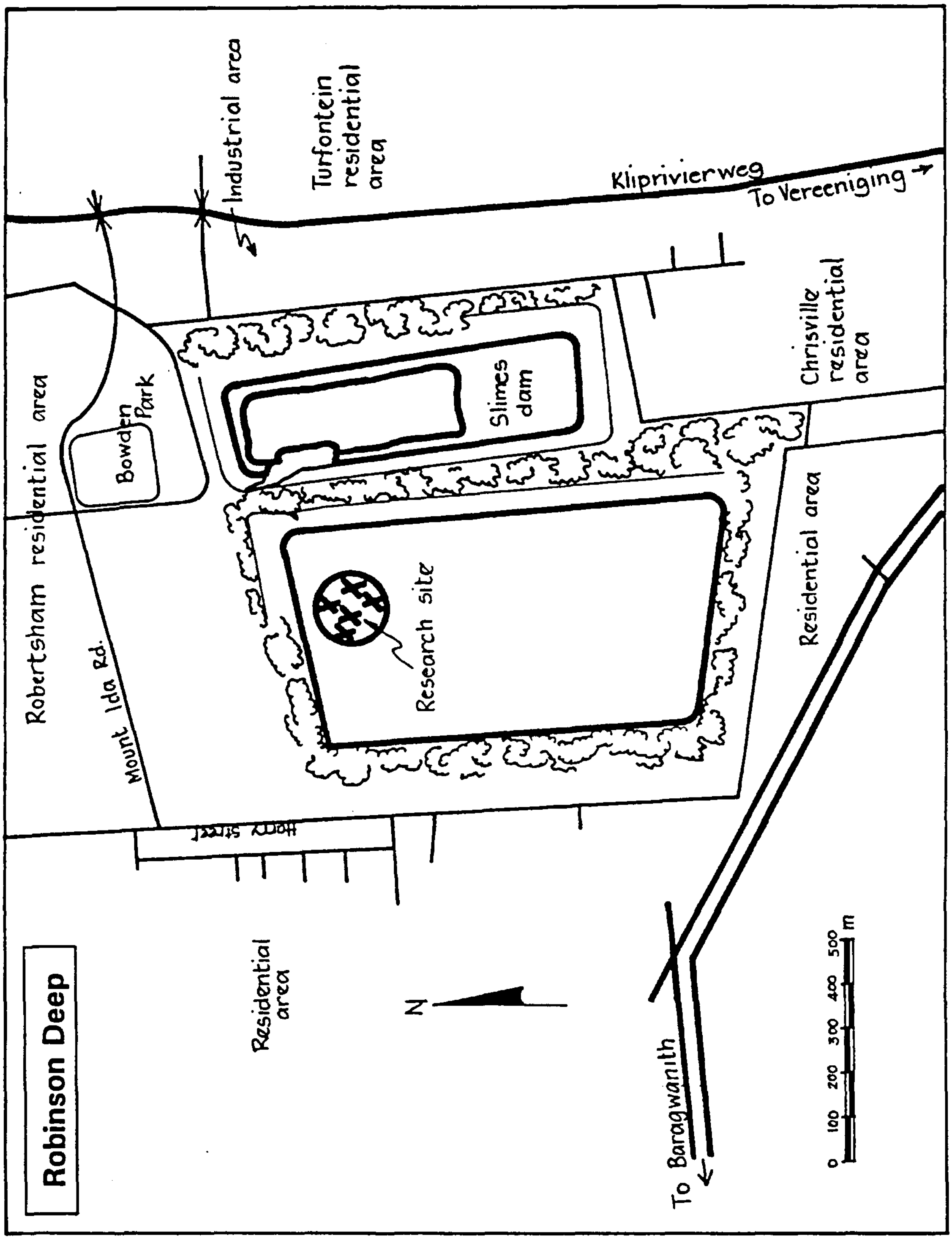


Figure 3.3: The Robinson Deep research site.

3.5.2 Western Areas

Site description:

A recently completed (± 1985) but well vegetated slimes dam.

Gold slimes dam	-	Trees on top perimeter
	-	Trees in toe paddock area
	-	Grass on top.

Location:

26° 22'S 27° 44'E. West Rand, 50 km west of Johannesburg and 10 km west of Lenasia.

Altitude:

1680 m

Vegetation:

A well grassed slimes dam. The grassland species are dominated by *Eragrostis curvula*. With regard to trees on the slimes young opportunistic eucalypts (*E. camaldulensis*) have seeded naturally at points around the perimeter of the dam and on some of the terraces. The slopes and terraces are irrigated. For these trees the average age is 4-5 years, average height 8.0 metres, and average dbh 12.6 cm.

E. sideroxylon has been planted around the bottom edge of the slimes dam in and adjacent to the toe paddocks. Trees vary in age (10-20 years) and size.

Soils:

Toe paddock: Shale
Slimes: Slurry

Rooting depth:

Toe paddock: Between 1 - 1.5 m (trees).
Slimes: Tree tap roots sink to 40 to 50 cm, while laterals sink to 70-80cm. Roots stop at an oxidised layer, orange in colour, at this depth. Eighty per cent of tree roots were concentrated within 1 metre radius of the tree stem. Grass roots on the slimes were only found in the first 30 cm.

Notes:

The grass surface of the slimes dam is mown annually and the grass on the slopes burned occasionally. Grasses on the slopes are still irrigated and this water benefits the opportunistic eucalypts. When burnt the canopies of the trees tend to be severely scorched.

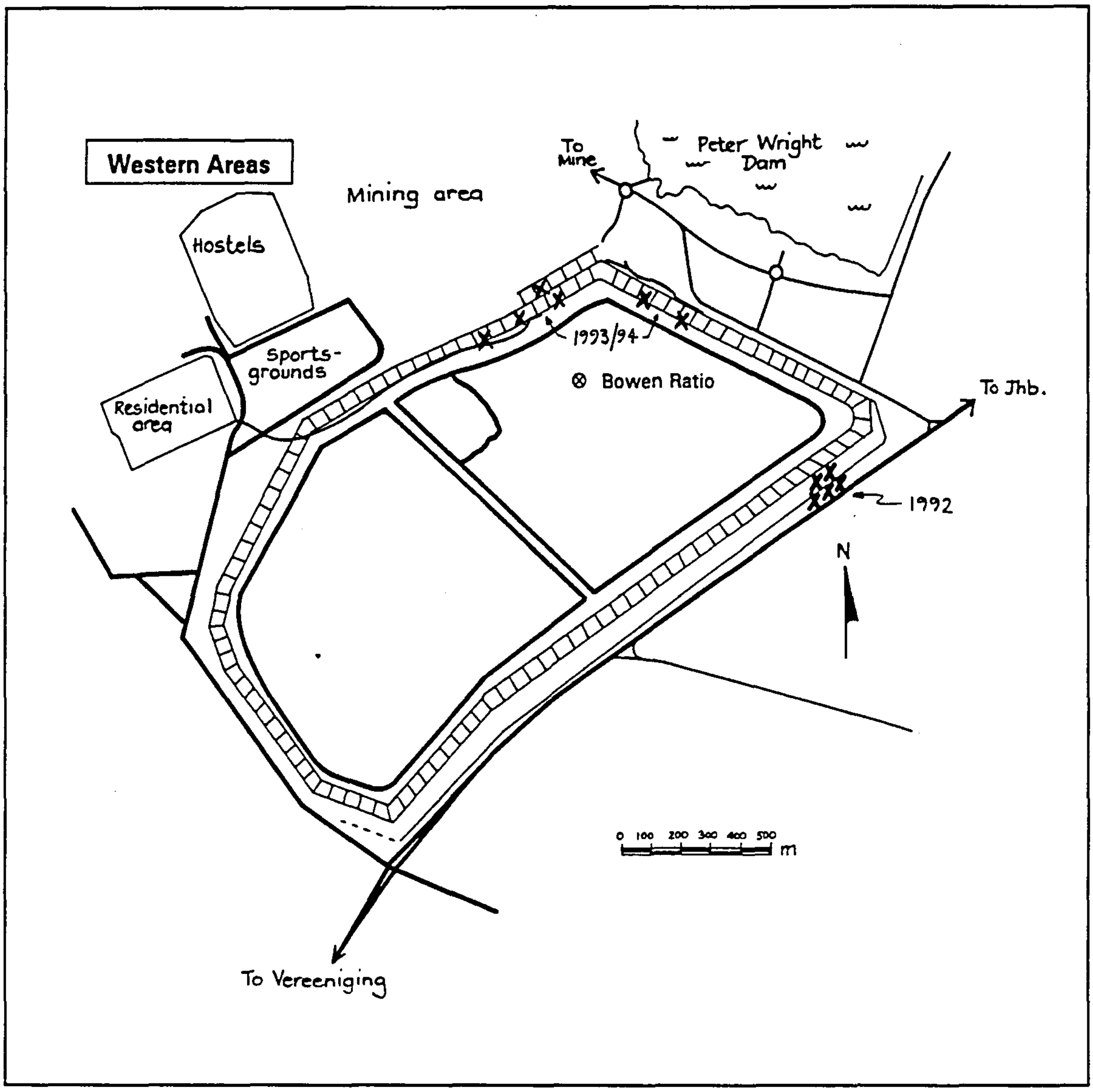


Figure 3.4: The Western Areas slimes dam indicating the location of the Bowen ratio system and the trees monitored for water use.

3.5.3 Durban Deep

Site description:

This is an old slimes dam, with trees to be found on the top, on the slopes, and around the base. The slimes is now 100 years old and has not seen revegetation intervention for the last 25 years.

Location:

26° 11'S 27° 52'E. Four km north of Roodepoort.

Altitude:

1700 m

Vegetation:

This slimes dam supports *Eucalypts viminalis* and *E. camaldulensis* - some probable established through seeding, others opportunistic. There are also a few single pine and poplar trees. Trees are growing on the top of the slimes (mainly around the perimeter), on the slopes, and more densely around the base. Mixed grasses and papyrus also occur. Trees are very variable in age, size and leaf area.

Soils:

Mine slurry.

Rooting depth:

Maximum rooting depth of the tap root 40-50 cm and secondary roots to 70-80 cm. Some deeper rooting (1.5m) was observed, but roots were noted to be following erosion pipes. The lateral roots of the trees growing on the side (ie mid-slope) of the slimes measured from 10 to 15 metres. This could be observed through root exposure resulting from surface erosion.

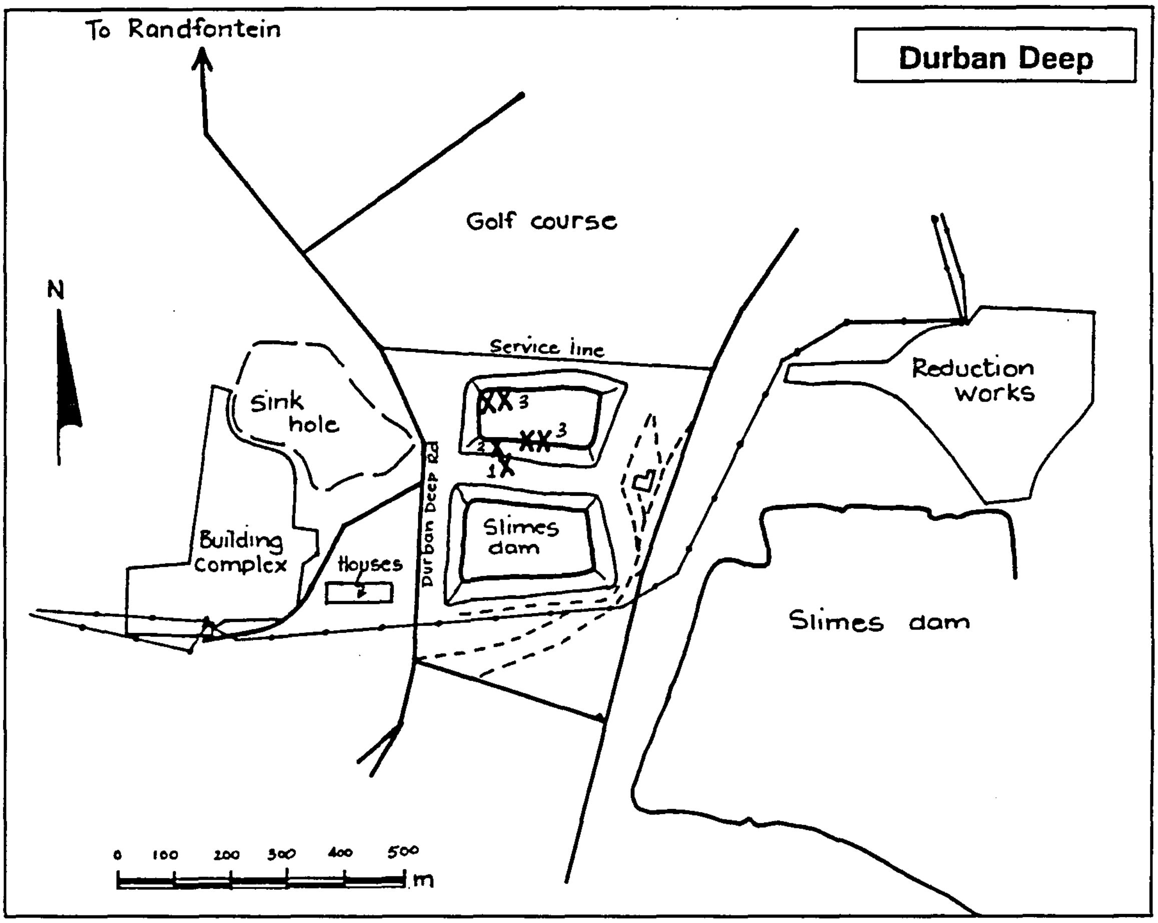


Figure 3.5: Durban Deep mine complex at Roodepoort. Trees for which water use was monitored are marked with an X.

3.5.4 West Extension

Site description:

Gold slimes dam. Trees on top of slimes. This site is called the West Extension since it was built following the bursting of the Grass Dam adjacent to West Extension (dump) in 1966.

Location:

27° 06′S 26° 43′E. Situated on the R502, 5 km outside Orkney, which is in the Potchefstroom district.

Altitude:

1360 m

Vegetation:

The vegetation consists of a tall grassland dotted with self sown *Eucalyptus camaldulensis* trees. HPV measurements were undertaken on 5 trees growing in a 10 m x 6 m plot. Leaf areas of these trees varied from 19 to 57 m^2. Trees 1 & 2 were situated on a toe dam, while trees 3 to 5 were on the slimes dam (refer to Fig. 3.6).

Soils:

Mine slurry.

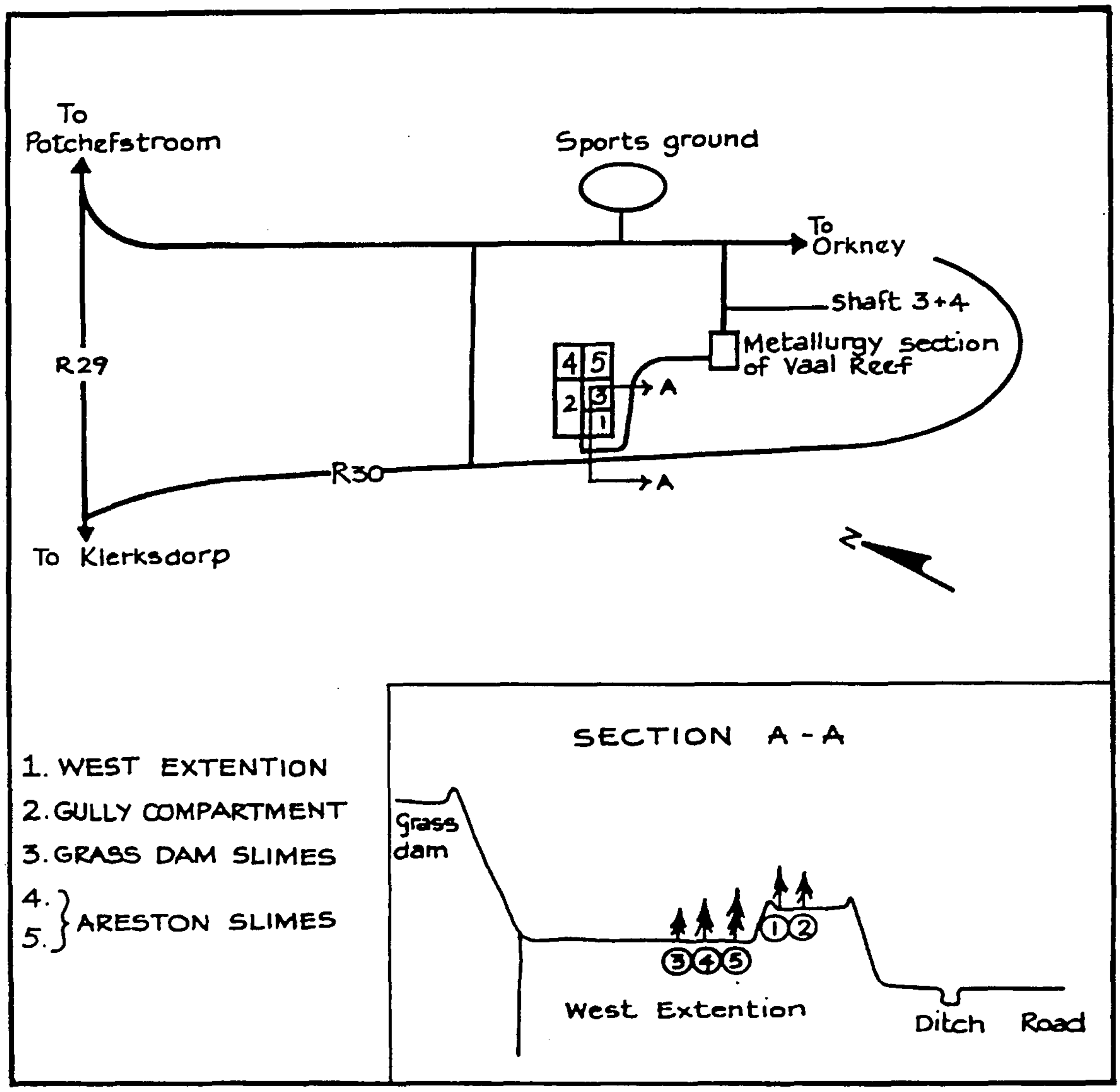


Figure 3.6: West Extension Mine outside Orkney. Trees for which water use was monitored are numbered.

3.5.5 Withok slimes

Site description:

A new and actively growing slimes dam covering about 1500 ha. The slimes has been built using the "cyclone" technique instead of the more accustomed dry packing system. There is very little vegetation on the top, mainly self-seeded *Eucalyptus cinerea*. *E. cinerea* and *E. viminalis* have been planted around the periphery, both for screening and for water uptake purposes. The water table in August 1994 was at 1.7 m below the soil surface on the site of these plantings.

Location:

26° 19'S 28° 19'E. On the old Heidelberg Road to the west of Springs, near the Withokspruit.

Altitude:

1580 m

Vegetation:

The trees researched were planted as a belt of three rows outside the primary cutoff drain, to the west of the slimes dam (the lowest point of the dam) and about 150 m from its edge. Species planted were *Eucalyptus cinerea* and *E. viminalis*. Trees were established at an espacement of 4 m (within rows) by 6 m (between rows). Water use measurements were on *E. viminalis*. Mean height: 10 - 15 m, Mean dbh 9 - 40 cm. This is a variable stand as the trees are either single or multi-stemmed, some with as many as five stems.

The trees are growing on old agricultural lands and have replaced a mixture of pioneer grasses and weeds.
Evaporation over this `natural' canopy was measured using the Bowen ratio technique.

Soils:

The trees were planted on a Swartland form (Sw 1211), Orthic A (3-30 cm) on Pedocutanic B (30-63 cm) on Saprolite which had two distinct layers (63-90 and 90-170 cm). The grasses were found on a Rensburg form (Rg 1000), Vertic A on a G horizon.

Rooting depth:

Ninety five per cent of the roots of trees growing adjacent to the slimes dam occur between 0-63 cm where there is a distinct stone layer, few roots penetrate this line. Due to the stone line the lateral spread of roots was measured at 7-8 m. The grass and weed roots penetrated to a depth of 1.5 m but 70 % of the roots were in the first 28 cm.

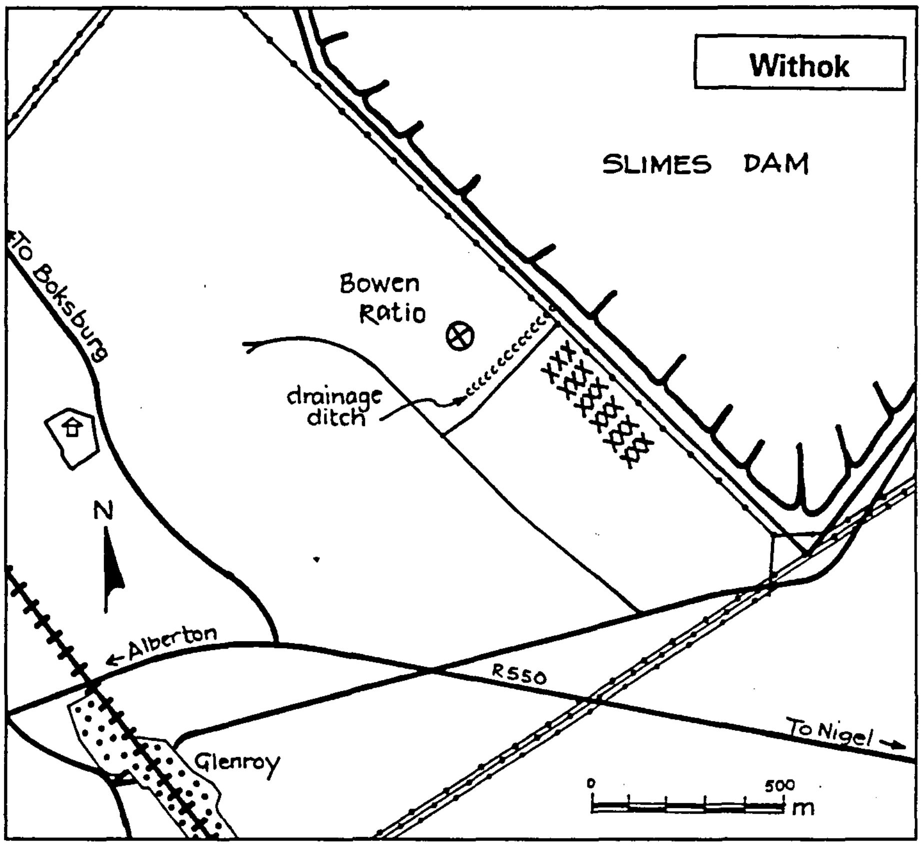


Figure 3.7: The research site in the toe area of the Withok slimes dam. The position of trees in the toe-area are marked X.

3.5.6 Hendrina (Optimum Colliery)

Site description:

Recently rehabilitated open-cast coal mine. Stands of trees have been established on some sites, with pastures on others. The coal was extracted at a depth of between 30 and 40 m below the soil surface. The water table is 15 to 20m from the soil surface.

Location:

26° 03′S 29° 37′E. Mpumalanga near Hendrina.

Altitude:

1600 m

Vegetation:

Some rehabilitated sites were planted to eucalypts on 10/02/1990 (*E. macarthurii, E. smithii, E. fastigata*). Only the *E. macarthurii* has established successfully, with the other species proving to drought susceptible. Trees were planted at an espacement of 3 m * 3 m and at time of water use measurement (age 3-4 years) had an average height of 6.6 m and a dbh of 8.8 cm. The average leaf area for the individual trees measured ranged from 26 to 54 m^2. Grass cover between the trees was poor.

Most of the mined area has been re-established with a grass pasture dominated by *Eragrostis curvula*. This provides a good density cover but generally low in height (< 50 cm).

Soils:

The trees and grasses were situated on 'sub-soil', mainly shale and weathered sandstone (brown spoil), replaced as the uppermost layer on top of mudstone mixed with 'number four upper coal seam' (black spoil). The classification term for these replaced soils is 'Witbank soil'. On the tree site the depth of 'sub-soil' varied from 30 to 103 cm while the pasture soils were generally between 30 and 40 cm deep. Below this the material is very variable in size, from giant boulders to broken material. This will often provide an impediment to rooting, but not to drainage.

Rooting depth:

The rooting depth appears to be dependent on the depth of the mudstone/coal spoil layer. Few roots penetrate this stratum and only then where it has been broken up. It was clearly seen that the roots turn horizontal as they hit the coal spoil.

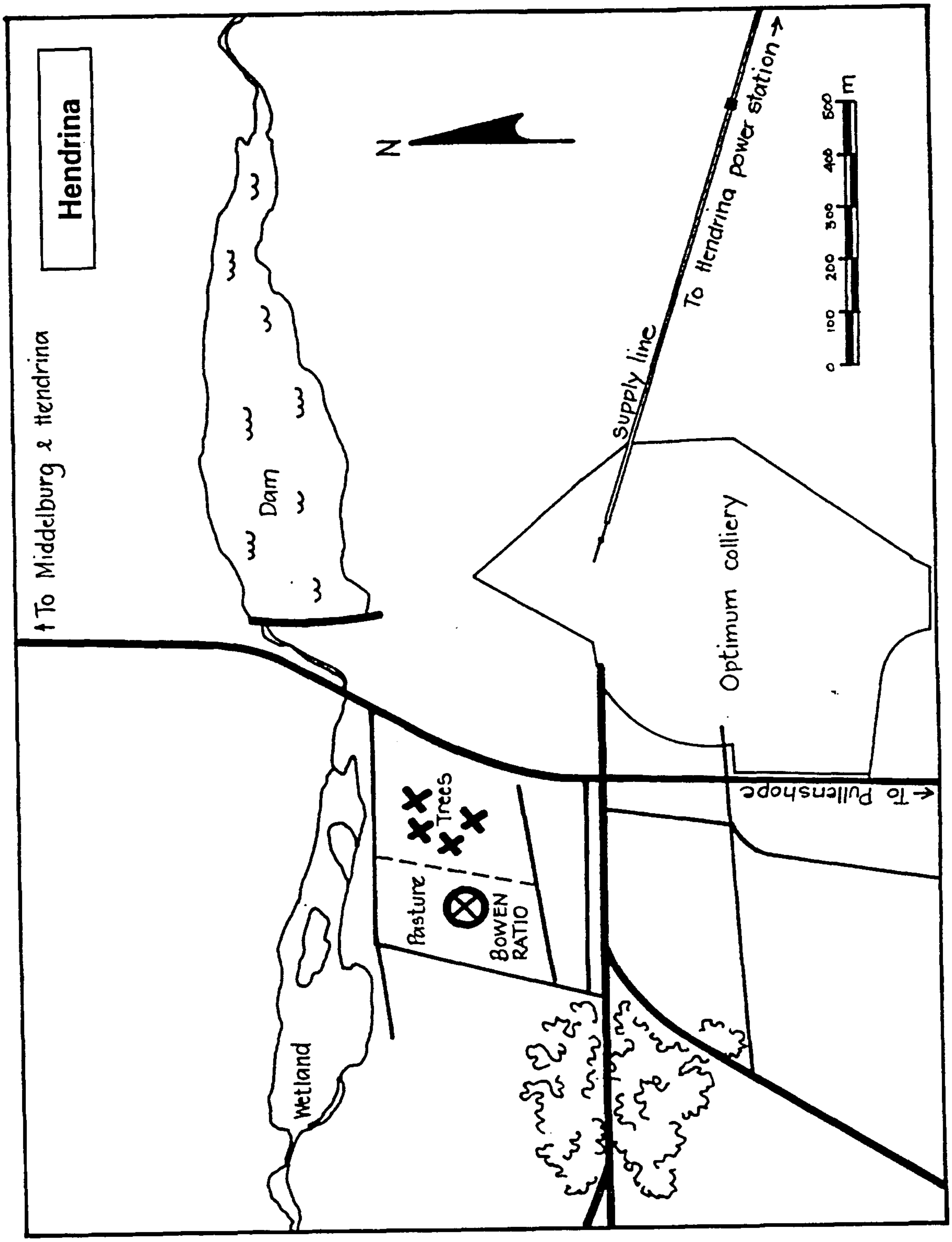


Figure 3.8: The research site at Optimum colliery near Hendrina.

3.5.7 Sasol, Secunda (Brandspruit Colliery)

Description:

Total extraction underground coal mining with coal mined at a depth of 110 - 120 m. There is no apparent disturbance of the surface although surface subsidence of 1 - 2 m occurs over extensive areas. Stands of trees have been successfully established on some areas. HPV work was carried out on the higher-lying areas at the Brandspruit Collieries

Location:

26° 36′S 29° 08′E. Close to Secunda on the Standerton road.

Altitude:

1600 m

Vegetation:

E. viminalis trees were successfully established on some sites, with planting on 12 December 1990. Trees were planted at an espacement of 2 X 3 m but deaths have also led to a number of gaps. Mean height was 6.4 m and dbh 8.3 cm at time of measurement.

The natural grassland in unplanted areas comprises dune sourveld grasses. These grasses grow to a height of at least 1 m in summer.

Soils:

The parent geology is sandstone, interspersed with a doloritic influence. The predominant soil form is Milkwood (Mw 1000), melanic A over hard rock. The depth of the melanic layer is undulating and varied from 10 to 70 cm. Vertisols predominate in the lower lying areas, with a soil depth of at least 2 m. Trees are growing successfully in both the melanic and vertic soils. All water use research was on melanic sites, while grassland evaporation was determined for a site on vertisols.

Rooting depth:

On the melanic soils the depth of the tap root is dependent on the depth of the melanic layer. Of the two trees excavated the layers varied from 10 to 70 cm. The smaller roots are able to penetrate the dolerite rock layer. Roots were found to go between the onion-shelling layers of the dolerite. The underlying rocks do not form a solid layer and roots have a probable maximum depth of at least 1.2 m. The roots seem to follow the shatter lines (70cm deep) ripped when the sites were prepared for planting. Ninety five per cent of the roots are in the first 70 cm. Roots also exhibit a lateral spread of at least 3 m.

On the vertisols the tree roots are evenly distributed in the first 95 cm and the rooting depth on these soils can go to 1.5 m. There is a lateral spread of roots at least 5 to 7 m from the tree stem.

Grassland rooting was found to a depth of 80 cm but the larger portion of the roots were found in the first 60 cm.

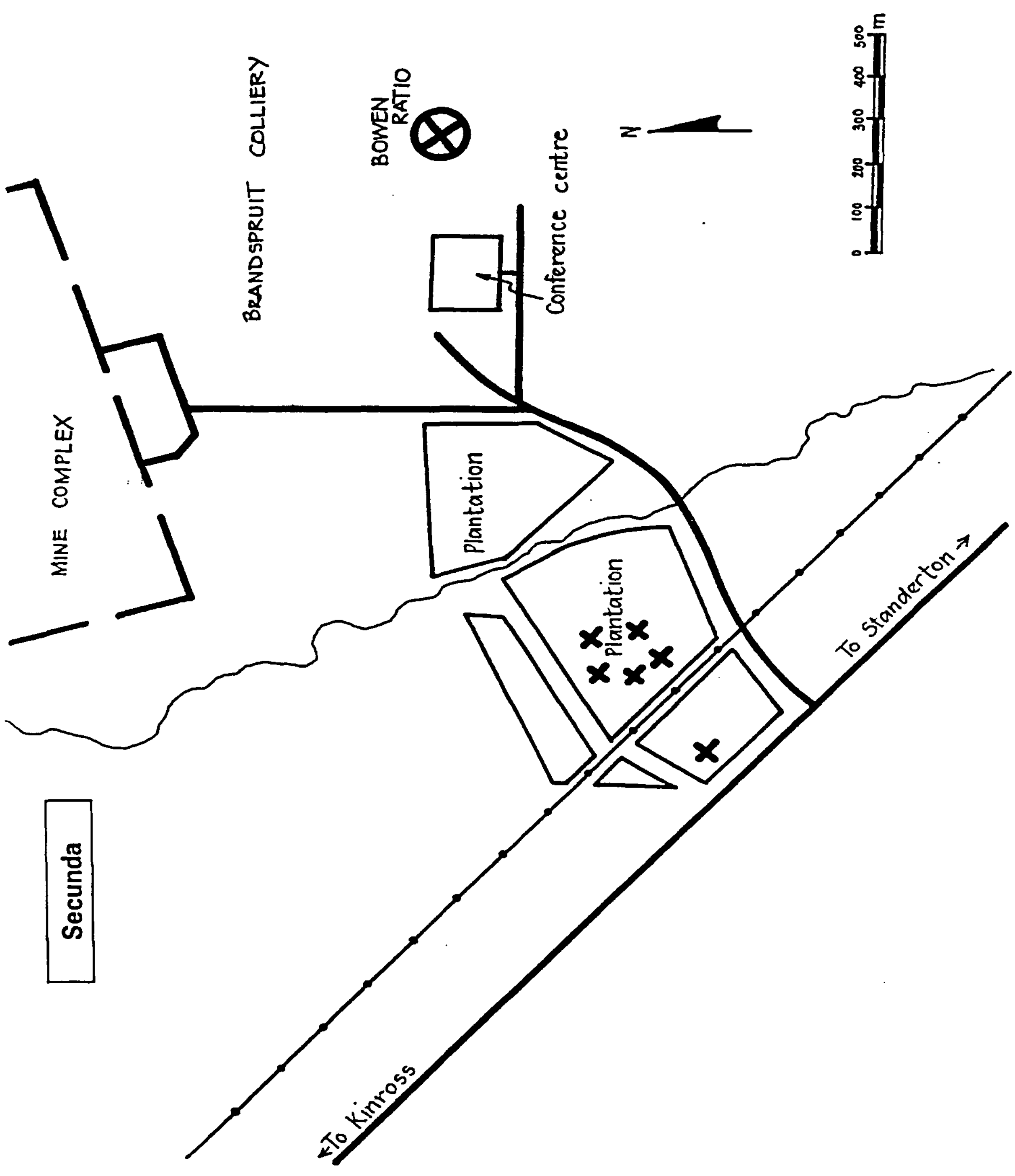


Figure 3.9: Brandspruit collieries at Sasol, Secunda indicating the area planted to *E. viminalis* in which tree water use was measured, and the site of the Bowen ratio system for measurement of grass evaporation.

3.6 CLIMATE

Mean monthly and annual rainfall, temperature and potential evaporation data for the various sites are presented in Table 3.2.

The rainfall distribution over this part of the South African Highveld has been extracted from the Computing Centre for Water Research, and is included as Figure 3.10.

3.7 GEOLOGY

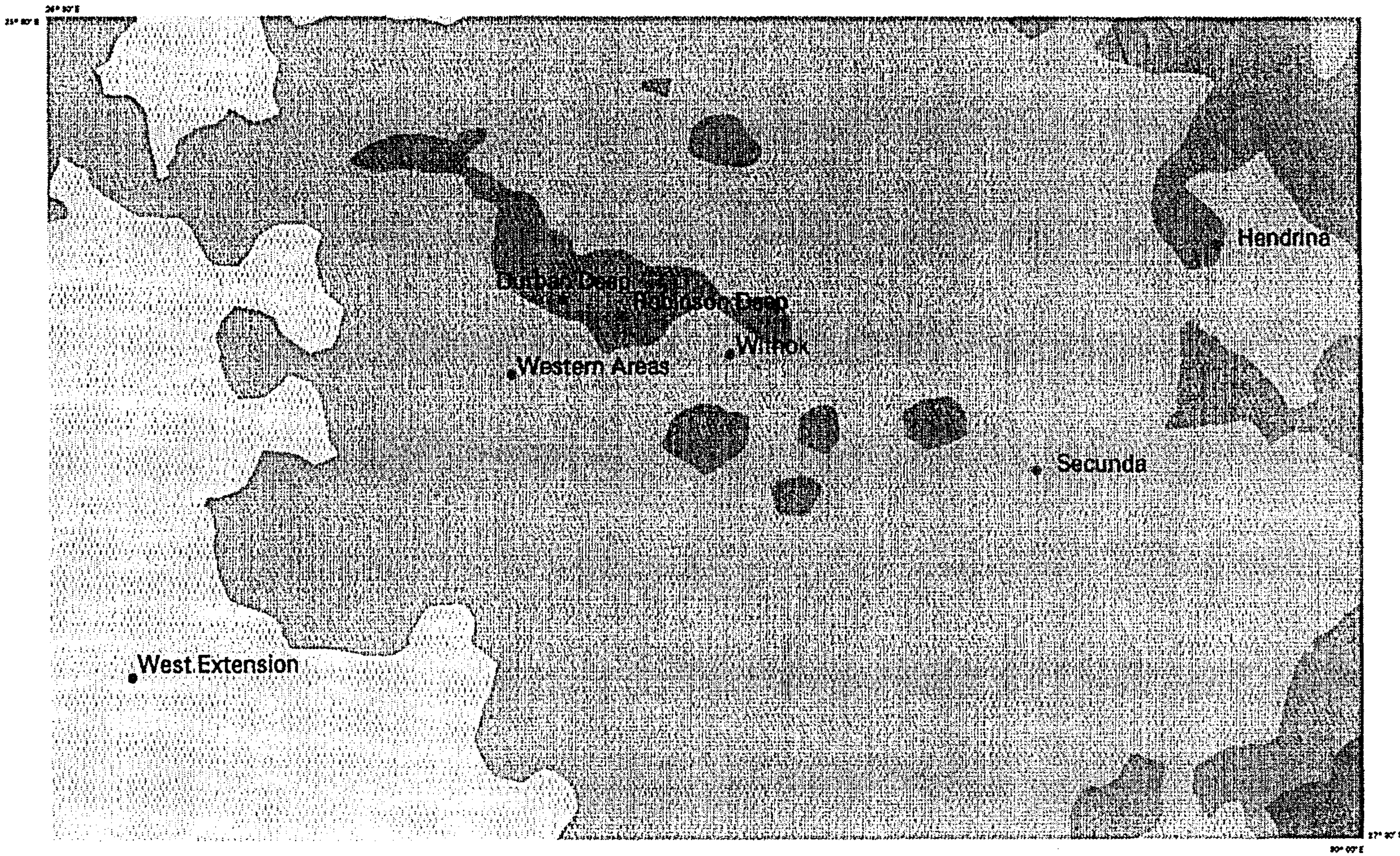
The geology of the region has been summarized in Figure 3.11 (nomenclature follows SACS, 1980). The shales, quartzites and conglomerates of the Witwatersrand Supergroup has a history of intrusions of diabase, gabbro, dolerite and other rock types (Truswell, 1977; Tankard *et al.*, 1982). The Durban Deep and Robinson Deep sites are situated on the Witwatersrand Supergroup, which also underlies the Withok site. The Supergroup is also heavily faulted. Gold is mined from the Main Reef of the Central Rand Group of the Witwatersrand Supergroup.

The Western Areas site lies on the quartzites and shales that dominate the Pretoria Group (Transvaal Sequence). Numerous diabase and other basic sills are found in various levels in the Pretoria Group. The latter lies unconformably on the Chuniespoort Group which consists mainly of dolomite zones in which sinkholes can occur.

The Hendrina and Secunda sites are situated on the younger coal-bearing layers of the Ecca Group, though being capped by Karoo Dolorites at the Secunda site. The coal is found mainly in the Vryheid formation of the Ecca Group. The predominantly shale layers are generally horizontal and there is no faulting or major disturbance (Truswell, 1977; Tankard *et al.*, 1982).

Table 3.2: Mean monthly values for rainfall (rain; mm), air temperature (temp; °C) and potential evaporation (Pet; mm) for the different study sites. The months are numbered from January (1) to December (12). Climatological data was not recorded at West Extension.

Study site	Month												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Annual
Robinson Deep													
Rain	121	85	90	35	12	0.7	0.7	0	16	61	106	108	738
Air Temp	19.7	19.1	17.9	15.1	11.7	8.5	8.6	11.4	15.1	17.0	18.1	19.1	15.1
Pet	218	175	178	137	131	111	121	141	219	233	225	234	2120
Western Areas													
Rain	108	85	76	37	8.4	0.3	1.0	0.5	12	54	96	104	671
Air Temp	20.2	19.6	18.2	15.3	11.9	8.6	8.7	11.6	15.4	17.4	18.5	19.6	15.1
Pet	223	179	180	137	138	112	121	144	227	240	235	242	2178
Durban Deep													
Rain	119	100	93	38	10	0.8	0	0.8	15	63	121	107	777
Air Temp	19.6	19.1	17.8	15.1	11.8	8.7	8.8	11.5	15.2	17.2	18.2	19.1	15.2
Pet	219	171	177	136	136	114	123	156	213	237	231	237	2151
Withok slimes													
Rain	111	82	74	30	12	0.4	0	0.6	14	57	101	104	665
Air Temp	20.4	19.9	18.5	15.5	12.0	8.8	8.9	11.7	15.5	17.6	18.7	19.9	15.6
Pet	220	179	179	142	128	109	121	145	214	234	226	234	2130
Hendrina													
Rain	118	84	73	38	8.9	0.2	0.3	1.2	15.9	68	116	112	710
Air Temp	19.4	18.9	17.9	15.4	12.0	9.1	9.3	11.8	15.0	16.8	17.8	18.9	15.2
Pet	197	167	168	133	126	106	118	136	188	208	189	202	1936
Sasol, Secunda													
Rain	100	64	59	31	12	2.1	0.5	1.4	17	56	96	94	
Air Temp	19.7	19.4	18.7	15.7	12.8	9.7	9.5	12.4	15.0	17.5	17.6	18.4	15.5
Pet	*n/a*												



Rainfall (mm)

- 400 - 500
- 500 - 600
- 600 - 700
- 700 - 800
- • Mining sites

Figure 3.10: Rainfall distribution on the Highveld between the West Rand and Hendrina. Data appears to be of poor resolution in the vicinity of Secunda.

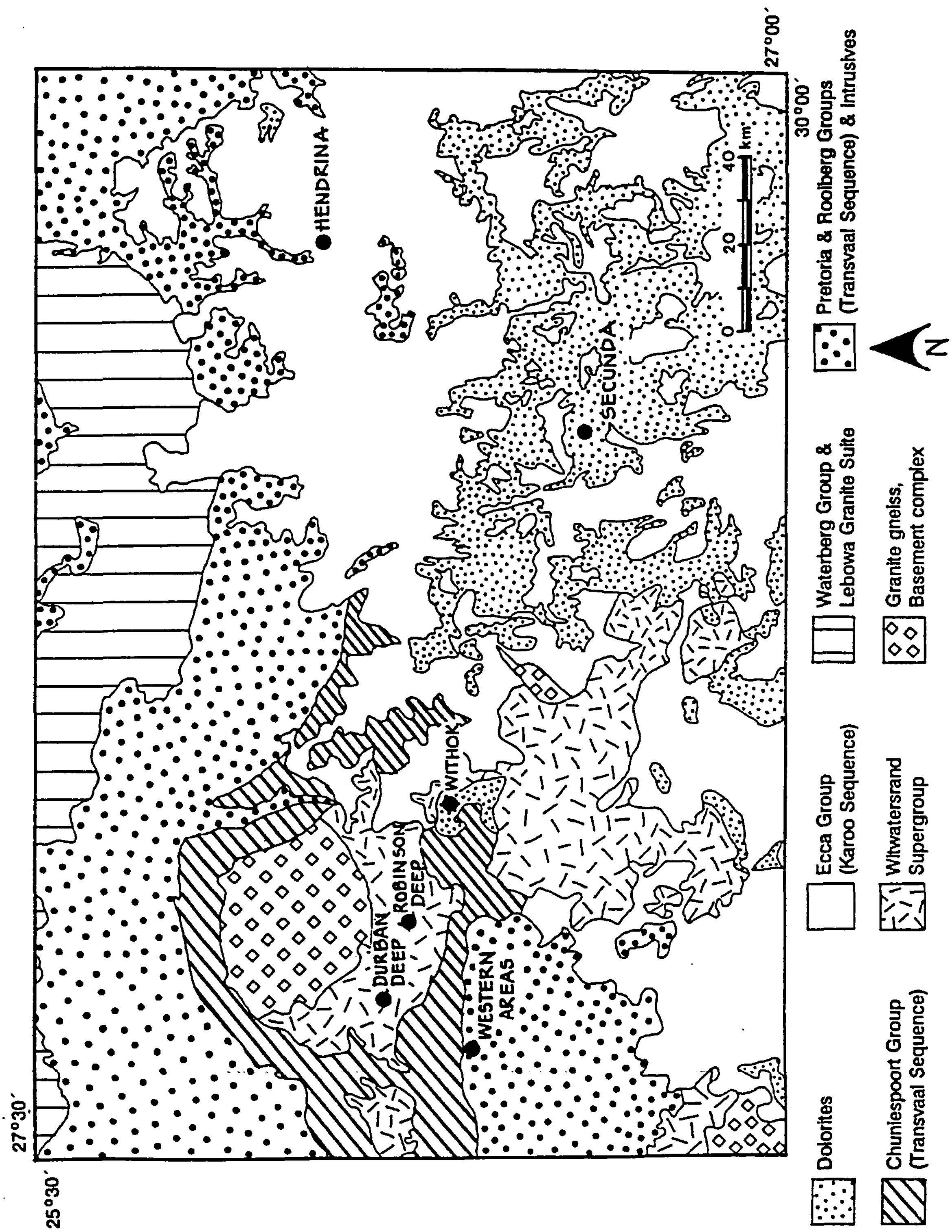


Figure 3.11: Geology of the Highveld for the region encompassing the research sites.

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CHAPTER 4

THE SOIL FEATURES AND ROOTING CHARACTERISTICS OF TREES GROWING IN MINING ENVIRONMENTS

4.1 INTRODUCTION

Root studies are generally difficult and it is not surprising that there is a lack of data on the rooting behaviour of trees. However, there is evidence from high production commercial forestry that trees, especially the eucalypts, can root extremely deeply given favourable soil conditions,. Research by Dye (1993) in the Sabie region of Mpumalanga Province indicates that 9 year old *Eucalyptus grandis* drew water from depths of more than 8 metres. The long hydrological recovery time of the Mokobulaan catchment in Mpumalanga (Scott & Lesch 1993) and the dry condition of the soil to a depth of 45 metres after 15 years of afforestation with *E. grandis* (Dye and Poulter, 1992) are also indicative of the ability of trees to dry out the profile to great depths. Research in northern KwaZulu/Natal (on the Zululand sand flats) showed that pines and eucalypts root routinely to the water table at depths of 3-5 metres (Scott 1993). Midgley *et al.* (1994) reports maximum rooting depths of 8 and 13 m, for pines and eucalypts respectively, from research using tracer uptake techniques in these Zululand plains.

Rooting depth is very dependent on the depth of the water table, both the physical and chemical permeability of the profile, and on the species itself. A minimum soil depth of 60 cm is the standard prerequisite for commercial tree planting. Tree roots are often limited by soil conditions to depths of less than one metre, even within the commercial forestry zone, although death from drought is a feature on very shallow soils. Of the South African commercial forest species, the eucalypts are generically the deepest rooting (although there may be great variation within the genus) followed by the pines, and finally the acacias.

This study serves as a preliminary investigation of the nature of tree root systems for eucalypts growing in mining environments, and of the relative differences between trees and grass growing in similar environments. The physical and chemical properties of soils occurring at these sites were also analysed.

4.2 RESEARCH DESIGN

Data on rooting depth and behaviour was obtained in the following ways:

(i) Observations of root systems of trees growing on gold slimes dams and sand dumps which were being reprocessed at the time. The reprocessing procedure led to root exposure which allowed us to take measurements.

(ii) A one page questionnaire forwarded to 26 roleplayers within the mining and mine revegetation fields to record knowledge, experience, and opinion with regard tree roots and the role which trees are perceived to play in utilizing unwanted water in mining environments.

(iii) Excavation of the roots of trees and grasses growing on the sites where water use measurements were undertaken (refer to Chapter 5). Roots were studied by digging pits adjacent to trees growing on a slimes dam (Western Areas), in a slimes seepage area (Withok), over high extraction coal mining (Secunda), and on a rehabilitated open-cast coal mine (Hendrina). Grasses were studied either through profile examination or through auger sampling for root density and depth determinations. Soils were sampled at regular depths (0 - 10 cm, 10 - 50 cm, 100 cm and deeper) for physical and chemical analysis.

4.3 KNOWLEDGE SURVEY

There were 13 responses to the 26 questionnaires distributed. These responses, together with our own observations, confirm the lack of formal investigation of rooting systems, particularly over coal, and also indicate a wide range of experiences and perceptions. On the basis of the responses received, this survey only covered the gold and coal mining industries.

Responses to each of the questions addressed are given below:

(i) *Are trees **seen** as being useful in controlling water?*
An unqualified **YES** from all respondents.

(ii) *Are trees seen as being a problem? If so, why?*
Not in terms of site management, except that trees may shade out grass cover, introducing a dust problem. The invasive spread of eucalypts, pines and especially wattles off mine sites, is seen as undesirable from an ecological perspective.

(iii) *How deep do trees root (maximum, average)?*

No response for coal.
Responses for gold very variable. Trees on slimes mostly seen to be shallow rooted (1m) but one respondent indicated that all trees root deeply with the rule of thumb being two thirds above ground and one third below - irrespective of site. A rooting depth of up to 9m was recorded for an old slimes dam, and we recorded 3m for a number of trees on the old Daggafontein slimes at Springs.

(iv) *How deep do grasses or other plants put down roots?*

To a maximum of 1m but mostly within the top 30 cm.

(v) *Do you see trees rooting more deeply, or occupying a greater soil volume, than grass?*

YES. One respondent suggested that despite deeper rooting, trees may not always occupy a greater soil volume than grass.

(vi) *Do you find rooting depth to be restricted? What is the barrier?*

Particular barriers to root penetration noted by respondents were iron pyrites in slimes, black spoil in coal, natural bands of impermeable material (rock, gleyed soils), compacted layers, a high water table (especially in slimes), and water quality.

4.4 ROOT STUDY - CHARACTERIZATION OF SOILS AND ROOTS

The rooting characteristics of trees and grasses were investigated at the following sites:

Western Areas gold slimes.

Grasses on top of slimes. Trees growing along the top perimeter.

Withok gold slimes.

Trees and grasses growing in natural soils in the seepage area around the base of the slimes.

Secunda high extraction coal.

Trees growing on melanic and vertic soils, grasses growing on melanic soils.

Hendrina rehabilitated open cast coal.

Trees and grasses growing on `Witbank' soils (open cuts refilled with spoil, rubble and covered with 30-60 cm of top soil).

The types of soil and the species occurring on these soils at the different mining sites are shown in Table 4.1.

Table 4.1: Soil type and vegetation type found at the various mining sites where root and soil studies were undertaken.

Site	Vegetation type	Soil characterization
Robinson Deep	*A. baileyana* *A. melanoxylon*	Slurry
Western Areas	*E. sideroxylon*	Shale
Western Areas	*E. camaldulensis*	Slurry
Western Areas	*Grassland*	Slurry
Durban Deep	*E. camaldulensis* *E. viminalis*	Slurry
Withok	*E. cinerea,* *E. viminalis*	Swartland
Withok	*Grassland*	Rensburg (vertisol)
Secunda	*E. viminalis*	Milkwood
Secunda	*Grassland*	Rensburg (vertisol)
Hendrina	*E. macarthurii &* *grassland*	"Witbank" (sub-soil)

4.4.1 Western Areas

• Grasses

Grass rooting was examined in a trench dug in the middle of the slimes to a depth of 1.1 m, and on the sites where trees were excavated along the perimeter of the slimes. Grasses rooted to a maximum depth of 30 cm in the middle of the slimes, to 20-25 cm on tree site A and to 40 cm on tree site B. Root hairs were abundant for the grasses, when compared to the tree roots.

On the top of the slimes the soils showed distinct bands of colouration within the first 36 cm of material. There were brown and orange layers, which are signs of iron pyrite oxidation. Below this level the profile was a uniform grey. These strata had a distinct effect on the grass roots, with roots extending horizontally when reaching the brown layers and failing completely to penetrate the orange band observed at 36 cm. This pattern of profile development and root growth was also observed for grasses on both the tree sites.

• Trees

Two trees were excavated along the top of the slimes dam wall: site A and site B.

Site A *(Figure 4.1)*

E. camaldulensis, age ± 5 years, stem diameter 14.4 cm, tree felled but coppicing.

A trench was dug across the front of the tree to a depth of 120 cm for soil and root sampling, after which a front -end-loader lifted the tree completely.

Vertical Distribution: Maximum rooting depth 60cm. The tap root split at 37 cm into three branches (A,B,C - Figure 4.1). Only one of 13 major roots was found to penetrate the orange pyritic layer in the sub-soil. All roots showed an inclination to divide and travel horizontally. All roots in the top 37 cm also had short branches with a high density of root hairs.

Depth (cm)	% Roots
0 - 10	0
10 - 50	90
50 - 60	10

Lateral distribution: Approximately 80% of the roots were within a 60 cm radius of the trunk and almost all remaining roots were within 2 metres. A maximum lateral spread (root A) of 5 metres was observed.

Root biomass was estimated at 5% of the tree total.

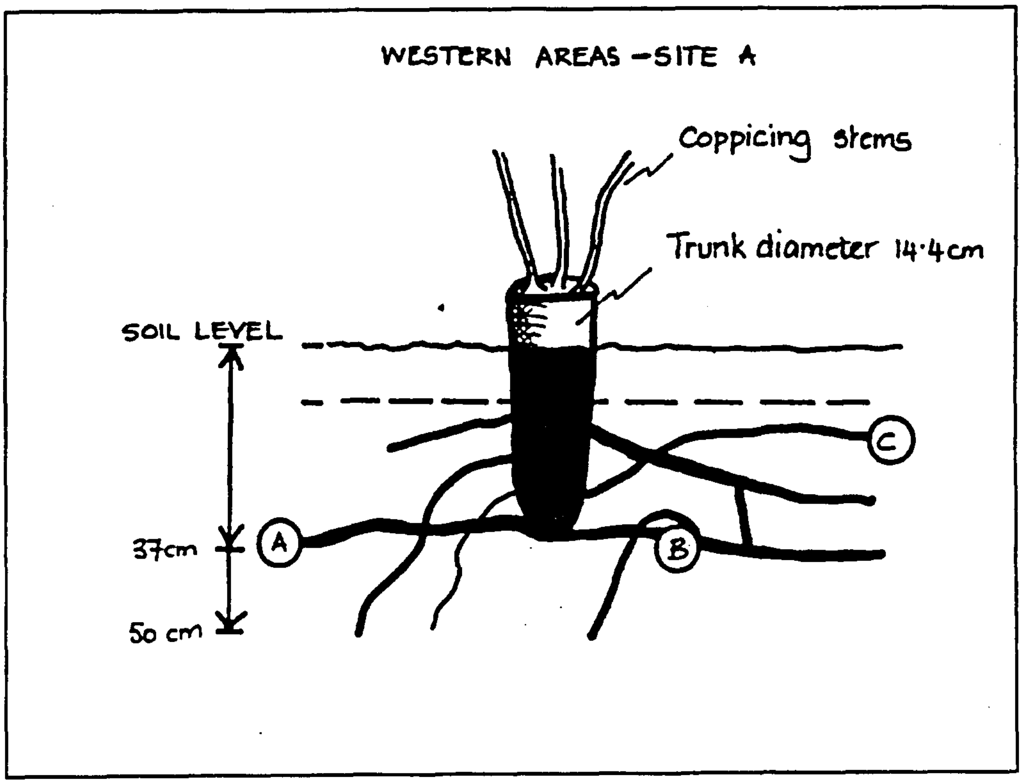

Figure 4.1: Root structure of *E. camaldulensis* (Site A) growing on the top perimeter of the Western Areas slimes dam. Maximum rooting depth - 60 cm.

Site B (Figure 4.2)

E. camaldulensis, age ± 5 years, stem diameter 11.2 cm, tree felled but coppicing.

A trench was dug across the front of the tree to a depth of 120 cm.

Vertical Distribution: A maximum depth of 75 to 80 cm was observed. Roots came into contact with the orange pyritic layer at this depth. The roots develop a feathery, fan-like appearance in this layer. No roots were observed in the grey sub-soil below this layer.

Depth (cm)	% Roots
0 - 10	0
10 - 80	100

Grass rooting depth at this site was 40 cm.

Lateral distribution: Approximately 80 % of the roots were within 50 cm radius of the tree. The lateral spread of root B (Fig 4.2) was 5 metres, at a depth of 20 cm below the soil surface. Most roots were limited in lateral spread to 2 metres. Root distribution at this site may be influenced by the irrigation applied to the grass on the slopes of the slimes.

Root biomass was estimated at 5% of tree total.

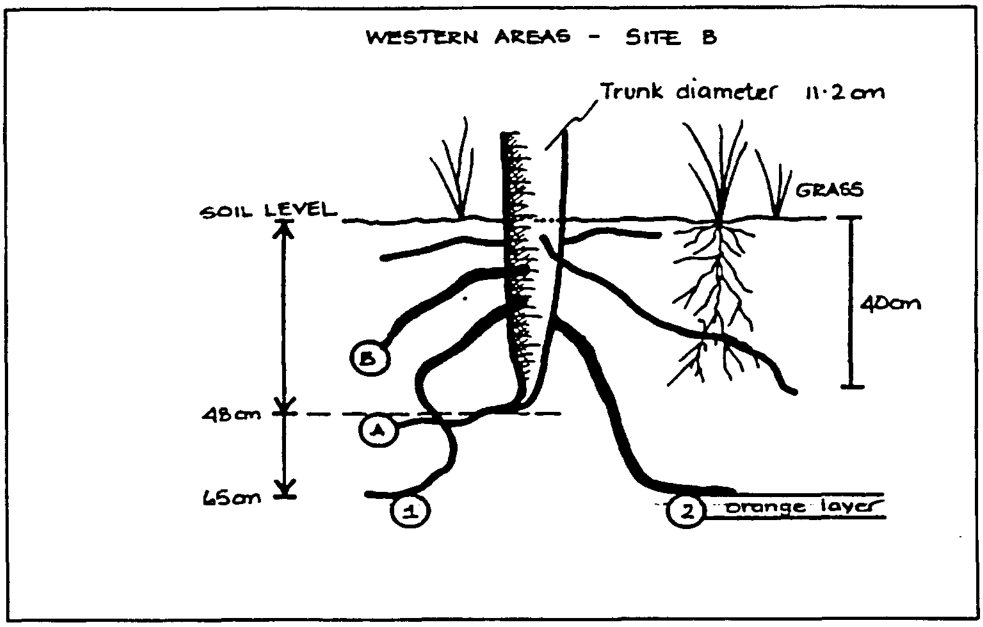

Figure 4.2: Root structure of *E. camaldulensis* (Site B) growing on the perimeter of Western Areas. Maximum rooting depth 80 cm.

4.4.2 Withok

- **Grasses**

The grasses studied were situated on Katspruit form 1000, orthic A on a gleyed horizon in the seepage area below the slimes dam. An excavator was used to dig a trench to 1.5 m. The whole soil profile was moist and once the trench was dug it immediately started filling up with water. Seventy per cent of the roots were concentrated in the A horizon (0-28 cm), twenty five per cent from 28 to 82 cm, and five per cent from 82 to 150 cm. This was the deepest rooting observed on any of the grass sites studied, and roots appeared to belong to the 'weed' species.

- **Trees**

E. viminalis. Height 12.6 m, diameter 24.0 cm. Excavation depth 11.7 m. Refer to Figure 4.3.

The trees were planted on a Swartland form - Sw 1211, orthic A (3-30 cm) on pedocutanic (30-63 cm) B on saprolite (63-90 with small rocks and 90-170 cm with large rocks). Only one tree was excavated.

Vertical distribution: The maximum rooting depth of 1.7 m was limited by a bouldery saprolitic layer. 80% of the roots were found between 0-63 cm, above the saprolite, but with very few roots in the upper 20 cm. 20% of roots grew into the saprolite but roots were thin (1 mm). The tap root was strong up to 60 cm, after which it split weakly into the saprolite. These roots sub-divided again and continued to penetrate more and more weakly to about 1.7 metres.

Depth (cm)	% Roots
0 - 20	8
20 - 63	70
63 - 90	20
90 -170	2

Lateral distribution: There were three major lateral roots (A,B and C in Fig 4.3) in the first 30 cm. Each had a diameter of 15 cm . There were many smaller cylindrical roots (subroots) in this region. Some 60% of all roots were growing laterally, and 40% vertically (Figure 4.3). Root hairs were present on all lateral and branch root structures. Roots were followed for 10-12 metres. At 7 metres, the roots still had a diameter of 10-15 mm at depths of 20-40 cm.

Estimated root biomass was 15-20 % of tree total.

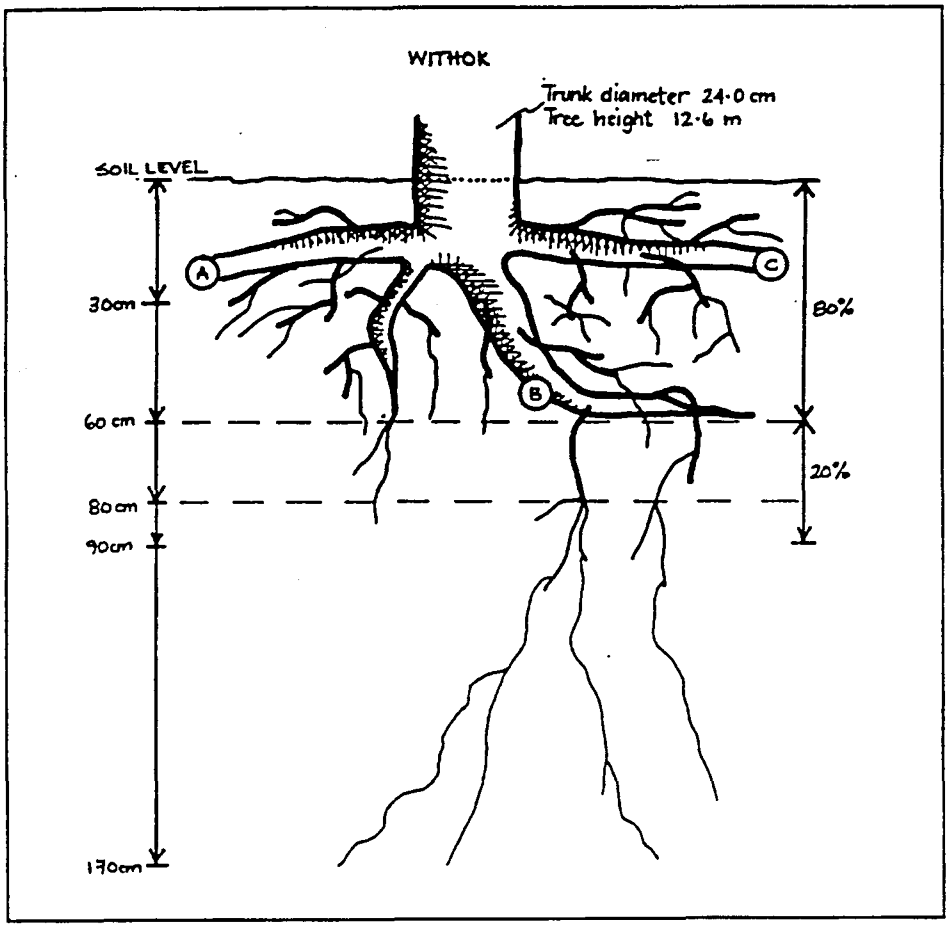

Figure 4.3: The root structure for *E. viminalis* growing in old agricultural lands adjacent to the Withok slimes dam.

4.4.3 Hendrina

- **Grasses**

The grasses *Eragrostis curvula, Cynodon dactylon, Digiteria eriantha*, and *Chlorus gayhana,* for which rates of water use were measured (Chapter 5), were growing on a Katspruit/Rensburg soil form (black waterlogged) with the soil replaced over open cast spoil. The soil depth varied between 25 and 40 cm over this black coal spoil. Roots only penetrated the coal spoil where it was weathered and soft. From a trench dug to 80 cm, grasses were observed to root as follows:

Depth (cm)	% Roots
0 - 20	60
20 - 40	25
40 - 60	13
60 - 80	2

- **Trees**

The trees (*E. macarthurii)* were planted on brown soils consisting of shale and weathered sandstone on top of mudstone and black coal spoil. An L-shaped trench was dug to a depth of 1.2 m around three trees, two of which were excavated.

Tree 1 (Figure 4.4)

Vertical root distribution:

Depth (cm)	% Roots
0 - 10	10
10 - 50	70
50 -100	20

Roots were found at 1 m, just above the coal spoil. There was very little penetration into the softer parts of this spoil. The maximum rooting depth is clearly limited by the depth of the coal spoil. At this level all roots were turned horizontal.

Lateral spread: Roots were observed to spread laterally to at least 4 m from the trunk.

Estimated root biomass was 10 % of tree total.

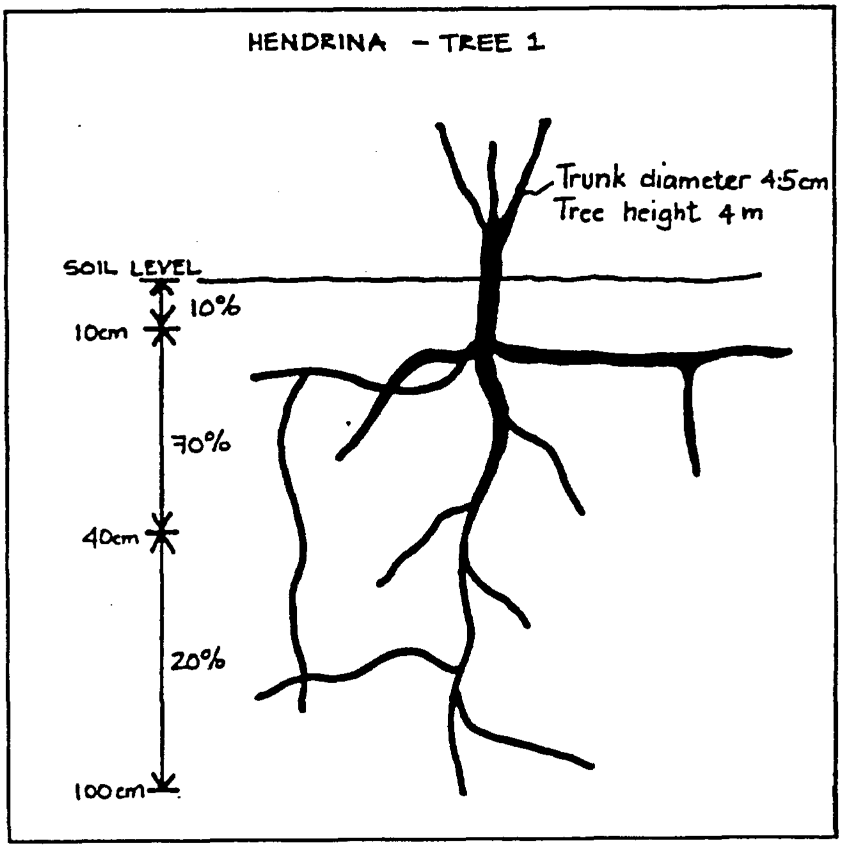

Figure 4.4: The roots of *E. macarthurii* (tree 1) growing on a rehabilitated open cast coal mine (Optimum Collieries, Hendrina).

Tree 2 (Figure 4.5)

Vertical root distribution:

Depth (cm)	**% Roots**
0 - 10	20
10 - 40	25
40 - 60	25
60 - 90	20
90 -120	10

As for tree 1 the tap root moves horizontally when it encounters the coal interface. Only very few fine roots penetrate the softer sections of the coal spoil - to a depth of 20 cm. Maximum depth is therefore to the coal interface.

Lateral spread: A spread of 4 m was observed although the majority of roots were within a 1.2 m radius of the trunk.

Estimated root biomass was 10 % of tree total.

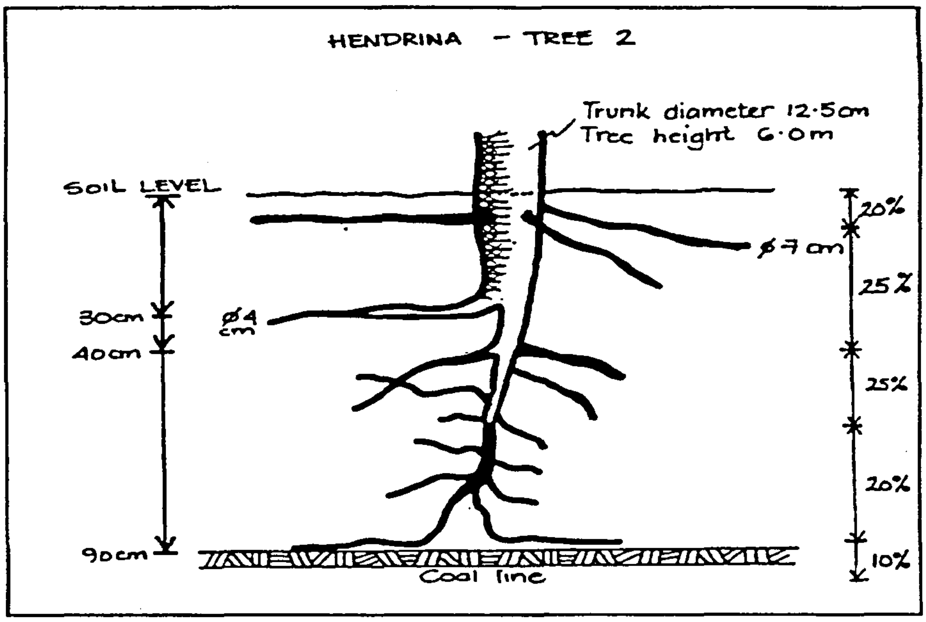

Figure 4.5: The roots of *E. macarthurii* (tree 2) growing on a rehabilitated open cast coal mine (Optimum Collieries, Hendrina).

Tree 3 (no diagram)

Roots were excavated to 1.5 m.
Tree dimensions: Diameter 13.7 cm, Height 7.5 m.

Vertical root distribution:

Depth (cm)	% Roots
0 - 40	70
40 - 80	20
80 -103	8
103-150	2

The coal spoil commenced at 103 cm. Maximum rooting depth was limited by this layer.

4.4.4 Secunda

- **Grasses**

A trench of 80 cm was dug at the site used for grass water use measurements (refer to Chapter 5). This was on a vertisol-type soil. Grass root distribution was as follows:

Depth (cm)	% Roots
0 - 30	80
30 - 60	15
60 - 80	5

Maximum rooting depth was 80 cm.

- **Trees**

Site A - E. viminalis on melanic soil (Figure 4.6)

A 3 m trench was dug to a depth of 1.2 m. The melanic soil varied in depth from 20 - 50 cm along this short length of trench. It is typical for these soils to undulate. A tree growing on the 50 cm deep soil showed excellent growth while the tree on 20 cm deep soil had barely 20% of the growth of its neighbour growing on the deeper soil. Prior to planting the soil had been ripped to 70 cm and roots were clearly seen to follow the ripline.

One tree was excavated on the melanic soil. The roots of this tree lay within a V-shaped doloritic stoneline (Figure 4.6). Soils were very stony below 10 cm.

Vertical root distribution

Depth (cm)	**% Roots**
0 - 10	1
10 - 25	70
25 - 70	25
70 -120	4

The average rooting depth on the site was estimated at 70 cm (the depth of the stone layer) with a maximum of 1.2 - 1.5 m. Two major roots were able to penetrate the stone layers. Depth of rooting was clearly controlled by the soil depth and penetrability of the rock layers.

Lateral spread was observed to 5 metres.

Estimated root biomass was 7% of tree total.

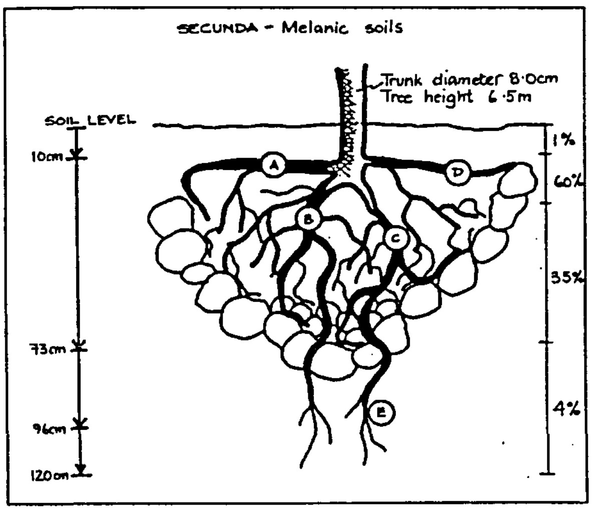

Figure 4.6: The roots of a young *E. viminalis* tree growing on a melanic soil at Secunda (Brandspruit Collieries). Variable soil depth affects rooting and survival.

Site B - E. viminalis on vertisol (Figure 4.7)

Roots were fairly evenly distributed within the profile. Roots appear to sink considerably deeper than 90 cm as a tap root of 5 cm diameter was found at this level. A maximum rooting depth is estimated at 3 m.

Vertical root distribution

Depth (cm)	**% Roots**
0 - 45	70
45 - 80	15
80 - 90	5
> 90	10 ? (not excavated)

Lateral roots were concentrated within 1.5 m of the tree but spread was found 7-8 m from the trunk.

Estimated root biomass was 10% of tree total.

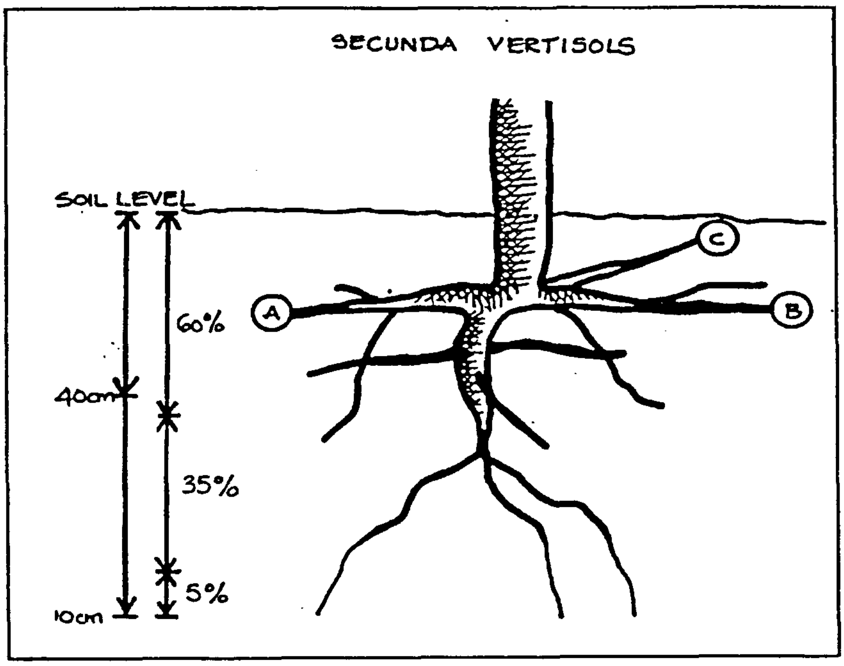

Figure 4.7: Roots of a young *E. viminalis* growing on a vertic soil at Secunda. The sinker roots do not stop at 90 cm and a possible maximum rooting depth may be 3 m.

4.5 SOIL CHARACTERISTICS

Forty six soil samples were analysed for a full range of physical and chemical characteristics. Very small amounts of exchangeable sodium and potassium were found to be present at all the sites (Table 4.2). In contrast, high concentrations of calcium and magnesium were found at all sites except at Western Areas, where the lowest concentrations of magnesium were measured. The high concentrations of these compounds in the material may be due to the mining process. The main sources of Ca and Mg in the slimes material, for example, may be due to the calcitic and dolomitic lime used in the extraction process (Beukes *et al.* 1994).

The mining process removes the vegetation and therefore leads to the loss of some plant nutrients from the site. This is particularly critical in areas where a large proportion of the nutrient pool of the ecosystem is stored in the vegetation or in the plant litter, as is the case in the Highveld. It is therefore not surprising that the nitrate and nitrite levels were particularly low, with the levels being undetectable in most cases (Table 4.3). The sulphate concentrations recorded at all sites were also extremely low (Table 4.3) compared to the levels of other highveld mining sites. Beukes *et al.* (1994), for example, measured sulphate concentrations in excess of 3950 mg/kg soil at a slimes dam close to Boksburg.

All the soils, apart from those at the Secunda and Withok sites, were found to be quite acidic (Table 4.2). Acidic soils can cause aluminium or manganese toxicity and reduce the availability of some nutrients, which in turn can limit plant growth. Acidic soils are usually corrected with lime application.

Particle size analyses revealed substantial differences among the different sites (Table 4.5). Western Areas slimes dam showed a high percentage of very fine sand or silt, with clay contents being generally quite low (3-7%). In contrast, the Withok slimes dam had a very high clay content ranging from 30 to 50%. The difference in clay contents of the two sites, and the attending differences in water conducting properties may explain why Withok is poorly vegetated while Western Areas has a healthy sward of grass and tree cover (Section 3.5).

There appear to be micro-site differences in the soil particle size distribution at the underground coal mine (Secunda) and at the open cast coal mine (Hendrina). These micro-site differences were also reflected in the Exchangeable Acidity values (Table 4.2) and Sodium Adsorption Ratios (Table 4.4). Sodium Adsorption Ratio is a useful parameter for detecting low water holding capacity, and for estimating the degree of sodic hazard. A SAR saturation percentage of 25% is considered a good indicator for low water holding capacity, while saturation percentages ranging from 80% to 90% indicate a sodic hazard which can result in swelling (Hossner & Hons 1992). The soils of most of the Highveld sites had intermediate SAR percentages which suggests that there will be some degree of water throughflow. Sodic hazard was only evident at a few sites.

Table 4.2: Soil Exchangeable Acidity at the study sites

	Ca	Mg	Na	K	pH	pH	P	Exch. Acidity
	m. moles charge / kg soil				(KCl)	(H_2O)	mg / kg	m.moles / kg
Withok grasses	98	77.40	1.60	0.70	5.05	6.36	1.35	0.30
Withok grasses	131	148.30	11.80	0.40	6.32	7.04	0.00	0.20
Withok grasses	187.30	163.70	5.00	0.60	6.73	7.74	0.00	0.10
Withok trees	74.50	29.70	0.60	5.10	6.30	7.55	0.75	0.10
Withok trees	140	43.90	0.80	8.60	6.38	7.37	0.00	0.10
Withok trees	147.60	111.90	4.30	5.20	6.14	6.82	0.00	0.10
Withok trees	-	-	-	-	-	-	0.00	-
Secunda grasses	166.90	115.80	0.80	1.60	6.21	7.78	0.00	0.20
Secunda grasses	138.60	242.50	11.30	0.50	5.62	7.28	0.00	0.20
Secunda grasses	139.40	114.20	11.20	0.70	7.23	8.90	0.00	0.00
Secunda trees	98.90	70.90	2.10	0.90	4.30	5.67	3.20	1.50
Western Areas grasses	205.50	2.10	0.20	0.40	4.05	4.02	0.00	4.30
Western Areas grasses	110	1.40	0.30	0.30	4.36	4.19	0.00	0.60
Western Areas grasses	200	1.90	0.20	0.40	4.10	4.11	0.00	1.60
Western Areas grasses	188.10	0.60	0.00	0.10	3.94	3.81	0.00	1.40
Western Areas grasses	201.90	2.10	0.30	1.00	3.96	3.93	0.00	5.90
Western Areas grasses	207.40	3.00	0.40	2.20	3.39	3.42	0.00	5.20
Western Areas grasses	173.60	2.60	0.20	3.30	3.70	3.82	0.00	3.90
Western Areas grasses	99.60	1.40	0.10	4.30	3.74	3.92	0.00	1.80
Western Areas trees	193.10	1.10	0.70	2.60	4.07	4.09	0.00	0.90
Western Areas trees	217.30	3.50	1.20	0.80	3.96	4.03	0.00	1.20
Western Areas trees	69	1.90	0.20	0.30	6.10	6.10	0.00	0.10
Western Areas trees	515.60	4.50	1.70	0.10	3.99	3.99	0.00	1.60
Western Areas trees	103	1.10	0.30	0.10	3.68	3.69	0.00	2.30
Western Areas trees	102.30	5.20	1.90	0.30	3.80	3.84	0.00	2.00
Western Areas trees	105.40	2.90	1.30	0.20	4.04	4.17	0.00	1.50
Western Areas trees	97.80	3.50	1.30	0.10	3.97	4.11	0.00	1.80
Hendrina trees	191.80	22.30	0.00	0.10	2.63	2.63	0.00	0.95
Hendrina trees	219	8.60	1.60	0.10	3.37	3.42	0.00	6.30
Hendrina trees	23.40	33.10	0.60	1.60	4.72	5.55	0.04	0.40
Hendrina trees	20.30	28.90	0.90	6.60	4.90	5.76	0.00	0.50
Hendrina trees	41.90	72.60	0.80	0.60	6.25	6.65	0.00	0.10

Table 4.3: Anions in Soil Extracts at Selected Study Sites

		Results in mg\kg soil			
	HORIZONS	Cl	NO_2	NO_3	SO_4
Withok grasses	A	10.343	0.066	0.101	4.827
Withok grasses	B	8953.807	0	0	30.397
Withok grasses	C	10119.93	0	34.827	14.903
Withok trees	A	12.541	0	0.369	3.264
Withok trees	B	11420.25	0	0	0
Withok trees	C	8935.186	2.039	0	17.001
Secunda grass	A	5996.469	0	0	0
Secunda grass	B	13020.36	0	0	0
Secunda grass	C	7040.798	0	0	0
Secunda trees	A	15.185	7.868	0	8.339
Western Areas grasses	0-10cm	4291.431	0	0	119.87
Western Areas grasses	0-10cm	15.022	0	0	51.822
Western Areas grasses	0-10cm	6033.129	0	0	203.859
Western Areas grasses	10-50cm	2324.935	0	0	70.605
Western Areas grasses	10-50cm	6114.548	0	0	194.456
Western Areas grasses	10-50cm	7274.988	0	2.572	217.383
Western Areas grasses	>50cm	4965.137	0	0	108.536
Western Areas grasses	>50cm	44.695	0	0.608	209.472
Western Areas trees	0-10cm	4288.295	0	0	119.047
Western Areas trees	0-10cm	4177.057	0	0	124.938
Western Areas trees	0-10cm	297.539	0	0	369.916
Western Areas trees	10-50cm	5052.773	0	0	76.482
Western Areas trees	10-50cm	21.077	0	0	46.528
Western Areas trees	10-50cm	29.571	0	0	83.767
Western Areas trees	>50cm	20.195	0	0.468	59.975
Western Areas trees	>50cm	28.599	0	0.190	55.778
Western Areas trees	Brown layer @ 50cm	5429.98	0	0	206.904
Western Areas trees	Orange layer @ 50cm	4515.4	0	0	153.913
Hendrina trees	A	10.398	5.211	0.783	19.739
Hendrina trees	B	5.663	0	0.724	4.086
Hendrina trees	C	12.839	0	1.045	122.467

Table 4.4: Soil Sodium Adsorption Ratio (SAR) for the study sites

	K	Ca	Mg	Na	EC	SAR	Sat %
		m. eq / litre			micro S/cm		
Withok grasses	0.01	1.43	0.68	0.80	313	0.78	61.83
Withok grasses	0.02	6.80	3.58	7.61	1400	3.34	94.70
Withok grasses	0.31	5.33	2.25	2.87	9016	1.47	85.81
Withok trees	1.46	1.15	0.25	0.18	295	0.22	47.38
Withok trees	1.06	1.58	0.33	0.39	276	0.40	99.30
Withok trees	1.88	11.65	5.43	2.52	2050	0.86	77.78
Secunda grasses	0.21	2.10	1.12	0.67	395	0.53	48.95
Secunda grasses	0.04	1.60	0.86	1.91	237	1.72	114.11
Secunda grasses	0.01	1.23	2.34	5.43	464	4.06	60.76
Secunda trees	0.34	1.75	2.59	1.91	471	1.30	62.90
Western Areas grasses	0.34	15.15	4.40	0.67	1620	0.21	36.66
Western Areas grasses	0.12	13.80	1.44	0.37	1560	0.13	39.13
Western Areas grasses	0.29	14.58	3.13	0.65	1520	0.22	48.92
Western Areas grasses	0.07	15.65	1.56	0.46	1560	0.16	21.96
Western Areas grasses	0.16	15.43	4.28	0.76	1520	0.24	52.48
Western Areas grasses	0.18	15.78	5.10	0.78	1680	0.24	57.59
Western Areas grasses	0.18	14.50	7.77	1.02	1590	0.31	35.94
Western Areas grasses	0.06	16.23	3.25	0.63	1560	0.20	32.92
Western Areas trees	0.33	15.23	2.67	1.80	1620	0.60	33.50
Western Areas trees	0.09	14.30	10.36	6.52	1880	1.86	32.78
Western Areas trees	0.34	14.55	2.51	0.93	1440	0.32	49.36
Western Areas trees	0.50	14.90	6.74	4.57	1780	1.39	39.08
Western Areas trees	0.13	15.65	2.75	1.15	1660	0.38	34.83
Western Areas trees	0.16	16.15	15.13	5.00	2230	1.26	36.81
Western Areas trees	0.12	14.75	8.51	2.61	1950	0.77	34.30
Westren Areas trees	0.16	15.20	10.28	4.34	2020	1.22	33.04
Hendrina trees	0.06	4.03	31.3	0.41	5430	0.10	43.14
Hendrina trees	0.10	13.08	20.11	0.20	2350	0.50	41.02
Hendrina trees	3.07	1.50	20.6	0.57	4852	0.43	82.23
Hendrina trees	0.17	0.98	1.19	0.78	200	0.75	60.41
Hendrina trees	0.87	12.33	32.94	1.13	2650	0.24	47.96

Table 4.5: Soil Particle size analysis (%) for the study sites

	Sand (C)	Sand (M)	Sand (F)	Silt	Clay	Total
Withok grasses	6.35	9.99	22.03	24.47	37.18	100.02
Withok grasses	5.99	9.30	16.64	17.35	50.33	99.61
Withok grasses	7.05	8.52	17.87	19.39	47.25	100.08
Withok trees	7.76	10.51	26.00	19.96	35.89	100.12
Withok trees	2.80	3.11	15.77	29.82	47.99	99.49
Withok trees	18.37	7.05	20.99	23.80	30.52	100.73
Withok trees	-	-	-	-	-	-
Secunda grasses	35.53	14.46	20.09	15.94	14.30	100.32
Secunda grasses	4.04	4.45	15.52	27.10	48.55	99.66
Secunda grasses	41.74	8.68	15.90	13.55	20.74	100.61
Secunda trees	8.10	9.57	35.26	19.24	26.85	99.02
Western Areas grasses	0.00	0.00	46.25	50.62	2.95	99.82
Western Areas grasses	0.00	0.00	75.81	20.50	4.00	100.31
Western Areas grasses	0.00	0.00	28.77	69.49	2.68	100.94
Western Areas grasses	0.00	0.00	78.07	18.95	2.67	99.69
Western Areas grasses	0.00	0.00	27.82	65.05	7.10	99.97
Western Areas grasses	0.00	0.00	12.63	82.49	4.31	99.43
Western Areas grasses	0.00	0.00	55.41	36.24	7.73	99.38
Western Areas grasses	0.00	0.00	77.05	18.88	3.72	99.65
Western Areas trees	0.00	0.00	73.29	21.13	5.88	100.30
Western Areas trees	0.00	0.00	63.77	28.54	6.93	99.24
Western Areas trees	0.00	0.00	73.77	20.18	5.57	99.52
Western Areas trees	0.00	0.00	66.12	29.95	3.48	99.55
Western Areas trees	0.00	0.00	82.27	13.31	3.99	99.57
Western Areas trees	0.00	0.00	85.51	11.19	3.20	99.90
Western Areas trees	0.00	1.13	80.75	14.36	4.26	100.50
Westren Areas trees	0.00	1.71	81.14	11.97	4.89	99.71
Hendrina trees	0.00	0.00	40.06	56.78	2.68	99.52
Hendrina trees	0.00	0.00	47.04	51.25	1.88	100.17
Hendrina trees	0.00	3.66	17.61	27.66	43.79	99.61
Hendrina trees	0.00	6.10	24.78	14.17	32.22	99.49
Hendrina trees	0.00	6.02	27.86	31.40	15.00	100.25

4.6 CONCLUSIONS

Plant available water is generally less on mined soils due to increases in bulk density, and decreased porosity, permeability and infiltration rates. The textural layering of slimes material, in particular, may cause large variations in water retentivity with depth. This material is also known to have lower water retention abilities compared to undisturbed soil with the same texture (Beukes *et al.* 1994). Observations indicate that this is probably not so for open cast coal mines (Hendrina), at least for the deeper horizons, which comprise fine fractured rock after rehabilitation, offering no barrier to either water infiltration, or root penetration.

Grass roots generally extended to a depth of 36 cm, and rarely grow deeper than 30 cm. In one exceptional case (Withok) some 5% of the grass roots were found between 82 cm and 150 cm. Tree roots generally penetrated to depths of 60 cm to 170 cm, depending on the age of the trees, species and the soil type. Root depth of the trees, while remarkably shallow compared to that of trees within the commercial forestry zone (Dye and Poulter, 1992; Lesch and Scott, 1993; Midgley *et al.*, 1994), exhibit the potential to utilise the soil profile to a far greater depth than the different types of grasslands.

The soils were found to be generally acidic. In a number of cases exceptionally high concentrations of cations were recorded which is probably due to the processes used in mining. The concentrations of plant available nutrients, particularly nitrogen levels, were found to be very low. All of these characteristics, in addition to the poor water retentivity features, may have significant negative effects on the re-establishment of vegetation on mines. Extensive soil rehabilitation programmes may therefore be necessary before mining sites can be revegetated. Our observations of rooting depths suggest that trees are able to draw upon a greater soil volume for moisture, and to draw more effectively from the water table, than grasses. The use of the appropriate tree species can therefore play a central role in any programme aimed at ameliorating the impacts of mining on water quality.

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CHAPTER 5

WATER USE BY TREES AND GRASSES ON HIGHVELD MINING SITES

5.1 INTRODUCTION

Comparative water use data for trees and grasslands are presented in this chapter. We focus on the differences in water use patterns of both trees and grass for a diversity of mining environments and on the variation in water use during different seasons. The rates of water use by different tree species are compared to evaluate their efficiency at minimizing throughflow of water to the sub-surface and groundwater. We start by reporting on a short-term pilot study which involved measurement of tree water uptake and grass evaporation at two Johannesburg slimes dams. Since this study was undertaken over a very short period (over two days), and because additional plant water relations data (eg. xylem pressure potentials) have been recorded in this study, these findings are discussed separately in section 5.2. The findings presented in the subsequent sections involved longer monitoring intervals and the focus in these sections is on variation in daily total water use at different sites and during different seasons. In section 5.5 we test whether the Penman-Monteith equations can be used to model grassland evaporation.

Water availability to plants is mostly dependent on the nature (intensity) and distribution of rainfall. The rainfall patterns for the five study sites are shown in Fig 5.1.1 and Table 5.1.1. The nature of the soils in which plants grow (water holding capacity and hydraulic conductivity) also determines water availability (refer to Chapter 4). However, soil surface and sub-surface water dynamics, which similarly have profound effects on water availability, have not been examined in this study. Plant use of available water is, in turn, determined by the plant species, the physical environment, climatic conditions (seasons) as well as the extent and nature of biomass cover.

5.1.1 Units of Water Use

Daily water use of single trees (in litres) was converted to mm, the unit for surface evaporation, to facilitate comparisons of water use between grasses and trees. The conversion was achieved by dividing the daily water use per tree (l day^{-1}) by the projected ground area perceived to be occupied by the tree. This was taken to be the dimensional area formed by the spacing distances between tree stems. The trees sampled at Durban Deep and Western Areas, however, were not from stands of trees established at regular spacing intervals. At these sites a closed canopy condition was assumed and the projected ground area for each tree was taken to be the drip area below the tree canopy. This assumes a closed canopy condition, failing which the computation could lead to an overestimation of water use by trees sampled at these two sites.

There was a fairly large variation in the dimensions of trees monitored at the different sites over the sampling periods. To facilitate comparisons among species at the different sites, the data was transformed from water use in mm per m^{-2} ground area occupied per tree, to sap flow per unit leaf area (l m^{-2}). This was achieved by dividing the water use (in mm) by the leaf area index (canopy area m^2 / projected ground area m^2).

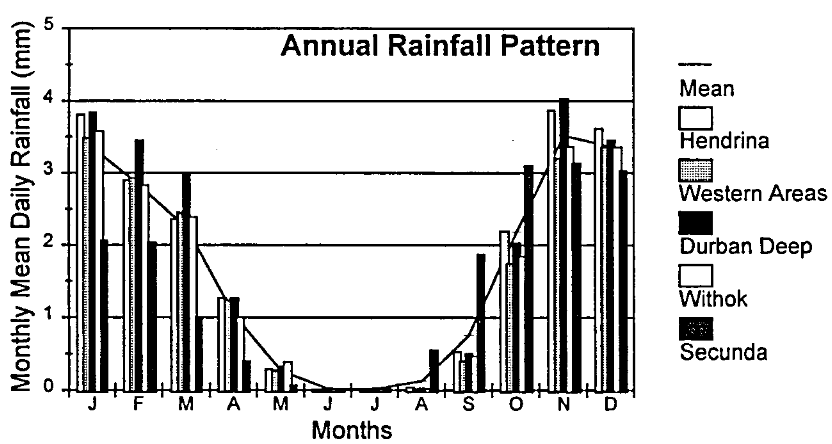


Figure 5.1.1 Annual rainfall pattern for Highveld mining sites. Monthly mean daily rainfall (mm) was determined by dividing the 50 year monthly means (Table 5.1.1) by the number of days in the month. This facilitates comparison with the measured water use by grass and trees (mm per day). No rainfall data is available for the West Extension site.

Table 5.1.1: Annual 50 year mean monthly rainfall for the study sites.

SITE	J	F	M	A	M	J	J	A	S	O	N	D
Western Area	108	85	76	37	8.4	0.3	1.0	0.5	12	54	96	104
Durban Deep	119	100	93	38	10	0.8	0	0.8	15	63	121	107
Withok	111	82	74	30	12	0.4	0	0.6	14	57	101	104
Hendrina	118	84	73	38	8.9	0.2	0.3	1.2	15.9	68	116	112
Secunda	100	64	59	31	12	2.1	0.5	1.4	17	56	96	94

5.2 INTENSIVE PILOT STUDY

The pilot study involved the measurement of evaporation from a grass vegetated slimes dam (Western Areas), which was compared with (i) transpiration rates of *Eucalyptus sideroxylon* trees growing adjacent to the Western Areas slimes dam and with (ii) transpiration rates of *Acacia baileyana* and *Acacia melanoxylon* trees growing on the Robinson Deep slimes dam. The period of measurement was 1 - 5 March 1992. Xylem pressure potentials of trees were recorded as a measure of internal plant water status. The findings from the pilot study are presented separately given that it was a short-term and intensive study and included measurements of xylem pressure potential.

5.2.1 Methodology

The techniques used for measuring evaporation from grasslands (Bowen ratio) and sap flows through trees (heat pulse velocity technique) have been described in detail in Chapter 3.

Bowen ratio: Instrument configuration for Bowen ratio measurements in the intensive pilot study was standard. The instrument was able to run uninterrupted for the full duration of the study. Measurements were on the grass cover at Western Areas slimes dam.

Sap flow: Adaptations to the conventional sap flow technique (described in Chapter 3) were required for security considerations and because of a shortage of instruments. Security considerations precluded the conventional use of the Heat Pulse Velocity apparatus where the instrumentation may be left to sample sap flow rates from selected trees for continuous periods. It was necessary to set up all instrumentation prior to each day of field measurement, and to remove the data loggers on completion of each day's sampling. One day was required to set up instrumentation at each site prior to sampling. Only four heat pulse velocity probes were attached to each of eight trees following the procedure described in Olbrich (1991). A limited number (four) of heat pulse loggers were available for use in this study. One logger was used to continuously monitor sap flow rates from one of the eight trees while the other three loggers were used to take readings from the remaining seven trees on a rotational basis throughout the day. These data were used to calculate the cumulative water use of all eight sample trees on each site for the sample day.

Tree Water Relations: Measurement of internal plant water status (or water stress) provides valuable information for the interpretation of daily transpiration estimates. The degree of water stress experienced by trees (due to soil water deficits) may be estimated by measuring pre-dawn xylem pressure potential with a Scholander pressure chamber (Scholander *et al.* 1965). Xylem pressure potential (XPP) is a measure of the tension of water within the xylem and leaf tissue of a plant. Such tensions develop in the sap of normally-transpiring trees as a consequence of transpiration from the leaves. Previous experience with *Eucalyptus* trees has shown that pre-dawn XPP of unstressed trees commonly varies between 0.1 and 0.6 MPa, and that readings above 1.0 MPa signify water stress.

XPP readings are ideally undertaken pre-dawn, prior to increases in temperature and solar irradiance at the start of the day when stomata are open and plants start to transpire. A variation of the standard procedure was required as it was not practical to undertake pre-dawn readings at these sites. Selected shoots from each of the sample trees were sealed in a plastic bag (to prevent loss of water) and covered with aluminium foil on the evening prior to sampling. The following morning these shoots were cut from the tree, the foil removed, and the shoots immediately taken to the pressure chamber for measurement. The last leaf was cut at approximately 08h30.

Leaf area measurement and tree physical data collection: Canopy projected area and total canopy leaf area of each of the sample trees were determined so that transpiration, or sap flux, can be expressed per unit leaf area. The canopy projected area was measured at eight radii from the stem of the tree to the outer edge of the projected canopy. The leaf area was estimated by stripping and weighing all the leaves of canopy sub-samples. Measurement of leaf areas was more labourious than initially anticipated. It proved difficult to remove both the eucalypt and blackwood leaves, which adhered tightly to the shoots. Moreover, *Acacia baileyana* trees were in flower, and it was difficult to separate leaflets from flowers and the pinnae from their rachae. It is likely that the leaf areas of the *A. baileyana* trees were over-estimated because of the inevitable inclusion of flowers with the leaflets. Sub-samples of fresh leaves taken from each of the three study species were taken to the laboratory to determine the relationship between leaf area and fresh leaf mass.

Data processing: This followed the procedure outlined in Olbrich (1991). Cumulative daily totals were derived from measured instantaneous sap flow estimates. The area under the curve was calculated to provide a measure of instantaneous sap flow rate through the course of the day. It was assumed that transpiration was negligible before 06h00 and after 19h00.

5.2.2 Results

5.2.2.1 Grassland Evaporation

The study period was characterised by clear sunny skies as indicated by the high midday net irradiance levels (Figure 5.2.1). The marked decrease in net irradiance at midday on day of year (DOY) 62 was caused by a severe dust storm on the Western Areas slimes dam. This dust storm was caused by high velocity winds which exceeded 6 m s^{-1}. Bowen ratio estimates of evaporation were generally low, seldom exceeding 0.04 mm in any 20 minute interval (Fig. 5.2.1). On a daily basis the evaporation rates were 1.03, 0.92, 0.92 and 1.00 mm on DOY 62 to 65 respectively. The average daily evaporation rate for the study period is 0.97 mm per day. The consistency of the daily evaporation values, even for this relatively short study period, suggests that we have obtained a fairly representative seasonal evaporation value.

An independent measure of evaporation was obtained using equilibrium evaporation rates calculated from data collected at a nearby weather station. A comparison of the evaporation values using the Bowen ratio technique and equilibrium evaporation is illustrated in Figure 5.2.2. This graph shows that the calculated equilibrium evaporation rate over-estimates actual evaporation rate by approximately 75%. The basis for this discrepancy is discussed in greater detail in section 5.6. Leaf Area Index (LAI) varied from 0.28 to 5.11. This large variation in LAI and biomass is indicative of the patchiness of the vegetation. The mean proportion of living material was low (18.8%), indicating that the grass was already in an advanced stage of senescence and that the lack of fire resulted in the accumulation of dead material. If these grasslands were burnt or mown more regularly to maintain vigour, then elevated transpiration rates could be expected.

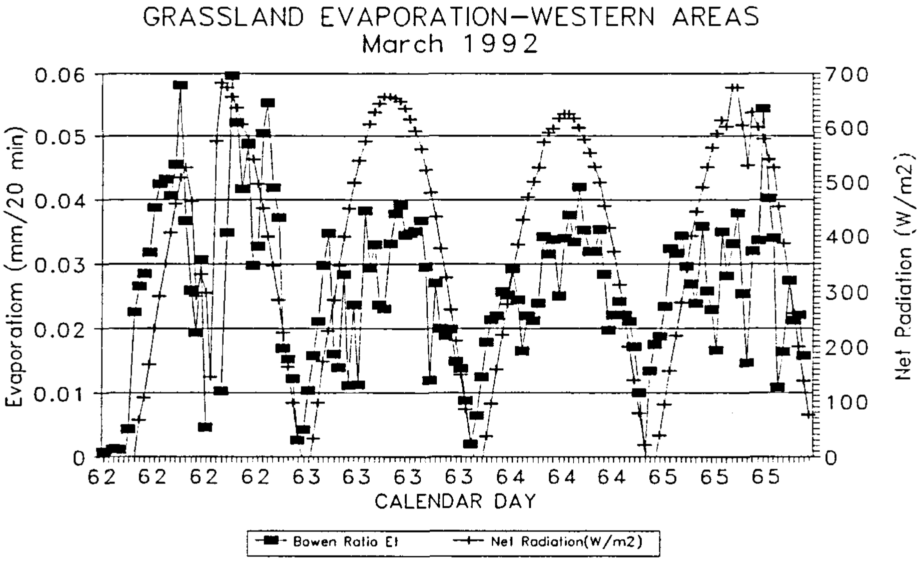


Figure 5.2.1: The diurnal trends in grassland evaporation (mm) and net radiation (Wm^{-2}) at Western Areas for DOY 62 to 65.

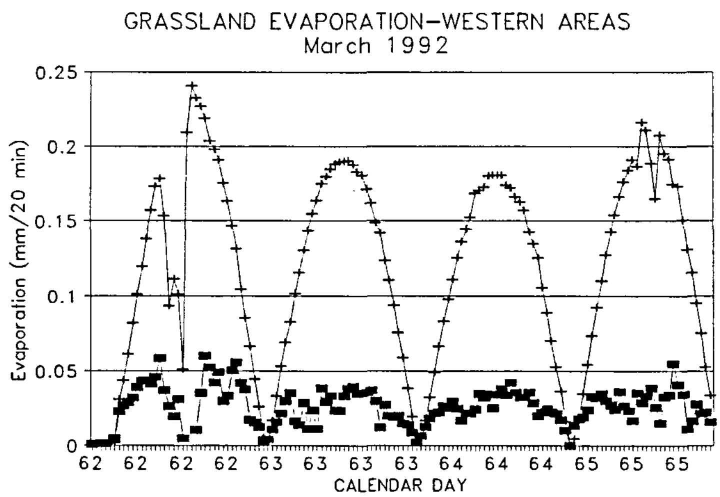


Figure 5.2.2: A comparison of Bowen Ratio and Equilibrium Rates of Evaporation from the Western Areas slimes dam from DOY 62 to 65.

5.2.2.2 Water use by trees

Tree water relations measurements were undertaken on *Eucalyptus* and *Acacia* trees growing around the slimes dam at Western Areas and at Robinson Deep respectively. Eight individuals of *Eucalyptus sideroxylon* were selected from the trees planted around the slimes dam. These were selected from three size classes ranging from 'small' to 'large' trees. The trees sampled around the slimes dam at Western Areas ranged from 6.5 m to 13.6 m in height and had leaf areas of up to 68 m^2 with a mean canopy spread of 7.1 m^2 (Table 5.2.1). Trees on Robinson Deep have established primarily on ridges of approximately 1 m high. These ridges were presumably built to compartmentalise the slimes during the final phase of construction. But trees were also found on the flat-bottomed pans at Robinson Deep, either in clumps or lone-standing. Sample trees were selected from each of these situations. The dominant tree species on these pans were *Acacia baileyana* and *Acacia melanoxylon* (blackwood). Four individuals of each species were selected, one growing in each of the following situations: a large tree on the ridge, a small tree on the ridge, a lone-standing tree in a pan, and a tree within a clump growing in a pan.

Pre-dawn xylem pressure potentials were generally low (mean = -2.76 MPa) indicating considerable water stress (Table 5.2.1). Given the degree of water stress experienced, one would have expected these trees to have extremely low transpiration rates. However, relatively high transpiration rates were recorded (Figures 5.2.3 & 5.2.4) while low xylem pressure potentials were maintained. For example, a *Eucalyptus sideroxylon* tree (number 3) had a pre-dawn XPP of -4.05 MPa (Table 5.2.1), yet its daily course of transpiration (Fig. 5.2.3) did not show any signs of water limitation. Transpiration rate increased steadily through the course of the morning and peaked at approximately 13h00. In cases where water is limiting, the peak transpiration rate is usually achieved early in the morning, followed by a mid-day depression in transpiration, and sometimes a partial recovery during the afternoon is evident (Kramer and Kozlowski, 1979). It is probable that these low XPP values reflect high salt concentrations in the soil horizons and that the trees have modified their physiology (osmotic adjustment) in a manner typical of plants adapted to saline environments. The daily course of transpiration recorded for this *Eucalyptus* tree suggests that water was not as limiting as the XPP data would lead one to expect. Rather, the low XPP values reflect a lowering in the osmotic potential in the cells to a point where the plant can still draw water from the saline soil environment. This hypothesis remains to be tested.

Similarly low XPP's were recorded in all trees sampled on the Robinson Deep site (Table 5.2.2). This strengthens the argument regarding the high salt content of the soil. The daily course of transpiration of a *A. baileyana* tree (number 7) also showed no dramatic signs of water stress (Figure 5.2.4) despite the low (-2.6 MPa) pre-dawn XPP recorded (Table 5.2.2). The peak transpiration rate was achieved at approximately noon coinciding with the peak in the level of photosynthetically active radiation (PAR). This suggests that the quality rather than the quantity of water available to the tree roots was responsible for the low XPP values recorded for tree 7.

The cumulative daily transpiration rates recorded in the 16 sample trees can be examined in Tables 5.2.3 and 5.2.4. The weather conditions recorded on the 3rd and 4th of March were relatively similar (Fig. 5.2.3 and Fig. 5.2.4) which allows comparison across the two sites. The only noticeable difference was found in the level of radiation with the passing dust storm resulting in a decrease in PAR values at Western Areas. On both days the vapour pressure deficit (VPD) reached a peak of almost 2 KPa, although the peak was achieved slightly earlier on the 4th than it was on the 3rd of March. This suggests that the evaporative demand was higher on the day on which the transpiration measurements were undertaken at Robinson Deep.

The highest transpiration rates were generally recorded from the *Eucalyptus* trees at Western Areas, with the exception of the 56 ℓ (tree 7) recorded from the large *A. baileyana* at Robinson Deep (Tables 5.2.3 and 5.2.4). An examination of the transpiration rates per unit leaf area suggests that the compound leaves of *A. baileyana* have the highest rates, followed by blackwood and then the eucalypt. It is likely that the leaf area of *A. baileyana* was over-estimated, which implies that its transpiration per unit leaf area was under-estimated. However, the spreading growth habit of this species is of such a nature that the high water use per unit leaf area, translates into a relatively conservative transpiration rate per unit ground area. The data for transpiration per unit projected canopy area shows a completely different picture. Because the *Eucalyptus* trees have relatively dense canopies which occupy a small projected area, they also have the highest transpiration rates per unit ground area occupied, averaging 3 mm per day (Table 5.3). In contrast, the generally sparse and spreading canopies of *A. baileyana* result in only 1 mm transpiration per day per unit projected canopy area (Table 5.2.4). *A. melanoxylon* was found to have the lowest rate with 0.86 mm per day.

The water use figures in mm/day are based on projected canopy leaf area. These values therefore apply to the area occupied by the tree and will be valid if expressed cumulatively for as many trees as are established in the landscape. However, it would be incorrect to express these values as water use on a per hectare basis unless a tree in a stand is capable of achieving the same leaf area developed by single trees.

Table 5.2.1: Tree heights, leaf areas, projected canopy areas and pre-dawn xylem pressure potentials recorded on each of the selected sample trees at the Western Areas site on the 4th March 1992.

Tree	Height (m)	Leaf area (m^2)	Projected canopy area (m^2)	Pre-dawn xylem pressure potential (MPa)
1	13.57	43.5	13.4	-1.95
2	10.64	53.1	9.6	-2.90
3	9.65	31.1	4.4	-4.05
4	9.66	68.3	8.4	-3.90
5	11.31	49.7	6.4	-2.00
6	8.56	44.1	5.4	-3.05
7	6.52	22.1	3.6	-1.80
8	9.12	37.0	5.8	-2.40
Mean ± SD	9.9 ± 1.9	43.6 ± 13.3	7.1 ± 3.0	-2.76 ± 8.2

Table 5.2.2: Tree heights, leaf areas, projected canopy areas and pre-dawn xylem pressure potentials recorded on each of the selected sample trees at the Robinson Deep site on the 5th March 1992.

Species	Tree	Height (m)	Leaf area (m^2)	Projected canopy area (m^2)	Pre-dawn xylem pressure potential (MPa)
A. melanoxylon	1	5.75	5.3	6.0	-3.20
A. melanoxylon	2	5.76	3.7	2.4	-3.90
A. melanoxylon	3	3.20	2.1	2.4	-2.80
A. melanoxylon	4	8.98	1.6	14.3	-3.50
	Mean ± SD	5.9 ± 2.1	9.0 ± 9.3	6.3 ± 4.9	-3.35 ± 4.0
A. baileyana	5	6.1	7.4	10.1	-2.60
A. baileyana	6	7.06	2.7	7.9	-2.60
A. baileyana	7	7.25	41.6	29.5	-2.60
A. baileyana	8	5.47	5.9	9.3	-3.60
	Mean ± SD	6.5 ± 0.7	14.4 ± 15.8	14.2 ± 8.9	-2.85 ± 4.3

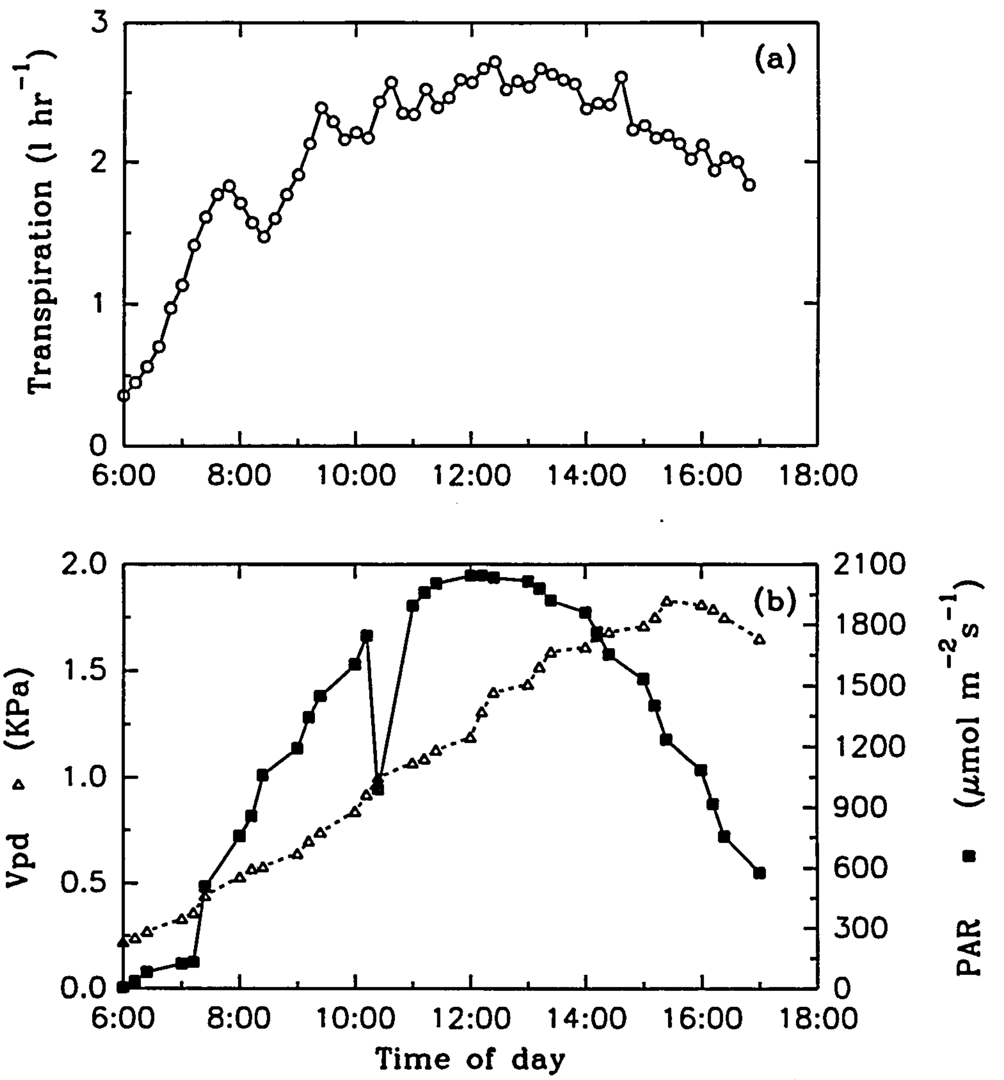


Figure 5.2.3: Transpiration rate (a) recorded on a *Eucalyptus sideroxylon* tree (tree no 3) on the 3.03.92 with the vapour pressure deficit and PAR (b) recorded by the automatic weather station on the same day at Western Areas slimes dam. A heavy dust storm blew over the site before noon resulting in the dramatic drop in PAR.

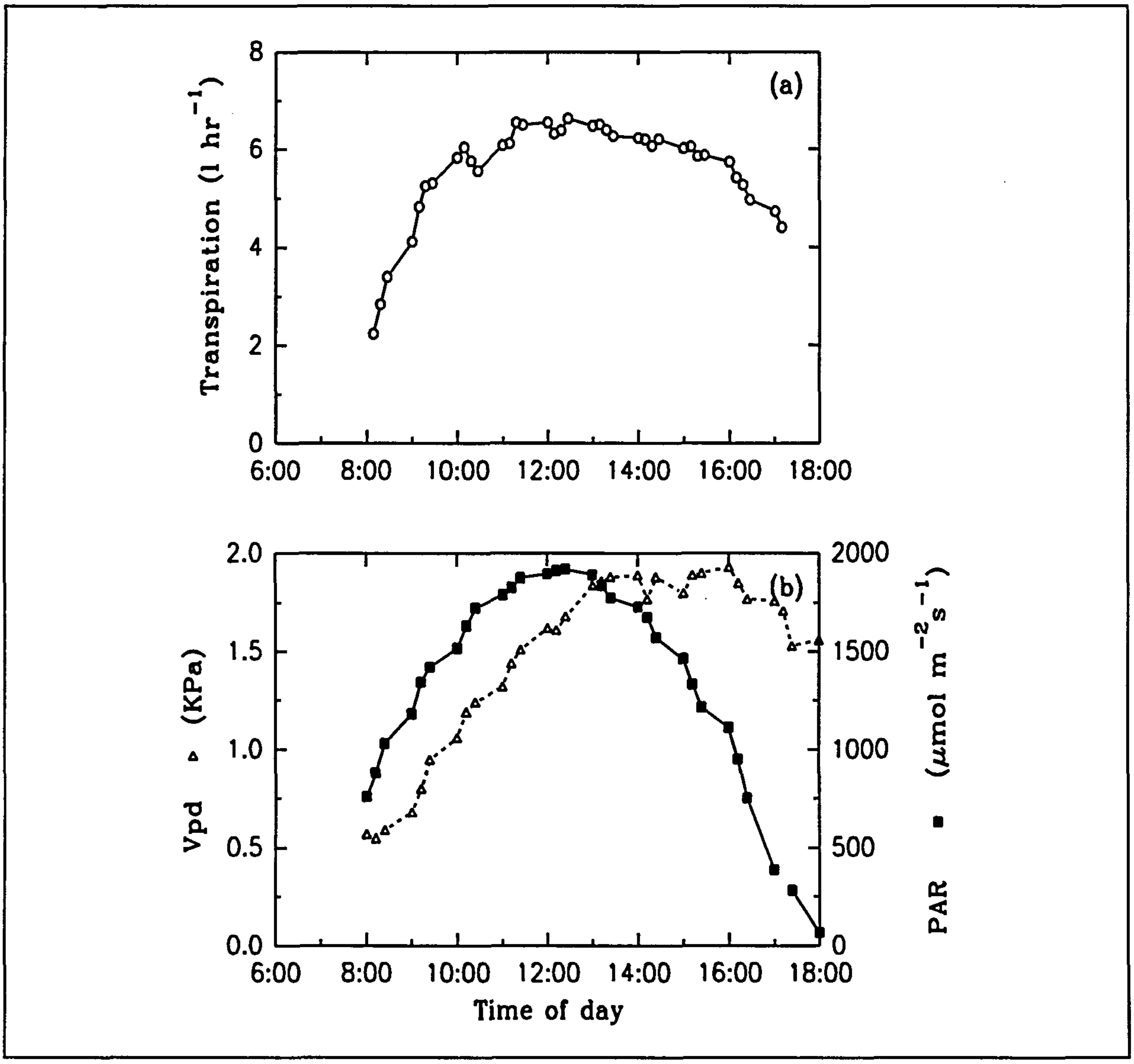


Figure 5.2.4: Transpiration rate (a) recorded on an *Acacia baileyana* tree (tree no. 7) on the 4.03.92 with the vapour pressure deficit (VPD) and photosynthetic active radiation (PAR) (b) recorded by the automatic weather station on the same day at Robinson Deep slimes dam.

Table 5.2.3: The cumulative daily transpiration recorded from the eight *E. sideroxylon* trees studied at Western Areas on the 3.03.92. The data have been expressed as: litres per tree, litres per square meter of foliage per day, and as mm of evaporation per projected canopy area. Total grassland evaporation at the site was 0.92 mm for the same day.

Tree	Transpiration		
	(l $tree^{-1}$ day^{-1})	(l m^{-2} day^{-1})	(mm day^{-1})
1	37.0	0.85	2.75
2	43.0	0.81	4.47
3	10.7	0.34	2.40
4	23.8	0.35	2.82
5	41.2	0.83	6.39
6	10.4	0.24	1.94
7	6.2	0.28	1.73
8	11.4	0.31	1.96
Average ± SD	22.9 ± 14.4	0.50 ± 0.26	3.06 ± 1.49

Table 5.2.4: The cumulative daily transpiration recorded from the four *A. melanoxylon* and four *A. baileyana* trees studied at Robinson Deep on the 4.03.92. The data have been expressed as: litres per tree, litres per square meter of foliage per day, and as mm of evaporation per projected canopy area. Total grassland evaporation at Western Areas for the same day was 0.92 mm.

Species	Tree	Transpiration		
		(l day^{-1})	(l m^{-2} day^{-1}) (leaf area)	(mm day^{-1})
A. melanoxylon	1	5.7	1.09	0.96
	2	2.5	0.69	1.07
	3	2.1	1.01	0.87
	4	7.8	0.31	0.55
	Average ± SD	4.6 ± 2.4	0.77 ± 0.31	0.86 ± 0.20
A. baileyana	5	11.4	1.55	1.13
	6	3.4	1.26	0.43
	7	56.2	1.35	1.90
	8	3.9	0.66	0.42
	Average ± SD	18.7 ± 21.9	1.20 ± 0.33	0.97 ± 0.61

5.2.3 Pilot Study: Conclusions

Evaporation rates from grassland during autumn are low, being on average 1 mm per day. These low rates are a result of the high proportion of dead material, brought about by senescence before the onset of winter. The degree of senescence could probably also be reduced through careful management of the grass cover (mowing, fire). Where evaporation is important in reducing the throughflow of water, consideration should be given to the propagation of temperate evergreen grasses (eg. *Merxmuellera)*, as opposed to seasonal grasses. The values obtained for evaporation from grassland at Western Areas are very similar to the observed water loss from trees at Robinson Deep, despite the poor condition of the grass. Total grassland evaporation at Western Areas for both of the days for which tree water use was recorded (3-4/03/92), was 0.92 mm. Only *E. sideroxylon* growing in the toe dam at Western Areas significantly exceeded this value on a land area basis.

Acacia baileyana transpired the most per unit leaf area, but no more than grassland (1 mm/day) due to the spreading nature of the canopy. *E. sideroxylon* transpired 3 mm/day in terms of the projected ground area overshadowed by the canopy. Although high internal water stresses were recorded in all the trees, they appeared to be transpiring quite normally.

5.3 WATER USE IN DIFFERENT MINING ENVIRONMENTS

5.3.1 Water use on gold slimes dams

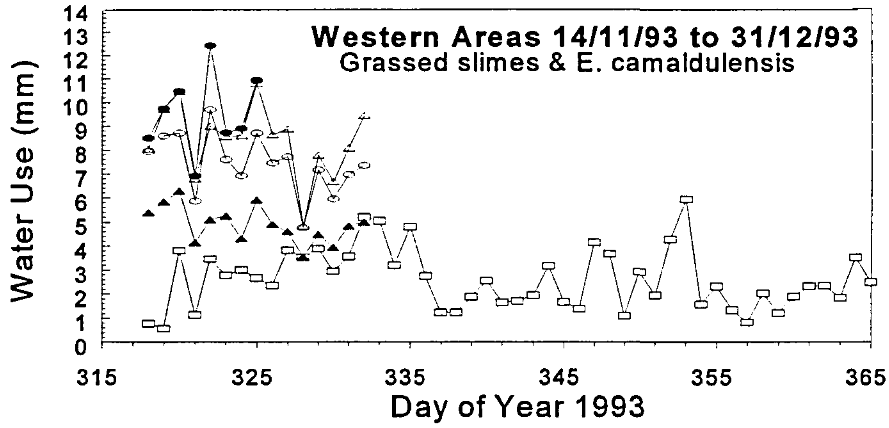
Comparative water use measurements of trees and grass at the tops of slimes dams were undertaken at Western Areas, Durban Deep and at West Extension. Since it was not possible to monitor grass water use at Durban Deep, data from Western Areas had to be used for comparative purposes. Species measured were *E. camaldulensis* (Western Areas and West Extension) and *E. viminalis* (Durban Deep). Data for slimes dams are also reported on in section 5.2 (pilot study), with measurements undertaken on *Acacia melanoxylon* and *A. baileyana* on the Robinson Deep slimes dam.

Rates of water use at the different sites varied substantially (Fig. 5.3.1 - 5.3.6) with differences in available moisture and canopy condition providing the most likely reasons. Ultimately this can be ascribed to the site. Water use of *E. camaldulensis* at Western Areas was particularly high, ranging between 5 mm and 8 mm per day, with the rates for grasses approximately 2 mm (Fig. 5.3.1). Relatively high rates of water use (2ℓ-3ℓ/m^2 leaf area/day) were also found when individual tree water use is expressed in terms of unit leaf area (Fig.5.3.2). These trees were resprouting following a fire. Additional water received by these trees from the irrigation water applied to grasses on the slopes of the slimes is likely to be a factor contributing to the high water use recorded.

Tree water use at Durban Deep (Fig. 5.3.3) differed markedly from that recorded at Western Areas (Fig. 5.3.1). The water use by *E. viminalis* at all sites (top, mid and bottom slope) was no higher than the grass water use rates for the Western Areas site. In fact, tree water use at Durban Deep was comparable to the nearby grassland (approximately 2 mm/day) for most of the study period, with grasses occasionally showing even higher rates of water use than these trees. It appears that trees situated at the top of the slimes dam transpired at the highest rates, compared to those at the bottom and at midslope localities. Tree water use per unit leaf area at Durban Deep were between 0.5 and 1.5 ℓ/m^2 (Fig. 5.3.4), which is comparable to the transpiration rates often recorded in plantation forest trees. Low total tree water use values can therefore be ascribed to relatively poorly developed, or sparse, canopies.

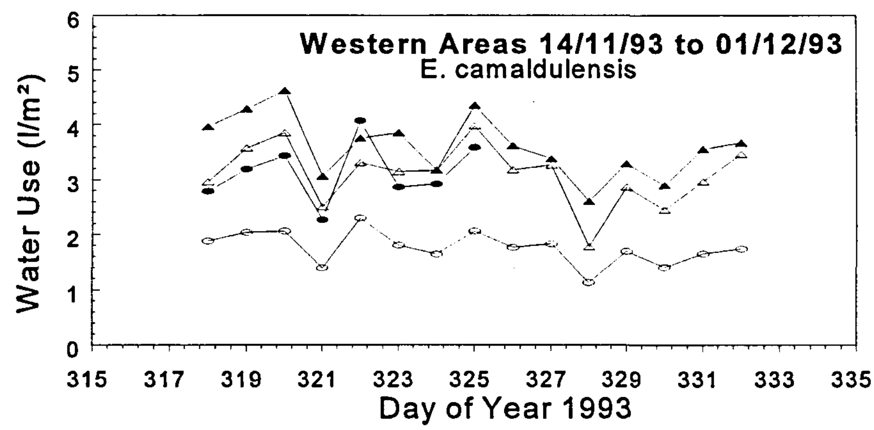
Rates of water use by *E. camaldulensis* trees at West Extension (Fig. 5.3.5) were of the same order (1 - 12 mm) as the values recorded for the same species at Western Areas (Fig. 5.3.1). Similar variation in rates of water use over the monitoring period were evident for all the trees measured. The greatest changes were recorded in tree 2, which also showed the highest water use of all the trees. The water use values expressed per unit leaf area (ℓ/m^2; Fig. 5.3.6) were more comparable to the values for *E. viminalis* trees at Durban Deep (Fig. 5.3.4), than to the values for trees of the same species (*E. camaldulensis*) at Western Areas (Fig. 5.3.2). High total water use values were therefore a result of relatively high canopy leaf area values. The tree water use values recorded at the three gold slimes dam sites (discussed above) are for the summer months only. Measurements undertaken at Durban Deep from May to June 1994 show that there is an appreciable decrease in tree water use during winter, with values ranging from 0.37 to 0.97 mm (Fig. 5.3.7). No comparative grass water loss data is available for this period. On the basis of grass water use data for other highveld sites one expects this to be in the order of 0.2 mm or lower, during the winter, and therefore much less than the measured tree water use.

In summary, summer water use by *E. camaldulensis* trees at Western Areas and West Extension was much higher than the values recorded for the grasses. At Durban Deep, however, the values for the two growth forms were found to be similar. Trees were still using significant amounts of water at Durban Deep during winter (0.4 - 1 mm), at a time when grassland evaporation is expected to be close to 0.



LEGEND	TREE LA (m²)
Grass	
Tree 1	8.53
Tree 2	4.26
Tree 3	9.80
Tree 4	29.84

Figure 5.3.1: Grass and tree water use on Western Areas slimes dam. Tree water use is expressed in mm on the basis of projected canopy area (ground area occupied).



Legend	Average water use (l/m²)
Tree 1	3.08
Tree 2	3.59
Tree 3	3.14
Tree 4	1.60

Figure 5.3.2: Tree water use, normalized for leaf area, at Western Areas. These trees have exceptionally high water use ranging between 2 and 4ℓ/m².

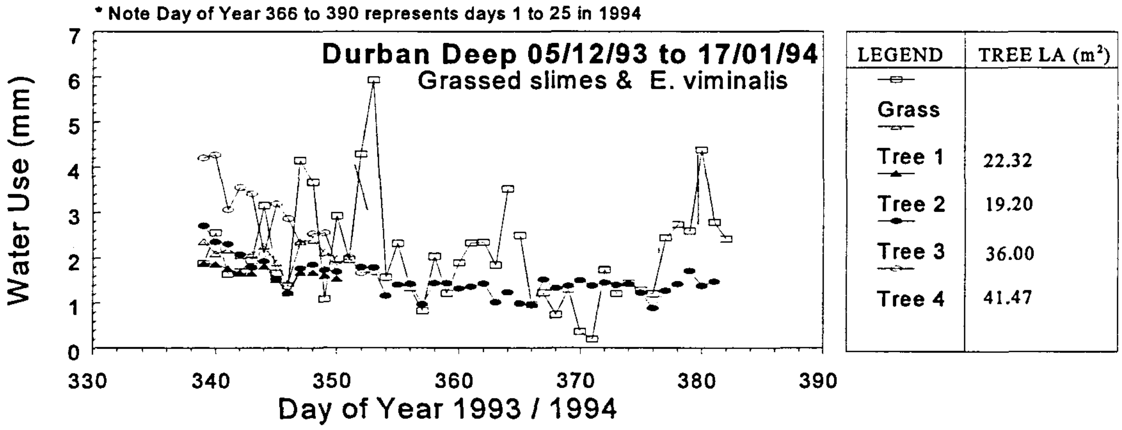


Figure 5.3.3: Tree water use recorded on Durban Deep and grass evaporation on Western Areas. The *E. viminalis* trees do not appear to be using any more water than the grassland. Tree 1 was situated at the bottom of the slope and tree 2 was at a mid-slope position. Trees 3 and 4 were situated at the top of the slope.

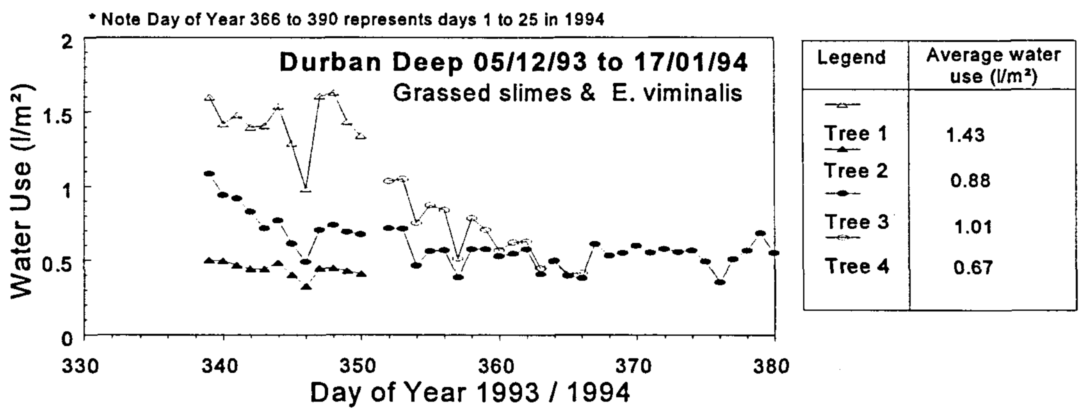


Figure 5.3.4: Water use by trees normalized for leaf area. These trees are transpiring at a significant rate (0,5ℓ/m^2), although not outcompeting the grassland. Tree 1 was situated at the bottom of the slope and tree 2 was at a mid-slope position. Trees 3 and 4 were situated at the top of the slope.

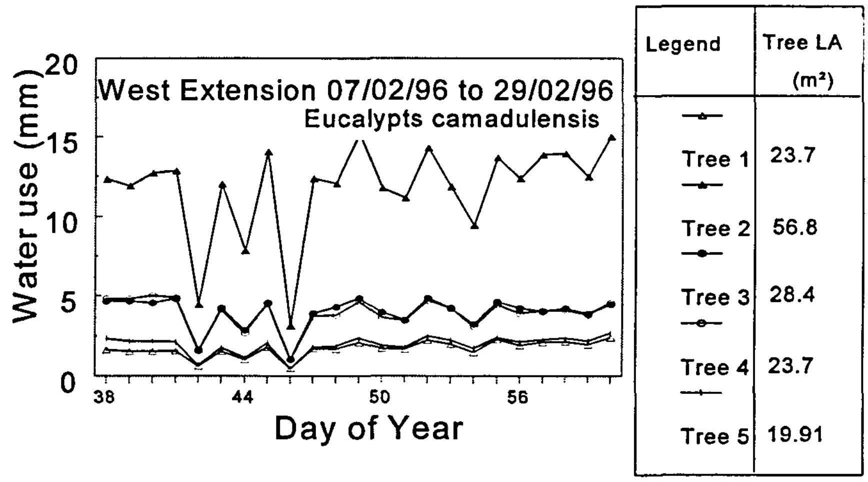


Figure 5.3.5: Water use of trees at West Extension slimes dam during summer. Tree water use is expressed in mm. No grass evaporation measurements were undertaken at this site.

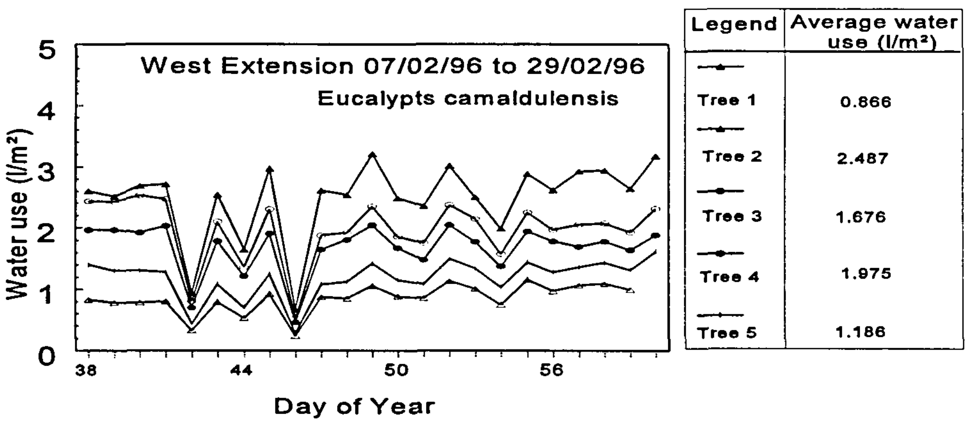


Figure 5.3.6: Water use (normalized for leaf area) of trees at West Extension.

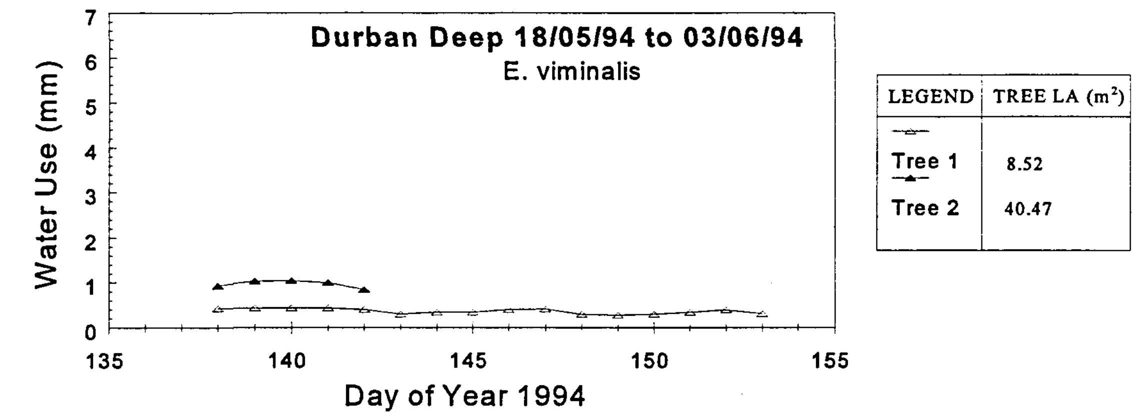


Figure 5.3.7: Low water used recorded by trees through the winter at Durban Deep. Grass evaporation was not measured as mid-winter values from other sites have been consistently close to zero.

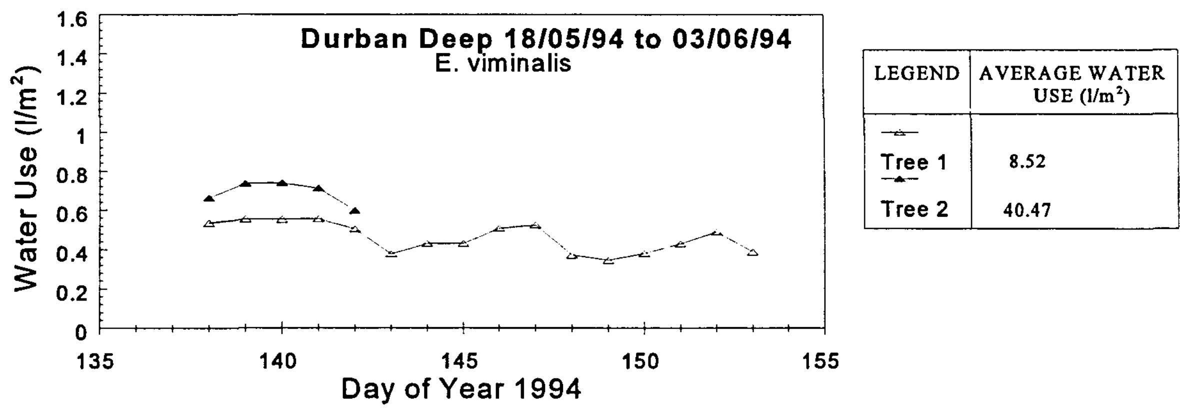


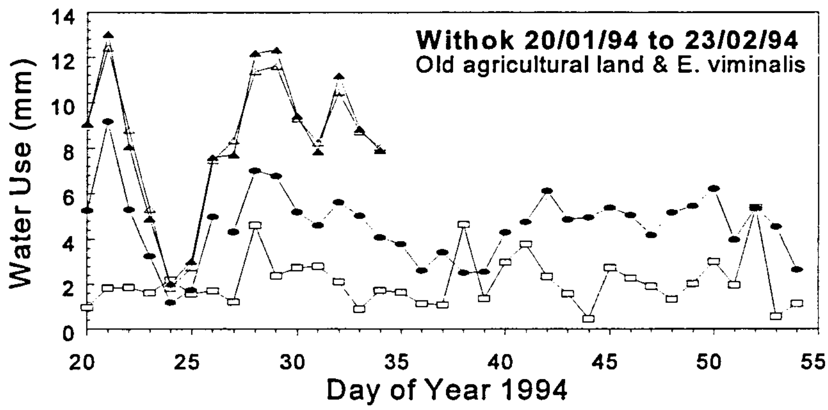
Figure 5.3.8: Winter water use (normalized for leaf area) of trees at Durban Deep. The trees appear to be transpiring at approximately 0.5ℓ/m² of leaf.

5.3.2 Water use on sites adjacent to gold slimes dams

Measurements undertaken at three different sites are used for the evaluation of plant water use in toe areas of slimes dams. These sites are Withok, Durban Deep, and Western Areas (*E. sideroxylon* - pilot study, 920303). The most comprehensive study was undertaken at Withok with results being available for mid-summer (940120 - 940223, Figs. 5.3.9 & 5.3.10) as well as late- autumn and early winter (930428 - 930603; Figs. 5.3.11 & 5.3.12).

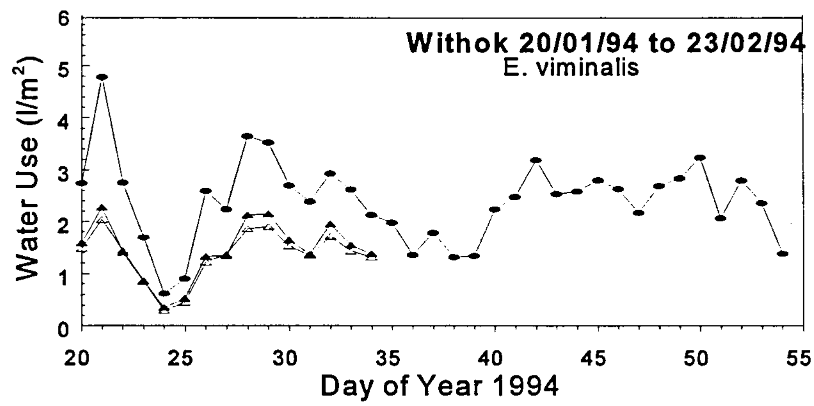
No significant differences were observed between grassland water use at Western Areas and *Eucalyptus viminalis* trees growing at the base of the Durban Deep slimes (tree 1, Fig. 5.3.3) over the measuring period 05/12/93 - 17/12/93. However, there were differences between grass and trees in toe localities at Western Areas (pilot study, section 5.2), with eight *E. sideroxylon* trees using 3.06 mm of water per day, compared to the 1.03 mm for grass on the top of the slimes. Studies at Withok also illustrate a clear difference in plant water use between the two growth forms. Water use by grass on old agricultural lands at Withok was approximately 2 mm /day during summer (Fig. 5.3.9). One of the three Withok *E. viminalis* trees (T3) used between 4 and 5 mm day over a full month and the other two trees (T1 and T2) both used an average of 8 mm per day. The difference in water use between grassland and trees is even more pronounced during autumn (Fig. 5.3.11) with grass water use declining from 1.5 mm to 1 mm over the measurement period and the two trees consistently using 3.5 to 5 mm. A mid-winter (dry season) soil survey found these trees to be deep rooting, with water freely available in the rooting zone (refer to Chapter 4). The seasonal variation in tree water loss can therefore be ascribed to changes in available energy rather than available water. Calculation of the water use per unit leaf area shows that the *E. viminalis* trees at Withok are moderately efficient water users. The summer values are in the order of 2ℓ/m^2/day (Fig. 5.3.10) and autumn values approximately 1ℓ/m^2/day (Fig. 5.3.12), which are lower than the 3 - 4ℓ/m^2/day recorded for *Eucalyptus camaldulensis* at Western Areas (Fig. 5.3.2) during summer. The high leaf area per unit ground area explains the comparatively high total tree water use on a daily basis, and moderate water use when expressed on a unit leaf area basis.

The results illustrate that trees planted in toe areas can use several times as much water as unmanaged grassland on old agricultural lands, even during the active growth season of grasses (i.e. during summer). It should be kept in mind that the grassland measured was in poor condition and that with appropriate management of the grassland, the difference between the water loss of grasses and trees during summer should be less than that observed in this study.



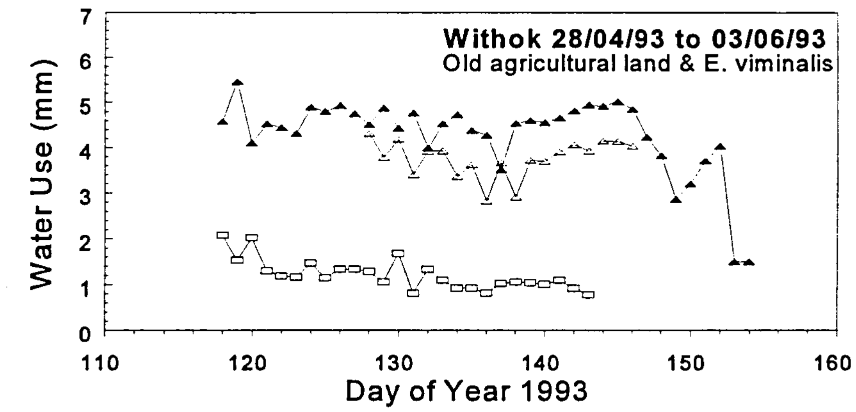
LEGEND	TREE LA (m^2)
Grass	
Tree 1	31.73
Tree 2	32.60
Tree 3	25.69

Figure 5.3.9: Water use by trees and grass in mid-summer in a slimes seep area at Withok. Trees here using significantly more water than grassland. This is a poor grassland and trees have their roots in the water table.



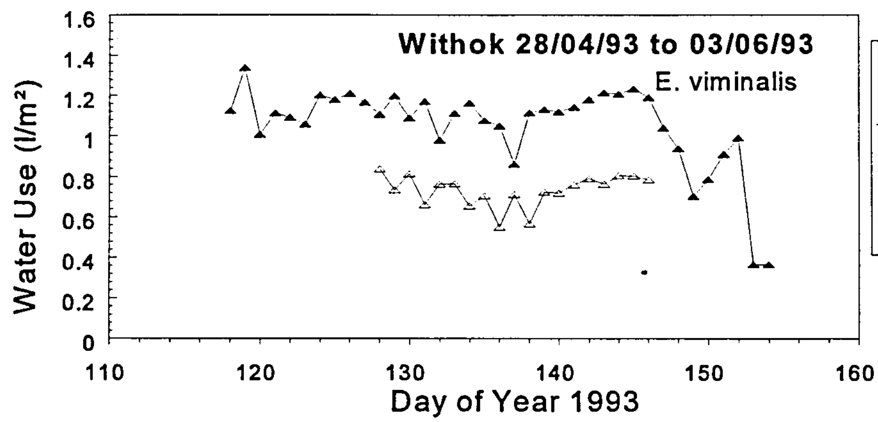
LEGEND	AVERAGE WATER USE (l/m^2)
Tree 1	1.36
Tree 2	1.46
Tree 3	2.55

Figure 5.3.10: Tree water use normalized for leaf area (ℓ/m^2). There is close similarity in the behaviour of these three trees.



LEGEND	TREE LA (m²)
Grass	
Tree 1	77.1
Tree 2	60.7

Figure 5.3.11: Water use by trees and grasses during autumn in a slimes seep at Withok. Trees are using 2-3 mm more water than grasses during this season.



Legend	Average water use (l/m²)
Tree 1	0.73
Tree 2	1.05

Figure 5.3.12: Tree water use normalized for leaf area. Water use is expressed as ℓ/m² of tree leaf area.

5.3.3 Water use on rehabilitated open-cast coal mines

Tree water use on a rehabilitated open-cast coal mine was investigated at Optimum's Hendrina colliery. Measurements were undertaken during the June-July period of 1993 (Fig. 5.3.13), and during March and April 1994 (Fig. 5.3.15). Grassland evaporation data is available for a 35-day period during June-July of 1993 but for only a few days during March 1994 due to instrument failure at the site. Despite the breakdown of instrumentation we managed to obtain adequate data to provide a good indication of grassland water use during early autumn (March).

Grassland water use for the winter period remained between 0.2 mm and 0.4 mm (Fig. 5.3.13). The days of apparently higher water use probably indicate evaporation of rainwater, and not elevated transpiration rates. Water use rates of the grassland increased to 1 mm during early autumn (Fig. 5.3.15). Water use varied greatly among *E macarthurii* trees during winter with values ranging from 0.56 mm to 2.6 mm (Fig. 5.3.13). There was similarly a great variation in water use rates of the different *E. macarthurii* tree individuals during autumn (Fig. 5.3.15). At the beginning of the autumn monitoring period the values were between 2.14 mm and 3.34 mm (early March) and declined to 1 - 1.5 mm towards the end of Autumn (mid - May).

The variation in water use among the *E. macarthurii* trees at Hendrina can be explained by the different leaf areas (tree size variation) of the different tree individuals. The smaller trees with their lower leaf areas had the lowest water use values. Water use of the various trees are quite similar when the rates are expressed in terms of unit leaf area (Figs. 5.3.14 & 5.3.16). Early autumn values ranged from 0.4 to 0.6ℓ/m^2 of leaf/day, while late autumn values were approximately 0.2 ℓ/m^2/day. The winter values ranged from 0.2 - 0.5 ℓ /m^2/day with one of the trees showing a high value of 0.7 ℓ /m^2/day.

The water loss values of trees at Hendrina are low compared to the rates of trees at the other gold mining sites (refer to section 5.3.1 and 5.3.2). The trees at Hendrina were quite small, and the rooting depth quite shallow (90 cm) at the time of measurement. With an increase in tree size and canopy dimensions, we expect that rates of water loss will increase. The trees at the Hendrina open-cast coal mine used approximately 1 - 2 mm water per day more than the grassland, irrespective of the season of measurement. This difference in water use between the two growth forms is likely to increase even more when tree canopies develop to their full potential at the site.

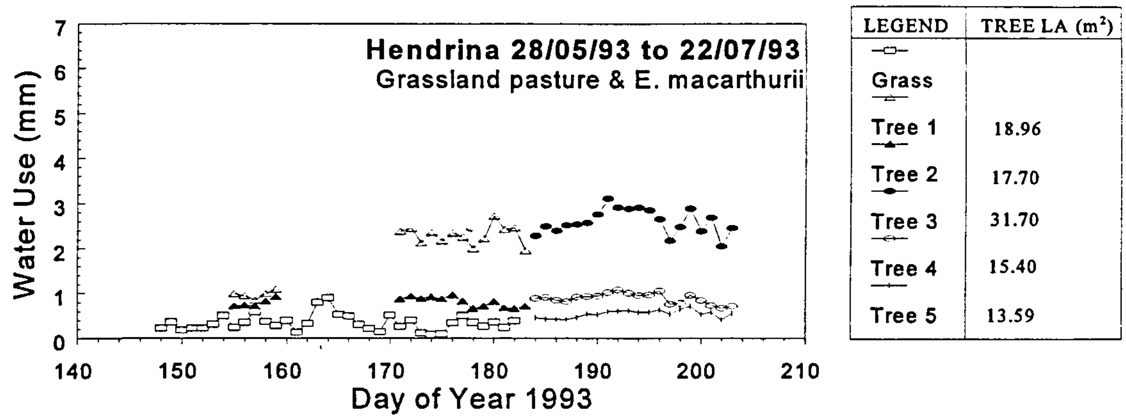


Figure 5.3.13: Water use by trees and grasses during winter on a rehabilitated coal spoil at Hendrina. Grasses use very little water through the winter (0,55 mm). Trees are variable in their winter water consumption.

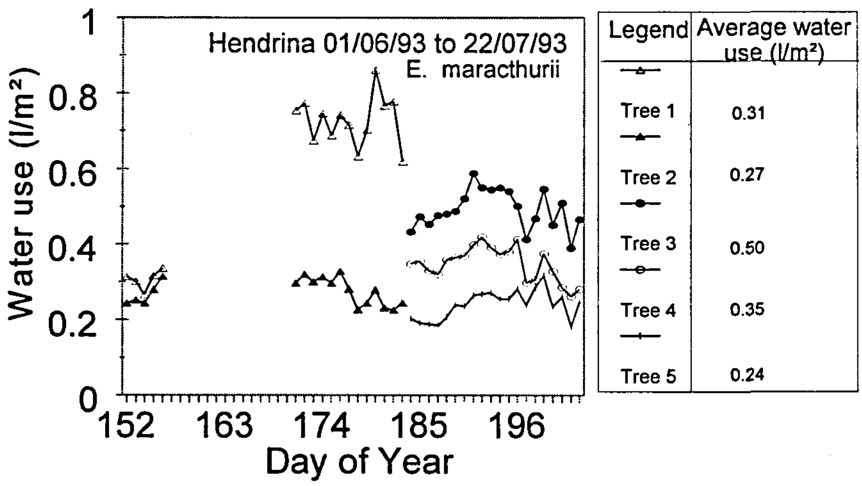


Figure 5.3.14: Tree water use at Hendrina during winter expressed for each tree in ℓ/m² of leaf area. Water use per unit leaf area remains variable.

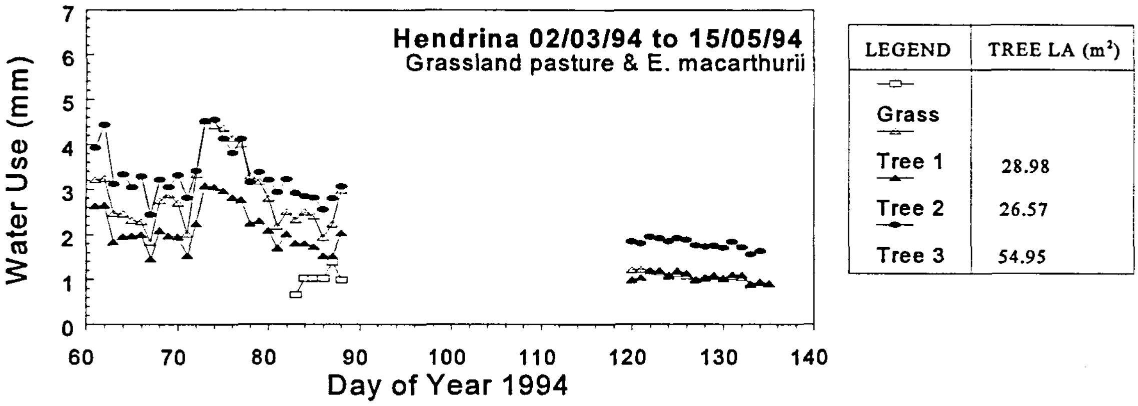


Figure 5.3.15: Tree and grass water use at Hendrina during summer and autumn. Instrument failure resulted in the capture of only 5 days of grass evaporation during this period.

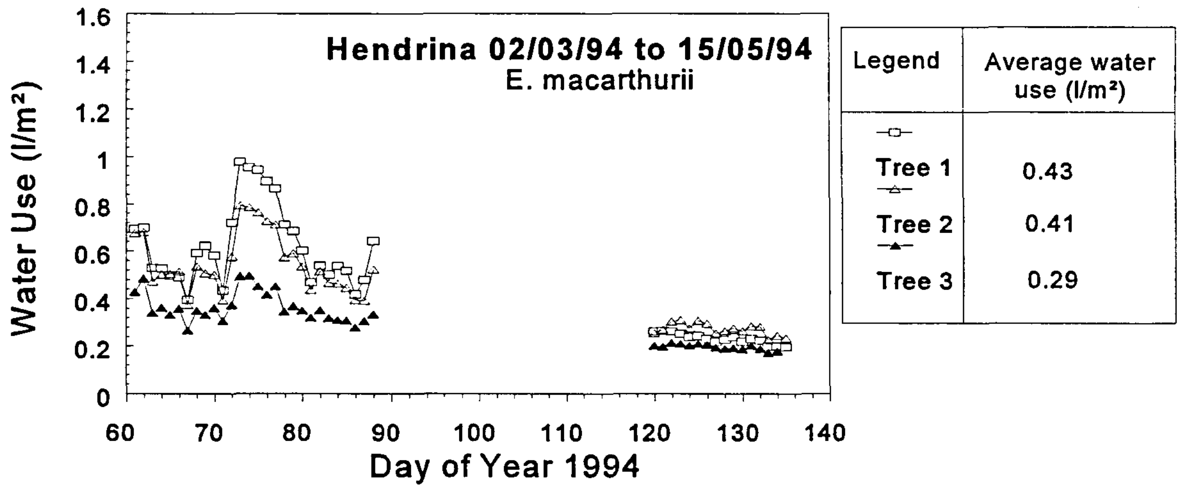


Figure 5.3.16: Using leaf area to normalize water use by trees at Hendrina during summer and autumn, results in a clustering of values around 0.5ℓ/m².

5.3.4 High extraction underground coal mines

Tree water use was investigated on *E. viminalis* trees growing in a plantation established on Brandspruit colliery, a high extraction underground coal mine at Secunda. Comparative grassland water use was measured at an adjacent site of natural grassland (dune sourveld) during winter, and on irrigated pastures during spring.

Grass water use at the close of winter (early spring) was almost zero (< 0.1 mm/day) (Fig. 5.3.17). Secunda has 115 frost days per annum, and this kills off all live grasses, resulting in the low rates of water use. Water use by irrigated pasture during spring (Fig. 5.3.17) was approximately 2 mm, which is comparable to the water use of the local natural grassland during summer (refer to Fig. 5.3.19). This may be an indication of the extent to which water consumption by grasses under natural conditions is determined by their ability to utilize the soil profile and therefore to access available water. It must be kept in mind that measurement of rates of water use of irrigated lands is predisposed to error introduced by soil evaporation of irrigated water. The results should therefore be interpreted with caution. This is a limitation of the Bowen Ratio technique used to measure water use by grasslands.

Tree water use during spring ranged between 0.6 and 0.7 mm/day for three small trees, and was approximately 2.5 mm/day for two mature trees (Fig. 5.3.17). This four-fold difference in water use between the two groups of trees cannot be interpreted solely in terms of different leaf areas since the water use rates expressed per unit leaf area (Fig. 5.3.18) also varied substantially during this season, although not in summer (Fig.5.3.20). A further explanation may be the observed micro-site differences in soil particle size distribution (refer to section 4.5) which in turn may affect soil water availability.

Under natural conditions tree water loss exceeded grassland evaporation during the late winter measuring period. However, during the summer measuring period this situation was reversed with grasslands showing higher rates of water loss than the young trees on the site (Fig. 5.3.19). Grassland water loss ranged from 1.5 mm/day to 4.2 mm/day, with an average of 2.4 mm, which represents the highest grassland water use rates recorded for any Highveld site throughout the entire study. This is of the same order as water use by irrigated pastures. Only the largest of the trees measured (tree 1; T1) showed higher transpiration rates (3.54 mm/day) than the grassland. The values for the smaller trees ranged from 0.44 to 1.30 mm/day. Measurements on an additional tree during the late-summer (early autumn) period (Fig. 5.3.21) showed water loss to be similar to that of T1.

The high water use of grasses at Secunda over the period 05/02/93 to 04/03/93 (Fig. 5.3.19) can be explained by the healthy condition of the grassland. The grass cover, while not quantified as biomass, appeared to be considerably greater at Secunda than at any of the other Highveld sites investigated, explaining the exceptionally high water consumption recorded.

The trees used in this study were growing in a stand in the early stages of development. Trees varied greatly in their canopy leaf areas. Since water use expressed in terms of leaf area (Fig. 5.3.20) shows remarkably similar values (0.5 ℓ/m^2) for the various trees, the variation in water use among trees during summer (Fig.5.3.19) can be explained by the differences in leaf area.

Most of the trees used at Brandspruit colliery had not developed the full complement of leaves of mature trees at the time when measurements were undertaken. Only tree number 1 (T1) had a leaf area representative of a mature *E. viminalis* tree. Given the high water use rates of T1, it can be assumed that the water loss of a full stand of mature *E. viminalis* trees will at least be comparable to grassland (dune sourveld) water loss during summer.

The benefit of trees as water consumers at Secunda is attributable primarily to their water use during the winter months. Since the difference in water use between mature trees and grassland during winter is approximately 2 mm, and this period of low grass water use may last for 6 months, we assume that the water consumption brought about by trees during winter will be in the order of at least 360 mm/year. Trees also intercept approximately 40 mm of rainfall during this period (6% interception), which gives a total of 400 mm of water being used by trees in excess of the water which can be used by grasslands at this site. This suggests that trees are capable of utilizing all of the annual rainfall at this site. However, there is likely to be some degree of percolation beyond the shallow root zone across much of the melanic soil type.

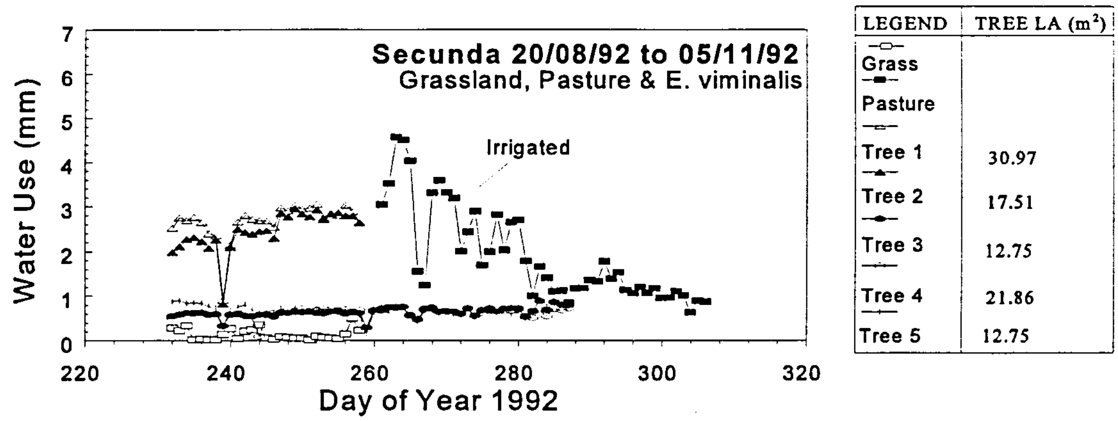


Figure 5.3.17: Water use expressed in mm by trees (*E. viminalis*), grassland and an irrigated pasture at Secunda between August and November 1992. Tree water use is variable and strongly related to leaf area. Grasses are dormant through the winter months.

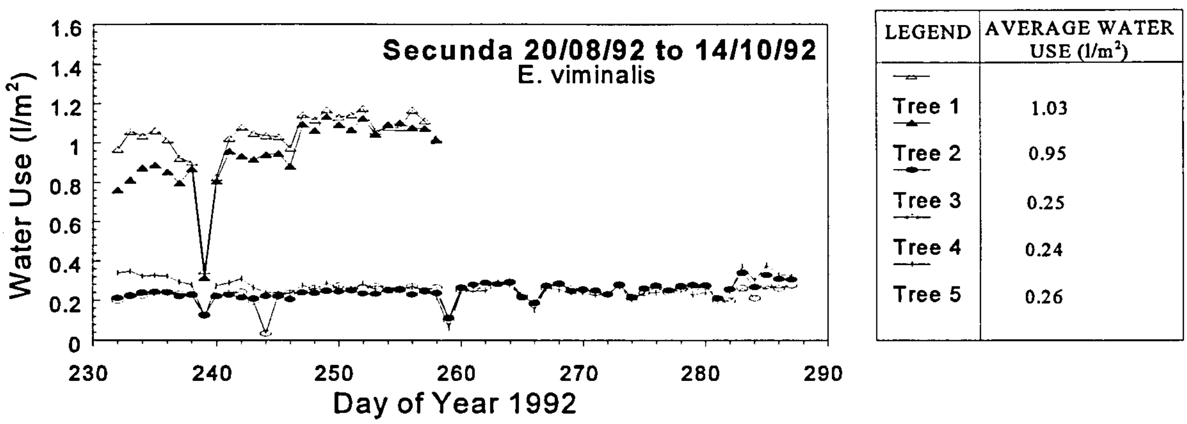


Figure 5.3.18: Water use for each of 5 trees at Secunda normalized for leaf area. Water use is expressed as ℓ/m² of tree leaf area.

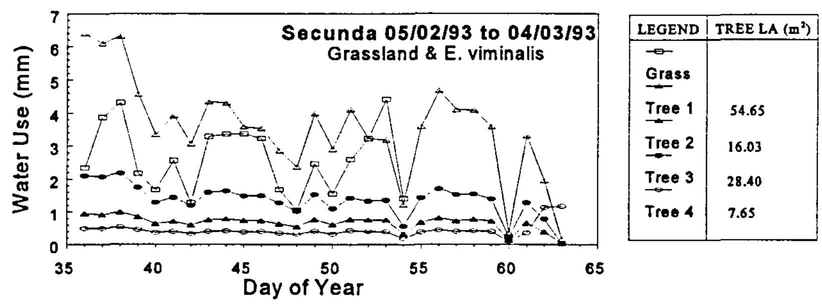


Figure 5.3.19: Evaporation from grass and trees at Secunda during the summer of 1993. Tree water use is correlated with the leaf area of the individual trees, with only the water use of the largest tree exceeding the water use of natural grassland. Note the high water use by the thick summer grass cover, especially in contrast to the values for winter (Fig. 5.3.17).

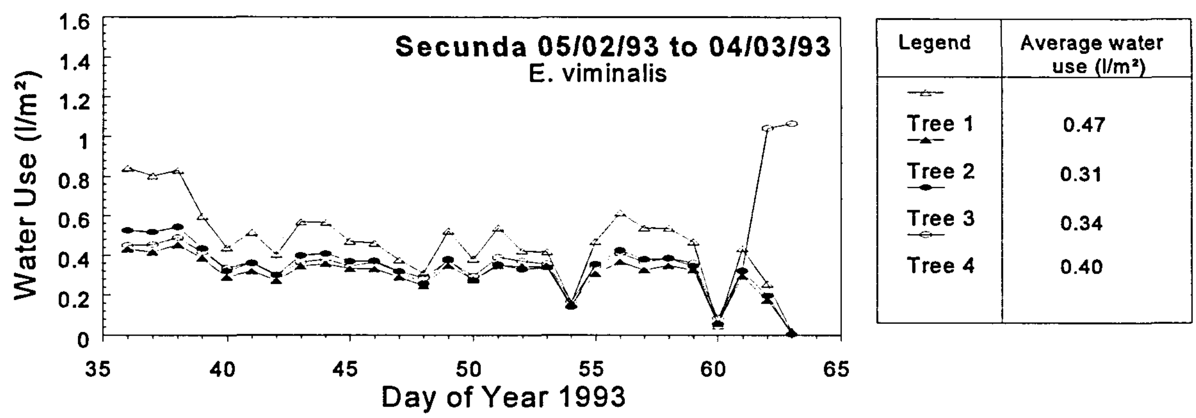


Figure 5.3.20: When water use values are normalized for leaf area (ℓ/m^2), these trees behave in a remarkably similar way during the summer months, transpiring at approximately $0{,}5\ell/m^2$.

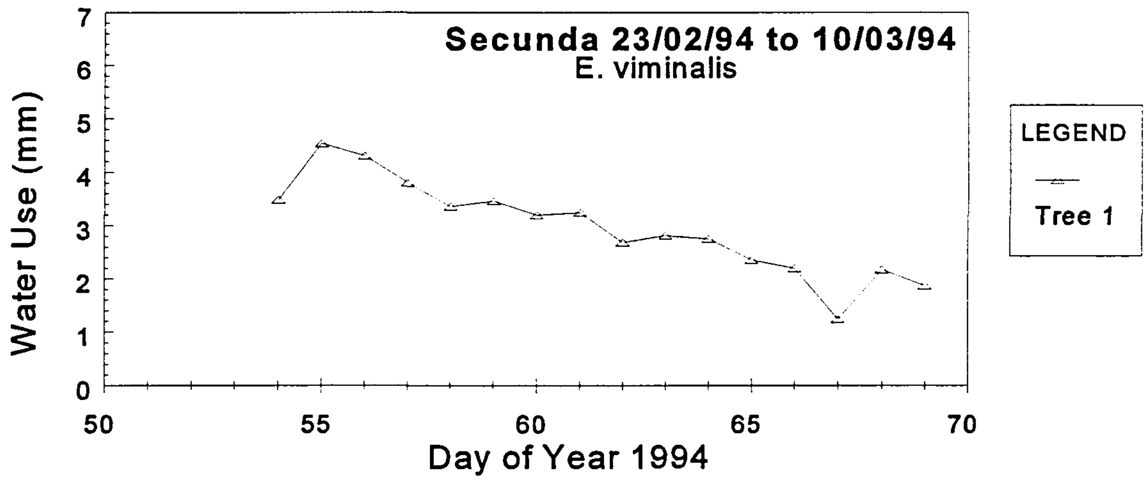


Figure 5.3.21: Water use by a single tree at Secunda during the summer of 1994. Grassland transpiration was not measured. Consumption is very similar to results obtained in 1993.

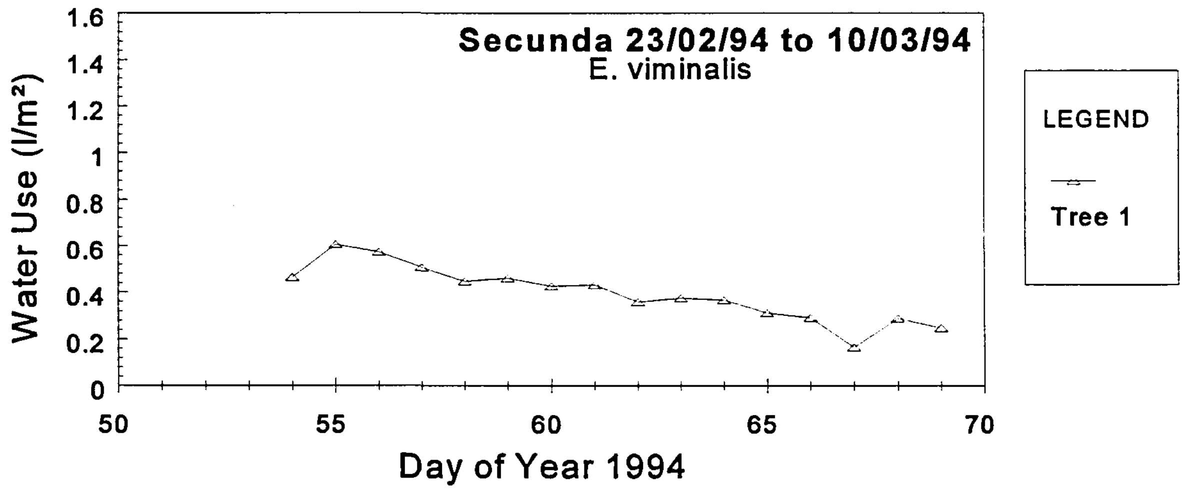


Figure 5.3.22: Water use of this tree at Secunda, normalized for leaf area, was approximately 0.5ℓ/m2, i.e. similar to the values observed during 1993.

5.4 WATER USE BY TREES AND GRASSES: SEASONAL VARIATION

In this section we focus on the seasonal variation in water use of grasses and shrubs, irrespective of the localities where measurements were undertaken. Water loss from grasses was the highest during the summer months, with values ranging from 1.7 mm at Western Areas slimes dam, to 2.6 mm at Secunda (Table 5.4.1). These values were generally quite similar to water use values recorded for *E. viminalis* trees (Durban Deep) during this period where values ranged from 1.53 mm to 2.65 mm. However, remarkably high summer rates of water loss were recorded for *Eucalyptus viminalis* trees found in the toe area of the Withok slimes dam (6.31 mm), for *Eucalyptus camaldulensis* trees on the West Extension slimes (4.66 mm), and on the Western Areas slimes (7.92 mm).

Water use by trees similarly exceeded the values for grasses during autumn (Table 5.4.2). The values for the eucalypt species were fairly similar, with *Eucalyptus sideroxylon* (Western Areas) and *Eucalyptus viminalis* (Secunda) using 3.06 and 2.97 mm respectively. These values are more than double the values recorded for grasslands during autumn. However, the water use of the two *Acacia* species at Robinson Deep was approximately 0.90 mm, similar to the evaporation values recorded for grassland at this site (Table 5.2.3). This illustrates that the eucalypts are far more efficient than the acacias at extracting soil water and releasing it back to the atmosphere through transpiration.

Tree water use was consistently more than double the values recorded for grasses during winter and spring (Tables 5.4.3 & 5.4.4). The only exception is the findings for a small *Eucalyptus viminalis* tree at Durban Deep, where water loss (0.365 mm) was of the same order as that measured for grasses at Hendrina (0.35mm) during winter. Tree water use during spring was approximately 0.5 mm/day for three small trees, and approximately 2.4 mm/day for two mature trees growing at Secunda (Table 5.4.4).

Table 5.4.1: Water Use (mm) of grass and trees at various sites during **summer.**

Growth form or species	**Site**	**Date of measurements**	**Average transpiration rate (mm)**	**Standard deviation**
Grass	Western Areas	01/01/94 - 17/01/94	1.7	1.025
Grass	Western Areas	01/12/93 - 31/12/93	2.29	1.08
Grass	Withok	20/01/94 - 23/02/94	2.16	1.1
Grass	Secunda	05/02/93 - 23/02/93	2.61	1.07
Tree *E.viminalis*	Durban Deep - top of slimes dam	02/01/93 - 16/01/94	1.53	0.52
Tree *E.viminalis*	Durban Deep - along the slopes of slimes dam	05/12/93 - 16/12/93	1.66	0.17
Tree *E.viminalis*	Durban Deep - at the base of slimes dam	05/12/93 - 16/12/93	2.097	0.25
Tree *E.viminalis*	Durban Deep - at the top of slimes dam	18/01/93 - 31/01/93	2.64	0.76
Tree *E.viminalis*	Withok - at the base of slimes dam	20/01/94 - 23/02/94	6.31	2.97
Tree *E. camaldulensis*	West Extension	07/02/96 - 29/02/96	4.66	3.97
Tree *E. camaldulensis*	Western Areas	14/11/93 - 01/12/93	7.92	2.12

Table 5.4.2: Water Use (mm) of grass and trees at various sites during **autumn.**

Growth form or species	**Site**	**Date of measurements**	**Average transpiration rate (mm)**	**Standard deviation**
Grass	Hendrina	25/03/94 - 29/03/94	1.10	0.17
Grass	Withok	28/04/93 - 24/05/93	1.21	0.33
Tree *E.viminalis*	Secunda	23/02/94 - 10/03/94	2.97	0.85
Tree *Acacia melanoxylon*	Robinson Deep (refer to section 5.2)	04/03/92	0.86	0.20
Tree *Acacia baileyana*	Robinson Deep (refer to section 5.2)	04/03/92	0.97	0.61
Tree *E.sideroxylon*	Western Areas (refer to section 5.2)	03/03/92	3.06	1.49

Table 5.4.3: Water Use (mm) of grass and trees at various sites during **winter**.

Growth form or species	Site	Date of measurements	Average transpiration rate (mm)	Standard deviation
Grass	Hendrina	27/05/93 - 30/06/93	0.35	0.18
Grass	Secunda	20/08/92 - 15/09/92	0.14	0.13
Tree *E. macarthurii*	Hendrina	04/06/93 - 22/07/93	1.36	0.84
Tree *E. viminalis*	Durban Deep - small tree	18/05/94 - 02/06/93	0.36	0.06
Tree *E. viminalis*	Durban Deep - bigger tree	18/05/94 - 22/05/93	0.97	0.07

Table 5.4.4: Water Use (mm) of grass and trees at various sites during **spring**.

Growth form or species	Site	Date of measurements	Average transpiration rate (mm)	Standard deviation
Grass	Secunda	20/08/92 - 15/09/92	0.14	0.13
Tree *E. viminalis*	Secunda - three small trees	20/08/92 - 15/09/92	0.49	0.06
Tree *E. viminalis*	Secunda - two mature trees	20/08/92 - 15/09/92	2.39	0.18

5.5 TESTING EVAPORATION MODELS FOR GRASSLAND

5.5.1 Models for grass water use

Grassland evaporation estimates from Bowen ratio measurements for mining sites in Gauteng and Mpumalanga (Highveld) have indicated that the equilibrium evaporation concept would grossly underestimate the actual evaporation (cf pilot study section 5.2.2.1). This is not surprising, as this concept assumes a weak flow of humid air over an irrigated crop. Such conditions occur when the vapour pressure deficit of the air is low, the wind speed is low and the stomatal resistance of the canopy is small. Since drought conditions prevailed at the study sites at the time measurements were taken, these conditions were seldom met.

The need for a reliable method of estimating evaporation on a daily or weekly basis using only regularly recorded climatological data has been long sought after by hydrologists and micrometeorologists. One of the first methods with a firm physical basis which could be applied using routinely recorded weather data was derived by Penman (1948):

$$Q_E = \frac{S}{S+\gamma}(R_n - G) + \frac{1}{S+\gamma}\rho c_p (1/r_{av})(e_a{*} - e_a) \qquad \textbf{(1)}$$

Where Q_E is the evaporation in energy units; S is the slope of the saturated vapour pressure versus temperature curve; γ is the psychometric constant; R_n is the net radiation, G is the ground heat flux; e_a is the vapour pressure in the air at the temperature T_a measured at the same point as the vapour pressure; r_{av} is the aerodynamic resistance for latent heat transfer, ρ is the density of air, and c_p is the specific heat of air at constant pressure. This equation combines the energy budget with a mass transfer equation to eliminate the need for measuring humidity and temperature at two levels. However, the resulting estimate is only applicable when the evapotranspiration rate is independent of the moisture content of the soil. Such conditions occur when the soil is wet or when actual evaporation is equivalent to potential evaporation. When there is a lack of soil moisture, plant water stress restricts the evaporation rate. Under these conditions the Penman equation can be applied with measured net radiation to estimate the potential evaporation: an upper bound to the actual rate of evaporation.

The Penman equation was adapted by Monteith (1965) to be applicable under all soil moisture conditions. The "combination" or Penman-Monteith equation still assumes a one dimensional flux of vapour, but otherwise it is applicable under all conditions. The modification introduced an extra term, the stomatal resistance (r_s), which results from the movement of water vapour from the sub-stomatal cavities to the surface of the leaf. The Penman-Monteith equation (PM) is expressed as:

$$Q_E = \frac{S}{S+\gamma(1+r_s/r_{av})}(R_n - G) + \frac{1}{S+\gamma(1+s/r_{av})}\rho c_p(1/r_{av})(e_a* - e_a) \quad \textbf{(2)}$$

This equation is based on a sound conceptualisation of the physical processes of evaporation from plant canopies, but cannot be applied easily because of the difficulties of estimating the stomatal resistance. A number of studies have shown that the Penman-Monteith form of the combination equation was consistently superior to the others. This equation includes more of the factors that influence canopy water loss than other equations, and is therefore expected to provide better estimates. It has not previously been used in operational applications because of its additional computational complexity and the need to define standard values for the reference crop. However, with the capabilities of microprocessor-based dataloggers to do online computations, such limitations have been removed, and the more physically sound Penman-Monteith equation has become feasible for operational applications.

Aerodynamic resistance

Estimates of aerodynamic resistance (r_{av}) and stomatal resistance (r_s) are required for solving the Penman-Monteith equation for evaporation. An estimate of the aerodynamic resistance for application to plant canopies can be derived from measurements of wind speed profiles. However, such measurements are time consuming and expensive because of the number of anemometers required. Alternatively, the aerodynamic resistance that occurs between a specific height above the ground and the apparent source or sink for heat can be derived from wind profile theory (Monteith, 1973):

$$r_{av} = \frac{[\ln(z-d)/z_0]^2}{k^2 U_z}$$

where z is the height above the ground,
d (the zero plane displacement) is 0.63 x canopy height (m),
z_0 (roughness parameter) is 0.13 x canopy height,
U_z is the mean wind speed at height z, and
k is von Karman's constant (0.4).

Stomatal resistance

A number of environmental factors including leaf temperature, light, leaf water potential and vapour pressure deficit affect stomatal resistance. Because the manner in which stomates control transpiration is so complex it is usually measured using steady state porometers. As this is not practical in mixed grass swards, we estimated mean values of the stomatal resistance for summer and winter, by using an inverse solution of the Penman-Monteith equation. This was possible because the detailed data sets collected included all the variables in the equation with the exception of stomatal resistance.

Soil heat flux density

When net radiation is positive the soil heat flux density is usually estimated as a fraction of the net radiation. For complete canopy cover (the condition specified for potential evaporation) the soil heat flux is estimated as 10% of the net incoming radiation. We tested this relationship by examining the ratio of soil heat flux to the net radiation.

Data collected from the Bowen ratio apparatus are used to test the Penman-Monteith equation and equilibrium equation for the grassland vegetation studied in this project. Comparisons are made for selected periods during summer (Secunda and Withok), autumn and winter (Optimum Hendrina). Two criteria are used to assess the success of the model fit. The first is to compare the 20 minute estimates of measured and modelled evaporation. The second criterion is the difference between the measured and modelled cumulative evaporation over the measurement period.

5.5.2 Comparisons of Bowen ratio, Equilibrium equation and Penman-Monteith equation evaporation

Values of the stomatal resistance calculated from the inverse Penman-Monteith equation showed that the average summer value was approximately 100 s m^{-1} (Fig. 5.5.1). This indicates that the grasses were transpiring freely during the day and soil water was not limiting. These values are close to the standard for reference crops (70 s m^{-1}, Smith 1991). By contrast, winter stomatal resistances were greater than 500 s m^{-1}, indicating the dormant state of the grasses (Figure 5.4.1). Stomatal resistance of 100 s m^{-1} (summer) and 500 s m^{-1} (autumn and winter) were used for calculating the Penman-Monteith evaporation.

Measurements of evaporation from grassland using the Bowen ratio technique, the Penman-Monteith equation and equilibrium rate in a summer period during 1993 (Secunda) are shown in Figure 5.5.2. All three sets of data followed the typical bell shaped curves of net radiation. The diurnal trends of the Bowen ratio and Penman-Monteith equation showed the closest agreement. Although the equilibrium evaporation followed a similar pattern, these estimates were always higher. Daily totals of evaporation for the Bowen ratio varied between 1.58 and 4.31 mm and were only 7% lower than the Penman-Monteith estimates (Table 5.5.1). The equilibrium evaporation rate was 35% higher than the Bowen ratio evaporation rate.

Table 5.5.1: Daily totals of evaporation: Day of year 36-40 (summer) in mm.

Day	36	37	38	39	40	Total
Bowen ratio	2.34	3.87	4.31	2.17	1.58	14.27
Equilibrium equation	3.48	4.62	5.62	3.42	2.18	19.33
Penman-Monteith	2.52	3.68	4.87	2.66	1.56	15.29

Close agreement between the Penman-Monteith (cumulative total 23,4 mm) and Bowen ratio technique (cumulative total 26.6 mm) was also evident at Withok over a 17 day period in summer 1994 (Figure 5.5.3). The equilibrium rate over-estimates evaporation (66.1 mm), suggesting that evaporation from these grasslands is limited by some factor, possibly low soil moisture.

During winter on the highveld, the grasses are dormant and radiation levels low, resulting in low daily evaporation rates. It was therefore necessary to set r_s to 500 s m^{-1} to simulate the closing of stomates during winter. The diurnal trends using the three techniques at Optimum's Hendrina Colliery again showed close agreement between the Bowen ratio and Penman-Monteith techniques and poor agreement with the equilibrium technique (Figure 5.5.4). The diurnal trends in the Penman-Monteith data were smooth in comparison to the Bowen ratio technique. The periods when no evaporation was recorded with the Bowen ratio technique (e.g. calender day 151) are a result of the temperature and vapour pressure gradients being too small to measure. In these instances the Penman-Monteith equation is likely to predict the evaporation more accurately. Daily estimates of the evaporation rate showed only a 13% difference between the Bowen ratio and Penman-Monteith techniques, while the equilibrium evaporation was 500% higher than the Bowen ratio technique (Table 5.5.2).

Table 5.5.2: Daily estimates of evaporation: Day of year 148 to 152 (winter) in mm.

Day	148	149	150	151	152	Total
Bowen ratio	0.22	0.18	0.10	0.18	0.26	0.95
Equilibrium equation	1.24	1.05	1.11	1.08	1.13	5.61
Penman-Monteith	0.19	0.16	0.16	0.15	0.16	0.82

During autumn of 1994 at Optimum's Hendrina colliery (Figure 5.5.5), both the Penman-Monteith equation and Bowen ratio estimated low levels of evaporation (<0.05 mm per 20 minute period). The equilibrium equation over-estimated evaporation at all times.

The average ratio of soil heat flux to net radiation in summer was 0.1, confirming the validity of reducing the net radiation by 10% (Figure 5.5.6). In winter the ratio varied from 0.9 in the morning to 0.1 in the late afternoon (Figure 5.5.6). However, the error associated with this variability will be small, since evaporation is negligible during winter.

These results indicate that the evaporation rate of grassland growing on various mining sites on the Highveld can be accurately modelled by using the Penman-Monteith combination equation. Although this is an elaborate model and requires detailed climatic data (net radiation, air temperature, vapour pressure and wind speed) its accuracy far outweighs these considerations. Net radiation is the only parameter that is not routinely measured at South African weather stations. It can, however, be easily estimated from solar radiation which is measured at most weather stations.

The results show that the stomatal resistance can be set to 100 s m^{-1} in summer and 500 s m^{-1} in autumn and winter for accurate measurements of evaporation. The simpler equilibrium equation, which does not take into account the aerodynamic and stomatal resistances, is unsuitable for estimating evaporation from grassland sites of this study.

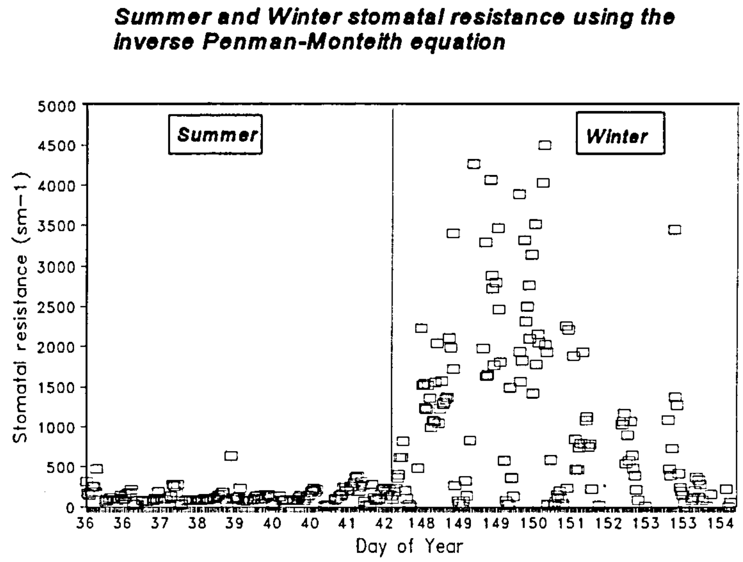


Figure 5.5.1: Stomatal resistance of summer and winter grassland.

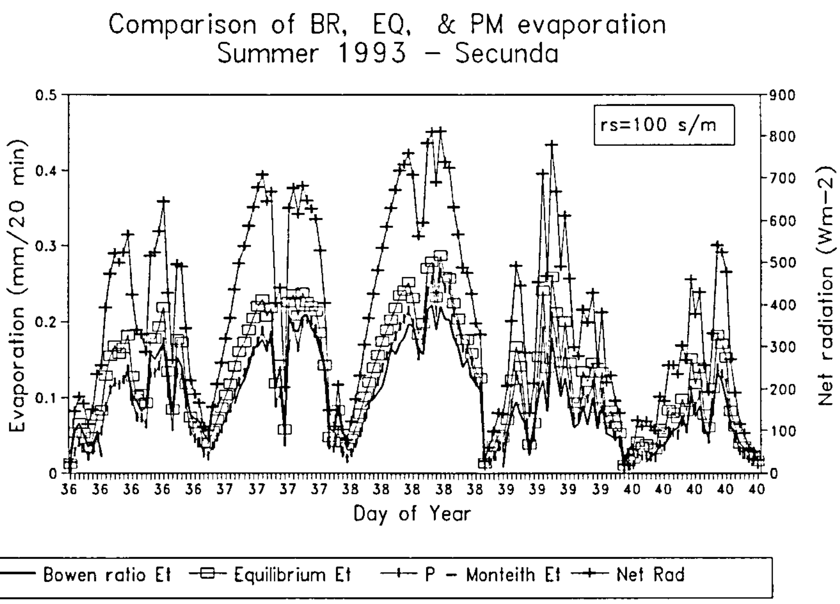


Figure 5.5.2: Comparison of Bowen ratio, equilibrium and Penman-Monteith methods of estimating evaporation in summer 1993 at Secunda.

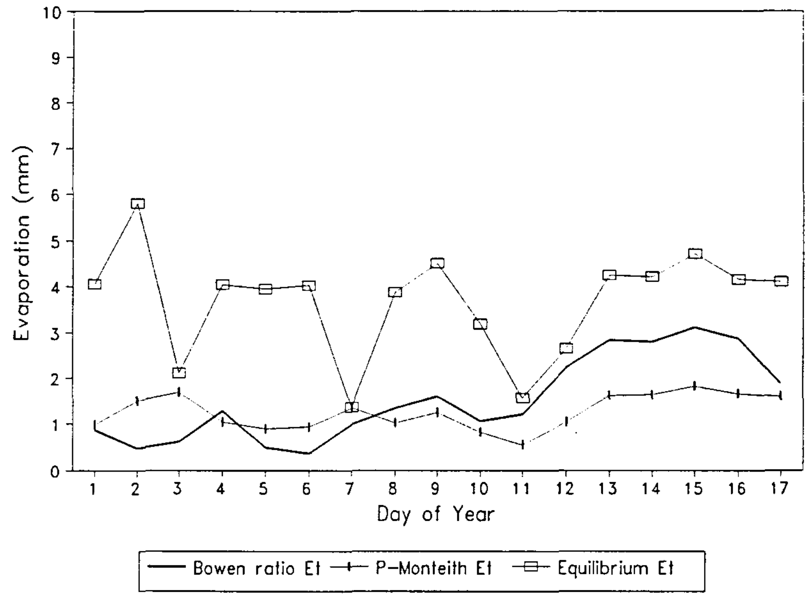


Figure 5.5.3: Comparison of Bowen ratio, equilibrium and Penman-Monteith methods of estimating evaporation in summer 1994 at Withok.

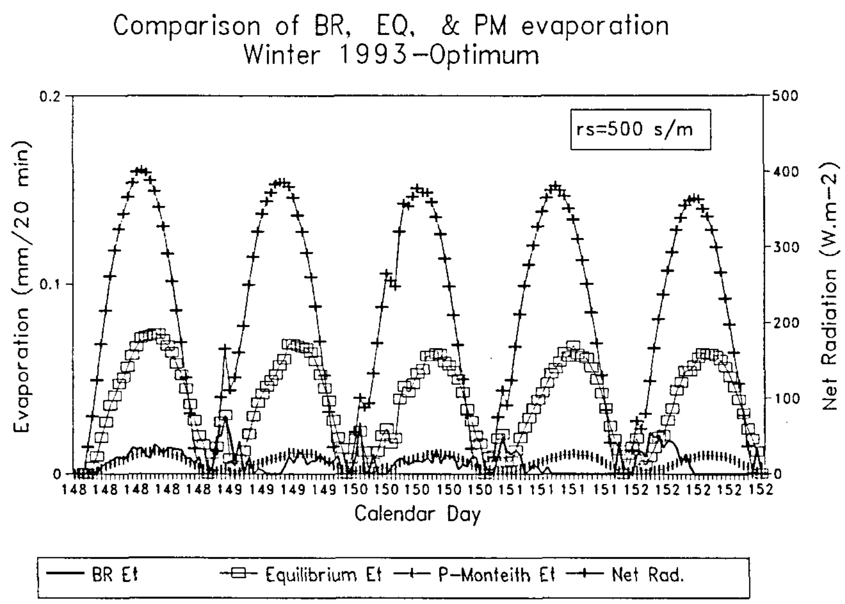


Figure 5.5.4 Comparison of Bowen ratio, equilibrium and Penman-Monteith methods of estimating evaporation in winter 1993 at Optimum.

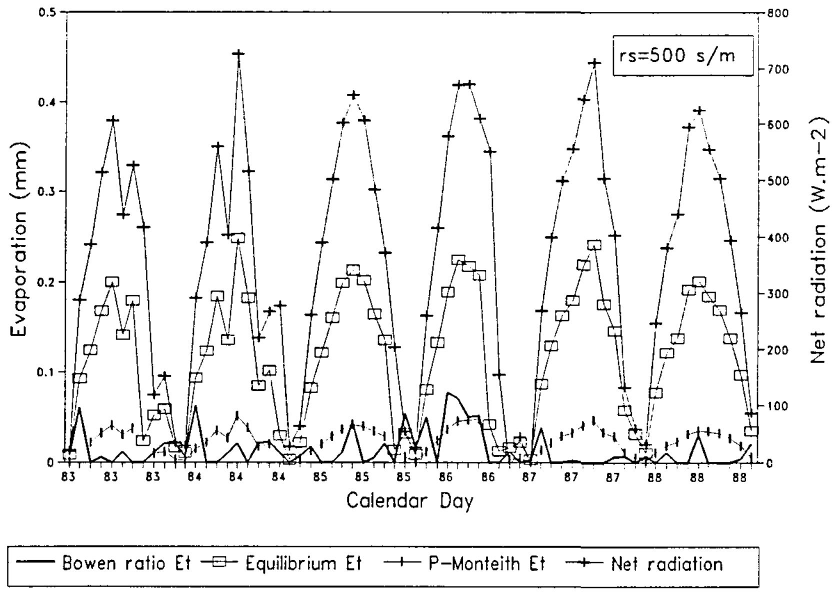


Figure 5.5.5 Comparison of Bowen ratio, equilibrium and Penman-Monteith methods of estimating evaporation in autumn 1994 at Optimum's Hendrina colliery.

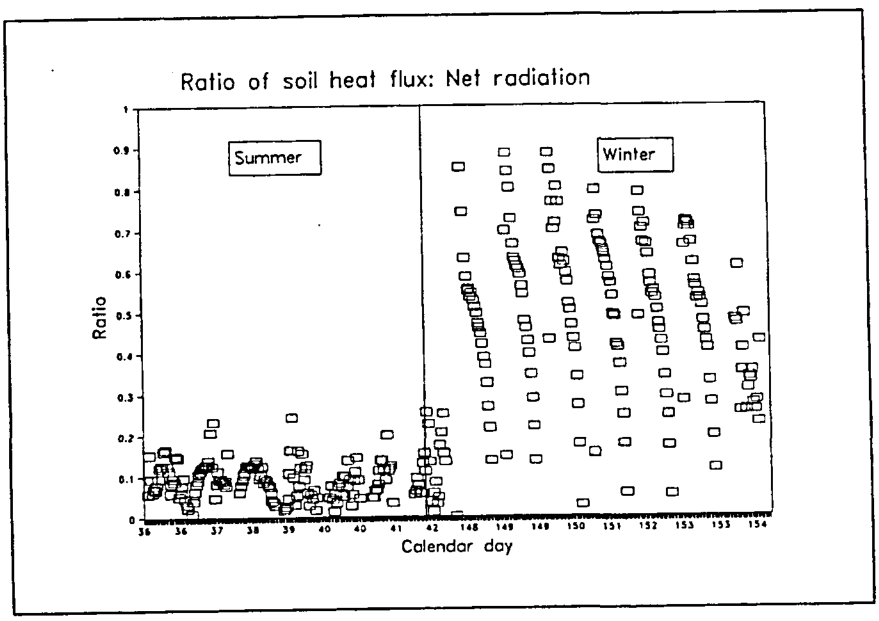


Figure 5.5.6 Ratio of soil heat flux and net radiation in summer and winter.

5.6 GENERAL DISCUSSION: WATER USE BY TREES AND GRASS

The mean daily water consumption by individual trees at all mining sites is shown in Table 5.6.1. The average rates of water use by these trees are compared with grassland water use in Table 5.6.2. These tables are useful for establishing generalizations. Grassland evaporation varied from 0.1 mm/day (Secunda, winter) to a maximum of 3.0 mm/day (Secunda, summer). Winter evaporation was generally less than 1 mm and tended towards zero as winter progressed. Summer values were in the range of 1 to 3 mm/day. In contrast, trees used between 0.5 and 3 mm/day throughout winter, with water use being dependent on the degree of canopy development. Water use during summer varied from 1.5 to 12 mm/day and always exceeded grass water use, except in those cases where tree canopies were not fully developed. Water use of trees was generally greater than grass water use throughout the year. The difference in water use between the two growth forms narrowed during the summer months, with grasslands sometimes exhibiting similar rates of water use to trees. Only trees growing in toe areas at Withok showed substantially higher rates of water use than grasses during summer.

Tree water use expressed on the basis of evaporation per unit leaf area was generally within the range expected for commercial forestry tree species. Most trees transpired at rates of less than 1ℓ/m^2/day, with rates during winter months being approximately 0.5ℓ/m^2/day. The exceptions were the summer values for trees growing in toe areas at Withok and Western Areas, and at West Extension where values of greater than 1ℓ/m^2/day were often recorded.

Distinct differences in rates of water use were evident among trees. Mature trees with fully developed canopies showed greater rates of water loss than younger trees. The increase in water use with tree age is well established for eucalypt species. The relationship between stand age and water loss is not necessarily a linear function because leaf areas of trees increase to a certain limit, after which time it remains fairly constant (Bosch 1979; Van Lill *et al.* 1980). Numerous catchment experiments have provided evidence for this relationship. Van Lill *et al.* (1980), for example, have shown that *E. grandis* trees exerted a substantial impact on catchment streamflow from approximately the third year after afforestation, reaching a maximum at about the fifth year.

A clear difference in water use with respect to tree genera was also found. Eucalypts maintained relatively high transpiration rates. The acacia species were not able to match the transpiration rates of the eucalypts. Differences in rates of water use among the various species of the genus *Eucalyptus* were also evident. The highest water use rates were recorded for *E. camaldulensis* trees at West Extension, and for *E. viminalis* trees at the base of Withok slimes dam during summer. However, eucalypt species such *E. sideroxylon* (Western Areas) and *E. macarthurii* (Hendrina) showed higher transpiration rates than *E. viminalis* during autumn and winter respectively. These differences among eucalypt species should be interpreted with caution since measurements were undertaken on trees growing in different physical environments and direct comparisons among species are therefore not entirely valid. Moreover, the literature provides evidence that the stomatal responses of eucalypt species differ greatly, and these responses vary with environmental conditions. This suggests that eucalypts species are able to adapt physiologically to different environmental conditions. On the basis of our findings it is therefore not possible to make any generalizations regarding which eucalypt species will be more efficient at ameliorating the impacts of mining water. We suggest that selection of the appropriate tree species for rehabilitating mines should be based on how well that particular species is suited to the soils and climate (soil depth, soil structure, temperatures, incidence of frost, salinity levels etc.) of a specific mine.

Table 5.6.1: Mean daily water consumption by trees at the different study sites.

TREE	LA	GR	LAI	HT	DBH	N	DAYS	WATER USE IN MM MEAN	WATER USE IN MM SD	WATER USE IN ℓ/m² MEAN	WATER USE IN ℓ/m² SD
HENDRINA 01/06/93 TO 22/07/93											
T1	18.96	6.00	3.16	6.50	8.10	5	152-156	0.98	0.086	0.31	0.027
T2	17.70	6.00	2.95	5.33	7.35	5	152-156	0.79	0.089	0.27	0.030
T1	17.70	6.00	3.16	6.50	8.10	13	170-182	2.29	0.206	0.73	0.065
T2	18.96	6.00	2.95	5.33	7.35	13	170-182	0.82	0.109	0.27	0.037
T3	31.70	6.00	5.28	7.50	11.48	20	184-203	2.60	0.270	0.50	0.052
T4	15.40	6.00	2.57	5.60	8.00	20	184-203	0.90	0.115	0.35	0.045
T5	13.59	6.00	2.27	3.97	6.00	20	184-203	0.56	0.086	0.24	0.038
HENDRINA 02/03/94 TO 29/03/94											
T1	28.98	6.00	4.64	7.20	8.00	27	61-79	2.908	0.782	0.63	0.168
T2	26.57	6.00	3.90	6.31	7.85	27	61-79	2.142	0.481	0.55	0.123
T3	54.95	6.00	9.16	6.40	11.48	27	61-79	3.345	0.583	0.37	0.064
T1	28.98	6.00	4.64	7.20	8.00	15	120-135	1.078	0.104	0.23	0.224
T2	26.57	6.00	3.90	6.31	7.85	15	120-135	1.062	0.099	0.27	0.025
T3	54.95	6.00	9.16	6.40	11.48	15	120-135	1.581	0.121	0.20	0.012
WESTERN AREAS 17/11/93 TO 01/12/93											
T1	8.526	3.14	2.72	7.66	11.65	8	318-325	9.013	0.687	3.31	0.483
T2	4.263	3.14	1.36	7.11	9.30	8	318-325	5.282	0.393	3.88	0.552
T3	9.800	3.14	3.05	7.46	9.58	8	318-325	9.581	0.888	3.14	0.556
T4	29.84	7.07	4.22	10.61	18.55	8	318-325	8.011	1.413	8.01	1.119
T1	8.526	3.14	2.72	7.66	11.65	7	326-332	7.768	0.822	2.86	0.577
T2	4.263	3.14	1.36	7.11	9.30	7	326-332	4.475	0.284	3.29	0.399
T4	29.84	7.07	4.22	7.46	18.55	7	326-332	6.771	1.233	1.60	0.248
T4	29.84	7.07	4.22	7.46	18.55	3	333-335	9.957	1.141	-	-
WEST EXTENSION 07/02/96 TO 29/02/96											
T1	23.70	-	-	9.52	-	24	37-61	1.712	0.470	0.867	0.238
T2	56.88	-	-	13.30	-	24	37-61	11.789	2.952	2.487	0.623
T3	28.40	-	-	12.00	-	24	37-61	3.967	0.944	1.676	0.399
T4	23.70	-	-	11.18	-	24	37-61	3.902	0.982	1.976	0.497
T5	19.91	-	-	10.55	-	24	37-61	1.968	1.968	1.186	0.318
DURBAN DEEP 05/12/93 TO 17/01/94											
T1	22.32	15.21	1.47	13.72	13.80	12	339-350	2.097	0.259	1.43	0.176
T2	19.20	10.18	3.76	9.14	13.65	12	339-350	1.662	0.176	0.44	0.047
T3	36.00	28.70	250	11.72	20,90	12	339-350	1.913	0.379	0.77	0.159

								WATER USE IN MM		WATER USE IN ℓ/m^2	
TREE	LA	GR	LAI	HT	DBH	N	DOY	MEAN	SD	MEAN	SD
T3	36.00	28.70	2.50	20.90	11.72	15	352-366	1.316	0.266	0.53	0.106
T4	41.47	10.18	4.07	8.14	12.80	15	352-366	2.750	0.856	0.68	0.210
T3	36.00	28.70	2.50	20.90	11.72	15	367-381	1.382	0.178	0.55	0.072
DURBAN DEEP 18/05/94 TO 03/06/94											
T1	8.52	10.78	0.79	6.41	9.83	16	138-153	0.365	0.594	0.46	0.075
T2	40.47	28.70	1.41	10.47	18.85	5	138-142	0.972	0.084	0.69	0.059
WITHOK 28/04/93 TO 03/06/93											
T1	77.1	15.00	5.14	11.78	19.60	37	128-143	3.770	0.404	0.73	0.078
T2	60.7	15.00	4.04	8.80	15.95	19	118-154	4.292	0.854	1.05	0.209
WITHOK 20/01/94 TO 23/02/94											
T1	31.73	5.00	6.09	9.40	12.00	15	20-34	8.253	2.005	1.36	0.493
T2	32.60	5.00	5.72	10.00	13.90	15	20-34	8.350	2.140	1.46	0.561
T3	25.69	15.00	1.92	13.00	17.85	15	20-34	4.902	1.978	2.55	1.030
T3	25.69	15.00	1.92	13.00	17.85	20	35-54	4.393	1.161	2.28	0.605
SECUNDA 20/08/92 TO 05/11/92											
T1	30.97	7.50	4.13	5.38	9.15	27	232-258	2.670	0.410	1.03	0.160
T2	17.15	7.50	2.33	6.12	8.56	27	232-258	2.460	0.440	0.95	0.170
T3	12.75	7.50	1.70	4.28	7.05	56	232-287	0.641	0.104	0.25	0.040
T4	21.86	7.50	2.91	5.28	7.67	56	232-287	0.620	0.116	0.24	0.045
T5	12.75	7.50	1.70	4.94	7.27	56	232-287	0.677	0.141	0.26	0.054
SECUNDA 05/02/93 TO 04/03/93											
T1	54.65	7.50	7.6	7.57	9.90	30	36-65	3.540	1.484	0.47	0.195
T2	16.03	7.50	2.2	5.91	7.20	30	36-65	0.671	0.219	0.31	0.099
T3	28.40	7.50	4.0	6.84	8.63	30	36-65	1.304	1.351	0.34	0.123
T4	7.65	7.50	1.1	5.32	5.85	30	36-65	0.442	0.220	0.40	0.201
SECUNDA 23/02/94 TO 10/03/94											
T1	-	7.5	-	6.85	10.1	16	54-69	2.972	1.1156	0.40	0.117

TREE - tree number
LA - leaf area of tree in m^2
GR - ground area
LAI - leaf area of tree/ground area
HT - tree height
DBH - diameter at breast height (1.3m)
N - number of sample days
DOY - day of year
MEAN - mean daily water use by trees (i) expressed in terms of ground area occupied (in mm) and (ii) expressed in terms of unit leaf area (ℓ/m^2)
SD - standard deviation

Table 5.6.2: Water use (daily evaporation) by trees and grasses at various Highveld mining sites and at different times of the year.

Site	Season	Daily evaporation		
		Grass (mm)	Trees (mm)	Trees (ℓ/m²)
Western Areas	Nov/Dec	2 mm (average)	-	-
		3 mm (18-30 Nov)	7.0 mm	2.5 ℓ
West Extension	Feb	-	1 - 12 mm	0.9 - 2.5 ℓ
Durban Deep	Dec/Jan	-	1.5 mm	1.0 ℓ
Withok	Jan/Feb	2 mm	7.0 mm	2.5 ℓ
Secunda	Feb	3 mm	0.5-4 mm	0.4 ℓ
	Feb/March	-	2.5 mm	0.4 ℓ
Hendrina	Feb/March	1 mm	2.6 mm	0.5 ℓ
Hendrina	May	-	1.5 mm	0.2 ℓ
Withok	May	1 mm	4.0 mm	1.0 ℓ
Durban Deep	May	-	0.5-1 mm	0.5 ℓ
Hendrina	June	0.2 mm	1-2.5 mm	0.4 ℓ
	July	-	1-2.5 mm	0.4 ℓ
Secunda	Aug/Sept	0.1 mm	0.8-3 mm	0.2-1.0 ℓ

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CHAPTER 6

GROWING TREES ON HIGHVELD MINING SITES

6.1 SPECIES SELECTION

6.1.1 Introduction

Selection of species will be dependent on a number of factors. These will include the objective of the planting, the nature of the site, the climate, intended management inputs, and aesthetics. For the purposes of water management the cardinal requirements will be the ability to use large amounts of available surface water, rapid growth and survival under harsh conditions of climate and soil, and sustainability of tree cover.

The Johannesburg-Witbank-Secunda region generally offers a combination of low rainfall, low temperatures, and poor soils. The area is considered marginal for afforestation although many trees have been successfully established in the landscape. Typically, the average frost period at Secunda is 115 days with sub-zero temperatures occurring between May and September. This period coincides with the dry season in which very little rain can be expected. On average, the majority of the season's rainfall occurs in the first half of the summer from October to January. Silviculturally, the area is classified as part of a sub-humid cooler-temperate climatic zone (+Cs5), where very few commercial trees are recommended for afforestation (Poynton, 1979). Different mining environments serve to confound this picture further, with plantings on undisturbed, natural soils; in seepage areas with water of varying quality; and in various forms of disturbed `man-made' soils.

For this reason the generic capabilities of a range of species are considered. Any exact recommendation on species would have to depend on site specific data.

6.1.2 Criteria for selection

General criteria for selection success for use in mining environments on the Highveld include:

- an ability to withstand severe frost and cold in the winter months;
- an ability to grow in an area receiving less than 700 mm mean annual rainfall;
- an ability to use large amounts of available surface water, i.e. trees should be proven effective as high water users.

Site specific criteria which will frequently apply include:

- an ability to grow in man-made `soils' of 300 - 600 mm;
- an ability to grow on gold slimes dams;
- an ability to grow in seasonally waterlogged soils;
- an ability to withstand saline soil conditions.

Based on literature reviews and field surveys of existing tree species some 36 tree species (indigenous and exotic) have been identified as having potential for including in rehabilitation plans on the highveld. These include five *Acacia* species, one *Albizea* species, two *Celtis* species, one *Combretum* species, 18 *Eucalyptus* species, one *Melia* species, one *Morus* species, three *Pinus* species, two *Populus* species, and one *Salix* species.

But species of *Eucalyptus* are usually most successful, and species recommendations are most frequently drawn from this genus.

Further lists of potential species, together with certain attributes, are added to this text as an appendix (Appendix 1).

6.1.3 Some suitable Eucalypts

A species review for silvicultural zone +Cs5 (Poynton, 1979) reveals only four potential *Eucalyptus* species suitable for extensive planting. These are *E. camaldulensis, E. crebra, E. melliodora, E. sideroxylon.* All are considered free from disease and insect attack.

Further potential frost-tolerant *Eucalyptus* species grown commercially on the higher rainfall areas of eastern Transvaal Highveld are *E. macarthurii, E. nitens* and *E. smithii.* Another potential species for afforestation in cold localities and formally growth on a larger scale than any other eucalypt in South Africa is *E. viminalis.* However, this species has fallen into disfavour primarily as a result of its susceptibility to attack by the Eucalypt Snout Beetle, *Gonipterus scutellatus* (Poynton, 1979).

Eucalyptus species observed growing within the highveld target area include *E. camaldulensis, E. cinerea, E. macarthurii, E. melliodora, E. nitens, E. sideroxylon* and *E. viminalis.* Of these the most hardy are *E. macarthurii, E. viminalis* and *E. camaldulensis.*

The characteristics of eight potential *Eucalyptus* species are presented, outlining:

- the natural range of species;
- the naturally occurring soil types within the species range;
- past experience with the species in South Africa, and
- the advantages or disadvantages of using the species.

The following discussion and particulars are based on the work undertaken by Boland *et al.*, 1984; Immelman *et al.*, 1973 and Poynton, 1979, 1984.

Eucalyptus camaldulensis Red Gum

> The most widely distributed of all the eucalypts, it is found in all the States of continental Australia. The climate ranges from temperate to tropical and from subhumid to semi-arid. A moderately large tree, it reaches its best development on alluvial, silty soils of

good depth, but grows satisfactorily also on sands or podsols overlying a clayey, moist subsoil. Essentially a riverine species, it occurs on flood-plains and badly drained flats. An extremely drought-tolerant species. In South Africa it has been cultivated geographically more widely than any other eucalypt. The species has the added advantage of being not only drought tolerant but also extremely salt and frost tolerant.

Eucalyptus crebra Narrow-leaved Ironbark

A small to medium sized tree growing to a height of 18 to 30 m. It has a distribution in a broadbelt along the east coast of continental Australia from Queensland into New South Wales. The climate ranges from tropical to temperate. Light frosts occur on 5 to 10 nights per year. It usually occurs on acid, sandy soils overlying an alkaline, sandy-clay subsoil. The species has only been planted on a limited experimental basis in South Africa, where it has fared moderately well under dry localities.

Eucalyptus macarthurii Camden Woolybutt

A medium-sized tree, attaining a height of between 18 and 40 m. It has a very limited distribution in the central tablelands of New South Wales. The climate is temperate and fairly humid. Frosts occur 30 to 40 nights of the year. The species is found in hilly country, where it occupies the banks of streams or flats subject to temporary flooding. These situations are colder and wetter than the surrounding hillsides. In South Africa it is grown on a modest scale on the eastern Transvaal Highveld for the production of mining timber and pulpwood. The species has the distinct advantage of being one of the most hardiest of all the commercially grown *Eucalyptus* species in South Africa.

Eucalyptus melliodora Yellow Box

A medium-sized tree commonly growing to a height of between 18 and 30 m. It has a very wide distribution in south-eastern Australia. The climate is warm and dry. In winter 5 to 30 frosts may occur. The tree is found on gentle slopes or on low-lying flats adjacent to watercourses. In South Africa it is grown for amenity purposes and is widely planted in the subhumid and semi-arid regions of the highveld. The main attraction of using the species is the proven record of the species on many diverse sites.

Eucalyptus nitens Shining Gum

A large tree attaining a height of 30 to 40 m. It has a somewhat restricted and disjunct distribution in south-eastern, continental Australia. The climate is cooler-temperate, and frost occurs 50 to 150 nights per winter. The tree is found in sheltered slopes and valleys. It is particularly common on podsols with a moderately clayey but well drained subsoil. In South Africa it is one of the most desirable species for commercial afforestation in areas where the frost is severe. The species has the distinct advantage of being one of the most hardiest of all the commercially grown *Eucalyptus* species in South Africa.

Eucalyptus sideroxylon Red Ironbark

A fairly large tree, often attaining a height in the region of 30 m. It has a wide distribution in south-eastern continental Australia. The climate in the interior is warmer-temperate and subhumid to semi-arid. In winter 5 to 20 frosts are experienced. It occurs mainly on poor shallow soils. In South Africa it is grown very widely in the cooler drier parts of the country for general amenity purposes. The main disadvantage of the species is the possible allelopathic nature of the tree on the surrounding vegetation.

Eucalyptus smithii Blackbutt Peppermint

A tree of fairly large to medium size, obtaining a height of up to 46 m. It has a limited distribution in New South Wales. The climate is temperate to cooler-temperate and humid. In winter frost occurs on 40 days of the year. In South Africa the species has been used on a moderate scale in the cooler temperate regions of the Transvaal Highveld for pulpwood production. The species shows a distinct drought-tolerance over other commercially grown species within the same aforementioned area.

Eucalyptus viminalis Manna Gum

A moderately large tree reaching a height of 30 to 37 m. It has a wide range in south-eastern, continental Australia and in Tasmania. The climate is temperate and humid to subhumid. Between 5 and 60 frosts are experienced a year. It grows best on fertile, moist but well-drained alluvial deposits, but also grows on a wide variety of soils, and it is common on sandy podsols overlying clay. At one time it was planted quite extensively for afforestation in the cooler and more humid parts of South Africa, but is now little planted chiefly on account of being attacked by the Eucalypt Snout Beetle. The species is not "wetfooted" and its main attraction is its extreme cold-tolerance. A disadvantage is the possibility of an attack by the Snout Beetle. The timber market for this tree is also not very favourable in South Africa.

6.1.4 Other wet footed trees

The poplars (*Populus canescens, P. deltoides*), the black wattle (*Acacia mearnsii*) and the green wattle (*A. decurrens*) grow well in very wet environments. The planting of poplars is by means of sets or 'truncheons' set into the ground. This usually presents logistical problems. *Acacia mearnsii* is almost too successful, and its ability to spread unchecked is a major drawback. Other species which could do well in the planting of very wet sites are the willows (*Salix*) and mulberries (*Morus*) which have a natural ability to withstand waterlogged conditions.

6.1.5 Indigenous trees

Although observations on naturally occurring indigenous trees are few it is probable that many may be suitable for establishment. These include *Acacia albida, A. galpinii, Celtis africana, Combretum erythrophyllum, Leucosidea sericea,* and *Rhus lancea.*

6.1.6 Agroforestry species

Water use by trees at different espacements still requires research, but where wide espacements are feasible and rooting depth is not seriously restricted, attention should be given to the possible introduction of agroforestry species with intercropping.

6.1.7 Genetic selection and hybridization

It is possible to genetically select tree species for superior performance under harsh conditions. There are several tree breeding initiatives aimed at combining eucalypt species that exhibit drought resistance and the ability to withstand frost. Single cross combinations of *E. camaldulensis* x *E. nitens* and triple cross combinations of *E. camaldulensis, E. nitens, E. saligna,* and *E. viminalis* may prove valuable in rehabilitation efforts under the marginal conditions of the highveld.

6.1.8 Salt and heavy metal tolerance

There is an increasing interest in the need for salt tolerant species, with *E. camaldulensis* identified as one of the most promising species. Alcoa of Australia are marketing an *E. camaldulensis* 'supertree' with very high salt tolerance qualities.

Some of the eucalypts have been observed growing in what appear to be the most uncompromising of chemical environments. It is important that material from these trees, which have demonstrated their genetic adaptability, should be collected and placed in clone banks for possible future use. There is some urgency with regard to a programme of this nature as many old sites, on which generations of natural selection has taken place, are rapidly disappearing through mine dump recycling and urban expansion.

6.1.9 Recommendations on species selection (eucalypts)

The most hardy of the eucalypts are *E. viminalis, E. macarthurii* and *E. camaldulensis.*

Species selection will always have an element of site specificity. Some guidelines are nevertheless provided:

- Rehabilitated open-cast coal mines, where soils are considered shallow with 30 - 60 cm of topsoil over broken rock and with a deep water table: *E. camaldulensis, E. crebra, E. melliodora* and *E. sideroxylon.* The ironbarks in general are good on shallow soils. Of the above species *E. camaldulensis* is the most naturally successful. Plant material for all of the above species may be difficult to obtain.

- Deep, undisturbed, well drained 'natural' soils: *E. macarthurii, E. nitens, E. smithii, E. viminalis.*
  Note: These species may also succeed on rehabilitated open cast mines where root penetration is not inhibited below the top soil layer. Successful growth will depend on the ability of these species to exploit the rock and soil mix below this topsoil.
- Seasonally wet 'natural' soils. *E. macarthurii* and *E. viminalis.*
- Saline soils: *E. camaldulensis.*

6.2 ESTABLISHMENT AND SILVICULTURE

The reader is referred to the Forestry Handbook (Southern African Institute of Forestry, 1993) for a detailed review of commercial forestry practice in South Africa.

Prescriptive recommendations for soil preparation, espacement, fertilisation, pruning, thinning and fire protection can only be made on a site specific basis (ie by site type). This is because the individual soil characteristics, climatic zone, type of mining activity & soil disturbance, and water quality will differ from site to site. But knowledge of the soil types, clay mineralogy, and rainfall pattern can be used to narrow the field in terms of species selection, soil preparation and silviculture.

6.2.1 Supply of trees

There are several nurseries on the highveld producing a limited range of commercial tree species. The hardening of young tree seedlings is highly recommended and the use of a highveld nursery is an important step in achieving this. One of the current shortcomings is in the range of available species and the planning and ordering of trees needs to be at least one year in advance of expected planting date. The seedling supplier should receive an exact specification of the product required (species, height, expected collar diameter, nature of container and root plug, degree of hardening). It is common practice for the tree grower to supply the nursery with selected seed of the grower's choice - particularly where the use of improved seed is important. The grower should establish a good relationship with the seedling supplier and should visit the nursery at intervals to check on seedling growth and quality. Inquiries with regard to the supply seed for less common trees should be directed to the Seed Store, Directorate of Forestry, Department of Water Affairs and Forestry.

Many small nurseries are beginning to produce trees. These nurseries are often accustomed to growing vegetable seedlings and tend to use trays with small rooting plugs which may result in the loss of trees on establishment. For optimal establishment success on the highveld trees should be supplied, in a growing medium containing some soil, in sleeves with a diameter of about 7,5 cm.

6.2.2 Hardening of nursery stock

The hardening of trees is normally achieved through the topping of all seedlings (removing the top one third of the plants), and then systematically reducing the availability of fertilizer in the growth medium. Trees are also automatically hardened for the winter if grown on cold sites. Seedlings imported from a nursery situated in a warmer region could, typically, be held in a 'holding nursery' until suitably acclimatized.

6.2.3 Time of planting

On the highveld the earliest plantings would normally be in September and plantings should not continue beyond mid-January at the latest. Seedlings *must* be hardened if trees are to survive late planting. Plantings after December always show bigger losses. It is however also possible to plant during the winter but this requires special precautions against frost damage, wind chill and wind desiccation. Wind chill will kill even frost resistant trees, and especially those still carrying juvenile leaves. For winter planting in cold areas the properly hardened seedling tree should be stripped of all but two single leaves and even these leaves can be cut in half so that half of the leaf remains attached to the petiole. This reduces frost damage. Winter planting requires the use of "puddle planting" with 2 litres of water given to each tree on planting and a further 1 litre after four weeks in the ground. The main reason for winter planting is to ensure that all trees are already in the ground before the first rains, in order to maximize use of the summer growing season.

6.2.4 Site preparation

Site and soil surveys are necessary prior to establishment. Species choice, method of establishment and fertilizer recommendations are made on the basis of these surveys. Deep ripping is generally used as the standard soil preparation but the success of this operation is very dependent on the site, the time of year, length and design of the tine. Ripping in summer, when the soils are wet, does not have the same shatter effect as ripping in the winter or spring. Ripping also appears to be of no value in certain heavy clay soils (eg. Arcadia, Rensburg soil types). A recommended alternative is contour ridging on wet or water-logged sites, using mould-board ploughs or off-set discs, with the trees planted on the ridges. This applies particularly to wet-sensitive trees. Ridges also have the advantage of preventing surface run-off. Care must be taken not to mix the A and B horizons.

If ripping and ridging then one must take into account catabatic air flows at night and the creation of frost pockets on the windward side of the ridge, i.e. the upside slope upon which one would normally plant. Trees can be pit-planted on coal dumps, rehabilitated open-cast coal mines, and on slimes dams.

Where trees are to be planted on undisturbed natural soils, where there is no waterlogging (typically old agricultural lands along the perimeter of slimes dams), preparation can be limited to a discing of the site, primarily for weed suppression.

Land preparation should be completed at least one month before planting to give the soil time to settle.

6.2.5 Espacement (stems per hectare)

There are a number of considerations in selecting tree espacement:

- The amount of water which needs to be taken up by trees and the urgency of the water management problem
- Biomass production and possible end uses for the timber
- Site quality (including soil depth, nutrients, salinity, possible heavy metal toxicity) and consequent expected growth rate
- Management considerations (access, weeding, fire management)
- Aesthetics
- Agroforestry options
- Tractor and implement width where mechanical site-preparation is to be used
- Cost

Some espacement standards for eucalypts are given below :

Saw Timber:

2.74 * 2.74 m = 1330 stems per hectare (sph).

These stands are then usually thinned to 750 stems at 4 years, to 500 stems at 6-7 years, and to 300 at 10-12 yrs. Stands are felled at 25 years.

Mining timber:

2.4 * 2.4 m or 1.8 * 3.6 m.

The latter spacing brings 1730 stems per ha (approx). The wider between-row espacement has a number of advantages (see below).

The greater the number of trees established initially the more rapidly a high canopy leaf area can be expected to develop (advantageous to high early water use). Beyond about 1730 stems per hectare this advantage is relatively short-lived as light to the canopy quickly becomes the limiting factor. Cost of establishment at a high stocking rate must be weighed up against the advantages of rapid canopy development.

Very wide initial espacements (eg 3,5 m * 3,5 m or 820 sph) result in short, stocky trees with heavy branching and concomitant management and utilization problems.

A density of 1500-1800 stems per hectare is recommended for maximal short term water uptake.

Over the longer term a very wide espacement may be adequate, with large trees occupying all the available soil root volume. This could also allow for agroforestry practices. Wide espacements may be particularly useful where trees are planted in seepage zones along the toes of dumps, and where trees are intended to intercept lateral flow.

The stocking density should be achieved through a design layout with wide inter-rows and close planting within rows. Rows should as far as possible be aligned in an east-west direction in order to optimize interception of available solar energy. The adoption of wide inter-row spacing significantly reduces the cost of establishment, especially where the site is to be ripped. Wide rows also saves on weeding as tractor mowing is easier. Plantations are more accessible to heavy machinery, improving fire protection and facilitating eventual harvesting.

6.2.6 Fertilization

As a general rule, 100 g 3:2:1 is applied to eucalypts to encourage maximum growth. However, this is a broad recommendation applicable to areas where commercial plantations exist. Foliar analyses of trees already growing in the area, as well as soil and water analyses can be used to establish more refined fertilizer norms.

6.2.7 Thinning and pruning

Minimal silviculture is usually practised within *Eucalyptus* stands grown for mining timber or pulpwood. Trees may be pruned (or 'brashed') to a height of 1,5 m. This is primarily intended to facilitate access and forest protection. The removal of lower branches may seem in conflict with the need to maximize the transpiring canopy but these leaves tend to be relatively inactive and pruning ultimately stimulates growth. Stands are not normally thinned unless grown specifically for saw log production (see 'Espacement'). Selective harvesting will have the short-term effect of a thinning while allowing for immediate regeneration within the gap created.

6.2.8 Fire protection

Fire protection is likely to be the most important of all management practices. Most trees are very susceptible to fire, although some of the eucalypts (especially those with thicker bark) are resistant and scorched leaves are quickly replaced with coppice regrowth. Fire amongst trees may however be far more severe than in the original grassland due to the increased biomass.

6.2.9 Rotation and sustainability

Trees are currently being planted on highveld mining sites with little thought for the fact that stands age, and will require harvesting and regeneration. Rotation age in commercial afforestation is very variable, depending on site quality and resultant growth rate, and on the purpose for which the trees are being produced. Rotations generally vary between 8 and 25 years. Highveld sites (including most mining sites) are likely to be low in productivity and trees may be kept for longer periods than in the case of typical commercial rotations. If timber is to be utilized for mining timber or pulp the maximum acceptable age is likely to be 10-11 years.

Work by Olbrich (1991) indicates that water use by *Eucalyptus grandis* in fact peaks at a relatively young age and then tails off. It is not desirable to allow stands to grow old and moribund where water use is the priority, and stands should be managed to ensure a state of continuous renewal. The eucalypts have an advantage in that trees can be regenerated through stump coppicing (with one to three resprouting leaders allowed to grow. This permits the continuous removal and regeneration of a stand, with perhaps every third tree in a row (or every 3rd row) removed every four years. Trees will only need to be replanted when stumps get too big, in which case the individual stumps may be poisoned and trees replanted.

This picture may be different where trees are grown singly or in single rows. Single trees do not age in the same way as stands, due to the lack of competition, and such trees would generally be allowed a far longer lifespan.

6.2.10 Research and pilot trials

Research is still required on optimal stocking densities and silviculture where trees are to be grown for water management. Pilot trials may be required to determine :

- what species to plant
- best method of establishment
- optimal espacement
- optimal fertilizer regimes
- rotation - cycles and regeneration methods

6.3 REFERENCES

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CHAPTER 7

RECOMMENDATIONS FOR RESEARCH AND MANAGEMENT

7.1 INTRODUCTION

This study offers substantial evidence that certain trees can and do use more water than pastures which otherwise might be established on the site, or the natural grassland which the trees might be replacing. This water use is dependent on successful establishment and growth of tree cover.

This additional water use by trees has been determined for a limited range of species, almost exclusively from the genus *Eucalyptus*, but for a range of sites and seasons. While our knowledge of water uptake by eucalypts does not yet provide us with exact predictive knowledge, it probably exceeds our knowledge of how sustainable tree planting within mining environments might be, how and what levels of tree cover can actually be attained, and what the impacts of such water uptake may ultimately be upon the environment - both in terms of local soils and the mine drainage problem which the use of water is meant to ameliorate.

Parallel research programmes funded by the Water Research Commission are addressing some of these questions. These include the `Regional Investigation into groundwater quality deterioration in the Olifantsriver catchment above the Loskop Dam with specialized investigation in the Witbank dam sub-catchment' (Institute for Groundwater Studies, UOFS), 'Establish guidelines and procedures to assess and ameliorate the impact of gold mining operations on the surface water environment' (Environmentek CSIR), and 'Screening of crop, pasture and wetland species for tolerance of polluted water originating in coal mines' (Department of Plant and Soil Science, University of Pretoria).

This research project on the water use by trees in mining environments on the Highveld has been for an area in which no tree water relations work has previously been undertaken. This is not a traditional `forestry' area and trees are generally scarce in the landscape. There is little or no indigenous woody material, either natural or re-established.

Research needs may be classified as either hydrological or silvicultural.

7.2 RESEARCH NEEDS - WATER USE BY TREES

Site water use

The wide ranging nature of this study suggests that there is merit in planting trees, and offers a quantification for this. It is now recommended that single, intensive studies be launched to examine the variability within each of the mining environments identified as most important. For example, measurement of water use by trees on rehabilitated open cast coal mines is at present limited to a single above-mine site where the nature of the spoil limits rooting (and hence growth) to a depth of one metre. Water use measurements need to be extended to include differences in spoil type, depth and drainage. The efficacy of trees planted in the decant zone has also not yet been tested. The survival success of some trees, observations on rooting, and results from actual measurements of water use all argue, on conclusion of this study, for more work on the establishment of trees on the tops of slimes dams.

Recommendation: *Additional site research on water use by Eucalyptus species prioritized as follows - on open-cast coal mines, within the decant zones of both coal mines and gold slimes, on gold slimes, over coal total extraction (longwall) mines.*

Species water use

This project has shown that trees are much better equipped than grasses to ameliorate the negative impacts of mining on water quality. In this study eucalypts have been identified as the most effective water users of all the species studied. However, further research needs to identify other successful species, to allow for a more diverse approach to tree planting in mining environments.

Recommendation: *Trials on a range of species for use as alternatives to eucalypts.*

Age class and water use

Most of the research on tree water use on mines has been undertaken on young stands which have not yet reached their full development (and evaporative) potential. Work needs to be carried through to mature trees. It is expected that optimal water use will depend upon maximum leaf cover but that this may be ameliorated by age.

Recommendation: *Research on water use rates by different age classes of eucalypt.*

Water use by grass - benefits of grass management

Grassland water use in this project was measured for swards established and managed for site stabilization and dust control. Further research should concentrate on how well this grass sward can be managed to increase water use to control the water table. All the water use measurements have been either for trees, or for grass swards, but never for trees and grass growing together. This will be the case in young stands, or in agroforestry stands. There are still many grass-tree combinations which can be explored.

***Recommendation**: Research on grassland and grass/tree management for water use. Particular consideration should be given to the propagation of temperate evergreen grasses (eg Merxmuellera) as opposed to seasonal grasses.*

Evaluating the benefits

Recognition of the transpiration capacity of forest trees has already led to the establishment of trees for water management purposes on some mining sites. How effective are these trees in achieving this purpose? For the most part trees are still too young to have had a meaningful impact. Research will however have to start assessing ways of evaluating the bottom-line impact. The water input to active mines, or reduced levels of outflow from areas over which trees have been planted, need to be measured. Intermediate evaluative measures could be the measurement of soil water content in profiles within stands of trees compared to that of adjacent sites.

***Recommendation**: Design ways of measuring the impact of trees on mine water budgets directly. Assess impacts on water tables, outflow or runoff, and compare with transpiration water use estimates.*

Modelling and extrapolation

The prediction and extrapolation of results on tree water use needs to be explored at a number of levels. What, for example, are the likely impacts at quaternary catchment scale, and even at the scale of the primary catchment?

***Recommendation**: Assess the costs and benefits of planting trees at the scale of the quaternary catchment.*

Water quality vs Water supply

Determine the potential impact of trees on regional water resources. The implications which the extensive introduction of trees for the management of water *quality* may have on water *supply* in the Olifants, Crocodile and Vaal river catchments, and for the economy of the Highveld, must

be considered.
***Recommendation**: This is largely a policy decision. The implications of a strategic shift in water management and wood production must be considered by the Department of Water Affairs and Forestry (DWAF), and other stakeholders.*

7.3 SILVICULTURAL AND SITE RESEARCH

Genetic selection and clonal propagation

Observations on gold mines around Johannesburg show that trees grow successfully in pyritic water. There has already been 100 years of natural selection on some of these sites and the trees we find are the `survivors'. These sites, and their trees, are however rapidly being lost to reprocessing and other development. Material from trees within these polluted environments needs to collected, screened, replicated, and stored in a tree bank, with a record of site origin and water quality. The University of Pretoria also has an interest in this research field.
***Recommendation**: Establish a clonal bank of trees from material currently growing successfully in polluted mining environments.*

Root studies

The pilot study on rooting depth indicates major limitations in most mining environments. Trees nevertheless clearly occupy a greater soil volume than grass. This study needs to be expanded, particularly with regard to gold slimes dams and rehabilitated open cast coal mines. The nature of barriers to rooting depth on slimes, and whether these can be overcome should also be investigated. The study also needs to look at other species, notably the acacias, with the objective of assessing which trees are better at utilizing the soil environment.
***Recommendation**: Root studies to determine the barriers to tree roots on gold slimes and rehabilitated open-cast coal mines, trees most able to penetrate these barriers, and ways of promoting deep rooting of trees.*

Forest management practice

Research will be required on optimal stocking densities and silviculture where trees are to be grown for water management. Pilot trials may be required to determine:

- What species to plant
- best method of establishment
- optimal espacement
- fertilization

- rotation cycles and regeneration methods

Silvicultural testing and selection of trees is usually on the basis of extensive plot trials of different species and different provenances. There is a wide range of ornamental planting from which 'non-commercial' species may be selected, but there have been no species trials on Highveld mining sites, with the exception of a trial introduced by Secunda Collieries in 1993. The establishment of a series of species test plots, based upon our knowledge of likely successful species, is highly recommended. These would include species trial plots on gold slimes dams, in seep areas adjacent to gold slimes dams, on sites with recognized toxicity problems and particularly salinity problems, on a range of rehabilitated coal open cast sites, and in the seep areas of such sites.
***Recommendation** : Perhaps twenty trials on a range of sites, each entailing about 20 species but with each trial also laid out as replicated plots which may contain anywhere from one to 100 trees, would provide invaluable research data on survival and growth, and a vast pool of material for future water use research.*

Espacement and agroforestry
Water use may be expressed for individual trees on the basis of size, projected canopy leaf area, or on the basis of stand water use. Projected canopy leaf area may be high if expressed as Leaf Area Index (canopy leaf area / projected ground area) - indeed very high if compared to expected stand leaf area index (total stand leaf area / stand surface area). This would be a natural result of competition between trees (for nutrients, light, and water) within a closed canopy stand. The implications are that very widely planted stands, or individually planted trees, may be more efficient in terms of water use per unit ground area occupied by the trees, although total water use on the area might be less. Grasses and other crops grown between trees will also use water. Widely spaced trees may therefore be more efficient in terms of numbers of trees planted. Open plantings are likely to achieve more per tree in terms of water use and offer other benefits. Future water use research should therefore include espacement as a variable.
***Recommendation**: Assess optimal espacement and agroforestry options.*

Site chemistry and sustainability - impact on soils
The effect which the continued removal of water from polluted sites may have on soil chemical build up needs to be evaluated with regard to the sustainability of any tree planting project on seepage areas. It is probable that this can be achieved through chemical water balance

modelling. The degree to which heavy metals may be removed from some sites through accumulation in the biomass is already being researched.

Recommendation: *Determine the impact of enhanced evaporation on soils and site sustainability.*

Irrigation with wastewater

There are many research opportunities with regard to irrigation with the seepage water which is trapped behind impoundments. This water is considered as being unsuited for release to rivers. Water use by vegetation would be advantageous to a number of industries other than the mining industry - most notably power generation. The constituents of such waste water would have to be carefully assessed with regard to site assimilative capacity and sustainability. (ie impacts on the soil). There may be little benefit to irrigation if chemicals are eventually to be flushed into rivers - unless perhaps such flushing could occur at times of high flow when the rivers themselves are able to accommodate the added constituents without harm.

Recommendation: *Establish irrigation trials with wastewater and test for impacts on soils.*

Do trees solve the problem?

There is a belief that the reductions in throughput of water only serve to increase the output concentrations of chemicals. This hypothesis needs to be rigorously debated and tested. If this contention is valid, it is likely to put a brake on tree planting activity for certain sites, notably over rehabilitated open cast coal mining for which the theory was developed. This may lead to a shift in emphasis to trees growing in seepage areas.

Recommendation: *Debate and test the importance of the leaching process to the long-term recovery of the system.*

7.4 RECOMMENDATIONS FOR MANAGEMENT

- *Assess permit and legislative constraints*

  There are political and legislative constraints to the planting of trees in any catchment area. Management needs to weigh up carefully the impacts of trees on the water resource with regard to both quality and yield. Legislative and permitting requirements must be met, but if these do not best serve the requirements of the catchment and the water resource, then change must be encouraged.

- *Trees are not the only remedy*
  Trees may be useful in controlling or reducing excess water but should not be seen as a solution to every problem. Trees may prove to be one of a suite of tools useful in containing water quality management problems.

- *Trees are not always a good solution*
  Trees may not be effective in every environment. The long term impacts of throughflow control are not fully understood. Use of trees must be carefully evaluated for every situation.

- *Trees as a site rehabilitation tool*
  Rehabilitation could be managed through the production of commercial timber, and/or establishment of ecological preserves. Longer-term objectives may include the rehabilitation of sites to former agricultural potential, or potential for urban development or recreation. Agro-forestry practices may prove ideal as an interim land management measure. The use of trees is not irreversible and should be viewed as a short to medium term option for the management of agricultural land, and through which such land can be brought back into agricultural production. The agricultural nature of small scale forestry operations, and the ability to mix farming and tree planting activities is an advantage.

- *Do not use trees as a rehabilitation short-cut*
  Trees must not be seen as a short-cut to site rehabilitation. Land must be restored, as best practically possible, to its original condition before the introduction of tree species for water management.

- *Take care in selecting the most effective planting site*
  The siting of trees is likely to be critical with regard to their effectiveness as water users. The most effective way of tackling the problem needs to be correctly identified. Extensive plantings aimed at cutting off rainfall at 'source' may not be necessary if small plantings of trees can be used as seepage interceptors. Management needs to quantify seepage paths, and the amount of water infiltrating and exfiltrating, in order to plant sufficient trees.

- **Site species matching**

  Selection of the appropriate tree species for rehabilitating mines should be based on how well that particular species is suited to the soils and climate (soil depth, soil structure, temperatures, incidence of frost, salinity levels etc) of a specific mine. This site species matching must be carefully applied.

- *Prepare a forestry management plan*

  The Highveld is a marginal area for the growing of trees, and has been considered sub-marginal for commercial forestry development. This is the result of a combination of soil and climatic factors. Professional advice is recommended with regard to species, establishment and site maintenance. This would normally entail the preparation of a forestry management plan.

- *Pre-plan tree planting operations*

  In the case of high extraction coal mining, it may prove effective to plant trees well in advance of the mining operation in order to minimize water influx to the mine workings. This would require 10 year advance planning for maximum impact.

- *Long-term maintenance of trees for water management*

  The problem of water management is not resolved once trees are established. Trees need to be managed as a continuous young crop in order to sustain maximized water use. This will require the introduction of techniques for cropping and utilization which may diverge from normal forest management practice.

- *Alternative species*

  Eucalypts have been targeted in this report as effective water users. Applications have also generally been expressed in commercial forestry terms. Management should however consider the range of species possible, and particularly the opportunities for mixed species planting.

- *Tree planting options*

  Options for planting trees may be commercial, woodlot, ornamental or in an agroforestry combination. This will depend on the need for water management, the water yield/water quality tradeoff, site suitability, environmental constraints, urban (need for recreation) and agricultural conflicts, and the market for timber products. The opportunities for agroforestry need to be explored in the light of hypothesis that wide tree spacing may be very effective in water management.

- *Market opportunities*
  Trees planted for water use will, in all likelihood, also have some commercial value. Market opportunities, particularly with regard to the country's needs for reconstruction need to be explored. Returns from tree crops can be used to offset the costs of establishment and maintenance.

- *Grassland management*
  Grasses may use as much water as trees - at least in certain environments and at certain seasons. It is important that tree management does not lead to the neglect of grassland, both within plantation areas and elsewhere. The implications of weed management for weed growth should be very carefully directed to minimize damage to the grass sward.

- *Land use conflicts*
  Can trees be reconciled with entrenched agricultural interests? The Transvaal Highveld carries a strong agricultural economy. Trees must be seen as additional to this landscape and not as a threat to agricultural land. There is a need to research the combination of these interests through agroforestry options on rehabilitated sites.

7.5 NEXT STEPS

Eucalypts are found to be very effective water users, even in surprisingly hostile mining environments. Intensive silvicultural research will, however, be required in order to optimize growth, survival and water use. Grassland too can perform surprisingly well as a water user, particularly in undisturbed environments. Trees should not be seen as a panacea, and not to the detriment of grassland management. Ways of achieving a grass cover with evergreen species in the mix should also be researched.

The first steps in implementing the use of trees in the management of mine water are to resolve the policy issues of water use vs water quality, and to assess the legislative and permitting aspects of growing trees within catchments upon which forestry moratoria have been placed in order to protect the water supply from a quantity perspective.

The benefits of trees in managing acid or toxic mine drainage still need to be assessed at the level of the 'bottom-line', i.e. the impact on actual mine outflow. But there is little doubt that this will be real, and that trees could become a desirable extensive management practice upon the South African Highveld. Acceptance of this principle would be a major strategic decision requiring a considerable shift in the use of water resources, primarily away from traditional forestry regions along the escarpment. Further research will be required in order to back a decision of this magnitude.

The best way in which to prepare for such an eventuality, and to create opportunities for research, is to allow and encourage extensive trial plantings over a range of sites. This should be concentrated on rehabilitated coal mines. Wherever possible monitoring and evaluation procedures must be established. The Department of Water Affairs & Forestry is encouraged to facilitate this process.

Mining houses are encouraged to establish formal plantings of trees using best available silvicultural advice, and to support the research needed to quantify benefits. Ultimately the decision is one of economics - an assessment of costs and benefits:

- is the value of water quantity greater than the cost of poor quality?
- can trees be used to evaporate the water in a cost effective way?
- are there additional economic benefits to be had (timber for water) to offset the costs?
- is the approach sustainable?

These analyses require good information and the industry must be proactive in supporting the growth of this information base.

CHAPTER 8

DATA STORAGE AND AVAILABILITY

8.1 NATURE OF THE DATA

The following data was captured in the execution of this project to determine water use by trees and grasses in mining environments.

8.1.1 Sap flow data (heat pulse velocity)

Data for sites and time periods as indicated in Chapter 5 of this report.

All data files comprise header data indicating the site, dates, species, tree parameters (including height, diameter and leaf area), and tree espacement.

All data is stored in Quattro Pro worksheets with labelled columns. Data is stored as hourly sap flow (ℓ/hr) together with estimates of evaporation on an hourly and a daily basis.

8.1.2 Bowen Ratio data

The Bowen ratio data comprises both a complete set of weather station data together with the net radiation, temperature and humidity flux data necessary for the calculation of the latent heat of evaporation. This includes measures of soil heat flux.

Bowen ratio evaporation is calculated from sampling conducted at 20 minutes intervals. The row data collected from the field is passed through several filtering and computational phases to provide a final spread sheet of 20 minutes evaporation data.

These data records are stored, together with all site header data, in Quattro Pro worksheets as 20 minute, hourly and daily site evaporation.

8.2 STORAGE OF DATA

8.2.1 Processed data

All processed data has been catalogued and stored at Environmentek CSIR, P.O. Box 320, Stellenbosch, 7599. Data also supplied on diskette to the Water Research Commission, P O Box 824, Pretoria, 0001. Tel: 012-3300340.

8.2.2 Raw data

Raw data, and data in various stages of compilation, has been stored as follows:

Heat pulse velocity and Bowen ratio: Environmentek CSIR, Pietermaritzburg. Contact persons: Dr C S Everson, Dr P J Dye.

These data are held on non-flexible diskette.

8.3 AVAILABILITY OF DATA

All data can be supplied to researchers and managers on non-flexible diskette. Data is the property of the Water Research Commission.

APPENDIX 1:

POTENTIAL SPECIES FOR USE IN HIGHVELD FORESTRY IN MINE SITE REVEGETATION AND IN THE CONTROLLING OF LEACHATE

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INTRODUCTION

Species below are recommended for normal soils, and water of acidity and sulphate levels within the natural ranges. Recommendations for direct plantings into ash or discard dumps cannot be made with confidence until trials have been carried out. Similarly the impact of highly acid or highly alkaline waters with an excess of salts, particularly over the long-term, will require research to assess. Educated guesses can be made in this regard based on literature surveys, past experience, and a survey of species found currently inhabiting such sites. Careful thought should be given to the logistics of obtaining seed and propagation of plants.

Literature surveys and international contacts are likely to produce a number of alternative tree species. If aesthetics are to be a consideration, mixed plantings of species is an option.

In addition to trees, both emergents (herbs and grasses) and shrubs should be considered where it is unsuitable to establish trees (dam walls), and as inter-row ground cover between trees.

POTENTIAL SPECIES

EUCALYPTUS spp.

Sub-genus Symphomertus

E. viminalis	Number one Highveld tree in the 1920's. Devastated in the past by eucalyptus snout-beetle. Biological control effective but not completely successful. The control parasite could be re-introduced to sites after each winter if necessary. The species performs well. Very hardy.
E. camaldulensis	River gum. Can handle excess water and flooding. This has also been an important Highveld species. Drought tolerant. Very hardy.
E. nitens	Cold resistant. Provenance trials conducted at Pan near Middelburg. The species is very provenance sensitive. Planted commercially in this area. Grown with *E. macarthurii* on poor, wet sites. A good species to consider.
E. macarthurii	Another major species for the eastern area. Will grow anywhere on the Highveld. Hard to kill. Timber suitable for mining timber and pulp. Very hardy.
E. ovata	Swamp gum. Good in cold areas and suitable on very wet sites.
E. sideroxylon	Black ironbark. Found all over the Highveld. Might have allelopathic properties. Very hardy.
E. crebra	Narrow-leaved ironbark. Drought and cold tolerant.
E. cinerea	Very successful in colonizing the Withok slimes. *This species still needs to be describned for purposes of this text.*
Wet-footed gums	Species include *E. ovata, E. viminalis, E. pauciflora, E. pulchella, E. dives, E. bridgesiana, E. stellulata* (wet sites and high elevations), *E. nitida, E. rubida, E. aggrenata.*
E. cinerea	Very successful in colonizing Withok slimes dam. To be described.

Hybrids

E. camaldulensis x nitens

Most promising combination to date and the most highly recommended tree to plant. Plant material requires special culture.

ACACIA spp.

A. mearnsii	Black wattle. All over the Highveld. Most prevalent in Witbank area but probably for historical reasons. Invasive.
A. decurrens	Green wattle. Found especially at Jessievale. Very similar to black wattle.
A. dealbata	Silver wattle. Prevalent in cold areas. Invasive. Frost resistant.
A. baileyana	Bailey's wattle.
A. melanoxylon	Blackwood.

None of the acacias have been considered for any form of extensive planting.

POPULUS spp.

Populus deltoides	Swamp poplar. Wet-footed species. Deciduous.
Populus canescens	Grey poplar. Wet-footed species. Deciduous.

LIST OF INDIGENOUS SPECIES IDENTIFIED AS SUITABLE FOR COLONIZATION OF SLIMES DAMS *(Compiled by M. Viviers and C. Jacobs)*

Acacia karroo
Agapanthus species
Arctotis calendula
Artotheca calendula
Carpobrotus deliciosus
Carpobrotus edulis
Carpobrotus muirii
Castalis species
Chrysanthemoides monolifera
Crassula multicava
Cynodon dactylis
Drosanthemum species
Euryops trifurca
Euryops vigineus
Gazania uniflora
Helichrysum petiolare
Lampranthus species
Leucadendron brunioides
Leucadendron coniferum
Leucadendron gandogeri
Leucadendron muirii
Leucadendron salignum
Leucospermum cordifolium
Leucospermum glabrum
Leucospermum pluridens
Leucospermum reflexum
Mimetes stokoei
Pelargonium capitatum
Pelargonium cordatum
Pelargonium peltatum
Portulacaria affra
Plumbago auriculata
Protea compacta
Protea coronata
Protea eximia
Protea repens
Protea grandiceps
Protea neriifolia
Protea scolymocephala
Protea susannae
Rushia species
Rhus erosa
Rhus lancea
Rhus leptodictya
Rhus pendulina
Rhus pyroides
Rhus undulata
Rhus viminalis
Stoebe plumosa
Tecomaria capensis
Tylecodon species