QUANTIFICATION OF THE WATER BALANCE OF SELECTED REHABILITATED MINE SOILS UNDER RAINFED PASTURES IN MPUMALANGA

JL Schoeman · SM Matlawa · MD Howard

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Report to the Water Research Commission
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ARC-Institute for Soil, Climate and Water

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INTRODUCTION

Background

Coal strip-mining was introduced in the Mpumalanga coalfields in 1971 and became widespread during the mid-1970s. The 1980s brought widespread awareness, both in mining and agricultural circles, of loss of agricultural potential and changes in soil hydrological properties.

This mining method involves the complete removal of overburden above the coal in adjacent strips. Following removal of the coal, the material from an adjacent strip (a mixture of shattered rock and soft overburden) is dumped into the void and graded to form the new surface topography. Usable soil materials stripped ahead of mining are then replaced on the new surface. Because of the large soil volumes involved, heavy machines are required and these exert a considerable compactive force on the soil over which they travel. Various soil amelioration and revegetation operations then follow on the re-established land surface to complete the rehabilitation process. The end product displays a high degree of random variability and differs from natural soils in many respects.

In an effort to improve rehabilitation and quantify impacts, a number of investigations were commissioned and conducted in-house by the larger mining houses over a number of years. This and other local research on mine soils provided insights into soil and other conditions and the pasture or crop production achieved. It is difficult, however, to extrapolate seasonal observations to the long term without modelling. A need thus existed for a study in which a number of soil, water, climate and pasture parameters are determined concurrently in order to facilitate modelling and the construction of cumulative frequency distributions.

In government circles, an inter-departmental liaison committee on high extraction coal mining was constituted in the early 1990s. It, in turn, constituted a technical committee to identify and address research needs regarding agricultural aspects of rehabilitation. A series of cooperative research initiatives followed, including this study. It is a joint venture between the National Department of Agriculture, the Water Research Commission and the Agricultural Research Council.

RESEARCH OBJECTIVES

The objectives of this study were as follows:

1. At three representative sites and over three growing seasons, to quantify the water balance, i.e. the proportion of rain water which takes part in runoff, storage in the soil, evapotranspiration and deep drainage.
2. To interpret the results in terms of the following:
    - Hydrological factors which affect runoff, sedimentation of streams, water quality (percolation of rain water to pyrite-containing rock-spoil) and availability of water for biomass production).
    - Land quality factors which affect plant growth such as slope, cover soil thickness, bulk density, sharpness of the soil-spoil contact and coarse fragments in the upper spoil.

3. To use the data to calibrate the PUTU-Veld and possibly other models in order to make long-term predictions of the water balance and resultant biomass production, using cumulative distribution function techniques to express the results.
4. To interpret the data to determine the effectiveness of various soil layers in representative pasture-soil-spoil combinations as growth media for biomass production.
5. To make recommendations with respect to rehabilitation methods and their influence on the water balance and plant growth.

APPROACH

The approach was to measure soil water changes down to 1.6 m depth and pasture above-ground biomass as well as light interception by the crop, at approximately bi-weekly intervals, to determine the runoff and to use the data in conjunction with weather station data to determine the water balance and pasture performance. Supporting data were collected on soil chemical properties, coarse fragments and their water retention, bulk density, clay mineralogy and soil drainage. Pasture modelling was done using PUTU15 software with the aim being to establish cumulative frequency distributions of pasture performance.

The results apply only to strip-mined areas in Mpumalanga which are rehabilitated with red, yellow-brown or grey sandy loams or loamy sands, derived from the Vryheid Formation, and not to areas rehabilitated with black clays or sands.

MATERIALS AND METHODS

Site selection

In order to link with work previously done, six sites used during 1994 to 1996 by the ARC-Range and Forage Institute for evaluating pastures on rehabilitated mine land for economical animal production were selected for use in this study. The sites were situated at three different mines (Kriel, Middelburg South and Optimum). Rehabilitation was completed between 5 and 13 (average 8) years before the start of the project. Slopes ranged from between 1 and 6%. The vegetation consisted mostly of grasses (52-70%, mainly *Digitaria eriantha, Cynodon dactylon, Chloris gayana*) with variable stands of lucerne and weeds.

Subsequent to the selection of the research sites, results became available of an extensive investigation into the properties of rehabilitated soils. The selected sites were shown to be representative of the rather better rehabilitated areas, as the cover soil depth was greater than the industry average at all sites; the cover soil density was lower than the industry average at all sites; the cover soil pH_{water} was higher than the industry average at two sites and lower at four sites; the cover soil organic carbon was higher than the industry average at all sites; the spoil density was higher than the industry average at three sites and lower at one site; the spoil pH_{water} was higher than the industry average at three sites and lower at three sites. The slope and kinds of geological materials at the experimental sites are representative as far as could be ascertained.

Site layout

At each of six sites, a 30 m x 30 m plot for water monitoring and 8 m x 8 m sub-plot for fertilizer treatments were laid out. The following were installed or marked out:

- A 20 m x 3 m runoff collecting area with tipping bucket and sump.
- Eight NWM access tubes, randomly situated.
- Eight 1 m x 1 m squares for ceptometer readings
- Four 1 m x 1 m squares for clipping during each month of the year (most of the squares to be clipped during the winter months were never used due to heavy frost). Apart from harvesting cuts twice or three times per season, each square was clipped only once per season.
- A weather station, recording rainfall and pulses from the runoff tipping bucket.

SITE CHARACTERISTICS

Fertility status

The pH of the cover soil was low in places (average pH_{KCl} 5.7, 5.5, 5.0, 4.8, 4.5 and 4.4 at the six sites respectively). That of the spoil material was low at two sites (average pH_{KCl} of 3.9 and 4.9, respectively) and neutral at the other four (6.3 to 7.6).

Phosphorus, potassium, calcium and magnesium levels were generally adequate. Nitrogen was not determined. Organic carbon varied between 0.7 and 1.2% in the plough layer.

Soil physical and mineralogical properties

The cover soils consisted of structureless sandy loam to sandy clay loam, derived from orthic, red, yellow-brown and plinthic soil horizons. The cover soil depth ranged from 0.55 to 1.05 m. Cover soils overlie spoil materials containing between 30 and 70 % fine to coarse rock fragments *via* an abrupt transition.

The average bulk density of the cover soil varies between 1.60 and 1.78 Mg m^{-3} at a depth of 200 to 400 mm. Between 400 and 600 mm depth, it varies between 1.68 and 1.87 Mg m^{-3}. Below 600 mm depth, it varies between 1.8 and 2.1 Mg m^{-3}.

The total water capacity (saturation minus the lower limit of plant availability) of the cover soils varies between 156 and 256 mm, depending mainly on the cover soil depth. Water held between the drained upper limit and the lower limit of plant availability varies between 37 and 64 mm. A further approximately 26 mm of water can be utilized by plants while the soils are draining during and after wet spells. The upper 1 m of the spoil materials have a total water capacity of approximately 188 to 237 mm, of which between 42 and 68 mm is, at least theoretically, available to plants.

Mineralogically, the fine fractions of the cover soils are strongly dominated by kaolinite (55 to 80%). Approximately 10% clay-size quartz occurs. Water-dispersible to total clay ratios varied between 0.01 and 0.34, indicating relatively high to intermediate aggregate stability. Texturally, mineralogically and due to their history of disturbance, the cover soils are susceptible to compaction, re-compaction and hardsetting behaviour.

Water extraction

Water extraction from the soils by the pasture crop is strongly affected by high bulk densities and hardsetting behaviour in the lower parts of cover soils. During the periods of strongest water extraction in midsummer, between 0 and 74% (average 32%) of the maximum plant-available water (water-holding capacity between saturation and the lower limit of plant availability) remains unextracted in the lower third of the cover soil. Root maps show poor root distribution in dense layers, often with patchy and stringy patterns. The effect of high bulk density is aggravated by hardsetting behaviour during drying cycles which prevents soil particles being pushed aside by the growing root tip. Dense layers in the lower cover soil also play a role in preventing crops from exploiting the soil water in the upper spoil, as well as nutrients becoming available from weathering rock flour.

Pasture production

Apart from water availability, pasture production is strongly dependant on levels of fertilization. Fertilization of the plots was aimed at relatively high production without too much of a risk of water uptake being restricted due to low soil fertility. In the beginning of each growing season, each plot was fertilized with 100 kg ha^{-1} N as LAN, 20 kg ha^{-1} K as KCl and 20 or 40 kg ha^{-1} P, depending on the site, as superphosphate. When the midsummer rainfall was adequate, a second dressing, consisting of half these quantities was applied. During two of the seasons under consideration, the rainfall was far above average, with the third below average.

To assess the influence of the level of fertilization on production, a fertilizer sub-plot was laid out at each site. Treatments were as follows: no fertilizer, optimum level (as for main plot), optimum minus 50%, optimum plus 50%. Due to an oversight, the fertilizer sub-plots were not sampled in 1997/98.

With the yield at the "optimal" level as reference (unity), the relative yields at the various treatments during the two remaining seasons varied as follows:

- No fertilizer: 0.06 of the optimum at previously poorly-fertilized sites, to 0.86 at previously well-fertilized sites, with an average of 0.44.
- Optimal minus 50%: 0.54 of the optimum at previously poorly-fertilized sites to 0.97 at previously well-fertilized sites, with an average of 0.77.
- Optimal plus 50%: 0.80 to 1.96 of the optimum, the latter at previously poorly-fertilized sites. The average is 1.30.

The above results indicate that the levels of fertilization applied were approaching the turning point in yield at one site, but not the others. The fertilization levels applied can thus be considered as yield-limiting to an extent.

Hay yields varied between 3400 and 11800 kg ha^{-1} in the first season, between 3200 and 4700 kg ha^{-1} in the second season and between 2900 and 6900 kg ha^{-1} in the third season. Pasture modelling, however, pointed to a 70 % probability that yields would not exceed 2200 kg ha^{-1} at three sites, 3000 at the fourth and 4500 at the fifth site (average 2700 kg ha^{-1}). Equivalent figures at 50% probability are 2650 kg ha^{-1} at four sites, 3150 kg ha^{-1} at the fifth, and 4650 kg ha^{-1} at the sixth site (average 3050 kg ha^{-1}). Average yields on natural soils in the vicinity with similar depth to the cover soil depths involved would be of the order of 8000 kg ha^{-1}.

Water balance

The water balance is expressed as $(E+T) = (P \pm \Delta S) - (R \pm D)$, where E denotes evaporation from the soil surface, T transpiration by the plant cover, P precipitation, ΔS water extracted from the root zone, R runoff and D drainage below the root zone.

Separation of E and T was not an objective of this study. The above relationship can thus be expressed as $ET = (P + \Delta S) - (R + D)$.

Of these components, P, ΔS and R were measured (the latter with limited success, and thus partly calculated). D was assessed my means of a procedure proposed by Bennie *et al.* (1998), and by using the time duration and extent of soil water contents above the drained upper limit in conjunction with derived average values of K and K_s. ET was obtained by subtraction.

Average annual values of the components of the water balance are shown in the table below:

Site	Season														
	1997/98 (mm)					1998/99 (mm)					1999/2000 (mm)				
	ET	P	ΔS	R	D	ET	P	ΔS	R	D	ET	P	ΔS	R	D
Kriel A	806	896	4	64	31	541	569	12	20	20	486	785	-68	52	179
Kriel B	728	940	35	47	200	486	613	39	43	123	359	805	-74	44	328
Middelburg South A	769	756	58	23	22	637	663	1	20	7	671	723	-32	20	14
Middelburg South B	750	752	26	26	2	588	600	4	15	1	635	681	-32	13	1
Optimum A	711	775	-16	25	23	Site unavailable									
Optimum B	737	753	32	39	9	694	727	8	39	3	663	796	-40	86	7

Components of the water balance, expressed as a percentage of the annual rainfall, *are shown in the table below:*

Site	Season											
	1997/98				1998/99				1999/2000			
	ET	ΔS	D	R	ET	ΔS	D	R	ET	ΔS	D	R
Kriel A	90	0.45	3.46	7.14	95	2.11	3.51	3.51	62	-8.66	22.8	6.62
Kriel B	77	3.72	21.3	5.00	79	6.36	20.1	7.01	45	-9.19	40.7	5.47
Middelburg South A	102	7.67	2.91	3.04	96	0.15	1.06	3.02	93	-4.43	1.94	2.77
Middelburg South B	100	3.46	0.27	3.46	98	0.67	0.17	2.50	93	-4.70	0.15	1.91
Optimum A	92	-2.06	2.97	3.23	Site unavailable							
Optimum B	98	4.25	1.20	5.18	95	1.10	0.41	5.36	83	-5.03	0.88	10.80

The following are to be noted:

- Water available for evapotranspiration (and thus, plant production), varied between 45 and more than 100% of the annual rainfall. Under the conditions of this study (relatively deep soils, moderate slopes and good or fair vegetation cover), differences were mainly between seasons, and reflect the effects of rainfall distribution. Maximum rates of evapotranspiration were in the order of 5 to 8 mm per day.

- The net gain or loss of soil water during the season (seasonal water transfer) was small. Prominent fluctuations occurred during the season. These are either positive (water extracted from the soil) or negative changes (water stored in the soil). The re-creation of soils that are able to take up, store and release sizeable quantities of water is thus of importance if runoff and deep percolation are to be minimized.
- Water lost through deep percolation varied from zero to 40%. It was strongly affected by the rainfall distribution. It also differed between sites. Calculating this parameter took into account the water content of the root zone. This, in turn, may reflect lateral water movement within the soil (sub-surface run-on). No attempt was made to assess this phenomenon.
- The calculated runoff varied between 1.9 and 10.8% of the annual rainfall. Runoff appeared to relate mainly to pasture vigour and slope and does not deviate greatly from published figures for pastures and natural veld at Glen and Pretoria (Du Plessis & Mostert, 1965; Haylett, 1960).

CONCLUSIONS

1. High bulk density, coupled with hardsetting behaviour, is a widespread phenomenon in replaced cover soils, and can be rated as the number one problem affecting land use.

2. Although pockets of strong acidity do occur in spoil materials, acidity due to pyrite oxidation was not identified as a major limitation to land use. The contrary was found, namely that neutral or slightly alkaline pH values may predominate in spoil material. In a naturally nutrient-poor environment, plant nutrient levels may be relatively high in some spoil materials.

3. Rehabilitated soil profiles with red or yellow medium-textured cover soils derived from Vryheid Formation parent materials, possess a moderate plant available water-holding capacity (DUL-LL) of approximately 60 to 70 mm per m of cover soil and 35 to 65 mm per m of spoil. To be added to this figure is a capacity of at least 26 mm of utilizable water, held during wet spells at potentials higher (wetter) than DUL. Due to poor root distribution and shallow root development in places, caused by high bulk densities, particularly below 200 mm depth, and hardsetting behaviour during dry periods, much of the available soil water (at some sites, the bulk of it) is not extracted and utilized by the pasture crop, even during periods of high water demand. Under conditions of poor to moderate root development, the actual profile extractable water capacity (taking root distribution into account) can be as low as 20 to 30 mm, excluding water held at higher potentials than DUL.

4. Spoil material occurring within the normal rooting depth of pasture grasses appears to be penetrated with difficulty by roots. The relative contribution of the following is still unclear:
   a. The cut-off effect of dense, hardsetting layers at the bottom 200 to 400 mm of the cover soil (where high bulk densities may be persistent due to difficulties in correcting it).
   b. Unfavourable properties of the cover soil/spoil transition (textural change, thin lenses of particularly compacted and smeared soil).
   c. The properties of the upper spoil itself (coarse fragments, "concrete mixture" particle size distribution, small pore size, soil strength).
   d. The suitability or otherwise of carbon from coal as a substrate for beneficial micro-organisms if nitrogen is introduced.

5. Although present results with regard to the measuring of runoff may be somewhat inconclusive, they suggest that where the pasture cover is moderately well fertilized, in productive condition and slopes are moderate, runoff does not exceed 10% of the annual rainfall and can be as low as 2 or 3 percent.

6. The generally high density of the lower cover soils and upper spoil appears to restrict deep percolation, except in situations where water accumulates due to lateral drainage ("melon holes"), and where settling cracks occur. Results suggest that deep percolation varies between zero and 40 percent of the annual rainfall and is strongly affected by rainfall patterns during the season. Some spoil materials are almost permanently dry below 1 or 1.3 m depth. High spatial variability can be expected.

7. The reconstituted soil profiles can generally be regarded as imperfectly or poorly drained. The situation differs, however, from, for example, a natural soil of the Avalon form, in that unlike the natural soil, the slowly draining water at depth cannot be effectively utilized by roots during dry spells unless high bulk densities and hardsetting characteristics are alleviated.

8. The imperfect to poor drainage of the soils causes certain topographical features (e.g. local hollows) to become water collection sites through lateral surface as well as subsurface run-on, particularly during wet periods.

9. Where soils are moderately deep and able to absorb precipitation efficiently, water available for evapotranspiration may vary between 45 and 100% of the annual rainfall. Under these conditions, differences mainly reflect the effects of rainfall distribution.

10. Pasture production is strongly dependent on water availability and levels of fertilization. The inability to utilize the soil water between a depth of 0.3 to 0.7 m where the soil is dense, has a severe negative effect on pasture vigour, production and drought resistance. At fertilization levels aimed at relatively high production without too much of a risk of water uptake being restricted due to low soil fertility, cumulative distribution yield functions show a 50% probability that hay yields would not exceed 2650 kg ha^{-1} at four of the sites, 3150 at the fifth site, and 4650 at the sixth site (average 3050 kg ha^{-1}). These yields compare unfavourably with a general average of approximately 8000 kg ha^{-1} attainable on good natural soils in the vicinity.

11. It is not implied that rehabilitated soils with current low productivity cannot be made productive, as important basic ingredients of productive land are exist such as moderate slopes, fair soil depth and manageable chemical hazards, when present.

12. The issue of fertilization, and whether or not fertilizer is gradually to be withdrawn to allow the pastures to revert to "natural" veld, is of high importance with regard to both the gradual improvement of rehabilitated land and the re-integration into farming systems:
    - Where no special measures are applied, e.g. mulching with organic matter-rich waste products, soil improvement (mainly sustained alleviation of hardsetting behaviour and the restoration of macro-pores) and erosion control is dependent on good pasture cover and root development. These, in turn, are dependent on adequate fertilization.

- If pastures are to be maintained by fertilization after re-integration into farming enterprises, the hay produced is too expensive to be economically utilized by unproductive (dry) livestock (De Beer, 1998). It could, theoretically, be marketed elsewhere or be used to round off animals for marketing or for lactating cows or growing animals, but an over-abundance of expensive fertilized hay would be difficult to utilize economically. A farm unit consisting solely of rehabilitated pastures would thus need specially adapted farming practices and extension efforts. The inputs needed may thus render the land unsuitable for resource-poor farmers participating in the Land Redistribution Programme.
- Withdrawal of fertilization to allow a return to natural veld is an extremely slow process. According to a spokesman of the Mpumalanga Department of Agriculture, there are currently no successful examples on the highveld where planted pastures eventually returned to a more natural situation and were managed successfully.

12. On the question of the relative merit of rehabilitation resulting in permeable soils, beneficial to plant growth, on the one hand, or dense soils, curbing the entry of rainwater into compartments containing acidifying pyrites, on the other, the following are concluded:
    - From a land capability or land use viewpoint, dense, poorly or imperfectly drained soils have little merit. It is also true, however, that soils with a relatively slowly drained layer at the bottom of the root zone are preferred to excessively drained soils. It is becoming clear, though, that mine soils on the Vryheid Formation do not suffer from excessive drainage due to the compaction that accompanies spreading and leveling.
    - The results suggest that an acceptable compromise probably lies in creating a root zone with a low bulk density, and as deep an effective soil depth as can be developed to sustain vigorous vegetation or crops. This would have to be attained by means of implements more powerful than normal farm implements. The maximum depth from the surface that can be reached with implements is in the order of one metre, depending on cover soil depth and rockiness of the upper spoil. The dense layers always present below that depth can be depended on to prevent the soil from becoming excessively drained. If recompaction and hardsetting behaviour can be curbed by biological means, and fertility attended to, such soils would be physically able to sustain vigorous crops, transpiring strongly during the rainy summer season when deep percolation is to be minimized. As much rain water as possible should thus be transpired by summer crops or pasture in order to minimize the water available for deep percolation. Water available for drainage below the root zone may concentrate in local hollows, where settling and shrinking cracks may or may not be present. Once in that position, only capillary forces can keep that water from percolating downwards.

The following are recommended:

1. The issue of land preparation and revegetation, as part of the rehabilitation process, is of high importance for subsequent land use and should be recognized as a focus area for research and development. Amongst the aspects in need of clarification are the following:
    a. Ways of optimizing the initial mechanical process of alleviation of machine-induced high bulk density ("kick-starting" the recovery process by various

methods of deep ripping). This includes ways of dealing with the abrupt transition between cover soil and spoil, and dealing with ripped-up rock.

b. Ways of improving the sustainability of the effects of the initial mechanical process. This involves optimizing the biological processes of re-establishing aggregate stability by stimulating the recovery of fungal, microbial and macro-faunal life in the soil as well as their products which stimulate aggregation (e.g. microbial gums and polysaccharides).
c. The issue of identifying and rating susceptibility to re-compaction.
d. The issue of identifying and rating hardsetting behaviour.
e. Novel rehabilitation plant species with emphasis on root penetrating ability, climatic adaptability, water requirements, nitrogen fixation, ease of eradication and economic value.
f. Lime requirement and ensuring adequate mixing into the soil.
g. The issue of withdrawal of fertilizer and the timing and requirements of returning fertilized pastures to natural veld or arable land.
h. Managing wet spots ("melon holes"); appropriate land use options for these spots; opportunities offered by these for measuring, characterizing or treatment of lateral run-on water.

2. The issue of adherence to standards during rehabilitation deserves the serious attention of all mining houses, Government, Organized Agriculture and environmentalists.

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Mr. J. van Wyk	Department of Water Affairs and Forestry

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LIST OF ACRONYMS AND SYMBOLS USED

ARC	Agricultural Research Council
ARC-RFI	ARC-Range and Forage Institute
CDF	Cumulative distribution function
Cl	Clay
D	Deep percolation
D_b	Bulk density
D_p	Particle density
DT	Draining rate
DUL	Drained upper limit
E	Evaporation from the soil surface
ET	Evapotranspiration
K	Soil hydraulic conductivity under unsaturated conditions
K_s	Soil hydraulic conductivity under saturated conditions
LAN	Limestone ammonium nitrate
LL	Lower limit of plant-extractable water
nd	Not determined
NWM	Neutron water meter
P	Precipitation
R	Runoff
SAT	Soil water content at air entry (0.85 total porosity); also referred to as saturation
Si	Silt
T	Transpiration
ULAW	Upper limit of plant-available water
USDA	United States Department of Agriculture
W	Water content of the root zone
WD	Rooting depth
W_e	Equivalent water
WRB	World Reference Base for Soil Resources
XRD	X-Ray diffractometry
ΔS	Change in the water content of the root zone
θ	Water content
Ψ	Matric potential of soil water

CHAPTER 1

INTRODUCTION

Coal strip-mining involves the complete removal of overburden above the coal in adjacent strips approximately 40 m wide. Following removal of the coal, the material from the adjacent strip (a mixture of shattered rock and soft overburden) is dumped into the void and graded to form the new surface topography. Usable soil materials stripped ahead of mining are then replaced on the new surface with trucks or bowlscrapers. Because of the large soil volumes involved, heavy machines are required and these exert a considerable compactive force on the soil over which they travel (Tanner *et al.*, 1986). Various soil amelioration and revegetation operations then follow on the re-established land surface to complete the rehabilitation process. The end product displays a high degree of random variability (De Villiers, 1992a) and differs from normal agricultural soils in many respects, two of which are lower total organic matter in upper layers and higher total organic matter in deeper layers due to mixing, and a source of minerals being present due to the cover soil being underlain by shattered rock (Tanner, 1993).

Strip-mining was introduced in the Mpumalanga coalfields in 1971 and became widespread during the mid-1970s. The 1980s brought widespread awareness, both in mining and agricultural circles, of loss of agricultural potential due to it. Van der Merwe (1989), reported that half of the high potential land available to commercial agriculture in South Africa is situated in and around the Mpumalanga coal fields. The total number of hectares in Mpumalanga underlain by exploitable coal reserves is put at 1.03 million. Of this total, 88% is expected to be mined by high extraction methods, resulting in subsidence or drastic land disturbance.

In an effort to improve rehabilitation and quantify the impacts of mining on the soil resources, a number of investigations were commissioned and conducted in-house by the larger mining houses over a number of years (Tanner, 1993; Viljoen, 1993; Van der Merwe, 1993). In government circles, an inter-departmental liaison committee on high extraction coal mining was constituted. It, in turn, constituted a technical committee to identify and address research needs regarding agricultural aspects of rehabilitation. A series of cooperative research initiatives followed, including this study.

This study is a joint venture between the National Department of Agriculture, the Water Research Commission and the Agricultural Research Council.

1.1 PREVIOUS OR RELATED RESEARCH ON MINE SOILS IN MPUMALANGA

1.1.1 PRODUCTIVITY OF MINE SOILS IN RELATION TO COVER SOIL DEPTH AND COMPACTION

In a soil depth trial conducted at Arnot during1980-1989 (Tanner, 1993), zero yields of maize and sorghum were attained where no cover soil was replaced. Mixed pastures containing *Digitaria*, Rhodes grass and lucerne were much less sensitive to soil depth, as yield where no soil was replaced was of the order of 80% of the maximum yield attained, and there was little additional increase in yield as soil depth increased beyond 200 mm.

A trial conducted at Kleinkopje during 1984-1992 on the effects of soil depth and soil compaction on pasture growth (Tanner, 1993), showed little response to increasing soil depth above 300 mm on adequately fertilized plots. The relation between soil hardness, as measured by penetrometer, and teff yield, was much closer than the relation between soil depth and teff yield. No clear interactive effect was observed. Compaction decreased pasture yield in every season.

In a ripping trial at Kleinkopje during 1984/85 (Tanner, 1993), deep ripping with a single tine drawn behind a dozer doubled pasture growth, but neither a big-ox ripper, nor a winged-tine ripper drawn behind a tractor resulted in any increase in pasture yield. The dozer tine penetrated through the cover soil into the spoil below (a total depth in excess of one metre), whereas tractor-mounted rippers penetrated only 300-400 mm into the soil. The conclusion was drawn that tractors pulling standard agricultural equipment were unable to penetrate to the depth required for lower horizon shattering.

In a further spoil ripping and soil depth trial, at Kleinkopje during 1985-1991 (Tanner, 1993), maximum yield of pasture was obtained where soil depth was 300 mm. Ripping the underlying spoil material increased yields significantly. Reasonable root growth was observed in the spoil. However, a considerable amount of large stone was lifted by ripping.

In a trial at New Vaal, (Tanner, 1993), pasture yields on plots with no cover soil were compared with that of plots where 250 mm of sandy cover soil was applied. Topsoiling resulted in increased yield only in the first season after establishment, after which yield was significantly greater from those plots to which no topsoil was applied.

In a spoil ripping and soil depth trial at Kriel conducted during 1988-1990, pasture yield increased with increasing soil depth up to 700 mm. The spoil was ripped prior to cover soil replacement using a standard agricultural ripper and the cover soil was replaced by a bowlscraper making subsequent passes on the same tracks, resulting in clearly defined zones of greater compaction with soft soil zones in between.

In a follow-up soil depth/fertilizer interaction trial conducted at Kriel during 1990/91 (Tanner, 1993), it was found that in the presence of adequate fertilizer, yield on spoil without cover soil was high (over 8 t ha^{-1}) and the effect of increasing soil depth on yield was relatively small. Yield maxima, approximately 20% greater than those from bare spoils, were obtained with soil depths of 460-540 mm. In the absence of adequate fertilizer, yields were low (approximately 2 t ha^{-1}) and the effect of increasing soil depth on yield was proportionately much greater.

1.1.2 PROFILE DEVELOPMENT IN MINE SOILS

Viljoen (1992), in a study of soil formation in spoil materials between 1 and 18 years old at Optimum, observed that dense layers appear to become less obvious over time and that coarse fragments in the upper spoil appear to weather rather rapidly. The clay content of the upper spoil and signs of wetness increase over time, particularly in low-lying landscape positions.

De Villiers (1992a), in a study of close to 100 profiles, found little evidence of pedogenetic re-organization in profiles that were ten or more years old. He noted, however, that dark, fissile shales, in particular, appear to soften and disintegrate quite rapidly and that it is consistent with their often high pyrite content.

A study of 70 of the above pits situated at Kriel, Kleinkopje and Arnot (Tanner, 1993) led to the conclusion that patterns of rooting varied considerably, and that the soil/spoil interface was a barrier to roots in some profiles but not in others. The ability of roots to penetrate into spoils was related to the depth of the cover soil and it is probable that compaction is the major cause of the differences observed. Major changes in soil morphology as a result of position of the profile in the slope do not seem to have occurred and the nature of the profiles depends mainly on the materials used in their construction.

1.1.3 CLASSIFICATION AND CHARACTERIZATION OF MINE SOILS

Characteristically, mine soils are binary as regards their provenance, and consist of an upper part that is soil or soil-like (cover soil) and a lower part that is clastic (spoil). De Villiers (1992b) was commissioned by the Chamber of Mines to produce a coding system for mine soils (see Appendix 1). He observed that, in natural soils, properties vary in ways that are comprehensible and have a high degree of covariance. Variation is thus systematic and there is little room for random variability. By contrast, the variability encountered in mine soils is, theoretically, completely random although in practice there are factors such as the homogenizing effects of machine handling and planned rehabilitation strategies (e.g. depth of cover soil replacement) which may limit the overall extent of variation. In terms of this system, the Kriel A experimental site, for example, would be coded as 60/60 K2 / Ae 40, having a kandic (apedal) cover soil of sandy loam or light sandy clay loam texture that is 60 cm deep, all of it permeable to roots. This overlies arenolithic (Ae, denoting sandstones and gritstones) spoil with 40%, by volume, of fines.

Nell and Steenekamp (1998) applied the above system in a study to create a database of rehabilitated soils. The study resulted in the description of over 1600 profile pits, laboratory analysis of over 600 samples, bulk density determinations of over 3000 samples and over 1000 samples stored for future reference. Summary results from the database provided valuable insights into the spatial and frequency distributions of soil properties potentially affecting soil water characteristics and plant production (see Table 2.1b).

1.1.4 FATE OF RAINFALL LANDING ON REHABILITATED LAND

Tanner (1993) reported on a first attempt to evaluate the fate of rainfall landing on rehabilitated lands. The average catchment size was found to be 30 and 28 ha respectively at Kriel and Kleinkopje and 17 ha at Arnot. In general the computations indicate that runoff quantities are low. Australian experience is quoted that indicates that on land covered with good pasture and more than 70 percent ground cover, approximately 3% of total rainfall will run off. The equivalent figure on land with poor pasture and low basal cover is approximately 10%. Bare, levelled spoil areas with low permeability produce 30% runoff. Assuming that the rehabilitated soils have on average a plant available water capacity of 50 mm, the average loss by evapotranspiration from vegetated areas was calculated as 70% of rainfall. The equivalent figure for bare areas is 10% of rainfall. Water lost by evapotranspiration will increase as the plant-available water capacity of the soil increases, computations showing evapotranspiration values of 70, 79, 86 and 90 percent at available water capacities of 50, 100, 150 and 200 mm water respectively. Deep percolation was calculated as the difference between rainfall and the evapotranspiration and runoff volumes. A considerable proportion of rain water is thus expected to percolate into the spoils. This should ultimately raise the water table, resulting in decantation of water to the surrounding streams.

1.1.5 Fertilizer response

The influence of rates of application of fertilizer and lime on soil fertility and plant growth was assessed in six field trials at Arnot, Kriel and Kleinkopje since 1987 (Tanner, 1993). Strong yield responses to applied nitrogen were recorded in trials where differential nitrogen rates were applied. Responses were almost linear up to the highest rate (225 kg N ha^{-1}) tested. Significant responses were also obtained to phosphorus treatments at five of the six sites, while potassium responses were present on two sites only. Responses to lime tended to be small or non-existent.

1.2 INDUSTRY STANDARDS RELATING TO SOIL WATER PROPERTIES

With respect to land qualities affecting the rehabilitated soil's water-holding properties, the following industry standards apply to coal mining (Chamber of Mines, 1981):

Slope of rehabilitated land

Emphasis is placed on the effect of slopes on erosion and slumping due to failure. The general guideline is to re-grade spoiled areas to approximate pre-mining contours. Concave slopes are recommended because they are more stable. Areas planned for rehabilitation to an arable standard are to be graded to a slope (%) which, when multiplied by the erodibility factor (K) of the new soil, gives a product of 2.0 or less.

Spoil surface

It is recognized that during disturbance, overburden expands in volume. This is followed by a degree of natural compaction and compaction induced at the surface by the heavy machinery used for grading and topsoiling. An initially well-graded surface may subside differentially, leaving a spoil and cover soil surface with localized hollows or wet spots.

Coarse fragments in the spoil

Large stones and boulders should as far as possible be buried below the final level of the graded spoil so as to permit ripping and scarifying operations.

Topsoiling

Suitable topsoil for rehabilitation is defined as all diagnostic horizons described in the Binomial System of soil classification (MacVicar *et al.*, 1977), except hard plinthic, gleyed or saline material. C horizon materials, particularly those of medium texture, that are not gleyed, not moderately or strongly cemented and do not become cemented on exposure, are also suitable. The minimum depth of replacement for grazing land was set at 0.25 m.

Compaction and land preparation

It is recognized that compaction is induced at the spoil surface by the heavy machinery used for grading, and at the cover soil surface by heavy machinery used for topsoiling. This results in drainage and root impedance. Because compaction is largely unavoidable and has such serious implications for successful revegetation and future land use, subsoiling is stated to be more or less mandatory. Because compaction may usually be expected to be particularly severe in the immediate vicinity of the cover soil–spoil contact, disturbance of the contact and some mixing of soil and spoil is important for keying the soil to the spoil and establishing hydraulic continuity between the two.

Liming and fertilization

Basal applications of lime and fertilizers designated to correct disorders and raise the fertility status to a suitable level prior to revegetation is recognized as an important aspect of rehabilitation. Lime application rates are to be determined by a prescribed way of sampling and laboratory analysis. The guidelines for land rehabilitated to grazing potential include liming to bring acid saturation down to 50% of total exchangeable cations where grasses are used, and to 25% where temperate legumes are included.

Relatively thorough incorporation is to be ensured during handling and spreading operations, resulting in amelioration throughout the entire depth of the new soil. Lime should also be applied to spoils recognized as having an acid-forming potential.

Basal applications of phosphorus to raise soil P levels (Bray 1 analytical procedure) to approximately 36 mg kg^{-1} are advocated. Likewise, basal applications of K are recommended to raise soil K levels to 120 mg kg^{-1}.

1.3 RESEARCH OBJECTIVES AND APPROACH

The local research on mine soils quoted above provided insight into soil and other conditions and the pasture production achievable under those conditions. It is difficult, however, to extrapolate seasonal observations to the long term without modelling. A need thus existed for a study in which a number of soil, water, climate and pasture parameters are determined concurrently in order to facilitate modelling and the identification of cumulative frequency distributions.

The objectives of this study were as follows:

1. At three representative sites and over three growing seasons, to quantify the water balance, i.e. the proportion of rain water which takes part in runoff, storage in the soil, evapotranspiration and deep drainage.
2. To interpret the results in terms of the following:

- Hydrological factors which affect runoff, sedimentation of streams, water quality (percolation of rain water to pyrite-containing rock-spoil) and availability of water for biomass production).
- Land quality factors which affect plant growth such as slope, cover soil thickness, bulk density, sharpness of the soil-spoil contact and coarse fragments in the upper spoil.

3. To use the data to calibrate the PUTU-Veld and possibly other models in order to make long-term predictions of the water balance and resultant biomass production, using cumulative distribution function techniques to express the results.
4. To interpret the data to determine the effectiveness of various soil layers in representative pasture-soil-spoil combinations as growth media for biomass production.
5. To make recommendations with respect to rehabilitation methods and their influence on the water balance and plant growth.

This report is organized as follows:

- In dealing with the first objective, the research sites and their properties are described in Chapter 2. The methodologies applied are also included in that chapter. Results concerning soil water content, runoff, deep percolation and pasture production are treated in Chapters 3, 4, 5 and 6 respectively, and integrated into a water balance in Chapter 7. The issue of sedimentation was not directly addressed.
- The second objective, interpretation of the short-term results in terms of hydrology and plant production, is addressed in Chapters 3 to 7 in order to keep results and their interpretation together.
- Objective three, applying measured and interpreted short-term results to the long term by means of modelling, is dealt with in Chapter 6.
- The purpose of objective four was to assess the potential productivity of the soils in the light of the final picture that emerged after measuring and modelling was completed. This objective is treated in Chapters 8 and 9.
- The last objective, to make recommendations in the light of all the foregoing, is treated in Chapter 9.
- Supportive data and information are presented in appendices. These are numbered in accordance with the chapters they are appended to.

The results are aimed at being of interest to the following:

- The coal mining industry, which needs information on the characteristics and quality of rehabilitated land for purposes of evaluating and refining rehabilitation standards.
- The National Department of Agriculture, which in its role of being responsible for norms and standards, needs information on the potential loss of production capability of land due to mining. It is also responsible for defining land quality indicators by means of which improvement or decline can be monitored in terms of international agreements.
- The Mpumalanga Provincial Department of Agriculture, which needs a scientific basis for providing appropriate extension. It needs information on those characteristics that would affect the re-integration of rehabilitated land into agriculture and the practical management of such land. It is also responsible for

implementing the Government's Land Redistribution and Agricultural Development Plan (IDT, 2000).

- The Department of Water Affairs and Forestry, which needs information on the hydrologic characteristics of the man-made land.
- Organized Agriculture, in its role as watchdog over the interests of agriculture.
- Local farmers, who will find themselves on the forefront of re-integrating rehabilitated land into existing farming enterprises.
- Local government, being responsible for the Government's Programme for Integrated Rural Development. Legislation is being prepared that would require local governments to produce pro-active or forward (structural) plans, delimiting farming and other classes of land.

CHAPTER 2

MATERIALS AND METHODS

2.1 SITE SELECTION

In order to link with work previously done, some of the sites used during 1994 to 1996 by the ARC-Range and Forage Institute for evaluating pastures on rehabilitated mine land for economical animal production (Trytsman *et al.*,1997) were selected for use in this study. Selected properties of the sites are given in Table 2.1a.

Table 2.1a Experimental sites

Site	Mine	Slope	Cover soil depth	Date of rehabilitation	Plant cover (after Trytsman *et al.*,1997)
KA	Kriel	6-7%	Deep	1989	Grasses 64% *(Cynodon dactylon, Digitaria eriantha)* Forbs 1% Dwarf shrubs 1%
KB	Kriel	3-4%	Deep	1991	Grasses 61% *(Digitaria eriantha, Eragrostis tef, Chloris gayana)* Forbs 4% Dwarf shrubs 0%
DA	Middelburg South	1-2%	Deep	1992	Grasses 52% *(Digitaria eriantha, Cynodon dactylon, Chloris gayana,)* Forbs 1% Dwarf shrubs 0%
DB	Middelburg South	1-2%	Deep	1990	Grasses 52% (D. eriantha, C. gayana E. curvula) Forbs 1% Dwarf shrubs 5%
OA	Optimum	2-3%	Shallow	1984	Grasses 70% (D. eriantha) Forbs 0% Dwarf shrubs 14%
OB	Optimum	6-7%	Shallow	1987	Grasses 57% (D. eriantha) Forbs 0% Dwarf shrubs 0%

Subsequent to the selection of the research sites, results became available of an investigation into the properties of rehabilitated soils (Nell and Steenekamp, 1998, see 1.1.3). Comparison of salient properties of the experimental sites and the median of all sites investigated by Nell and Steenekamp (Table 2.1b) shows that the experimental sites are representative of the rather better rehabilitated areas:

- Cover soil depth is greater than the industry average at all sites.
- Cover soil density is lower than the industry average at all sites.
- Cover soil pH_{water} is higher than the industry average at two sites and lower at four sites.
- Cover soil organic carbon is higher than the industry average at all sites.
- Spoil density is higher than the industry average at three sites and lower at one site.
- Spoil pH_{water} is higher than the industry average at three sites and lower at three sites.

The slope and kinds of geological materials at experimental sites are representative as far as could be ascertained.

2.2 SITE LAYOUT

At each site, a fenced-off area, approximately 4 ha in size, used for previous research work by the ARC-RFI (Trytsman *et al.*, 1997) was utilized. Within each fenced off area, a 30 m x 30 m plot for water monitoring and 8 m x 8 m sub-plot for fertilizer treatments were laid out (Figure A2.1f, Appendix 2). The following were installed or marked out:

- A 20 m x 3 m runoff collecting area with tipping bucket and sump.
- Eight NWM access tubes, randomly situated.
- Eight replicates of 1 m x 1 m squares for ceptometer readings
- Four replicates of 1 m x 1 m squares for clipping during each month of the year (most of the squares to be clipped during the winter months were never used due to heavy frost). Apart from harvesting cuts twice or three times per season, each square was clipped only once per season.
- A weather station, recording rainfall and pulses from the runoff tipping bucket.

Table 2.1b Properties of the experimental sites in relation to the wider context of rehabilitated soils. Percentile data after Nell and Steenekamp (1998)

Site	Cover soil depth		Cover soil density		Cover soil pH		Cover soil carbon		Spoil density		Spoil pH		Spoil carbon	
	m	Percentile	Mg m^{-3}	Percentile	pH (H_2O)	Percentile	%	Percentile	Mg m^{-3}	Percentile [2]	pH (H_2O)	Percentile [2]	%	Percentile [2]
Kriel A	0.60	50-75	1.82	25-50	6.1	50-75	0.78	>75	2.05	50-75	7.7	50-75	1.40	50-75
Kriel B	0.70	>75	1.67	<25	6.3	>75	0.66	50-75	2.11	>75	8.2	>75	1.01	25-50
Middelburg A	1.05	>75	1.83	<25	5.6	25-50	1.26	>75	1.70	<25	4.5	<25	2.23	<25
Middelburg B	0.85	>75	1.79	<25	5.0	<25	0.85	>75	-	-	5.5	25-50	4.94	50-75
Optimum A	0.60	50-75	1.69	<25	5.3	25-50	1.05	>75	1.93	50-75	7.0	50-75	3.28	25-50
Optimum B	0.55	50-75	1.69	<25	5.1	<25	1.05	>75	1.80	<25	6.9	50-75	4.36	50-75
Median of rehabilitated soils [1]	0.40		1.86		5.65		0.53		1.91		6.53		1.83	
Number of Samples [1]	1645		625		316		208		415		301		301	

[1] Nell and Steenekamp (1998)

[2] Quartiles identified for the particular spoil type, e.g. arenolithic, carbolithic, etc (Nell and Steenekamp (1998); De Villiers, 1992b; see Appendix 1).

2.3 SITE CHARACTERIZATION

Site characterization took place by chemical analysis on samples taken by soil auger when installing NWM access tubes and by means of root mapping, bulk density determinations, wet sieving and screening of coarse fragments, as well as determination of matrix potential on undisturbed cores.

2.3.1 SOIL FERTILITY STATUS

Soil chemical and bulk density data are shown in Table A2.1a to Table A2.1f, Appendix 2. Soil Chemical methods were as described by the Non-Affiliated Soil Analysis Work Committee (1990).

ACIDITY

Liming of the plough layer to pH_{KCl} >4.5 during rehabilitation had not been successful everywhere. At the two sites at Middelburg South, three and six out of eight samples, respectively, had pH_{KCl} values of below 4.5. At the two Optimum sites, two and five samples out of eight, respectively, were below 4.5. At the two Kriel sites, none of the 16 plough layer samples showed pH_{KCl} values below 4.5.

Cover soil materials below the plough layer generally showed their original acidity levels: At the two Middelburg South sites, the number of samples with pH_{KCl} below 4.5 was five and seven, respectively out of eight. At the two Optimum sites, two and five out of eight had values below 4.5. At the two Kriel sites, again, none of the 16 deeper cover soil samples showed pH_{KCl} values below 4.5.

Spoil materials from the two Middelburg South sites showed pH_{KCl} values lower than 4.5 in all eight samples analyzed. At the Optimum and Kriel sites, average pH_{KCl} values were above 6.0 and 7.1 respectively.

PHOSPHORUS

Average P (Bray 1) values in the plough layer varied between 7 (Optimum) and 71 mg kg^{-1} (Kriel A). Values at Middelburg South and Kriel B varied around 12 mg kg^{-1}.

POTASSIUM

Average levels of K in the plough layer varied between 41 (Middelburg South A) and 225 mg kg^{-1} (Kriel B).

CALCIUM AND MAGNESIUM

On average, calcium values were adequate for pastures in the plough layer. Relatively low magnesium, and thus high Ca:Mg ratios, occurred in the plough layer at the Middelburg South and Optimum B sites. At the Kriel and Optimum A sites, high magnesium and middle-of the-range Ca:Mg ratios occurred at the time of analysis.

ORGANIC CARBON

Organic carbon levels in the plough layer varied between 0.7 and 1.2 %. This is equal to or slightly higher than the values of natural topsoils in the vicinity (Land Type Survey Staff, 1985; Land Type Survey Staff, 1987).

2.3.2 SOIL PHYSICAL PROPERTIES

BULK DENSITY

In cover soils, bulk density values were determined by the core method. In spoil materials, the following improvised excavation method was used: At the bottom and sides of backhoe pits, between ten and 40 kg of spoil material (the mass depended on coarse fragment size) was excavated and the material collected. The excavation was lined with thin refuse bag plastic and filled with water of a known volume. The oven-dry mass of the collected material was determined. Application of the excavation method was restricted to the first 300 to 400 mm of spoil depth due to the difficulty of digging into the spoil material.

Bulk density values are shown in Table A2.2, Appendix 2.

In the upper cover soil, values above 1.75 Mg m^{-3} were common at the Kriel sites only. Below 400 mm depth, however, high values predominate at all sites with the exception of Optimum A. Bulk density values of the spoil materials are commonly very high, mostly due to a high coarse fraction content. The results being reported apply mostly to the particularly compacted upper 300 to 400 mm of the spoil material. Pockets of uncompacted fines were found to occur between larger course fragments in deeper pits. This phenomenon is expected to increase with depth.

WATER RETENTION

The following approaches were employed to determine the water retention characteristics of the soil and spoil materials:

Undisturbed cores

A number of relatively undisturbed core samples from Kriel Mine (11 from 0.2-0.4 m depth and 13 from 0.4-0.6 m depth, were subjected to water retention measurements at four suction values (-33, -80, -500 and -1500 kPa) in a pressure membrane apparatus (Figure A2.2a and A2.2b, Appendix 2).

Land type data

Ratliff *et al.* (1983) found that for many sandy clay loam soils in the USA, pressure chamber determination at -33 kPa predicts field measured DUL to within ± 2%. As a fair number of applicable land type modal profiles with pressure chamber data exist, comparisons could be made. These profiles were of comparable geology and soil forms to the present experimental sites. To enable application of land type water data to soils with particular clay content, regressions of predicted land type water content on clay content were first established:

-33 kPa:	$Y = 0.383 X + 3.04$	($r^2 = 0.77$)
-80 kPa:	$Y = 0.405 X + 0.79$	($r^2 = 0.93$)
-500 kPa:	$Y = 0.336 X + 0.27$	($r^2 = 0.92$)
-1500 kPa:	$Y = 0.319 X - 0.55$	($r^2 = 0.94$)

Where Y = water content (mass) and X = clay percentage.

Figure A2.2c in Appendix 2 shows water retention constants as derived from land type modal profiles (20 samples) from the vicinity. An arbitrary bulk density value of 1.6 Mg m^{-3} (representing natural land type samples) was used.

Empirical relationships

As a third measure, relationships developed by Prinsloo *et al.* (1998), Schultze *et al.* (1985) and Gupta and Larson (1979) were used to assess the drained upper limit (DUL; Ratliff *et al.*, 1983) and the lower limit (LL) of plant-available water (Table 2.3.2a to Table 2.3.2f). Adjustments were made to accommodate the presence of coarse fragments in spoil materials where applicable. Water-holding capacities of the coarse fragments, as determined by Schoeman *et al.* (1997) were used to estimate the contribution of coarse fragments to the water-holding capacity. Saturation was taken as 85% of pore space, as determined by 1-(Db/Dp) where Db denotes bulk density and Dp, particle density. Particle density was derived from the type of minerals present.

As a final measure, the data and information obtained, as indicated above, were compared with values from routine neutron probe readings during periods of near-saturation, drained upper limit conditions and strong wilting conditions. These field values were mostly used for the construction of water retention graphs (Figures 2.3.2 and 2.3.3).

Plant-extractable water

In order to assess the ability of the pasture cover to extract plant-available water from dense, hardsetting layers (see 2.3.3), use was made of a rooting density scale, ranging from zero to one. Soil layers of the various sites were rated on this scale in accordance with the aid of root maps (Figure A2, Appendix 2) and soil water extraction data (Appendix 3). The plant-available water capacity is corrected with this factor to arrive at an estimate of profile extractable water (Table 2.3.2a to Table 2.3.2f).

Availability of water held at potentials higher than the drained upper limit

The drained upper limit was assessed as indicated above. The "draining upper limit", however, is a dynamic property due to the fact that plants take up water while the soil is draining. Bennie *et al.* (1998) and Hensley *et al.* (1993) define this upper limit of plant-available water (ULAW) as the point on the soil's drainage curve at which the drainage rate is equal to the evapotranspiration rate. It is based on the premise that any water moving through the root zone at a rate slower than the ET rate will be extracted by plant roots as it moves through the soil, and will contribute towards ET.

In applying this method, a commonly attained ET rate was identified of approximately 4.6 mm per day in January. The Middelburg South drainage curve (Figure A2.3b. Appendix 2), shows that 138 mm water is present in the cover soil 3 days after wetting, when the drainage rate is 4 mm per day. As the slope of drainage curves at more waterlogged sites, such as the Kriel site, can be expected to be steeper than the one used, this should be regarded as a maximum value. The capacity for plant-available water held at matric potentials higher than DUL, as represented by ULAW minus DUL, is thus estimated to have a minimum value of 26 mm.

DEEP DRAINAGE

In the estimation of deep drainage, use was made primarily of relationships between water content and matric potential (Figure 2.3.2) and drainage curve data (Appendix 2, Figure A2.3).

Drainage experiment

Results of a study to determine the drained upper limit and the water content at saturation of the soil-spoil combination at a site at Middelburg South are shown in Figure A2.3, Appendix 2. The site used is somewhat shallower than the Middelburg South A and B sites, and the cover soil clay content is one or two percentage points lower. For the construction of Figure A2.3b, values were extrapolated after 27 days. Some drainage still took place after 27 days. However, rain events started to occur and the plastic covering was punctured by sedge grass, causing measurements to be stopped. The slow drainage is in accordance with Ratliff *et al.* (1983), who pointed out that soils with restrictive layers require up to 20 days of drainage.

From this data, and data from various published sources, a set of three hydraulic conductivity curves was established (Figure 5.2, Chapter 5).

TABLE 2.3.2a Water retention of soil and spoil layers at Kriel A, taking coarse fragments into account, compared to values from literature

Depth (m)	Clay (%)	Coarse frag-ments (%)	Satura-tion (vol. %)	Drained upper limit (volumetric %)						Lower limit (volumetric %)						Plant-available water (DUL-LL) (%)	Rooting density scale (0-1)	Estimated profile extractable water (%)
				Core sam-ples	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]	Core sam-ples	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]			
0.0-0.2	22	0	27	15.5	20	18	19.2	18.7	18.4	11.5	10.5	18	10.6	11.0	12.0	6.4	1.00	6.4
0.2-0.4	22	0	27	15.5	20	18	19.2	18.4	18.4	11.5	10.5	18	10.6	10.6	12.0	6.4	0.90	5.8
0.4-0.6	22	16	25	18.5	20	16.7	17.7	17.1	16.9	12.7	10.5	15.7	9.5	9.5	11.0	5.9	0.75	4.4
0.6-0.8	15	36	21	-	-	13.7	15.3	14.4	13.8	-	-	10.6	7.4	6.7	9.0	4.8	0.10	0.5
0.8-1.0	14	49	19.5	-	-	12.5	14.2	12.9	12.9	-	-	8.0	6.9	5.7	8.0	4.9	0	0
1.0-1.3	14	49	19	-	-	12.5	14.2	12.9	12.9	-	-	8.0	6.9	5.7	8.0	4.9	0	0
1.3-1.6	14	53	18	-	-	12.3	13.9	12.5	12.0	-	-	7.7	6.7	5.7	7.7	4.3	0	0
1.6-1.9	14	53	18	-	-	12.3	13.9	12.5	12.0	-	-	7.7	6.7	5.7	7.7	4.3	0	0

[#] Values used

TABLE 2.3.2b Water retention of soil and spoil layers at Kriel B, taking coarse fragments into account, compared to values from literature

Depth (m)	Clay (%)	Coarse frag-ments (%)	Satura-tion (vol. %)	Drained upper limit (volumetric %)						Lower limit (volumetric %)						Plant-available water (DUL-LL) (%)	Rooting density scale (0-1)	Estimated profile extractable water (%)
				Core sam-ples	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]	Core sam-ples	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]			
0.0-0.2	23	1	28.0	15.5	20	19.2	19.9	18.6	18.6	11.5	10.5	18.6	11.2	10.9	12.5	6.1	0.95	5.8
0.2-0.4	23	1	28.0	15.5	20	19.2	19.9	18.6	18.6	11.5	10.5	18.6	11.2	10.9	12.5	6.1	0.60	3.7
0.4-0.6	23	1	28.0	18.5	20	19.2	19.9	18.6	18.6	12.7	10.5	18.6	11.2	10.9	12.5	6.1	0.40	2.4
0.6-0.8	16	23	22.0	-	-	16.8	18.9	14.8	15.0	-	-	13.3	10.6	7.2	10.1	4.9	0.05	0.2
0.8-1.0	16	48	18.2	-	-	14.6	16.0	13.5	12.8	-	-	10.3	8.5	6.2	8.7	4.1	0	0
1.0-1.3	16	50	18.0	-	-	14.4	15.8	13.2	12.6	-	-	10.1	8.3	6.1	8.6	4.0	0	0
1.3-1.6	16	50	18.0	-	-	14.4	15.8	13.2	12.6	-	-	10.1	8.3	6.1	8.6	4.0	0	0
1.6-1.9	16	50	18.0	-	-	14.4	15.8	13.2	12.6	-	-	10.1	8.3	6.1	8.6	4.0	0	0

[#] Values used

TABLE 2.3.2c Water retention of soil and spoil layers at Middelburg South A, taking coarse fragments into account, compared to values from literature

Depth (m)	Clay (%)	Coarse frag-ments (%)	Satura-tion (vol. %)	Drained upper limit (volumetric %)						Lower limit (volumetric %)					Plant-available water (DUL-LL) (%)	Rooting density scale (0-1)	Estimated profile extractable water (%)
				Drainage curve	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM#	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM#			
0.0-0.2	17	0	27	17.0	18.0	17.2	18.6	16.8	16.8	9.0	15.5	10.0	8.6	10.0	6.8	0.95	6.5
0.2-0.4	17	0	27	17.0	18.0	17.2	18.6	16.8	16.8	9.0	15.5	10.0	8.6	10.0	6.8	0.80	5.4
0.4-0.6	17	0	27	17.0	18.0	17.2	18.6	16.8	16.8	9.0	15.5	10.0	8.6	10.0	6.8	0.65	4.4
0.6-0.8	17	4	24	17.0	17.0	16.6	18.3	16.6	15.3	9.0	15.0	9.8	8.4	9.5	5.8	0.40	2.3
0.8-1.0	17	15	23	-	-	15.9	17.3	15.8	14.8	-	13.5	9.1	7.9	9.1	5.7	0.25	1.4
1.0-1.3	10	39	21	-	-	13.2	13.4	12.2	12.2	-	8.3	7.3	4.9	6.2	6.0	0	0
1.3-1.6	10	66	19	-	-	11.9	11.7	11.2	11.0	-	6.2	5.8	4.5	5.0	6.0	0	0
1.6-1.9	10	64	19	-	-	11.9	11.8	11.3	11.0	-	6.3	6.0	4.5	5.0	6.0	0	0

Values used

TABLE 2.3.2d Water retention of soil and spoil layers at Middelburg B, taking coarse fragments into account, compared to values from literature

Depth (m)	Clay (%)	Coarse frag-ments (%)	Satura-tion (vol. %)	Drained upper limit (volumetric %)						Lower limit (volumetric %)					Plant-available water (DUL-LL) (%)	Rooting density scale (0-1)	Estimated profile extractable water (%)
				Drainage curve	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM#	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM#			
0.0-0.2	18	0	28	17.0	16.1	18.3	18.8	17.2	17.2	9.4	15.9	10.6	9.0	10.0	7.2	1.00	7.2
0.2-0.4	18	0	28	17.0	16.1	18.3	18.8	17.2	17.2	9.4	15.9	10.6	9.0	10.0	7.2	0.85	6.1
0.4-0.6	18	0	28	17.0	16.1	18.3	18.8	17.2	17.2	9.4	15.9	10.6	9.0	10.0	7.2	0.80	6.0
0.6-0.8	18	0	23.5	17.0	16.1	18.3	18.8	17.2	14.9	9.4	15.9	10.6	9.0	8.5	6.4	0.70	4.5
0.8-1.0	15	27	21.5	-	-	13.1	15.4	14.4	12.5	-	9.8	6.5	6.8	6.5	6	0.10	0.6
1.0-1.3	10	53	19	-	-	12.6	12.4	11.7	11.5	-	7.1	5.6	4.7	5.5	6	0	0
1.3-1.6	10	54	19	-	-	12.9	12.3	11.7	11.5	-	7.0	5.6	4.7	5.5	6	0	0
1.6-1.9	10	68	19	-	-	12.7	11.6	11.2	11.5	-	6.2	5.1	4.5	5.5	6	0	0

Values used

TABLE 2.3.2e Water retention of soil and spoil layers at Optimum A, taking coarse fragments into account, compared to values from literature

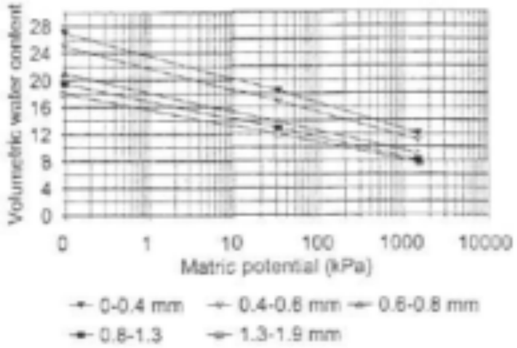
Depth (m)	Clay (%)	Coarse frag-ments (%)	Satura-tion (vol. %)	Drained upper limit (volumetric %)					Lower limit (volumetric %)					Plant-available water (DUL-LL) (%)	Rooting density scale (0-1)	Estimated profile extractable water (%)
				Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]			
0.0-0.2	17	0	28.0	15.8	17.2	16.9	16.8	17.0	8.0	15.1	9.0	8.6	10.0	7.0	0.95	6.7
0.2-0.4	17	0	28.0	15.8	17.2	16.9	16.8	17.0	8.0	15.1	9.0	8.6	10.0	7.0	0.75	5.3
0.4-0.6	17	8	26.0	15.3	16.6	16.4	16.3	16.0	7.7	14.2	8.6	8.3	9.3	6.7	0.60	4.2
0.6-0.8	9	40	22.0	-	10.7	13.1	11.8	12.2	-	7.8	6.3	4.6	6.0	6.2	0.20	1.2
0.8-1.0	8	60	20.0	-	10.2	11.9	10.9	11.3	-	6.4	5.4	4.2	5.5	5.8	0.05	0.3
1.0-1.3	8	54	18.5	-	10.2	12.2	11.0	10.5	-	6.7	5.6	4.2	5.0	5.5	0	0
1.3-1.6	9	56	18.5	-	10.5	12.2	11.3	10.5	-	6.8	5.7	4.4	5.0	5.5	0	0
1.6-1.9	8	60	18.5	-	10.2	11.9	10.9	10.5	-	6.4	5.4	4.2	5.0	5.5	0	0

[#] Values used

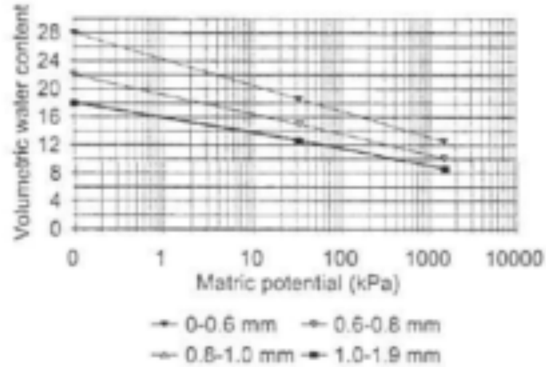
TABLE 2.3.2f Water retention of soil and spoil layers at Optimum B, taking coarse fragments into account, compared to values from literature

Depth (m)	Clay (%)	Coarse frag-ments (%)	Satura-tion (vol. %)	Drained upper limit (volumetric %)					Lower limit (volumetric %)					Plant-available water (DUL-LL) (%)	Rooting density scale (0-1)	Estimated profile extractable water (%)
				Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]	Land type data	Gupta & Larson	Schultze *et al.*	Prinsloo *et al.*	NWM[#]			
0.0-0.2	19	0	28.8	17.0	18.1	17.7	17.5	17.7	9.1	16.2	9.9	9.4	10.4	7.3	0.90	6.6
0.2-0.4	19	0	28.8	17.0	18.1	17.7	17.5	17.7	9.1	16.2	9.9	9.4	10.4	7.3	0.75	5.5
0.4-0.6	19	9	27.5	16.4	17.4	17.0	16.8	17.0	8.6	15.1	9.4	8.9	9.9	7.1	0.65	4.6
0.6-0.8	18	36	25.0	13.5	14.8	14.7	14.6	14.5	7.2	11.4	7.6	7.2	7.5	7.0	0.05	0.4
0.8-1.0	15	42	23.8	-	13.4	13.5	13.5	13.4	-	9.6	6.7	6.2	6.7	6.7	0	0
1.0-1.3	13	44	23.2	-	12.7	13.0	12.9	13.2	-	8.7	6.2	5.6	6.5	6.7	0	0
1.3-1.6	13	35	23.2	-	13.1	13.5	13.4	13.2	-	9.5	6.5	5.9	6.5	6.7	0	0
1.6-1.9	13	38	23.2	-	13.0	13.4	13.2	13.2	-	9.2	6.4	5.8	6.5	6.7	0	0

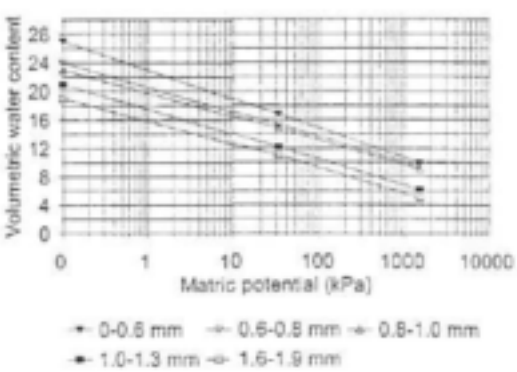
[#] Values used



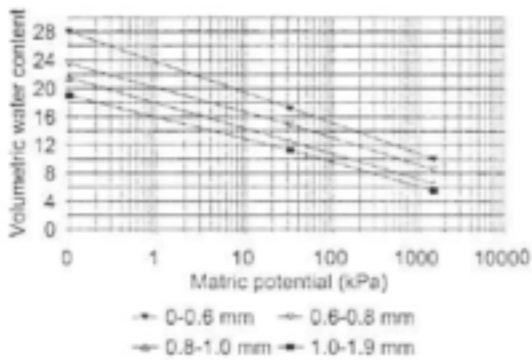
(a) **Kriel A**



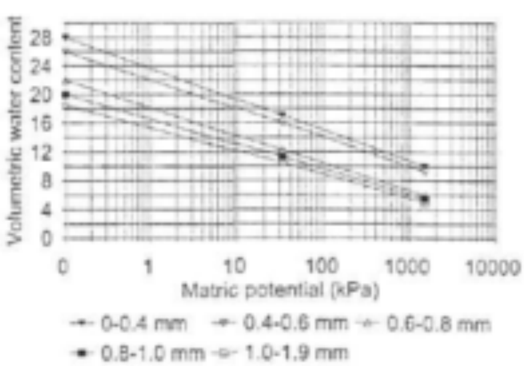
(b) **Kriel B**



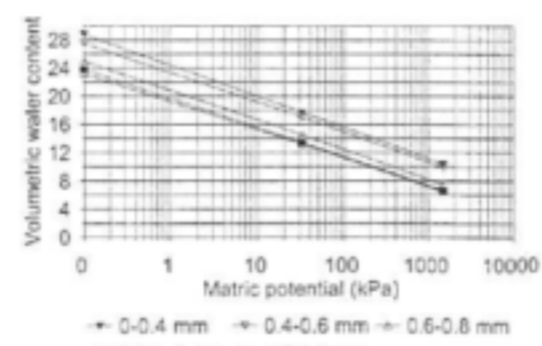
(c) **Middelburg South A**



(d) **Middelburg South B**



(e) **Optimum A**



(f) **Optimum B**

Figure 2.3.2 Water retention graphs

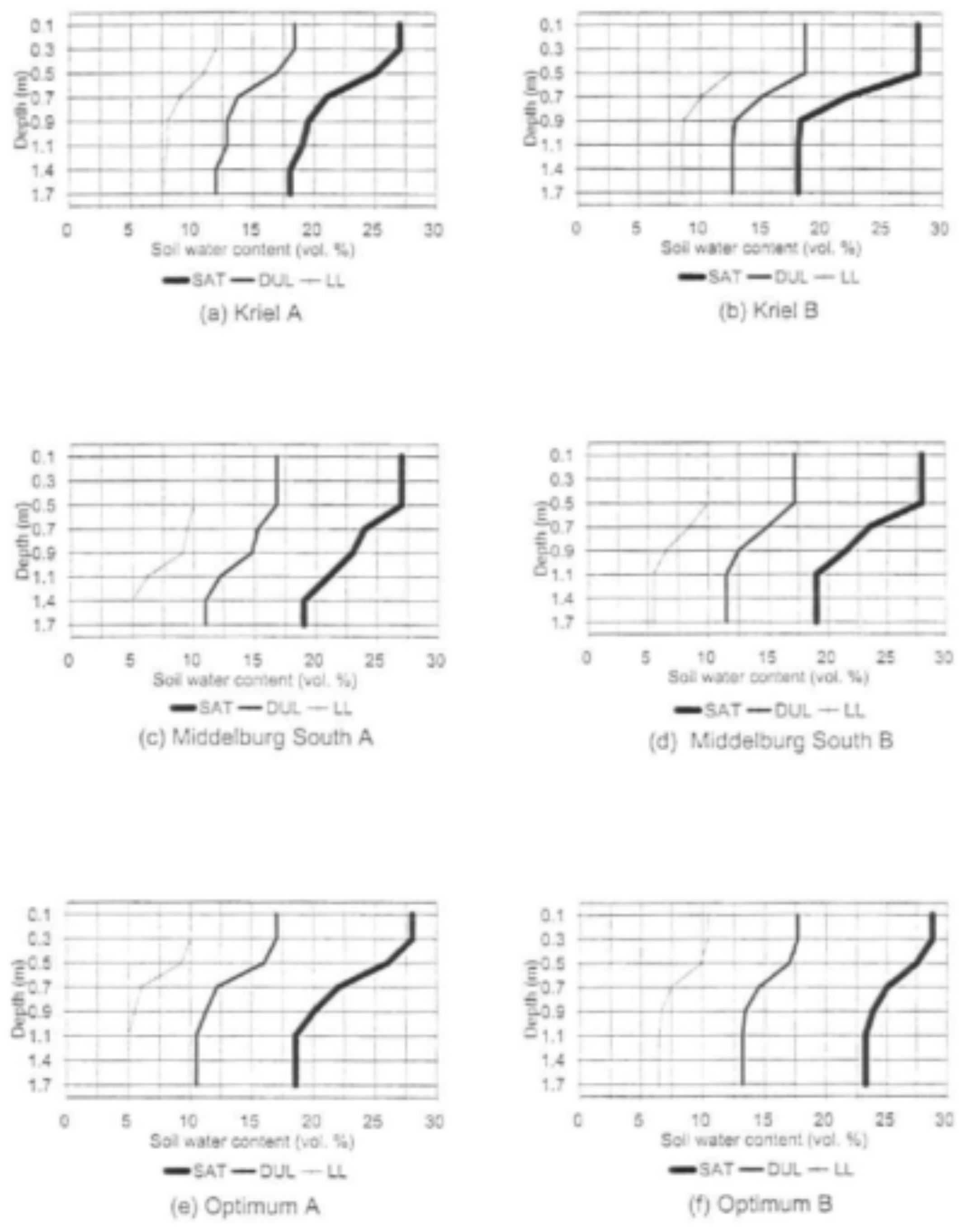


Figure 2.3.3 Water profile diagrams

2.3.3 SOIL MINERALOGICAL PROPERTIES

In order to obtain an indication of possible hardsetting characteristics, instability or re-compactibility of cover soils, data sets were compiled on the clay mineralogy and water-dispersible clay to total clay ratios. Data are shown in the following tables in Appendix 2:

Table A2.4a	Natural soils, Optimum
Table A2.4b	Cover soils under pasture, Optimum
Table A2.4c	Cover soils under maize, Optimum
Table A2.4d	Cover soils under maize, Middelburg South
Table A2.4e	Cover soils under maize, Kriel

CLAY MINERALOGY

The soils are shown to contain between 50 and 80% (average 70%) kaolinite, between 10 and 40% (average 20%) quartz, between 5 and 15% (average 10%) mica. Traces of goethite occur.

The water-dispersible clay fraction was shown to contain less kaolinite than the total clay (average 50 percent, compared to 70) and more quartz (average 40 percent compared to 20).

Clay size quartz is known to play a negative role in aggregate stability due to its low electric charge (Bühmann, Van der Merwe & Laker, 1997). Bühmann (personal communication) concludes from the data that we are dealing with soils which may have low to intermediate inherent instability due to the clay-size quartz fraction.

WATER-DISPERSIBLE CLAY

Water-dispersible clay was determined using USDA method 3A2c (Soil Survey Staff, 1996). Clay mineralogy was by XRD.

Average water-dispersible to total clay ratios varied between 0.01 and 0.34. The average of all five data sets is 0.21 (Table A2.4, Appendix 2).

Unpublished work by Samadi (Samadi, M., personal communication) showed that the ratio of water-dispersible to total clay is a useful parameter for establishing aggregate stability. He analyzed a set of 23 subsoil horizons from Estcourt and Sterkspruit soil forms which are known to be dispersible and a set of 16 subsoil samples from the Shortlands soil form, known to have high aggregate stability. For the unstable group, the ratio ranged between 0.33 and 1.00 with an average of 0.63. For the stable group, the ratio ranged between 0.02 and 0.17 with an average of 0.09. The World Soils Reference Base (ISSS-ISRIC-FAO, 1994) sets the lower limit for the stable Nitic soils (Shortlands form) at 0.10. Results and tentative norms are summarized below in Table 2.3.3.

If these norms are applied, the cover soils under consideration appear to lie in the slightly unstable to intermediate range. If the data are correct (selected samples were analyzed twice and similar results were obtained), they do seem to point to an ability of the soils to re-compact. Building-up and conservation of soil organic matter then becomes an important issue.

Table 2.3.3 Grouping of water-dispersible clay to total clay ratios in terms of stability classes, following Samadi (personal communication) and WRB (ISSS-ISRIC-FAO, 1994). Averages are in brackets.

	Stable	Intermediate	Unstable
WRB	0.10		
Samadi	0.02-0.17 (0.09)		0.33-1.00 (0.63)
Optimum (natural soils)		0.22	
Optimum (pasture)	0.05		
Optimum (maize)	0.16		
Middelburg South (maize)		0.33	
Kriel (maize)		0.30	

HARDSETTING BEHAVIOUR

Hardsetting behaviour (Mullins *et al.*,1987) was frequently observed in cover soils by Nell & Steenekamp (1998). The following characteristics of hardsetting soils (Mullins *et al.*, 1987; Ley *et al.*, 1988; Mullins *et al.*, 1990; Mullins, Blackwell *et al.*, 1992; Mullins, Cass *et al.*, 1992; Smith *et al.*, 1992; Franzmeier *et al.*, 1996) apply to a greater or lesser degree to the cover soil materials of this study:

- Hardsetting soils are relatively soft when moist but become unusually hard when dry.
- The hardsetting behaviour observed in mine soils appears to relate to organic matter, microbial activity, clay mineral type, texture, soil handling and exposure.
- Susceptible soils contain too little clay to shrink and crack on drying, but contain sufficient clay and silt to bridge sand grains in order to hold them together in a rigid matrix.
- Hardsetting behaviour is associated with loamy sand to sandy clay textures, and high silt and fine sand contents.
- In many but not all hardsetting soils, the clay mineralogy is dominated by kaolinite. Artificial mixtures of sand with as little as 2% kaolinite can exhibit hardsetting behaviour.
- Hardsetting behaviour can be induced by aggregate dispersion caused by mechanical stress. Chemically susceptible soils disperse even under small amounts of stress. Large stresses can disperse most of the clay, even in chemically stable soils.
- Hardsetting is predominantly observed in soils with low concentrations of organic matter.
- It is suspected that all soils with appropriate particle size distribution and clay mineralogy are potentially hardsetting in the absence of a sufficient concentration of organic matter or inorganic cementation or stabilization of micro-aggregates.
- The paradox of low strength during wetting and high strength when dry is explained as follows: wetting of a soil releases a range of powerful disruptive forces due to double-layer swelling, trapped air, and the heat of wetting, which are sufficient to rupture rigid short-range chemical bonds, whereas the flexible polymer bonding such as that provided by polysaccharides in water-stable aggregates may be able to withstand wetting although making a modest contribution to soil strength.
- Hardsetting characteristics are most likely to be found in hot, dry regions, but it is possible under humid temperate conditions to diminish soil organic matter content sufficiently to produce hardsetting behaviour.

- It is difficult to establish boundaries for delimiting hardsetting behaviour from other forms of soil behaviour. It is closely related to susceptibility to compaction.

It follows from the above that texturally, mineralogically, climatologically and with respect to their history of disturbance, the soils should be regarded as susceptible to the development of hardsetting properties.

2.3.4 ROOT DISTRIBUTION PATTERNS

In order to assess the pasture root distribution patterns, root map diagrams (Figures A2.5 to A2.8, Appendix 2) were made. Roots were exposed in cleaned backhoe pit faces by means of a pressurized water jet and counted per 50 mm square with the aid of a movable grid.

Root distribution patterns were variable:

- At the Middelburg South A site (Figure A2.6), abundant roots were restricted to the upper 300 to 350 mm, with isolated "beards" or thinly interwoven mats of roots down to 800 mm along planes of weakness. This pattern corresponds well with the high bulk densities reported for the cover soil layers at that depth zone in Table A2.2, Appendix 2. The mine could not provide backhoe pits at the B site.
- At the Kriel A and B sites, roots were abundant above 250 mm, common or frequent to approximately 650 mm (very dense deeper cover soil), and isolated to approximately 900 mm (upper spoil).
- At the Optimum A site, roots were abundant or common down to the spoil contact at 600 to 800 mm, where bulk densities of less than 1.8 Mg m^{-3} were found, and common in the upper spoil. At the Optimum B site, roots were abundant in the first 200 to 250 mm, below which they were common but patchy, and concentrated in planes of weakness. Bulk densities were not particularly high. Roots reached into the spoil contact at 850 mm. A second set of root maps was prepared for the Optimum B site with the aim of assessing the situation after the plot has been fertilized at known levels for two seasons. The excavations were thus done by hand inside the plot area (the first set of root maps was made in a backhoe trench outside the plot area). Two of three pits mapped (Figure A2.8a and Figure A2.8c, Appendix 2) still showed the typical non-uniform root distribution pattern found in dense soils. The third (Figure A2.8b, Appendix 2) showed a uniform rooting pattern with abundant roots down to the cover soil-spoil contact at 0.5 m depth. The root distribution patterns did not appear to have improved due to fertilization. As attempts to penetrate the spoil material by hand were unsuccessful, information from the new set is restricted to the cover soil.

2.4 INSTRUMENTATION, DATA COLLECTION AND FERTILIZATION

2.4.1 NEUTRON PROBE ACCESS AND CALIBRATION

The installation of neutron probe access tubes in rocky materials called for special equipment and care. Lubricated coring could not be done because of the oils used. Despite warnings by Greacen *et al.* (1981) against using jackhammer tools, access tubes were installed by means of a jackhammer fitted with a purpose-made 1.8 m hollow shaft to which a hollowed-out standard 50 mm outside diameter core bit was welded. This produced a near-perfect, tight-fit hole. It was found (e.g. when a stuck core bit had to be dug out) that the typically elongated, oriented, shaly rock fragments are so firmly embedded in the spoil matrix that disturbance (creating artificial voids) by concussion drilling can be expected to be minimal.

CALIBRATION

The option of field calibration (in contrast to drum calibration) was chosen due to the rocky nature of the spoil. Factors critical to calibration were proper installation, bulk density data, coarse fragment percentage and coarse fragment density. Other factors considered include equivalent water and the presence of strong absorbers of thermal neutrons, such as boron, chloride and iron. Carbon is not reported in the literature to be a strong absorber.

Bulk density and calibration

The bulk density data reported in Table A2.2 (Appendix 2) were extrapolated for purposes of calibration. As bulk density is critical to calibration, readings from a gamma density probe, calibrated against the measured data, were used to assess the bulk density of layers for which no measured bulk density data was available.

Coarse fragment content and calibration

Data on the coarse fragment percentages of spoil materials were obtained from the material excavated during bulk density determinations. The coarse fragments (>2mm) were separated out by wet-sieving. After oven-drying, the coarse fraction mass and the coarse to fine fraction ratio were determined. The coarse fraction was subsequently screened into five size fractions (2-4 mm, 4-10 mm, 10-26 mm, 26-75 mm and >75 mm) and the mass of each sub-fraction determined. These data, together with water retention values obtained for various rock types (Schoeman *et al.* 1997), were used in the calibration of NWM readings.

In calculating the percentage water in coarse fragment-rich material, the following approaches were considered:

Approach of Russo (1983) and Knight & Moolman (1992)

Russo (1983), reporting on water movement in desert soils, found that the stony fraction did not absorb water. Knight and Moolman (1992), reporting on water movement in stony, alluvial soils of the Breede River valley in South Africa, found that water retention measurements on the particular coarse fragments show that, although these fragments have a total porosity of 11.06%, water is held at matrix potentials below -1500 kPa, rendering it unavailable to plant roots.

Approach of Berger (1976), Coile (1953), Hanson and Blevins (1979) and Flint and Childs (1984)

Hanson and Blevins (1979) reported approximately 5% available water, on a dry mass basis, in small sandstone fragments, and 5 to 13% in small shale fragments. Similar values were reported by Coile (1953) for small sandstone fragments. Using data from several authors, Flint and Childs (1984) concluded that rock fragments in soils may contain considerable pore volume (as much as 20 to 60% porosity). They also concluded that rock fragments may contribute an average of 15% of the total available water in soils rich in coarse fragments and that this may range from 1.6 to 52.1%. Hanson and Blevins (1979) reported that wilting point estimates by -1500 kPa laboratory measurements compared very closely with wilting point plant extraction in the greenhouse for sandstone coarse fragments. These authors, as well as Berger (1976) suggest that water is also held in the contact angles between small rock fragments.

Schoeman *et al.* (1997) found the average volumetric plant-available water-holding capacity of rock fragments between 2 and *circa* 100 mm in size, of four rock types associated with the coal-bearing strata, to be in the order of 13.7% (range: 2-40%).

Partitioning of water in the soil-coarse fragment mixtures was done according to the method put forward by Berger (1976). This is discussed more fully in Schoeman *et al.* (1997).

Knight and Moolman (1992) reported very low bulk densities (0.82 Mg m^{-1}) of the fine soil material between coarse fragments, and found it to be corroborated by high permeability of the soil-stone mixture. This is in accordance with the fixed relationship between volume, density and mass. If it is known, for example, that a spoil sample contains 40% fines and 60% coarse fragments by volume, the mass of fines and coarse fragments, respectively, is 5.2 and 13.8 kg, the bulk density of the total sample is 1.7 Mg m^{-3} and the coarse fragment apparent density is 2.3 Mg m^{-3}, the relationship between volume, mass and density implies that the density of the fine fraction is 1.3 Mg m^{-3}.

Coarse fragment density

Mean values of coarse fragment densities were needed in order to calculate the bulk density of the fine fraction. The density of a number of representative fragments was determined by coating with candle wax in order to determine the volume. Average values obtained for the two rock types constituting the bulk of all coarse fragments, viz. dark bluish-grey, laminated, micaceous sandy shale, and whitish, massive, coarse-grained sandstone, were 2.35 and 2.40 Mg m^{-3} respectively.

Equivalent water

In order to obtain information on equivalent water (tightly-held water remaining in the soil after heating to 105°C), twelve representative soil and spoil samples were selected for determination of loss on ignition. The samples were split into a set treated with hydrogen peroxide to remove active carbon and an untreated set. Each set was heated to 550 °C and the loss of mass determined (Table A2.6, Appendix 2).

The results (varying between 1 and 8.5 %) deviated quite markedly from that suggested by an equation proposed by Greacen *et al.* (1981), which gives values around 3%:

$W_e = 0.124\ (\pm 0.012)\ C + 0.015$, where C = clay content in $g \cdot g^{-1}$

The results, when extrapolated to a Kriel site, did not improve the r^2 value of NWM calibration curves. Due to the fact that some aspects of the results in Table A6, e.g. the role of carbon in loss on heating, could not be explained, and the fact that calibrations were not improved, led to a decision to report total water and abandon the attempt to distinguish between tightly-bound crystal (equivalent) water and other water in the soils.

Water content measurements

Neutron probe readings were taken at approximately bi-weekly intervals (except when unusually heavy rain prevented access to the terrain or when the probe had to undergo maintenance). The counting period per reading was 30 seconds. Standard readings were taken at the start and end at each site for the calculation of a count rate ratio. Results are shown in Appendix 3.

2.4.2 RUNOFF

Galvanized sheeting, 30 mm high, driven into the soil and sealed with soil ridges against the outside wall, was used to concentrate runoff water into a funnel, which led to a tipping bucket recorder. The latter was linked to a channel in the weather station.

Due to problems with the signal from the tipping buckets, totalizing recorders supplied by the ARC-Institute for Agricultural Engineering were installed. The pulses registered by these recorders were noted approximately every two weeks and were used for correcting data for errors due to lightning-induced pulses.

2.4.3 LIGHT INTERCEPTION

The fraction of light intercepted by the plant canopy, as an indicator of the leaf area, was determined at approximately two-week intervals by means of ceptometer readings above and below the canopy. Readings were always taken at the same locality. At each site, eight randomly situated blocks were staked out for this purpose (see site diagrams in Figure A2.1a-f, Appendix 2). Results are shown in Appendix 6.

2.4.4 DRY MATTER PRODUCTION

The above-ground biomass was determined once a month by means of clippings from four replicate 1 m^2 clippings per site. As shown in the site diagrams in Appendix 2, any quadrangle was, apart from harvesting, clipped only once per season. At approximately early flower stage (one to three times per season, depending on weather conditions), the pastures were cut down with a brush cutter and the material removed. At the same time, the dry matter production was determined at the main plot as well as at the fertilizer sub-plots.

2.4.5 FERTILIZATION

Fertilization of the plots was aimed at relatively high production without too much of a risk of water uptake being restricted due to low soil fertility. In the beginning of the growing season, each plot was fertilized in accordance with Table 2.4.5. When the midsummer rainfall was adequate, a second dressing, consisting of half the quantities in Table 2.4.5 was applied.

Table 2.4.5 Fertilizer applications

Fertilizer/ Element	Kriel (A) and (B) Middelburg South (A) and (B)	Optimum (A) and (B)
	kg ha^{-1}	kg ha^{-1}
N (as LAN)	100	100
K (as KCL)	20	20
P (as super phosphate)	20	40

To assess the influence of the level of fertilization on production and plant cover composition, a fertilizer sub-plot was laid out at each site (Figure A2.1f, Appendix 2). Treatments were as follows: no fertilizer, optimum level (as for main plot), optimum minus 50%, optimum plus 50%.

2.4.6 PASTURE SIMULATION

Pasture modelling was done by means of PUTU15. Modelling operations were as follows:

1. Validation of model accuracy, using the measured data of all the sites for the 1998/99 season. Standard statistical tests as described by Willmot (1982) were used. Two methods to quantify goodness of fit of model performance were used. Firstly, the root mean square error and mean absolute error between simulations and measurements were calculated. Secondly, linear regressions were fitted to observed versus predicted data.
2. Obtaining and preparation of long-term climatological data (supplied by National Department of Agriculture).
3. Application of the calibrated model to long-term climatological data to produce cumulative distribution function curves for each site (Appendix 6B).
4. Interpretation of modelling results.

CHAPTER 3

SOIL WATER

Data collected on the temporal variation of the water content of different soil layers provided an indication of the water regimes of rehabilitated soils under pasture cover (as affected by particular climatic conditions experienced during the three seasons involved). Relationships between water content and matric potential provided an indication of water available for deep percolation (Chapter 5). Together with other data, it also allowed calibration of the pasture model used for extrapolation to the long term (Chapter 6).

3.1 CLIMATIC CONTEXT

The monthly rainfall during the seasons of data collection, averaged for all sites, is shown in Figure 3.1a in relation to the long-term monthly average of the relevant land type climate zone. Average temperatures are shown in Figure 3.1b. Monthly maximum temperatures are shown in Figure 3.1b in relation to the long-term average for the land type climate zone. Data from the Wildebeestfontein weather station near Bethal are used. Temperature data from this station apply to all the experimental sites as they are situated in the same physiographic area.

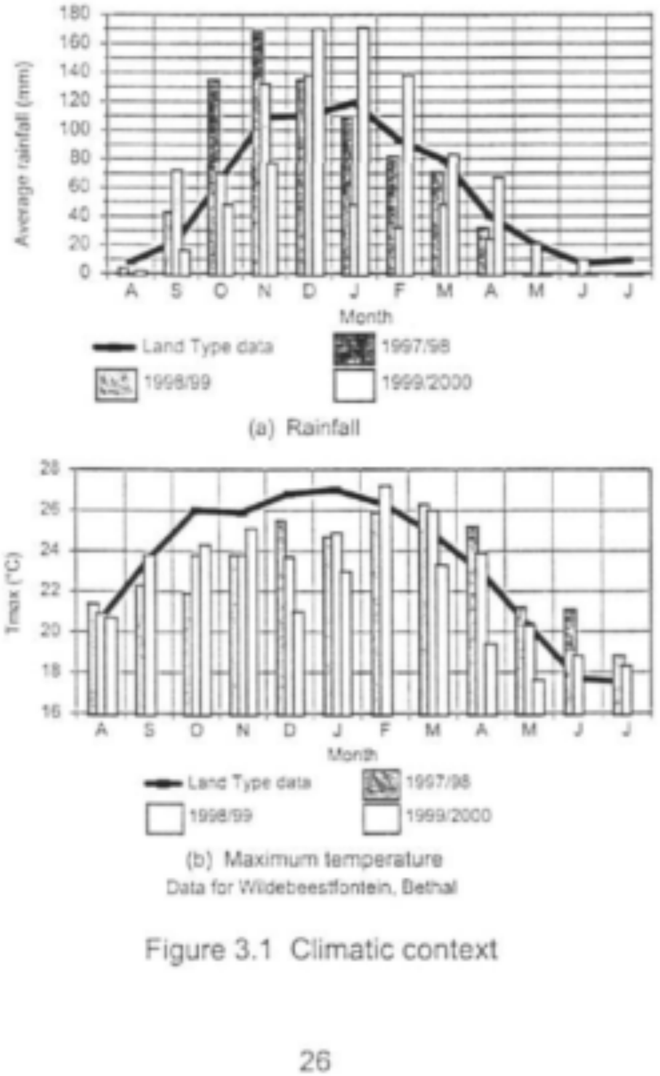


Figure 3.1 Climatic context

The main climatological trends during the seasons involved are summarized in Table 3.1. Seasonal differences, as shown in Figure 3.1 and Table 3.1, illustrate the need for crop modelling to enable extrapolation to the long term.

Table 3.1 Climatological trends

Season	Overview of the season
1997/98	Far above average rainfall and far below average temperatures till December; below average rainfall and above average temperatures in second half of season.
1998/99	Above average rainfall and below average temperatures till December; very low rainfall and above average temperatures in second half of season.
1999/2000	Below average rainfall and high temperatures till November; far above average rainfall and cool temperatures from December onwards.

3.2 KRIEL

3.2.1 COVER SOIL

At the A site, with a cover soil thickness of 600 mm, approximately 158 mm of water is contained at saturation (Table 2.3.2a). Approximately 37 mm of this water is held between the drained upper limit and the lower limit of plant availability. A further approximately 26 mm, held at potentials higher than DUL (see 2.3.2), can be utilized by plants during periods of soil water drainage. The total of both components of plant-available water capacity of the cover soil thus amounts to 63 mm.

The cover soil of the B site, 700 mm thick, contains approximately 196 mm of water at saturation. Of this water, 43 mm is held between the upper and lower limits of plant availability. With approximately 26 mm utilizable water held at potentials higher than DUL added, the total plant-available water amounts to 69 mm.

At both sites, large seasonal changes in water content occurred throughout the cover soil depth (Figures A3.2, A3.4 and A3.6, Appendix 3). Although water is generally strongly extracted from the cover soil, variable quantities of plant-available water (depending on the season) remained present below approximately 0.5 m depth during periods of high water demand (Table 3.2). This water is shown as "bulges" between 0.5 m and approximately 1.0 m in Figure 3.2.

Table 3.2 Kriel A and B: Water remaining in the soil profile during periods of highest extraction, expressed as a percentage of the maximum (undrained) plant-available water capacity (SAT-LL)

Depth (m)	Kriel A			Kriel B		
	1997/98	1998/99	99/2000	1997/98	1998/99	99/2000
0.0-0.2	0	0	0	10	0	0
0.2-0.4	10	7	0	42	53	12
0.4-0.6	27	23	0	74	66	13
0.6-0.8	20	15	0	104	106	52
0.8-1.0	48	67	39	124	107	89
1.0-1.3	12	64	40	89	89	74
1.3-1.6	10	60	37	61	82	69

The inability of the pasture crop to make use of the available water is mainly ascribed to high bulk densities in the lower cover soil and upper spoil (Table A2.2, Appendix 2). The effect of high bulk density is expected to be aggravated by hardsetting behaviour during drying cycles by preventing soil particles from being pushed aside by the growing root tip.

Root development varied from good to moderate and some roots penetrated into the spoil. Patchy and stringy patterns, commonly found in cover soils with high bulk density (Nell & Steenekamp, 1998) were observed (e.g. Figure A2.5, Appendix 2). This led to estimating the profile extractable water capacity (taking into account water extraction and root distribution patterns) as approximately 15% and 25% lower than the plant-available water capacity for the A and B sites respectively (Table 2.3.2a and b).

3.2.2 SPOIL MATERIAL

Seasonal changes in water content extended down to at least 1.6 m depth. The water content of the lower spoil generally varied around the drained upper limit. In the absence of plant roots below approximately 700 mm (Figure A2.5, Appendix 2), changes in water content are ascribed to capillary forces and drainage under the influence of gravity. Saturated or near-saturated conditions at depth, giving rise to appreciable deep drainage, were not recorded.

The plant-available water in the upper 1 m of spoil material is estimated at 47 mm for the A site and 42 mm for the B site (Table 2.3.2a and b). Almost none of this water can be regarded as contributing to profile extractable water, except through capillary rise.

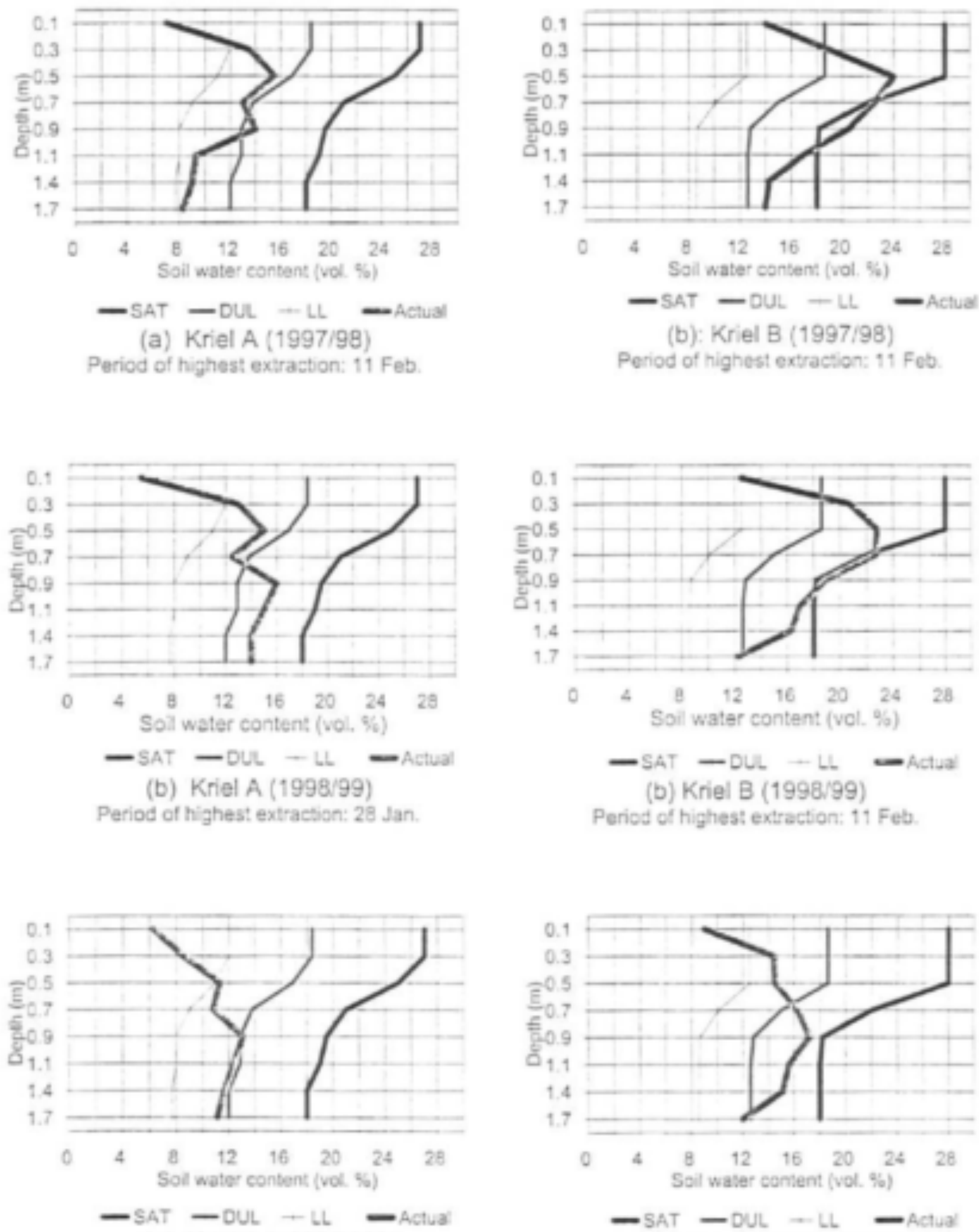


Figure 3.2 Kriel: Water profiles during the periods of highest water extraction (1997/98 to 1999/2000)

3.3 MIDDELBURG SOUTH

3.3.1 COVER SOIL

At the A site, approximately 256 mm of water can be taken up by the 1050 mm of cover soil (Table 2.3.2c). Approximately 64 mm of this water is held between the drained upper limit and the lower limit of plant availability. A further approximately 26 mm, held at potentials higher than DUL (see 2.3.2), can be utilized by plants during periods of soil water drainage. The total of both components of plant-available water capacity of the cover soil thus amounts to approximately 63 mm. The cover soil of the B site, 850 mm thick, can absorb 228 mm of water before saturation. Of this water, 60 mm is held between the upper and lower limits of plant availability. With approximately 26 mm utilizable water held at potentials higher than DUL added, the total plant-available water amounts to 86 mm.

At both sites, prominent seasonal changes in water content were restricted to a depth of 0.8m (Figures A3.8, A3.10 and A3.12, Appendix 3). This depth is slightly shallower than the cover soil depth of 1.05 and 0.85 m respectively.

Table 3.3 Middelburg South A and B: Water remaining in the soil profile during periods of highest extraction, expressed as a percentage of the maximum (undrained) plant-available water capacity (SAT-LL)

Depth (m)	Middelburg South A			Middelburg South B		
	1997/98	1998/99	99/2000	1997/98	1998/99	99/2000
0.0-0.2	6	7	13	3	0	9
0.2-0.4	19	14	18	10	7	27
0.4-0.6	35	38	34	17	9	32
0.6-0.8	41	65	70	23	12	49
0.8-1.0	60	71	71	13	7	28
1.0-1.3	43	51	42	2	15	24
1.3-1.6	8	7	11	6	10	22

At the A site, shallow, patchy and stringy root development (Figure A2.6, Appendix 2) and high bulk densities (Table A2.2, Appendix 2) are an indication of restricted root ramification. These conditions resulted in plant-available water remaining present in the lower cover soil (0.7 to 1.0 m) of the A site, even during peak water extraction periods (Table 3.3; Figure 3.3). The remarks on hardsetting behaviour (2.3.3 and 3.2.1) would apply.

In contrast, water extraction at the B site was the most complete of all sites.

3.3.2 SPOIL MATERIAL

The spoil material of the A site is calculated to contain 196 mm water at saturation and 60 mm plant-available water, respectively, per metre depth. The equivalent figures for the B site is 195 and 44 mm respectively (Table 2.3.2d). Almost none of this water can be regarded as contributing to profile extractable water, except through capillary rise.

At both sites, remarkably little seasonal change occurred in the soil water content of the spoil material, particularly the deeper layers. The water content at this depth generally was only slightly above the lower limit of plant water availability. Saturated or near-saturated conditions at depth, giving rise to appreciable deep drainage, were at no time recorded.

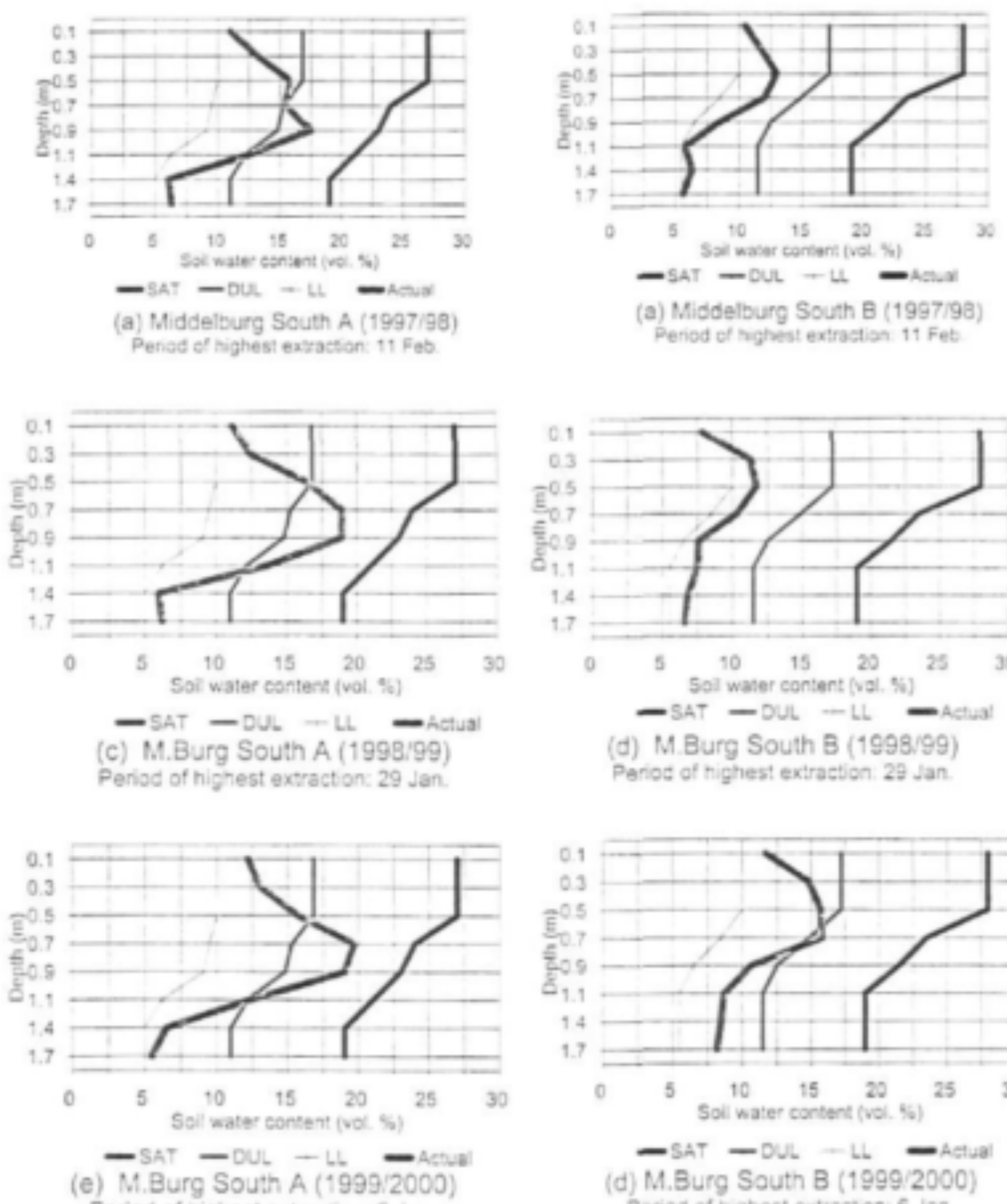


Figure 3.3 Middelburg South: Water profiles during the periods of highest water extraction (1997/98 to 1999/2000)

3.4 OPTIMUM

After the first season, data could only be collected for the B site, as the A site became unavailable.

3.4.1 COVER SOIL

At the A site, approximately 164 mm of water can be taken up by the 600 mm of cover soil (Table 2.3.2e). Approximately 41 mm of this water is held between the drained upper limit and the lower limit of plant availability. A further approximately 26 mm, held at potentials higher than DUL (see 2.3.2), can be utilized by plants during periods of soil water drainage. The total of both components of plant-available water capacity of the cover soil thus amounts to approximately 67 mm. The cover soil of the B site, 550 mm thick, can absorb 156 mm of water before saturation. Of this water, 40 mm is held between the upper and lower limits of plant availability. With approximately 26 mm utilizable water held at potentials higher than DUL added, the total plant-available water amounts to 67 mm.

At both sites (the cover soil depths are 0.6 and 0.55 m respectively), large changes occurred in water content throughout the cover soil (Figures A3.14 and A3.16, Appendix 3). Root development (Appendix 2) varied from good or average at the A site to poor at the B site, where patchy and stringy root distribution patterns occurred. At the latter site, both high and relatively low bulk densities were found (Table A2.2, Appendix 2). Incomplete water extraction during periods of peak demand was noticeable between 0.3 and approximately 0,5 or 0.7 m depth (Table 3.4; Figure 3.4). This is ascribed to high bulk density with consequent poor root development. Comments on hardsetting behaviour (see 2.3.3 and 3.2.1) would apply.

Table 3.4 Optimum A and B: Water remaining in the soil profile during periods of highest extraction, expressed as a percentage of the maximum (undrained) plant-available water capacity (SAT-LL)

Depth (m)	Optimum A			Optimum B		
	1997/98	1998/99	99/2000	1997/98	1998/99	99/2000
0.0-0.2	24	Site not available		9	0	4
0.2-0.4	32			23	12	35
0.4-0.6	37			35	21	37
0.6-0.8	31			14	16	27
0.8-1.0	7			17	14	16
1.0-1.3	10			17	21	14
1.3-1.6	10			25	27	18

3.4.2 SPOIL MATERIAL

The spoil material of the A site is calculated to contain 199 mm water at saturation and 57 mm plant-available water, respectively, per metre depth. The equivalent figures for the B site is 237 and 68 mm respectively (Table 2.3.2f). As at the other sites, almost none of this water can be regarded as contributing to profile extractable water, except through capillary rise.

Only slight seasonal changes in soil water content were noted in the spoil material (Appendix 3). At both sites, the water content remained considerably below the drained upper limit. At no time during the three seasons was evidence found of saturated or near saturated conditions below the root zone which could lead to substantial deep percolation.

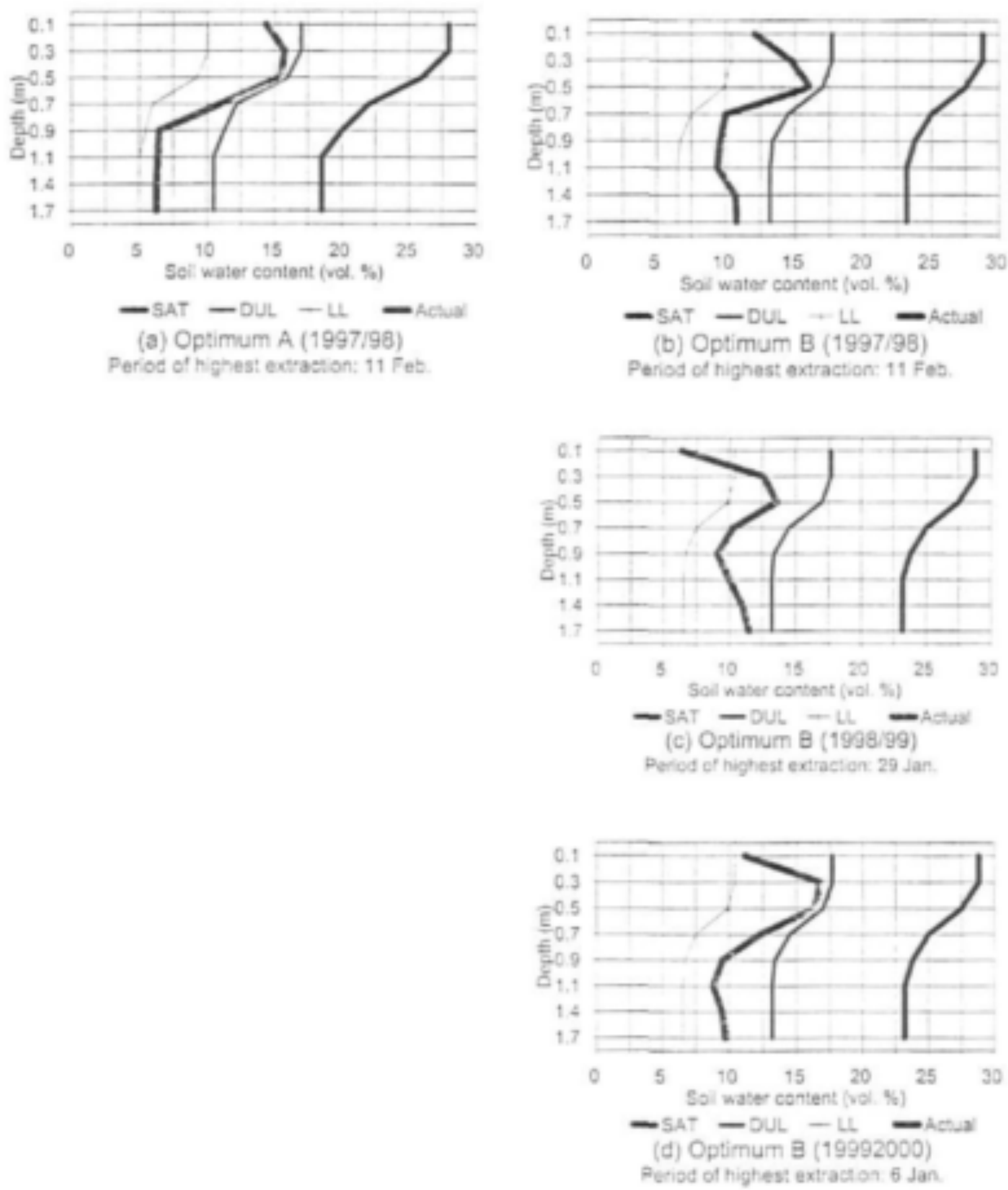


Figure 3.4 Optimum: Water profiles during the periods of highest water extraction (1997 to 2000)

CHAPTER 4

RUNOFF

Due to incomplete data records caused by faulty equipment and false tipping bucket pulses (probably induced by lightning) a way had to be found to make use of the runoff data that was congruent with rainfall quantities and intensities.

After discarding suspect data, a fair number of useable rainfall-runoff data sets remained. Runoff, as a percentage of the rainfall on the particular day, varied between 0.1 and 25. For three sites, a regression was obtained between runoff, as recorded, and the total rainfall on the day on which runoff occurred. These were as follows:

Kriel A:	$y = 0.2754x + 0.2184$	($r^2 = 0.74$)
Middelburg South A:	$y = 0.3296x$	($r^2 = 0.55$)
Optimum B:	$y = 0.2575x + 8.128$	($r^2 = 0.78$)

Where: y = runoff (% of rainfall)
x = rainfall on day of runoff event (mm)

The above regressions were used, together with visible signs of runoff and erosion, to construct Table 4.1.

Table 4.1 Average runoff values for daily rainfall classes

Rainfall on day of runoff (mm)	Runoff (% of rainfall)		
	Middelburg South A and B; Optimum A	**Kriel A and B**	**Optimum B**
0-10	0	0	0
11-25	3	4	5
26-50	8	10	11
51-75	12	15	17
>75	20	25	27

Estimated runoff values, obtained by applying Table 4.1 to rainfall data, were used in water balance calculations (Appendix 7). The runoff calculated in this way varied between 1.9 and 10.8 percent of the total annual rainfall. Values corresponded well with pasture vigour and slope.

Du Plessis and Mostert (1965) reported average runoff figures for natural veld and pastures at Glen. These varied between 2.7 and 12.2 percent of the annual rainfall. The soil was texturally similar to the soils of this study. The slope was 5%, which corresponds to the relatively steep Optimum B site of this study. Their figure of 4.8% of the annual rainfall for a Digitaria pasture site corresponds well with the figure of 5.2 obtained for Optimum B during 1997/98 and 1998/99.

Haylett (1960) reported runoff figures for similarly textured soils under veld and pastures near Pretoria with slopes of 3.75 and 7% respectively. These ranged from 2.5 to 7.1% of the annual rainfall.

CHAPTER 5

DEEP PERCOLATION

Deep percolation is the internal drainage of water out of the soil profile to a depth greater than the bottom of the root zone. In determining deep percolation, information is needed on at least two parameters: the water content of the root zone, θ, and the hydraulic conductivity, K, of the various layers involved.

Bennie *et al.* (1998) described deep percolation as the unidirectional vertical flux q (mm d^{-1}) through an arbitrary plane, the bottom of the root zone (WD, m). It is mainly determined by the hydraulic conductivity (K(θ), mm d^{-1}), which is a logarithmic function of the average water content, θ, so that $q = K(\theta)$.

The water content of the cover soil and spoil material is known as far as it has been determined at approximately two-week intervals. Measuring the hydraulic conductivity of the spoil material was not undertaken due to the unusually high spatial variability to be expected due to the presence of large coarse fragments. An indication of the hydraulic conductivity at one 4 m x 4 m plot was obtained, however, by data from a drainage curve experiment at Middelburg South (see 2.3.2).

The following were considered in estimating K and deep percolation:

- Levelling and landscaping of spoil by heavy equipment inevitably leads to compaction. The rock fragment and rock flour mixture contains sufficient fines (20 to 60 percent, see Table A2.5, Appendix 2) to be susceptible to compaction. High bulk densities of the total coarse fragment-fines mixture tend to confirm the presence of overall compaction, although proportioning of densities between rock and fines indicates rather low densities of some fines between coarse fragments (see 2.4.1).
- Macro-pores, caused by faunal activity (mainly earthworms), which normally greatly influence saturated flow, are absent. As a result, the permeability of the upper spoil is low. This is shown by temporary build-up of water above the cover soil–spoil contact during wet spells (Appendix 3).
- Root development appears to be restricted in the upper spoil material (Figure A2.5, Appendix 2).
- Jovanovic *et al.* (1999), reporting on a study in which *inter alia* rehabilitated land is irrigated with gypsiferous water, point to the fact that ponding occurred above spoil layers at certain sites during the rainy season and that yield losses were experienced due to water-logging. They suspect lateral drainage to be a contributing factor.
- Paterson and Laker (1999), reporting on the use of ground penetrating radar to map the micro-topography of spoil materials, show examples of very smooth but also quite undulating spoil topography and point to the possibility of ponding at the spoil surface.
- At Kriel, water was observed to seep strongly out of the soil in the cover soil-spoil contact.

- Cracks in cover soil and spoil material, caused by settling, may play a major role in allowing water to percolate to deeper layers.
- Nell (1991) reported K_s values for B horizons of poorly-drained irrigated soils (Valsrivier soil form) of below 0.4 (average 0.3) mm h^{-1}. Despite the poor drainage, these soils remained relatively salt-free and were able to produce citrus crops.
- Drainage data for Middelburg South indicated a flux out of the potential root zone of 0.1 mm h^{-1} after 1 day of draining. Saturated conditions occurred at the particular depth and time.

The picture emerging from the above is one of slowly permeable spoil materials with K_s values of less than 0.3 mm h^{-1} and smooth to uneven micro-topography. Seasonally, lateral drainage may occur along major slopes, leading to water accumulation in hollows. Although percolation through the spoil matrix is slow, it may be greatly influenced by settling-cracks. The contribution of the latter would be almost impossible to estimate by means of the approaches used in this study.

Two approaches were used in estimating the water flux below the rooting zone:
- A method proposed by Bennie *et al.* (1998).
- Estimates based on the time duration of the presence of water above DUL.

5.1 ESTIMATION OF DEEP PERCOLATION FOLLOWING BENNIE *ET AL.* (1998)

Bennie *et al.* (1998) proposed a procedure for the derivation of deep percolation. It is based on the drainage data of a number of diverse soil profiles, resulting in the following relationship: $W = a.\ln t + b$

Where
- W = Water content of the root zone (mm)
- T = Time (d)

The procedure involves the following:

1. Determination of the maximum potential rooting depth. The following equation is proposed for this step:

   $WD_{max} = WIT.D$ if $WD_{max} < Z_g$
   $WD_{max} = Z_g$ if $WD_{max} \geq Z_g$

   Where
   - WD_{max} = The maximum rooting depth of the crop
   - WIT = Root penetrating rate (mm d^{-1})
   - D = Duration (days) of the vegetative phases of growth
   - Z_g = Soil depth (mm)

2. If unknown, the a and b coefficients of the drainage equation, ($W = a.\ln t + b$), have to be estimated from the silt plus clay percentage of the root zone by means of the following relationships:

   $$a = 32.6104 - 0.5099\ (Si + Cl)_{ave} \quad (1)$$

$b = b'.WD_{max}/100$ (2)

Where:

a represents the hydraulic conductivity

b represents the profile water content after saturation

Si = silt

Cl = clay

b' $= 1.76.9453 + 6.255\ (Si + Cl)_{ave} - 0.0324\ (Si + Cl)_{ave}^2$

Wd_{max} = potential rooting zone (mm)

3. The daily percolation (P, mm) is estimated at a given water content of the root zone (W, mm) by the following equation:

$DT = a/e^x$

Where:

$X = (b-W)/a$

4. The degree of over saturation (OV, mm) of the root zone is determined by :

$OV = \sum_{i=1}^{n} (\theta_i - \theta_{bi}).Z_i$ only if $\theta_i > \theta_{bi}$

Where:

θ_i = Volumetric water content of layer i

θ_{bi} = Volumetric water content of layer I at the upper limit of plant-available water

In applying the procedure, the parameters a and b were calculated from silt and clay contents, as indicated above. The potential rooting depth value selected was found to have a very strong effect on the outcome. A check on the validity of the parameters was provided by whether or not zero, as opposed to negative, values of deep percolation were indicated for dry conditions. For an example of a calculation table, see Table A5.1, Appendix 5. Results are shown in Table 5.2.

5.2 ESTIMATION OF DEEP PERCOLATION FROM THE TIME DURATION OF CONDITIONS ABOVE DUL AND HYDRAULIC CONDUCTIVITY OF THE UPPER SPOIL

In this approach, the water available for drainage (water content above DUL) was summed for all layers. Deep drainage of water held at lower potentials than DUL was considered to be determined by the hydraulic conductivity, K, of the deeper spoil layers.

K was estimated as follows: values of the saturated hydraulic conductivity, K_s were inferred from published and other sources (Nell, 1991; Paterson & Laker, 1999; Jovanovic *et al.*, 1999; Foth, 1984). Relationships were subsequently established between K and matric potential on the basis that that K_s corresponds to zero kPa, and K approaches zero at 1500 kPa (Figure 5.2).

The water content, θ (%) at saturation (taken as 0.85 of total porosity, i.e approximately air entry value), DUL and LL (see Table 2.3.2a-f) was subsequently used to relate W (mm) to the matric potential,Ψ:

Kriel A	$y = -1.404\ln x + 17.628$
Kriel B	$y = -1.282\ln x + 17.687$
Middelburg South A	$y = -1.909\ln x + 18.550$
Middelburg South B	$y = -1.841\ln x + 18.570$
Optimum A	$y = -1.840\ln x + 17.965$
Optimum B	$y = -2.276\ln x + 22.500$

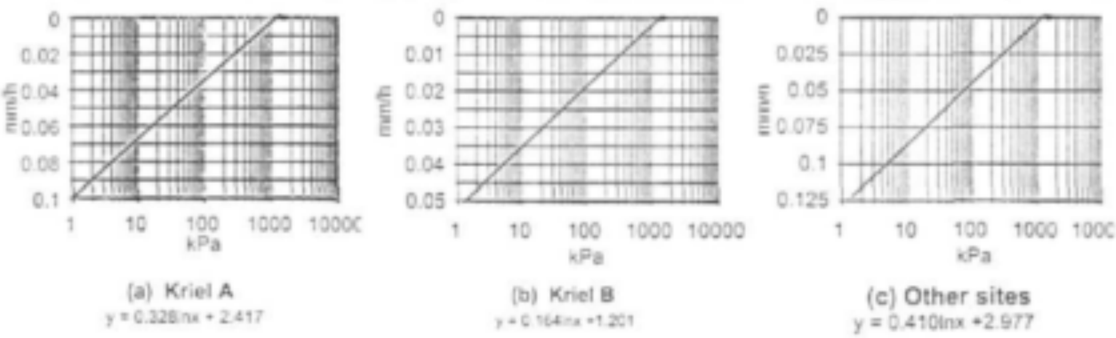


Figure 5.2 Derived hydraulic conductivities for groups of spoil materials and their relationship with matric potential

The relationships between W, K and Ψ were subsequently used to calculate the drainage flux through the lower spoil (Table A5, Appendix 5). Results are shown in Table 5.2.

Table 5.2 Estimates of deep percolation

Site	Season	Derived range in K_s (mm h^{-1})	Percolation below root zone (mm) (Bennie *et al.*)	Percolation below the root zone (mm) based on water above DUL, its time duration and estimated K
Kriel A	1997/98	0.05-0.15	31	29
	1998/99		20	1
	1999/2000		179	177
Kriel B	1997/98	0.02-0.06	217	226
	1998/99		123	147
	1999/2000		330	324
Middelburg South A	1997/98	0.06-0.20	22	0
	1998/99		7	0
	1999/2000		12	5
Middelburg South B	1997/98		1	0
	1998/99		1	0
	1999/2000		1	0
Optimum A	1997/98		23	10
Optimum B	1997/98		9	0
	1998/99		3	0
	1999/2000		7	0

CHAPTER 6

PASTURE PRODUCTION

6.1 DRY MATTER YIELD

The dry matter harvested annually varied between less than 3000 to more than 14000 kg per hectare (Table 6.1). The average yield for all sites and all three seasons was 5250 kg per hectare. Yields from growth curve clippings, taken at approximately fortnightly intervals, as well as from harvest cuts, are shown in relation to light interception in Figures A6.1 to A6.3, Appendix A6.

TABLE 6.1 Dry matter yield

Site	Season									
	1997/98				1998/99			1999/2000		
	1st cut	2nd cut	3rd cut	Total (kg ha^{-1})	1st cut	2nd cut	Total (kg ha^{-1})	1st cut	2nd cut	Total (kg ha^{-1})
Kriel A	2320	1930	1550	5800	2880	1830	4710	1950	2270	4220
Kriel B	2200	2260	1980	6440	1920	1260	3180	2430	1250	3680
Middelburg South A	400	4200	550	5150	3390	750	4140	2770	1300	4070
Middelburg South B	1300	11850	1050	14200	3610	720	4330	4420	2470	6890
Optimum A	6530	-	-	7040	Site unavailable					
Optimum B	3440	-	-	3440	2900	-	3780	1710	1200	2910

6.1.1 EFFECT OF FERTILIZATION

Dry matter yields were strongly affected by NPK fertilization. Yields obtained from fertilizer sub-plots are shown in Table A6.1, Appendix 6. Due to an oversight, the fertilizer sub-plots were not sampled in 1997/98.

With the yield at the "optimal" level (Table A6.1) as reference (unity), the relative yields at the various treatments during the two remaining seasons varied as follows:

- No fertilizer: 0.06 of the optimum at previously poorly-fertilized sites (Kriel A and Optimum B), to 0.86 at previously well-fertilized sites (Middelburg South), with an average of 0.44.
- Optimal minus 50%: 0.54 of the optimum at previously poorly-fertilized sites to 0.97 at previously well-fertilized sites, with an average of 0.77.
- Optimal plus 50%: 0.80 to 1.96 of the optimum, the latter at previously poorly-fertilized sites. The average is 1.30.

6.2 PASTURE SIMULATION

Measured and simulated results correlated well for all sites after calibration of the PUTU15 software (Figure 6.2.1), although high yields remained underestimated. Model calibration produced a correlation coefficient of 92 percent. The mean absolute error was 117 kg ha^{-1} with a root mean square error of 156 kg ha^{-1}. Simulation results are discussed in more detail in Appendix 6A.

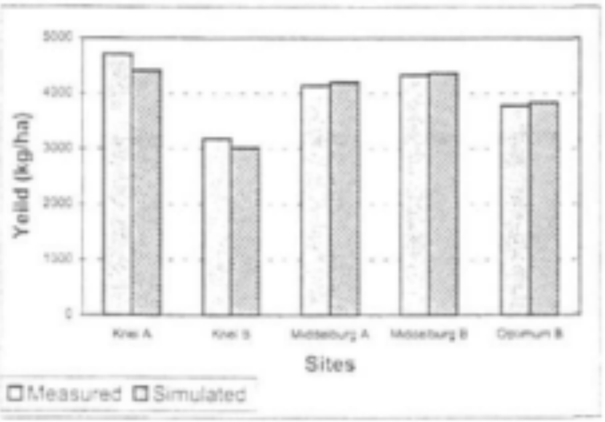


Figure 6.2.1 Measured and simulated yields

Application of the calibrated model to long-term climatological datasets prepared for each mine, produced cumulative distribution functions as shown in Figure 6.2.2.

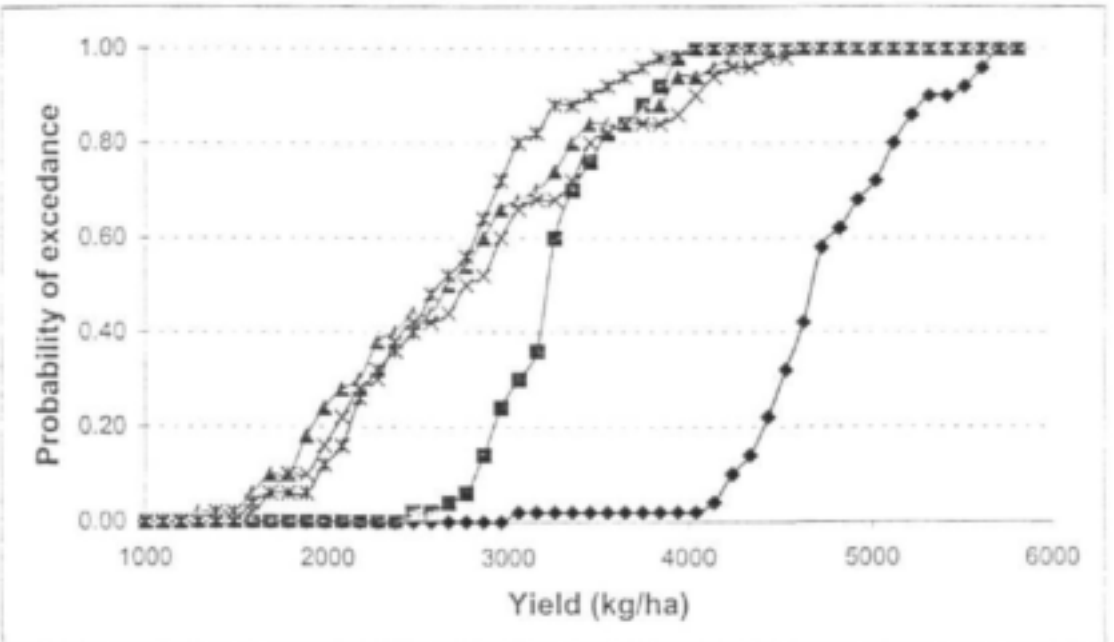


Figure 6.2.2 Cumulative distribution functions

The following are to be noted from figure 6.2.2:

Probability to exceed the yield as indicated (kg ha^{-1})	Kriel A	Kriel B	Middelburg South A	Middelburg South B	Optimum B
20%	5100	3500	3350	3450	3050
50%	4650	3150	2650	2875	2700
80%	4450	2900	1900	2100	2200

The average yield of 3200 kg ha^{-1} at the 50% probability level clearly compares unfavourably with approximate 8000 kg ha^{-1} harvested from natural soils with similar depth and texture in the vicinity (N. Rethman, personal communication).

The long-term outlook of low yields generally is in harmony with findings and observations regarding inefficient soil water extraction. That the soil-landscape system is complex, however, is shown by discrepancies which cannot be explained. For example, at Middelburg B, soil water extraction is the most efficient of all sites, but it does not correlate well with measured or simulated yields.

The large differences between the measured results from three seasons and the long-term outlook illustrate the improved perspective offered by crop modelling, even if calibration is not perfect.

CHAPTER 7

WATER BALANCE

The water balance can be expressed as follows (Bennie *et al.*, 1998):

$$(E+T) = (P \pm \Delta S) - (R \pm D)$$

Where

- E = evaporation from the soil surface
- T = transpiration by the plant cover
- P = precipitation
- ΔS = change in soil water content
- R = runoff
- D = drainage below the root zone.

Separation of E and T was not an objective of this study. The above relationship can thus be expressed as:

$$ET = (P \pm \Delta S) - (R + D) \qquad (1)$$

Of these components, P, ΔS and R were measured (the latter with limited success, and thus partly calculated, as indicated in Chapter 4). D was assessed as indicated in Chapter 5. ET was obtained by subtraction, as shown in Table A7.1, Appendix 7.

Seasonal variation in the components of the water balance is illustrated by Figure A7.1 to Figure A7.3 in Appendix 7.

Average annual values of the components of the water balance are shown in Table 7.1a.

Table 7.1a Components of the water balance: annual values

Site	Season														
	1997/98 (mm)					1998/99 (mm)					1999/2000 (mm)				
	ET	P	ΔS	R	D	ET	P	ΔS	R	D	ET	P	ΔS	R	D
Kriel A	806	896	4	64	31	541	569	12	20	20	486	785	-68	52	179
Kriel B	728	940	35	47	200	486	613	39	43	123	359	605	-74	44	326
Middelburg South A	769	756	58	23	22	637	663	1	20	7	671	723	-32	20	14
Middelburg South B	750	752	26	26	2	588	600	4	15	1	635	681	-32	13	1
Optimum A	711	775	-16	25	23	Site unavailable									
Optimum B	737	753	32	39	9	694	727	8	39	3	663	796	-40	86	7

Relationships between annual rainfall and the annual averages of the other water balance components are shown in Table 7.1b.

Table 7.1b Components of the water balance expressed as a percentage of the annual rainfall

Site	Season											
	1997/98				1998/99				1999/2000			
	ET	ΔS	D	R	ET	ΔS	D	R	ET	ΔS	D	R
Kriel A	90	0.45	3.46	7.14	95	2.11	3.51	3.51	62	-8.66	22.8	6.62
Kriel B	77	3.72	21.3	5.00	79	6.36	20.1	7.01	45	-9.19	40.7	5.47
Middelburg South A	102[#]	7.67	2.91	3.04	96	0.15	1.06	3.02	93	-4.43	1.94	2.77
Middelburg South B	100	3.46	0.27	3.46	98	0.67	0.17	2.50	93	-4.70	0.15	1.91
Optimum A	92	-2.06	2.97	3.23	Site unavailable							
Optimum B	98	4.25	1.20	5.18	95	1.10	0.41	5.36	83	-5.03	0.88	10.80

[#] Depletion of soil water carried over from the previous season accounts for high ratio.

The following should be noted from the above tables and Appendix 7:

- Water available for evapotranspiration (and thus, plant production), varied between 45 and more than 100% of the annual rainfall. Under the conditions of this study (relatively deep soils, moderate slopes and good or fair vegetation cover), differences were mainly between seasons, and reflect the effects of rainfall distribution. Maximum rates of evapotranspiration were in the order of 5 to 8 mm per day.
- The net gain or loss of soil water during the season (seasonal water transfer) was small. Prominent fluctuations occurred, however, during the season. These are shown in Figure A7, Appendix 7 as either positive (water extracted from the soil) or negative changes (water stored in the soil). The re-creation of soils that are able to take up, store and release sizeable quantities of water is thus of importance if runoff and deep percolation are to be minimized.
- Water lost through deep percolation varied from zero to 40%. It was strongly affected by the rainfall distribution. It also differed between sites. Calculating this parameter took into account the water content of the root zone, W (see 5.1). This, in turn, may reflect lateral water movement within the soil (sub-surface run-on). No attempt was made to assess this phenomenon.
- As indicated in chapter 4, the calculated runoff varied between 1.9 and 10.8% of the annual rainfall. This appeared to relate mainly to pasture vigour and slope.

CHAPTER 8

DISCUSSION

The results apply to those strip-mined areas in Mpumalanga which are rehabilitated with relatively deep red, yellow-brown or grey sandy loams or loamy sands, derived from the Vryheid Formation. They would not apply to areas rehabilitated with black clays or sands.

Rehabilitated landscapes constitute an artificial system with high variability, being less ordered and predictable than natural systems (Appendix 1). The information presented can be compared to a few snapshot pictures taken of a few individuals amongst a crowd of thousands. Although there is some certainty that the sites to which the results apply are representative of the rather better rehabilitated areas (Chapter 2), generalization and extrapolation to the industry as a whole, e.g. in efforts to refine industry standards, would thus require care and insight.

Ideally, geostatistical principles should have been employed before starting a study such as this in order to assess the scale and intensity of variability of the materials to be dealt with. Requirements with respect to cost, manpower and time needed to satisfy geostatistical principles would probably have been prohibitive.

Topographical features at meso and micro scales are suspected of playing a more important role than was realized when the sites were selected and probably should have been studied and taken into account more thoroughly. This is due to the complicated nature of the re-created topographical features and drainage systems (and the mechanical actions involved in creating them) as well as the further complicating effects of subsequent slumping and cracking. It is suspected, for example, that low level radar remote sensing would show up parallel features which would be related to the pre-rehabilitation cuts and dumps and the number of bulldozer passes involved in re-creating the new landscape. Methodologies for characterizing such land are suspected not to be readily available in the country.

Probably due to the complexity of topographical effects, some of the results are incompletely understood, e.g. why the deeper spoil material at some sites are constantly close to DUL (as at Kriel), while others are constantly close to LL (Middelburg South) and others are intermediate (Optimum). The relationship between water content of the spoil material and position in the landscape, rooting patterns, the sealing-off effect by dense lower cover soils and pasture vigour thus have not nearly been elucidated.

Hardsetting behaviour of the cover soils may affect water extraction in various ways, two of which are the following:

- Pasture roots appear to be able to penetrate hardsetting layers in cover soils while the latter are at relatively high water content, provided the bulk density is not very high. Once they have penetrated through these layers, the roots are able to draw water from reserves often present in the cover soil-spoil contact and upper spoil due to slight ponding, causing pastures to remain green and productive when drought sets in.

- When hardsetting behaviour sets in early in the season, however, it appears to be able to effectively prohibit new root development and water extraction from deeper layers and pasture production suffers as a result.

The above may explain the less than perfect relationship found between the presence of roots and high bulk density. As a general rule, however, roots were absent where bulk densities exceeded 1.8 Mg m^{-3} or where pH_{water} values were below approximately 5.3.

Runoff results could have been affected to a degree by incomplete removal of mowed hay after harvesting. Mowed hay particles left on the soil surface theoretically could have retarded the overland flow of runoff water. No hay was observed in conduits or tipping buckets, however.

Signs of interrill erosion, indicating substantial runoff, either present or past, were observed only at Optimum B, the steepest site with the lowest pasture vigour. At this site, the surface of bare soil patches was observed to be commonly approximately 40 or 50 mm lower than adjacent grass tufts. Indications of present high runoff (from tipping bucket data and physical signs of high levels of water in the runoff sump) were absent, however.

The assessment of deep percolation and its spatial variability is severely complicated by factors requiring great sophistication or the expenditure of great effort to be elucidated. These include uneven spoil topography, cracking caused by subsidence, sub-surface water run-on, the coarse fragment content and size of the spoil, and the density and other properties of pockets of fines between large rock fragments in the spoil.

Ideally, evapotranspiration should have been independently assessed. Determination of the Bowen ratio was considered, but was not attempted due to the small size of the plots affecting the fetch distance and the dusty conditions prevailing in mine areas.

Without elaborate fertilizer trials, there is a risk of under or over-fertilization in a study such as this. Selection of fertilization levels close to what can be considered as optimal is of great importance, as water extraction is strongly affected by the level of fertilization (Chapter 6).

As N was not determined in the assessment of the fertility status of the sites, N applications were not finely tuned to previous levels of N. Large variations in levels of previous fertilization complicated yield results (probably related to N, as P and K were added in accordance with soil analyses). At the Middelburg South B site, for example, yields of 70-86% of the "optimal" treatment were obtained at sub-plots where no fertilizer was applied. In contrast, at the Optimum B site, yields at the unfertilized sub-plots varied between only 12 and 37% of the "optimal" (see Table A6.1, Appendix 6).

Results of the fertilizer sub-plots show that the fertilizer levels applied might generally have been on the low side, as the high treatments ("optimal" plus 50%) resulted in increases in dry matter production of between 0 and 100% (average 30%), above the yield at the "optimal" treatment) in 18 out of 19 harvests. The "turning point" in fertilizer response was thus not reached. Theoretically, higher yields could thus have been attained with the available water. Put differently, fertility might have been more limiting than water at times.

The issue of fertilization, and whether or not fertilizer is gradually to be withdrawn to allow the pastures to revert to "natural" veld, is of high importance with regard to both the gradual improvement of rehabilitated land and the re-integration into farming systems:

- Where no special measures are applied, e.g. mulching with organic matter-rich waste products, soil improvement (mainly sustained alleviation of hardsetting behaviour and the restoration of macro-pores) and erosion control is dependent on good pasture cover and root development. These, in turn, are dependent on adequate fertilization.
- If pastures are to be maintained by fertilization after re-integration into farming enterprises, the hay produced is too expensive to be economically utilized by unproductive (dry) livestock. It could, theoretically, be marketed elsewhere or be used to round off animals for marketing or for lactating cows or growing animals, but an overabundance of expensive fertilized hay would be difficult to utilize economically (De Beer, 1998). A farm unit consisting solely of rehabilitated pastures would thus need specially adapted farming practices and extension efforts. The inputs needed may thus render the land unsuitable for resource-poor farmers participating in the Land Redistribution Programme.
- Withdrawal of fertilization to allow a return to natural veld is an extremely slow process. According to De Beer (1998), there are currently no successful examples on the interior highveld (high rainfall areas) where planted pastures eventually returned to a more natural situation and were managed successfully. C. Wessels (personal communication) expressed the opinion that it does not happen in nature that planted pastures revert to natural veld.

The study touches on the issue of the relative merit of rehabilitation creating permeable soils, beneficial to plant growth, on the one hand, or dense soils, curbing the entry of rain water into compartments containing acidifying pyrites, on the other.

From a land capability or land use viewpoint, dense, poorly or imperfectly drained soils have little merit. It is also true, however, that soils with a relatively slowly drained layer at the bottom of the root zone are preferred to excessively drained soils. Contrary to earlier belief in some circles e.g Organized Farming, it is now clear that mine soils on the Vryheid Formation are never excessively drained due to the compaction that accompanies spreading and levelling.

The results suggest that an acceptable compromise probably lies in creating a root zone with low bulk density, and as deep an effective soil depth as can be developed to sustain vigorous vegetation or crops. This would have to be attained by means of implements more powerful than normal farm implements. The maximum depth from the surface that can be reached with implements is in the order of one metre, depending on cover soil depth and rockiness of the upper spoil. The dense layers always present below that depth can be depended on to prevent the soil from becoming excessively drained. If recompaction and hardsetting behaviour can be curbed by biological means, and fertility attended to, such soils would be physically able to sustain vigorous crops, transpiring strongly during the rainy summer season when deep percolation is to be minimized. As much rain water as possible should thus be transpired by summer crops or pasture in order to minimize the water available for deep percolation. Water available for drainage below the root zone may concentrate in local hollows, where settling and shrinking cracks may or may not be present. Once in that position, only capillary forces can keep that water from percolating downwards.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

The following are concluded:

1. High bulk density, coupled with hardsetting behaviour, is a widespread phenomenon in replaced cover soils, and can be rated as the number one problem affecting land use.

2. Although pockets of strong acidity do occur in spoil materials, acidity due to pyrite oxidation was not identified as a major limitation to land use. The contrary was found, namely that neutral or slightly alkaline pH values may predominate in spoil material. In a naturally nutrient-poor environment, plant nutrient levels may be relatively high in some spoil materials.

3. Rehabilitated soil profiles with red or yellow medium-textured cover soils derived from Vryheid Formation parent materials, possess a moderate plant-available water-holding capacity (DUL-LL) of approximately 60 to 70 mm per m of cover soil and 35 to 65 mm per m of spoil. To be added to this figure is a capacity of at least 26 mm of utilizable water, held during wet spells at potentials higher than DUL. Due to poor root distribution and shallow root development in places, caused by high bulk densities, particularly below 200 mm depth, and hardsetting behaviour during dry periods, much of the available soil water (at some sites, the bulk of it) is not extracted and utilized by the pasture crop, even during periods of high water demand. Under conditions of poor to moderate root development, the actual profile extractable water capacity (taking root distribution into account) can be as low as 20 to 30 mm, excluding water held at higher potentials than DUL.

4. Spoil material occurring within the normal rooting depth of pasture grasses appears to be penetrated with difficulty by roots. The relative contribution of the following is still unclear:
   a. The cut-off effect of dense, hardsetting layers at the bottom 200 to 400 mm of the cover soil (where high bulk densities may be persistent due to difficulties in correcting it).
   b. Unfavourable properties of the cover soil/spoil transition (textural change, thin lenses of particularly compacted and smeared soil).
   c. The properties of the upper spoil itself (coarse fragments, "concrete mixture" particle size distribution, small pore size, soil strength).
   d. The suitability or otherwise of carbon from coal as a substrate for beneficial micro-organisms if nitrogen is introduced.
   e. The effect that landscape position and landscaping processes (e.g. number of bulldozer passes or distance from the centre of the leveled dragline dump) might have on the hydrological properties of the spoil.

5. Although results with respect to runoff may be somewhat inconclusive, they suggest that where the pasture cover is moderately well fertilized, in productive condition and slopes are moderate, runoff does not exceed 10% of the annual rainfall and can be as low as 2 or 3 percent.

6. The generally high density of the lower cover soils and upper spoil appears to restrict deep percolation, except in situations where water accumulates due to lateral drainage ("melon holes"), and where settling cracks occur. Results suggest

that deep percolation varies between zero and 40 percent of the annual rainfall and is strongly affected by rainfall patterns during the season. Some spoil materials are almost permanently dry below 1 or 1.3 m depth. Deep percolation is considered to be particularly variable spatially.

7. The reconstituted soil profiles can generally be regarded as imperfectly or poorly drained. The situation differs, however, from, for example, a natural soil of the Avalon form, in that the slowly draining water at depth cannot be effectively utilized by roots during dry spells unless high bulk densities and hardsetting characteristics can be alleviated.

8. The imperfect to poor drainage of the soils causes certain topographical features (e.g. local hollows) to become water collection sites through lateral surface as well as subsurface run-on, particularly during wet periods.

9. Where soils are moderately deep and able to absorb precipitation efficiently, water available for evapotranspiration may vary between 45 and 100% of the annual rainfall. Under these conditions, differences mainly reflect the effects of rainfall distribution.

10. Pasture production is strongly dependent on water availability and levels of fertilization. The inability to utilize the soil water between a depth of 0.3 to 0.7 m where the soil is dense, has a severe negative effect on pasture vigour, production and drought resistance. At fertilization levels aimed at relatively high production without too much of a risk of water uptake being restricted due to low soil fertility, cumulative distribution yield functions show a 50% probability that hay yields would not exceed 2650 kg ha^{-1} at four of the sites, 3150 at the fifth site, and 4650 at the sixth site (average 3050 kg ha^{-1}). These yields compare unfavourably with a general average of approximately 8000 kg ha^{-1} attainable on good natural soils in the vicinity.

11. It is not implied that rehabilitated soils with current low productivity cannot be made productive, as important basic ingredients of productive land exist such as moderate slopes, fair soil depth and manageable chemical hazards, when present.

12. It is not implied that rehabilited soils with current low productivity cannot be made productive, as important basic ingredients of productive land are present, such as moderate slopes, fair soil depth and manageable chemical hazards, when present.

The following are recommended:

1. The issue of land preparation and revegetation, as part of the rehabilitation process, is of high importance for subsequent land use and should be recognized as a focus area for research and development. Amongst the aspects that need clarification are the following:
   a. Ways of optimizing the initial mechanical process of alleviation of machine-induced high bulk density ("kick-starting:" the recovery process by various methods of deep ripping). This includes ways of dealing with the abrupt transition between cover soil and spoil, and dealing with ripped-up rock.
   b. Ways of improving the sustainability of the effects of the initial mechanical process. This involves optimizing the biological processes of re-establishing aggregate stability by stimulating the recovery of fungal, microbial and macro-

faunal life in the soil as well as their products which stimulate aggregation (e.g. microbial gums and polysaccharides).

c. The issue of identifying and rating susceptibility to re-compactibility.
d. The issue of identifying and rating hardsetting behaviour.
e. Novel rehabilitation plant species with emphasis on root penetrating ability, climatic adaptability, water requirements, nitrogen fixation, ease of eradication and economic value.
f. Lime requirement and ensuring adequate mixing into the soil.
g. The issue of withdrawal of fertilizer and the timing and requirements of returning fertilized pastures to natural veld or arable land.
h. Managing wet spots ("melon holes"); appropriate land use options for these spots; opportunities offered by these for measuring, characterizing or treatment of lateral run-on water.

2. The issue of adherence to standards during rehabilitation deserves the serious attention of all mining houses, Government, Organized Agriculture and environmentalists.

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APPENDIX 1

Appendix to Chapter 1

CLASSIFICATION OF MINE SOILS

The classification system for mine soils by De Villiers (1992a,1992b) provides an overview of the kinds of materials encountered in these soils and some of their properties. As it can assist the reader in understanding these materials, a synopsis is included below.

SOIL VARIABILITY

De Villiers pointed out differences in variability between mine soils and natural soils. A summary is given in Table A1.1.

Table A1.1 Differences in variability between mine soils and natural soils (after De Villiers, 1992b)

Type of variability		Mine soils	Natural soils
Spatial	Vertical	• Some systematic variability present, e.g. relatively constant depth or cover soil, some reduction in profile variation due to averaging or homogenizing effects of mechanical disturbance. • Much random variability present, e.g. coarse fragments in spoil, density caused by machine traffic.	• Predominantly systematic variability, observed as predictable depth sequences; governed by soil forming factors (parent materials and factors operating on them). • Little or no random variability present.
	Lateral	• Geometric patterns present. • May be confined within lower limits than under natural conditions due to homogenization. • Random "noise" tends to be present.	• Regional and local variation (e.g. catenary effects) may cause fundamental differences between blocks of land after rehabilitation, requiring customized management techniques.
Temporal		• Dis-equilibrium phenomena; dynamic. • Both rapid (e.g. acid/salt production) and slow changes (e.g. changes in soil structure) occur.	• Equilibrium phenomena; natural changes predominantly slow.

CRITERIA FOR DIFFERENTIATING MINE SOILS

COVER SOIL TYPE

Six cover soil types are recognized:

HUMIC (H) Materials enriched with humified organic matter to the extent that they have granular or crumb structure and Munsell values and chromas of less than 5 and less than 4, respectively.

KANDIC (K) Soil materials with micro-aggregate structure, kaolinitic mineralogy and "red" or "yellow" colours as defined in the National Soil Classification System.

VERTIC (V) Dark, strongly structured (blocky), high clay soil materials dominated by expansive bisilicic clay materials.

GLEYIC (G)	Soil materials having grey, low chroma colours with or without pale yellowish, reddish and brown mottles.
PLINTHIC (P)	Properties as defined for the soft plinthic B horizon in the National soil Classification System.
SAPROLITIC (S)	Unhomogenized weathered rock which is thoroughly disintegrated but still retains vestiges of the host lithology in respect of colour and/or structure.

COVER SOIL TEXTURE

Four broad clay content classes are recognized:

0-10% clay, referred to as quartzic; symbol (1)
10-25% clay, referred to as sandy; symbol (2)
25-40% clay, referred to as loamy; symbol (3)
>40% clay, referred to as clayey; symbol (4)

SPOIL TYPE

Five spoil types are recognized:

CARBOLITHIC (Cr)	Clastic materials containing at least 50% black or very dark grey carbon-rich shale or coal.
PYROLITHIC (Pr)	At least 50% of the material consists of cindery, ashy or glassy particles resulting from the burning of coaliferous rock.
ARGILITHIC (AG)	Clastic, fine-textured non-carbolithic materials. Usually fissile shales or mudstones.
ARENOLITHIC (Ae)	Clastic, coarse-textured materials (sandstones and gritstones).
MATRIC (Mt)	Non-clastic materials (less than 10% of clasts larger than 75 mm) of mixed provinance that do not qualify as one of the preceding types. Examples are mechanically pulverized rock, and raw alluvium and colluvium.

PERCENTAGE FINES IN SPOIL

The state of disaggregation of the spoil is given as the proportion (percentage by volume) of the fines (particles < 2 mm).

ACID/BASE STATUS OF THE FINES IN THE SPOIL

The following classes are proposed:

Ac	Acid spoil; pH in water <4.0
N	Non-acid spoil; pH in water >4.0
Ca	Calcareous spoil

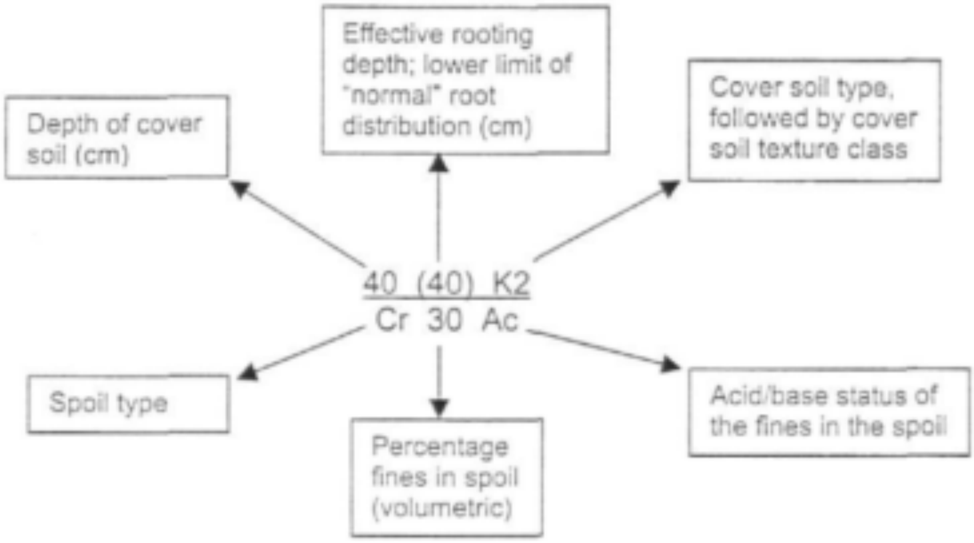


Figure A1 Example of mine soil classification code

APPENDIX 2

Appendices to Chapter 2

LIST OF TABLES

LIST OF FIGURES

a1 S	a2	a3 May	a4 May	a5 Sep	a6 Mar	a7 • KA1	a8 KAa
b1 May	b2 Oct	b3 • KA2	b4 Dec	b5 Jun	b6 KAb	b7 Jul	b8 KAc
c1 ws • KA3	c2 Mar	c3 Apr	c4 Jun	c5 Jul	c6 Nov	c7 Jan	c8 Aug
d1 Oct	d2 • KA4	d3 Jan	d4 KAd	d5 Sep	d6 • KA5	d7 Dec	d8 Feb
e1 Nov	e2 KAe	e3 Jul	e4 Sep	e5 Jun	e6 Mar	e7 Aug	e8 • KA6
f1 Feb	f2 May	f3 Aug	f4 KAf	f5 Jan	f6 Jun	f7 Aug	f8 Nov
g1 Dec	g2 KAg	g3 Sep	g4 Kah	g5 Jul	g6 • KA7	g7 Feb	g8 Oct
h1 Mar	h2 Nov	h3 Apr	h4 Feb	h5 Dec	h6 • KA8	h7 Oct	h8 Jan

Figure A2.1a Site layout: Kriel A

Notes:

1. a1 to a8: 3 m x 3 m blocks.
2. KA1 to KA8: the position of NWM access tubes.
3. KAa to Kah: 1 m x 1 m squares where ceptometer readings were taken at fortnightly intervals.
4. ws Weather station, measuring rainfall and pulses from a tipping bucket.
5. Jan to Dec: 1 m x 1 m squares, clipped in the particular month.

a1 Dec	a2 Apr	a3 May	a4 May	a5 Sep	a6 Mar	a7	a8 ws May
b1 KBa	b2 Oct	b3 Jul	b4 • KB1	b5 Jun	b6 KBb	b7 KBc	b8 • KB2
c1 • KB3	c2 Mar	c3 KBd	c4 Jun	c5 Jul	c6 Nov	c7 Jan	c8 Aug
d1 Oct	d2 • KB4	d3 Jan	d4 KBe	d5 Sep	d6 • KB5	d7 Dec	d8 Feb
e1 Nov	e2 KBf	e3 Jul	e4 Sep	e5 Jun	e6 Mar	e7 Aug	e8 • KB6
f1 Feb	f2 May	f3 Aug	f4 KBg	f5 Jan	f6 Jun	f7 Aug	f8 Nov
g1 Dec	g2 KBh	g3 Sep	g4 Apr	g5 Jul	g6 • KB7	g7 Feb	g8 Oct
h1 Mar	h2 Nov	h3 Apr	h4 Feb	h5 Dec	h6 • KB8	h7 Oct	h8 Jan

Figure A2.1b Site layout: Kriel B

Notes:

1. a1 to a8: 3 m x 3 m blocks.
2. **KB1** to **KB8**: the position of NWM access tubes.
3. KBa to KBh: 1 m x 1 m squares where ceptometer readings were taken at fortnightly intervals.
4. ws Weather station, measuring rainfall and pulses from a tipping bucket.
5. Jan to Dec: 1 m x 1 m squares to be clipped in the particular month.

a1 DAa	a2 Apr	a3 May	a4 May	a5 Sep	a6 Mar	a7 Oct	a8 May
b1 May	b2 DAb	b3 Nov	b4 DAc	b5 Jun	b6 Feb	b7 Jul	b8 Nov
c1 Jan	c2 Mar	c3 Aug	c4 Jun	c5 Jul	c6 Nov	c7 • **DA1**	c8 Aug
d1 Oct	d2 Jan	d3 • **DA2**	d4 Dec	d5 Sep	d6 Jan	d7 • **DA3**	d8 Feb
e1 DAd	e2 Mar	e3 Jul	e4 Sep	e5 Jun	e6 Mar	e7 Aug	e8 DAe Apr
f1 • **DA4**	f2 May	f3 Aug	f4 Dec	f5 • **DA5**	f6 Jun	f7 Aug	f8 DAf
g1 • **DA6**	g2 Oct	g3 Sep	g4 Apr	g5 Jul	g6 Jan	g7 Feb	g8 DAg
h1	h2 Nov	h3 ws Apr	h4 Feb	h5 • **DA7**	h6 Oct	h7 DAh	h8 • **DA8**

Notes:

1. a1 to a8: 3 m x 3 m blocks.
2. **DA1** to **DA8**: the position of NWM access tubes.
3. DAa to Dah: 1 m x 1 m squares where ceptometer readings were taken at fortnightly intervals.
4. ws Weather station, measuring rainfall and pulses from a tipping bucket.
5. Jan to Dec: 1 m x 1 m squares to be clipped in the particular month.

Figure A2.1c Site layout: Middelburg South A

a1 DBa	a2 Apr	a3 May	a4 ws May	a5	Mar	a7 Oct	a8 May
b1 May	b2 • **DB1**	b3 Nov	b4 Dec	b5 Jun	b6 Feb	b7 Jul	b8 Nov
c1 Jan	c2 Mar	c3 Aug	c4 Jun	c5 Jul	c6 • **DB2**	c7 Sep	c8 DBb
d1 • **DB3**	d2 Jan	d3 Sep	d4 Dec	d5 DBc	d6 DBd	d7 Oct	d8 Feb
e1 • **DB4**	e2 Mar	e3 Jul	e4 • **DB5**	e5 Jun	e6 Mar	e7 DBe	e8 • **DB6**
f1 Sep	f2 Dec	f3 DBf	f4 Dec	f5 Aug	f6 Jun	f7 DBg	f8 Sep
g1 Aug	g2 Okt	g3 DBh	g4 Apr	g5 Jul	g6 Jan	g7 Feb	g8 • **DB7**
h1 Nov	h2 Nov	h3 Apr	h4 Feb	h5 Oct	h6 • **DB8**	h7 Aug	h8 Jan

Notes:

1. a1 to a8: 3 m x 3 m blocks.
2. **DB1** to **DB8**: the position of NWM access tubes.
3. DBa to DBh: 1 m x 1 m squares where ceptometer readings were taken at fortnightly intervals.
4. ws Weather station, measuring rainfall and pulses from a tipping bucket.
5. Jan to Dec: 1 m x 1 m squares to be clipped in the particular month.

Figure A2.1d Site layout: Middelburg South B

a1 OAa	a2 Apr	a3 OA1	a4 May	a5 Sep	a6 Mar	a7 Oct	a8 May
b1 May	b2 Jan	b3 OAb	b4 Dec	b5 OA2	b6 Feb	b7 OA3	b8 Nov
c1 OAc	c2 Mar	c3 Aug	c4 OA4	c5 Jul	c6 Jun	c7 Sep	c8 Apr
d1 Nov	d2 OAd	d3 Sep	d4 Dec	d5 Jan	d6 Jul	d7 Oct	d8 Feb
e1 Jun	e2 Mar	e3 Jul	e4 Jun	e5 OA5	e6 OAe	e7 Nov	e8 Apr
f1 Sep	f2 OA6	f3 Dec	f4 Dec	f5 Aug	f6 OA7	f7 May	f8 Jun
ws Aug	g2 Oct	g3 Jan	g4 Apr	g5 Jul	g6 OAf	g7 Feb	g8 Mar
h1	h2 Nov	h3 OAg	h4 Feb	h5 OA8	h6 OAh	h7 Aug	h8 Jan

Notes:

1. a1 to a8: 3 m x 3 m blocks.
2. **OA1** to **OA8**: the position of NWM access tubes.
3. OAa to Oah: 1 m x 1 m squares where ceptometer readings were taken at fortnightly intervals.
4. ws Weather station, measuring rainfall and pulses from a tipping bucket.
5. Jan to Dec: 1 m x 1 m squares to be clipped in the particular month.

Figure A2.1e Site layout: Optimum A

a1 Feb	a2 Apr	a3 Aug	a4 May	a5 Sep	a6 Mar	a7 Oct	a8 OBa
b1 May	b2 Jan	b3 Nov	b4 Dec	b5 OB1	b6 OBb	b7 OB2	b8 OBc
c1 May	c2 Mar	c3 OBd	c4 OB3	c5 OB4	c6 Jun	c7 Sep	c8 Apr
d1 Nov	d2 Feb	d3 Sep	d4 OBe	d5 Jan	d6 Jul	d7 Oct	d8 Feb
e1 Jun	e2 OBf	e3 Jul	e4 Jun	e5 OB5	e6 Oct	e7 Nov	e8 Apr
f1 Sep	f2 OB6	f3 Dec	f4 OBg	f5 Aug	f6 OB7 Dec	f7 May	f8 Jun
g1 Aug	g2 OBh	g3 Jan	g4 Apr	g5 OB8	g6 Jul	g7 Feb	g8 Mar
h1 Dec	h2 Nov	h3 Mar	h4	h5 Oct	h6 Nov ws	h7 Aug	h8 Jan

Notes:

1. a1 to a8: 3 m x 3 m blocks.
2. **OB1** to **OB8**: the position of NWM access tubes.
3. OBa to Obh: 1 m x 1 m squares where ceptometer readings were taken at fortnightly intervals.
4. ws Weather station, measuring rainfall and pulses from a tipping bucket.
5. Jan to Dec: 1 m x 1 m squares to be clipped in the particular month.

Fertilizer sub-plots (2 m x 2 m squares), attached to each main plot:

N	O	H	O
L	L	H	O
N	L	N	L
N	H	H	O

Legend:
N = No fertilizer
O = Optimum level
L = Optimum - 50%
H = Optimum+ 50%

Figure A2.1f Site layout: Optimum B with fertilizer sub-plot layout shown to the right

TABLE A2.1a Soil analysis of Kriel A

ACCESS TUBE No.	DEPTH (m)	ORG. CARBON (%)	pH (KCL)	P Bray 1 (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	ELECT. RESIST. (ohm)
KA1	0.0-0.2	0.96	5.16	68.5	133	523	112	2200
	0.2-0.6	0.65	5.49	12.9	66	542	121	2600
	0.6-1.9	0.71	7.86	1.6	73	3299	206	1200
KA2	0.0-0.2	0.83	6.07	121.5	159	812	134	1900
	0.2-0.6	0.69	5.28	11.9	61	541	121	2200
	0.6-1.9	2.00	7.21	1.4	82	2839	237	1600
KA3	0.0-0.2	0.94	5.68	70.2	156	755	103	1900
	0.2-0.6	0.69	5.94	4.6	58	648	106	1800
	0.6-1.9	0.31	7.32	0.8	85	1019	188	1600
KA4	0.0-0.2	0.82	5.23	116.9	115	516	84	1600
	0.2-0.6	0.91	5.59	11.7	76	670	132	1400
	0.6-1.9	1.29	7.46	0.4	79	1589	283	1400
KA5	0.0-0.2	0.65	5.77	58.4	117	668	96	1800
	0.2-0.6	0.95	6.81	0.7	70	969	120	1600
	0.6-1.9	1.45	7.23	0.6	89	1529	192	1500
KA6	0.0-0.2	0.57	4.46	23.9	282	373	87	2500
	0.2-0.6	0.80	5.18	2.8	130	532	101	2000
	0.6-1.9	1.45	7.48	1.9	86	3339	246	1400
KA7	0.0-0.2	0.76	5.18	51.2	151	441	85	1800
	0.2-0.6	1.27	5.76	5.0	94	874	120	1800
	0.6-1.9	2.21	6.74	0.7	89	1289	207	320
KA8	0.0-0.2	0.69	5.18	59.1	201	416	70	2000
	0.2-0.6	1.67	5.68	1.5	130	1579	137	360
	0.6-1.9	1.79	7.11	0.8	100	2349	206	340
Upper cover soil	Mean	0.78	5.34	71.2	164.3	563	96.4	1963
	St.Dev.	0.13	0.46	30.8	51.4	153	18.6	260
	Variance (%)	16	9	43	31	27	19	13
Deeper cover soil	Mean	0.95	5.72	6.4	86	794	120	1720
	St.Dev.	0.33	0.47	4.7	28	333	11	619
	Variance (%)	35	8	73	32	42	9	36
Spoil	Mean	1.40	7.12	1.0	85	2157	221	1170
	St.Dev.	0.60	0.62	0.5	8	864	30	500
	Variance (%)	43	9	50	9	40	14	43

TABLE A2.1b Soil analysis of Kriel B

ACCESS TUBE No	DEPTH (m)	ORG. CARBON (%)	pH (KCL)	P Bray 1 (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	ELECT. RESIST. (ohm)
KB1	0.0-0.2	0.64	5.24	10.9	239	573	123	1800
	0.2-0.6	0.62	5.26	3.3	134	794	151	1800
	0.6-1.9	1.48	7.47	0.4	246	3649	333	361
KB2	0.0-0.2	0.69	5.27	12.5	202	614	119	1900
	0.2-0.6	0.52	5.98	1.7	117	937	237	1800
	0.6-1.9	0.52	7.44	1.7	313	4539	328	380
KB3	0.0-0.2	0.67	5.64	16.6	300	653	161	1800
	0.2-0.6	0.50	5.18	2.3	114	523	166	2000
	0.6-1.9	1.56	7.93	0.8	122	2009	173	400
KB4	0.0-0.2	0.60	5.14	9.9	206	559	137	1800
	0.2-0.6	0.54	5.26	2.1	128	581	167	2000
	0.6-1.9	0.66	7.46	0.8	260	4589	292	360
KB5	0.0-0.2	0.67	6.06	13.0	230	892	154	1700
	0.2-0.6	0.73	5.32	9.7	106	611	121	1800
	0.6-1.9	1.54	7.48	1.3	230	4179	330	300
KB6	0.0-0.2	0.65	5.86	10.4	220	797	152	1600
	0.2-0.6	0.43	5.53	1.3	141	698	215	1800
	0.6-1.9	1.22	7.44	0.7	164	3579	246	1500
KB7	0.0-0.2	0.64	6.14	11.3	205	617	151	1800
	0.2-0.6	0.57	6.08	3.7	124	788	186	1900
	0.6-1.9	0.62	7.74	0.0	182	3779	205	440
KB8	0.0-0.2	0.69	6.29	19.9	199	586	143	1800
	0.2-0.6	0.53	7.04	2.5	135	1979	188	1600
	0.6-1.9	0.50	7.61	0.4	211	4009	193	360
Upper cover soil	Mean	0.66	5.71	13.1	225	661	126	1775
	St.Dev.	0.03	0.42	3.2	31	112	44	83
	Variance (%)	4	7	25	14	17	35	5
Deeper cover soil	Mean	0.56	5.71	3.3	125	864	179	1838
	St.Dev.	0.08	0.60	2.5	11	440	34	122
	Variance (%)	15	10	76	9	51	19	7
Spoil	Mean	1.01	7.57	0.8	216	3792	263	513
	St.Dev.	0.45	0.17	0.5	56	761	62	375
	Variance (%)	45	2	63	26	20	24	73

TABLE A2.1c Soil analyses of Middelburg South A

ACCESS TUBE No.	DEPTH (m)	ORG. CARBON (%)	pH (KCl)	P Bray 1 (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	ELECT. RESIST. (ohm)
DA1	0.0-0.2	0.60	5.60	16.7	47	294	42	2800
	0.2-0.6	0.40	4.17	3.2	34	118	21	2200
	0.6-1.9	3.15	3.27	2.1	8	596	21	1800
DA2	0.0-0.2	0.64	7.01	9.6	60	616	57	2400
	0.2-0.6	0.47	4.12	4.5	27	136	37	2400
	0.6-1.9	0.29	3.85	2.9	58	119	15	2600
DA3	0.0-0.2	0.71	6.68	12.8	50	560	61	1700
	0.2-0.6	0.35	4.20	3.2	36	134	30	2500
	0.6-1.9	3.04	3.52	2.4	16	127	16	2000
DA4	0.0-0.2	0.37	4.68	6.0	36	148	29	3000
	0.2-0.6	0.78	6.27	4.5	46	538	66	2000
	0.6-1.9	0.34	4.12	2.2	26	96	27	3600
DA5	0.0-0.2	2.07	4.02	7.0	25	957	41	1800
	0.2-0.6	0.33	5.45	5.3	77	213	43	2800
	0.6-1.9	0.32	4.22	1.9	19	114	27	2800
DA6	0.0-0.2	3.08	3.41	14.3	17	302	14	1800
	0.2-0.6	0.47	5.88	2.6	33	334	57	2200
	0.6-1.9	0.39	4.18	2.2	20	126	32	3400
DA7	0.0-0.2	3.08	3.41	14.3	17	302	14	1800
	0.2-0.6	0.47	5.88	2.6	33	334	57	2200
	0.6-1.9	0.39	4.18	2.2	20	126	32	3400
DA8	0.0-0.2	0.79	7.12	27.0	75	786	78	2200
	0.2-0.6	0.64	4.30	4.4	21	148	36	2400
	0.6-1.9	5.88	3.95	1.7	15	918	16	500
Upper cover soil	Mean	1.26	5.26	12.3	41	469	43	2240
	St.Dev.	0.89	1.45	6.8	20	291	21	450
	Variance (%)	71	28	55	49	62	49	20
Deeper cover soil	Mean	0.48	4.81	3.9	37	217	39	2360
	St.Dev.	0.14	0.84	0.9	17	139	15	220
	Variance (%)	29	17	23	46	64	37	9
Spoil	Mean	2.23	3.91	2.2	24	303	27	2290
	St.Dev.	2.06	0.33	0.3	14	283	15	960
	Variance (%)	92	8	15	60	93	56	42

TABLE A2.1d Soil analysis of Middelburg South B

ACCESS TUBE No.	DEPTH (m)	ORG. CARBON (%)	pH (KCl)	P Bray 1 (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	ELECT. RESIST. (ohm)
DB1	0.0-0.2	0.75	6.21	5.6	36	442	135	2400
	0.2-0.6	0.52	5.26	3.5	17	217	102	2100
	0.6-1.9	2.48	4.73	1.6	39	1757	110	1800
DB2	0.0-0.2	1.02	4.34	11.3	123	254	53	1800
	0.2-0.6	0.47	4.27	3.5	35	166	45	2600
	0.6-1.9	2.60	3.18	3.0	19	637	146	300
DB3	0.0-0.2	0.73	4.49	6.0	35	228	55	2000
	0.2-0.6	0.61	4.05	3.7	22	109	33	2600
	0.6-1.9	4.23	6.18	1.6	62	1567	227	400
DB4	0.0-0.2	0.71	4.65	5.7	172	225	62	nd
	0.2-0.6	0.61	4.03	2.5	58	79	20	2800
	0.6-1.9	1.67	5.31	1.5	117	1017	207	370
DB5	0.0-0.2	0.86	3.79	7.2	32	82	17	2600
	0.2-0.6	0.63	4.03	2.6	29	103	24	1800
	0.6-1.9	3.27	3.10	1.7	71	547	87	340
DB6	0.0-0.2	0.80	3.79	14.3	117	74	25	nd
	0.2-0.6	0.55	3.97	4.5	36	98	15	2400
	0.6-1.9	3.17	5.15	1.8	69	833	201	360
DB7	0.0-0.2	1.12	4.38	27.1	72	290	57	700
	0.2-0.6	0.53	4.13	4.1	20	162	24	430
	0.6-1.9	4.11	6.23	1.5	100	492	219	460
DB8	0.0-0.2	0.79	4.21	9.1	42	179	35	4400
	0.2-0.6	0.62	4.00	4.1	13	130	22	4000
	0.6-1.9	3.39	5.66	1.6	62	617	249	520
Upper cover soil	Mean	0.85	4.48	10.8	79	222	55	1660
	St.Dev.	0.14	0.71	6.8	49	110	34	810
	Variance (%)	16	16	63	62	50	62	49
Deeper cover soil	Mean	0.57	4.22	3.6	29	133	36	2340
	St.Dev.	0.05	0.40	0.7	13	43	27	940
	Variance (%)	9	10	19	45	32	75	40
Spoil	Mean	4.94	4.94	1.8	67	933	181	570
	St.Dev.	1.14	1.14	0.5	29	451	55	470
	Variance (%)	23	23	28	43	48	30	82

TABLE A2.1e Soil analysis of Optimum A

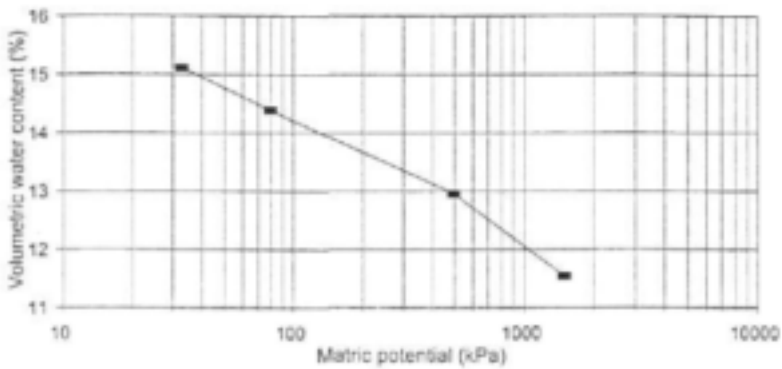
ACCESS TUBE No.	DEPTH (m)	ORG. CARBON (%)	pH (KCl)	P Bray 1 (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	ELECT. RESIST. (ohm)
OA1	0.0-0.2	1.01	4.60	7.3	155	298	87	3700
	0.2-0.6	0.74	4.45	2.9	65	260	129	500
	0.6-1.9	3.03	5.78	1.7	86	585	305	3200
OA2	0.0-0.2	0.90	5.43	4.5	171	432	108	2700
	0.2-0.6	0.55	4.66	3.1	40	244	103	1800
	0.6-1.9	2.85	6.69	1.5	67	1297	301	380
OA3	0.0-0.2	1.10	4.87	7.5	75	428	98	780
	0.2-0.6	0.62	4.73	2.1	31	247	105	2400
	0.6-1.9	3.23	6.64	1.6	103	705	305	840
OA4	0.0-0.2	1.04	6.03	6.5	118	678	167	720
	0.2-0.6	0.61	4.63	2.5	39	270	109	700
	0.6-1.9	3.17	6.67	1.7	90	671	343	760
OA5	0.0-0.2	0.79	4.79	12.8	66	402	92	3000
	0.2-0.6	0.70	4.39	3.0	27	242	91	730
	0.6-1.9	3.55	6.33	1.5	138	1000	378	440
OA6	0.0-0.2	1.10	4.32	6.5	78	346	85	800
	0.2-0.6	1.16	5.02	3.2	75	284	124	3200
	0.6-1.9	3.63	6.25	1.8	103	796	287	720
OA7	0.0-0.2	1.16	4.90	5.6	58	422	107	620
	0.2-0.6	1.05	4.24	3.0	26	183	90	630
	0.6-1.9	3.53	6.11	1.5	92	968	392	500
OA8	0.0-0.2	1.12	4.23	6.8	90	279	83	4200
	0.2-0.6	1.24	4.63	3.8	44	280	116	780
	0.6-1.9	3.28	6.68	1.7	99	735	327	520
Upper cover soil	Mean	1.05	4.90	7.2	101	411	103	2070
	St.Dev.	0.08	0.55	2.3	40	115	26	1400
	Variance (%)	8	11	32	40	28	25	68
Deeper cover soil	Mean	0.83	4.59	3.0	43	251	108	1340
	St.Dev.	0.26	0.22	0.5	17	30	13	940
	Variance (%)	31	5	17	40	12	12	70
Spoil	Mean	3.28	6.39	1.6	97	845	330	920
	St.Dev.	0.25	0.31	0.1	19	217	36	880
	Variance (%)	8	5	6	20	26	11	96

TABLE A2.1f Soil analysis of Optimum B

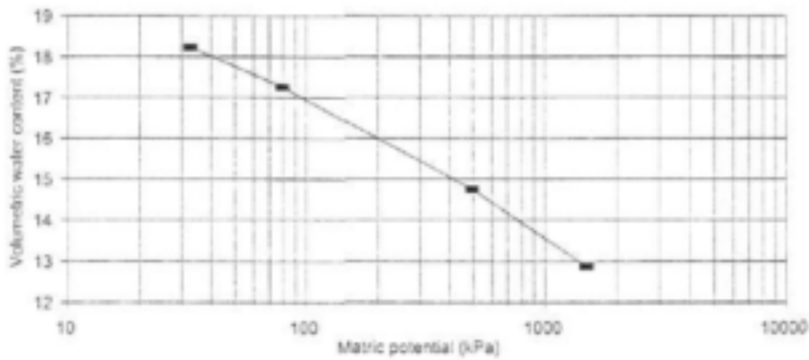
ACCESS TUBE No.	DEPTH (m)	ORG. CARBON (%)	pH (KCl)	P Bray 1 (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	ELECT. RESIST. (ohm)
OB1	0.0-0.2	1.51	6.22	5.3	92	759	84	2800
	0.2-0.6	1.19	4.62	2.1	39	456	136	650
	0.6-1.9	3.29	6.52	1.5	110	1207	500	480
OB2	0.0-0.2	0.75	5.55	2.3	83	517	86	6600
	0.2-0.6	0.56	4.67	2.0	32	265	72	580
	0.6-1.9	3.65	7.14	1.6	93	1207	277	480
OB3	0.0-0.2	0.71	4.33	7.5	52	223	41	520
	0.2-0.6	0.54	4.11	4.1	31	145	33	460
	0.6-1.9	4.75	4.71	1.8	82	1518	245	600
OB4	0.0-0.2	1.48	5.47	4.5	110	533	72	580
	0.2-0.6	1.64	4.06	2.1	41	301	106	1600
	0.6-1.9	5.03	4.77	1.6	101	1527	325	420
OB5	0.0-0.2	0.86	3.93	4.4	100	148	56	2600
	0.2-0.6	0.69	4.18	2.0	65	188	92	3000
	0.6-1.9	4.89	6.95	1.5	103	945	357	360
OB6	0.0-0.2	1.12	4.12	17.3	83	175	47	2200
	0.2-0.6	1.39	4.59	3.0	67	240	104	1900
	0.6-1.9	3.82	6.72	1.7	97	481	253	2000
OB7	0.0-0.2	1.11	4.03	7.5	87	208	61	2200
	0.2-0.6	0.62	4.10	2.9	42	187	65	2600
	0.6-1.9	4.18	6.92	1.6	92	625	285	1900
OB8	0.0-0.2	0.76	3.75	3.8	35	134	33	2200
	0.2-0.6	0.46	3.91	1.8	53	141	63	2400
	0.6-1.9	5.25	6.24	1.5	87	654	119	440
Upper cover soil	Mean	1.05	4.68	6.6	80	337	60	2460
	St.Dev.	0.31	0.87	4.4	23	218	18	1760
	Variance (%)	30	18	67	29	65	30	72
Deeper cover soil	Mean	0.89	4.28	2.5	46	240	84	1650
	St.Dev.	0.42	0.28	0.7	13	97	30	930
	Variance (%)	47	7	28	28	40	36	56
Spoil	Mean	4.36	6.25	1.6	96	1021	295	840
	St.Dev.	0.68	0.91	0.1	8	381	102	650
	Variance (%)	16	15	8	8	37	35	77

TABLE A2.2 Bulk density values

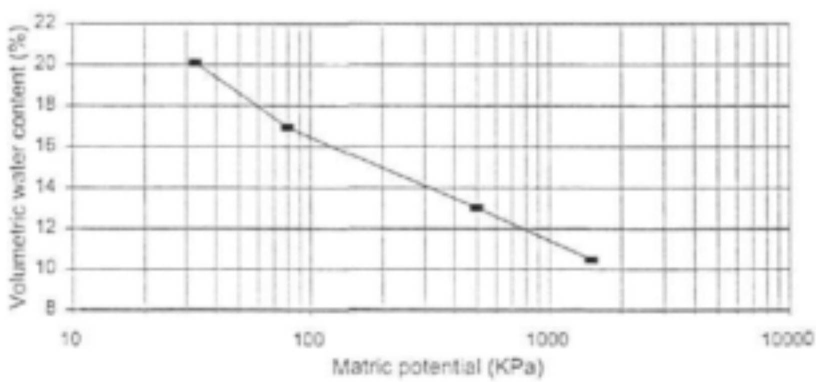
SITE			SITE			SITE		
NWM tube no.	Depth (mm)	Bulk density (Mg m^{-3})	NWM tube no.	Depth (mm)	Bulk density (Mg m^{-3})	NWM tube no.	Depth (mm)	Bulk density (Mg m^{-3})
KA1	0.2-0.4	1.74	DA1	0.0-0.2	1.58	Average	0.0-0.2	1.68
KA1	0.4-0.6	1.93	DA1	0.2-0.4	1.76	Average	0.2-0.4	1.67
KA1	0.6-0.8	1.93	DA1	0.2-0.4	1.71			
KA4	0.2-0.4	1.81	DA1	0.4-0.6	1.85	OA3	0.2-0.4	1.60
KA4	0.4-0.6	1.81	DA1	1.3-1.6	1.83	OA8	0.4-0.6	1.77
KA4	0.8-1.0	2.16	DA3	0.2-0.4	1.72	OA8	0.4-0.6	1.65
Average	0.2-0.4	1.78	DA3	0.4-0.6	1.81	OA3	0.8-1.0	1.93
Average	0.4-0.6	1.87	DA3	1.3-1.6	1.5 0	Average	0.2-0.4	1.60
Average	>0.6	2.05	DA6	0.0-0.2	1.60	Average	0.4-0.6	1.71
			DA6	0.2-0.4	1.89	Average	>0.6	1.93
KB2	0.2-0.4	1.73	DA6	0.2-0.4	1.86			
KB2	0.4-0.6	1.6	DA6	0.4-0.6	1.91	OB1	0.2-0.4	1.74
KB2	0.6-0.8	2.11	DA8	0.0-0.2	1.59	OB1	0.2-0.4	1.69
KB3	0.2-0.4	1.73	DA8	0.2-0.4	1.71	OB1	0.4-0.6	1.68
KB3	0.4-0.6	1.75	Average	0.0-0.2	1.59	OB1	0.8-1.0	1.80
KB3	0.6-0.8	2.05	Average	0.2-0.4	1.78	OB5	0.0-0.2	1.63
KB8	0.2-0.4	1.8	Average	0.4-0.6	1.86	OB5	0.2-0.4	1.64
KB8	0.4-0.6	1.83	Average	>0.6	1.67	OB8	0.0-0.2	1.64
KB8	0.8-1.0	2.16				OB8	0.2-0.4	1.65
Average	0.2-0.4	1.75	DB1	0.0-0.2	1.66	Average	0.0-0.2	1.64
Average	0.4-0.6	1.73	DB1	0.2-0.4	1.69	Average	0.2-0.4	1.68
Average	>0.6	2.11	DB4	0.0-0.2	1.64	Average	0.4-0.6	1.68
			DB4	0.2-0.4	1.70	Average	>0.6	1.80



(a) Undisturbed cores
0.2-0.4 m depth

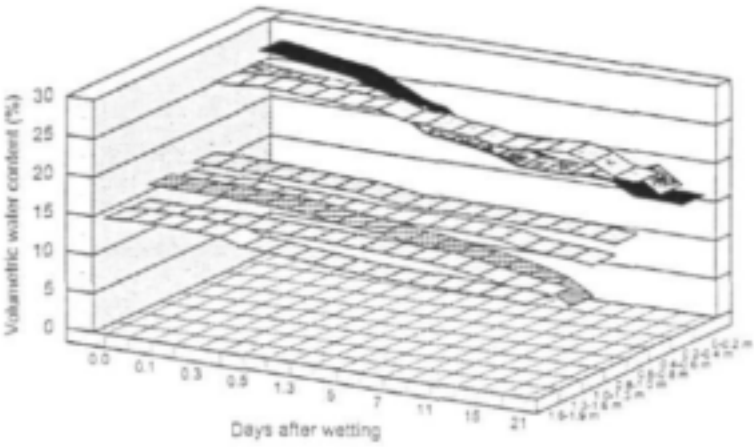


(b) Undisturbed cores
0.4-0.6 m depth

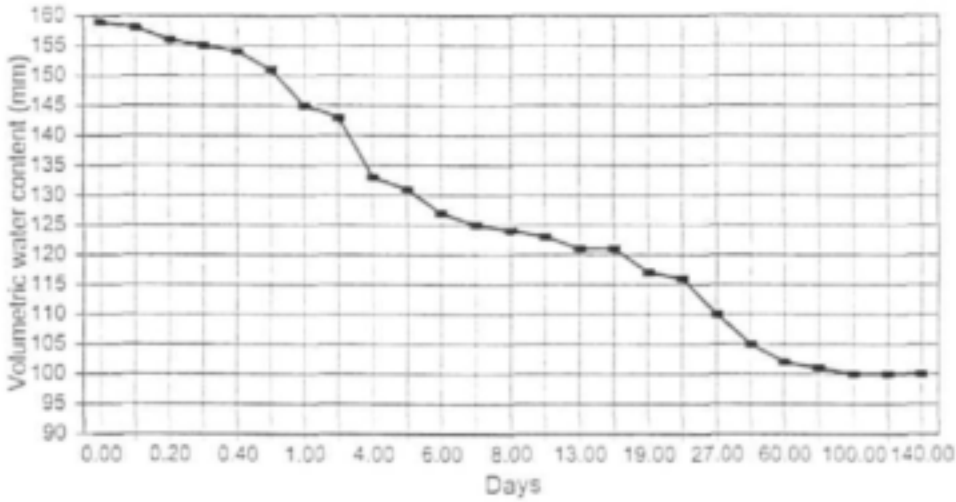


(c) Land Type data
Cover soil (0.0-0.6 m depth)

Figure A2.2 Kriel: Water retention based on soil cores and land type data



(a) All depths



(b) Cover soil

Figure A2.3 Middelburg South drainage curve

TABLE A2.4a Water-dispersible clay to total clay ratios and clay minerals of natural soils at Optimum

Lab. No.	Depth (m)	Water disper-sible clay (%)	Total clay (%)	Water disper-sible/total clay Ratio	Minerals in total clay fraction (%)								
					Kao-linite	Mica	Quartz	Goe-thite	Smec-tite	Kao-linite	Mica	Quartz	Goe-thite
M573	0.0-0.2	3.33	14.30	0.23	83	5	12	0	0	59	0	41	0
M567	0.4-0.6	3.17	13.60	0.23	78	6	16	0	0	17	6	69	8
M566	0.0-0.2	3.22	13.70	0.24	69	6	18	7	0	24	0	67	9
M572	0.4-0.6	2.91	17.30	0.17	75	6	15	0	4	42	0	58	0
M569	0.0-0.2	2.98	15.00	0.20	78	5	12	5	0	47	5	43	5
M583	0.4-0.6	3.26	14.10	0.23	94	6	0	0	0	54	8	38	0
M565	0.0-0.2	3.54	15.90	0.22	74	5	16	5	0	52	5	36	7
M584	0.4-0.6	4.97	23.60	0.21	78	5	17	0	0	54	9	37	0
M579	0.0-0.2	3.78	15.60	0.24	80	4	12	4	0	62	5	26	7
M589	0.4-0.6	3.56	16.30	0.22	79	8	13	0	0	69	7	17	7
Average	0.0-0.2	3.37	14.90	0.23	77	15	14	4	0	49	3	43	6
Std. Dev.		0.31	0.81	0.02	5	1	3	3	0	15	3	15	5
Average	0.4-0.6	3.57	16.98	0.21	81	6	12	0	1	47	6	44	3
Std. Dev.		0.81	4.00	0.02	8	1	7	0	2.00	19	4	20	4

TABLE A2.4b Water-dispersible clay to total clay ratios and clay minerals of rehabilitated soils under pastures at Optimum

Lab. No.	Depth (m)	Water disper-sible clay (%)	Total clay (%)	Water disper-sible/total clay Ratio	Minerals of total clay fraction (%)					Minerals in water dispersible clay fraction (%)				
					Kao-linite	Mica	Quartz	Goe-thite	Smec-tite	Kao-linite	Mica	Quartz	Goe-thite	Smec-tite
M571	0.0-0.2	1.31	22.20	0.06	81	6	8	5	0	13	0	87	0	0
M576	0.3-0.4	0.10	24.50	0.00	80	7	10	3	0	81	6	13	0	0
M577	0.0-0.2	0.81	26.70	0.03	85	4	9	2	0	83	2	12	3	0
M574	0.3-0.4	0.76	25.70	0.03	79	5	13	3	0	61	8	21	10	0
M582	0.0-0.2	3.42	19.50	0.18	84	6	10	0	0	72	10	18	0	0
M570	0.3-0.4	0.30	23.20	0.01	79	8	10	3	0	14	0	82	4	0
Average	0.0-0.2	1.85	22.80	0.09	83	5	9	4	0	56	4	33	1	0
	0.3-0.4	0.39	24.47	0.01	79	7	11	3	0	52	5	39	5	0

TABLE A2.4c Water-dispersible clay to total clay ratios and clay minerals of rehabilitated soils under maize at Optimum

Lab. No.	Depth (m)	Water dispersible clay (%)	Total clay (%)	Water dispersible/total clay Ratio	Minerals of total clay fraction (%)					Minerals in water dispersible clay fraction (%)				
					Kaolinite	Mica	Quartz	Goethite	Smectite	Kaolinite	Mica	Quartz	Goethite	Smectite
M575	0.0-0.2	3.07	15.90	0.19	79	4	13	4	0	24	0	65	11	0
M585	0.3-0.4	0.45	20.10	0.02	90	5	0	5	0	73	6	12	9	0
M581	0.0-0.2	3.87	13.50	0.29	79	4	14	3	0	42	9	49	0	0
M586	0.3-0.4	4.97	13.6	0.37	75	6	13	6	0	85	3	9	3	0
M580	0.0-0.2	2.97	20.10	0.15	79	6	15	0	0	74	0	26	0	0
M587	0.3-0.4	0.45	17.70	0.03	79	8	13	0	0	84	5	11	0	0
M568	0.0-0.2	3.32	16.50	0.20	82	4	10	4	0	46	6	39	9	0
M588	0.0-0.2	1.76	18.30	0.10	88	7	0	5	0	79	6	15	0	0
M578	0.3-0.4	1.56	16.80	0.09	76	5	15	4	0	69	7	17	0	7
Average	0.0-0.2	3.00	16.86	0.19	81	5	10	3	0	53	4	39	4	0
Std. Dev.		0.78	2.50	0.07	4	1	6	2	0	23	4	19	6	0
Average	0.3-0.4	1.86	17.05	0.13	80	6	10	4	0	78	5	12	3	2
Std. Dev.		2.14	2.69	0.16	5	1	7	3	0	8	2	3	4	4

TABLE A2.4d Water-dispersible clay to total clay ratios and clay minerals of rehabilitated soils under maize at Middelburg South

Lab. No.	Depth (m)	Water disper-sible clay (%)	Total clay (%)	Water disper-sible/total clay Ratio	Minerals of total clay fraction (%)					Minerals in water dispersible clay fraction (%)				
					Kao-linite	Mica	Quartz	Goe-thite	Smec-tite	Kao-linite	Mica	Quartz	Goe-thite	Smec-tite
M3867	0.0-0.2	4.6	12.0	0.38	74	6	20	0	0	37	5	37	9	0
M3869	0.0-0.2	5.7	11.5	0.50	66	6	21	7	0	59	7	34	0	0
M3870	0.4-0.6	5.0	12.4	0.40	64	6	30	0	0	53	7	40	0	0
M3871	0.0-0.2	4.5	14.3	0.31	59	7	29	5	0	54	9	37	0	0
M3872	0.4-0.6	5.3	14.5	0.37	82	7	11	0	0	57	6	29	8	0
M3873	0.0-0.2	4.5	17.4	0.26	59	9	26	6	0	41	8	51	0	0
M3874	0.4-0.6	6.0	18.1	0.33	69	8	18	5	0	65	4	24	7	0
M3875	0.0-0.2	4.6	15.3	0.30	64	6	30	0	0	32	7	52	9	0
M3876	0.4-0.6	4.4	14.4	0.31	59	5	29	7	0	38	8	54	0	0
M3877	0.0-0.2	3.3	24.2	0.14	71	7	22	0	0	52	7	33	8	0
M3878	0.4-0.6	4.9	14.3	0.34	68	8	18	6	0	42	9	49	0	0
M3879	0.0-0.2	4.8	14.2	0.34	57	8	28	7	0	44	8	38	10	0
M3880	0.4-0.6	4.0	14.4	0.28	69	5	20	6	0	41	7	52	0	0
Average	0.0-0.2	4.6	14.1	0.32	64	7	25	4	0	46	7	40	5	0
Std. Dev.		0.7	2.0	0.11	6	1	4	3	0	10	1	8	5	0
Average	0.4-0.6	4.9	14.7	0.34	69	7	21	4	0	49	7	41	3	0
Std. Dev.		0.7	1.9	0.04	8	1	7	3	0	11	2	13	4	0

TABLE A2.4e Water-dispersible clay : total clay ratios and clay minerals of rehabilitated soils under maize at Kriel

Lab. No.	Depth (m)	Water disper-sible clay (%)	Total clay (%)	Water disper-sible/total clay Ratio	Minerals of total clay fraction (%)					Minerals in water dispersible clay fraction (%)				
					Kao-linite	Mica	Quartz	Goe-thite	Smec-tite	Kao-linite	Mica	Quartz	Goe-thite	Smec-tite
M3881	0.0-0.2	5.5	28.1	0.20	51	11	38	0	0	21	7	62	10	0
M3882	0.4-0.6	5.4	27.2	0.20	57	16	27	0	0	25	8	67	0	0
M3883	0.0-0.2	6.9	29.8	0.23	50	11	39	0	0	36	7	57	0	0
M3884	0.4-0.6	7.7	29.4	0.26	57	16	27	0	0	33	10	57	0	0
M3885	0.0-0.2	5.6	24.2	0.23	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3886	0.4-0.6	7.2	25.5	0.28	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3887	0.0-0.2	8.7	26.0	0.33	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3888	0.4-0.6	4.6	22.1	0.21	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3889	0.0-0.2	8.9	20.6	0.43	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3890	0.4-0.6	7.8	20.4	0.38	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3891	0.0-0.2	4.2	18.9	0.22	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3892	0.4-0.6	8.8	18.0	0.49	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3893	0.0-0.2	8.8	19.2	0.46	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
M3894	0.4-0.6	5.7	16.1	0.35	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Average	0.0-0.2	6.9	23.9	0.30	51	11	39	0	0	29	7	60	5	0
Std. Dev.		1.9	4.4	0.11	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Average	0.4-0.6	6.7	22.7	0.31	57	16	27	0	0	29	9	62	0	0
Std. Dev. Dev.Dev De		1.5	4.9	0.10	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

TABLE A2.5a Coarse fragment content of spoil materials at Kriel

Access Tube No.	Depth (mm)	Coarse fragments (%)					
		2-4 mm	4-11 mm	11-26 mm	26-75 mm	>75 mm	Total
K1	0.8-1.0	3	7	10	9	15	45
K3	0.6-0.8	3	7	17	11	7	46
K3	0.8-1.0	3	8	10	22	10	52
K3	1.0-1.3	3	7	10	14	18	52
K5	0.8-1.0	2	7	11	10	9	39
K5	0.8-1.0	3	8	12	20	3	46
K5	0.8-1.0	2	7	12	31	0	52
K9	0.8-1.0	2	7	8	11	7	46
K10	0.6-0.8	3	10	15	10	0	39
K10	1.0-1.3	3	8	14	17	3	44
K12	0.6-0.8	3	8	13	19	0	43
K12	1.0-1.3	2	6	10	19	0	36
K14	0.8-1.0	3	9	14	17	0	43
K14	1.0-1.3	4	10	18	15	0	47
K15	0.8-1.0	3	7	9	16	0	35
K15	1.0-1.3	4	11	11	16	4	46
K17	0.8-1.0	1	8	9	10	9	39
K17	0.8-1.0	1	5	7	18	0	32
K17	1.0-1.3	2	6	11	14	0	33
K19	0.6-0.8	2	6	8	5	9	29
K19	1.0-1.3	1	3	6	23	23	57
K20	0.8-1.0	2	6	11	29	16	61
Average	0.6-1.0	2	7	11	15	5	43
Average	1.0-1.3	3	7	11	18	7	46

TABLE A2.5b Coarse fragment content of spoil materials at the Middelburg South (M) and Optimum (O)

Access Tube No.	Depth (mm)	Coarse fragments (%)					
		2-4 mm	4-11 mm	11-26 mm	26-75 mm	>75 mm	Total
M1	0.6-0.8	8	17	23	17	0	65
M1	1.3-1.6	7	18	23	26	10	83
M4	0.6-0.8	7	16	18	26	0	67
M8	0.6-0.8	6	13	28	20	0	67
M8	1.0-1.3	4	12	19	24	10	68
M10	0.6-0.8	9	20	23	14	0	67
M10	1.0-1.3	6	15	19	15	33	87
M14	0.6-0.8	11	18	21	23	0	73
M14	1.3-1.6	6	13	16	22	10	67
M15	1.0-1.3	6	15	24	24	0	70
M17	0.6-0.8	5	12	17	24	15	74
M17	1.3-1.6	6	15	18	24	13	76
M18	0.6-0.8	8	15	24	26	0	72
M18	1.6-1.9	3	7	18	45	23	95
M19	0.6-0.8	8	15	16	19	0	58
M19	1.3-1.6	14	14	14	10	31	83
Average	0.6-1.0	8	16	21	21	2	68
Average	>1.0	7	14	19	24	16	79
O3	0.8-1.0	5	11	17	16	19	67
O6	0.6-0.8	5	12	20	26	0	64
O9	0.6-0.8	6	15	22	24	12	79
Average		5	13	20	22	10	70

TABLE A2.6 Loss of mass on heating to 550 °C

SAMPLE NUMBER	DEPTH (mm)	LOSS OF MASS ON HEATING TO 550 °C (expressed as percentage of oven-dry mass)	
		TREATED WITH H_2O_2	UNTREATED
DD2	0-200	0.8	3.4
K12	0-600	2.4	1.0
DD1	400-600	2.2	3.2
K4	200-600	2.0	3.0
K8	300-900	3.4	2.0
D13	600-800	6.0	8.5
K9	600-1200	3.0	2.0
M6	1500-1800	3.0	2.0
K5	2000-2400	5.0	2.0
E8	2400-2700	6.0	2.0
E11	2400-2700	6.0	4.2
E7	2700-3000	4.0	7.0

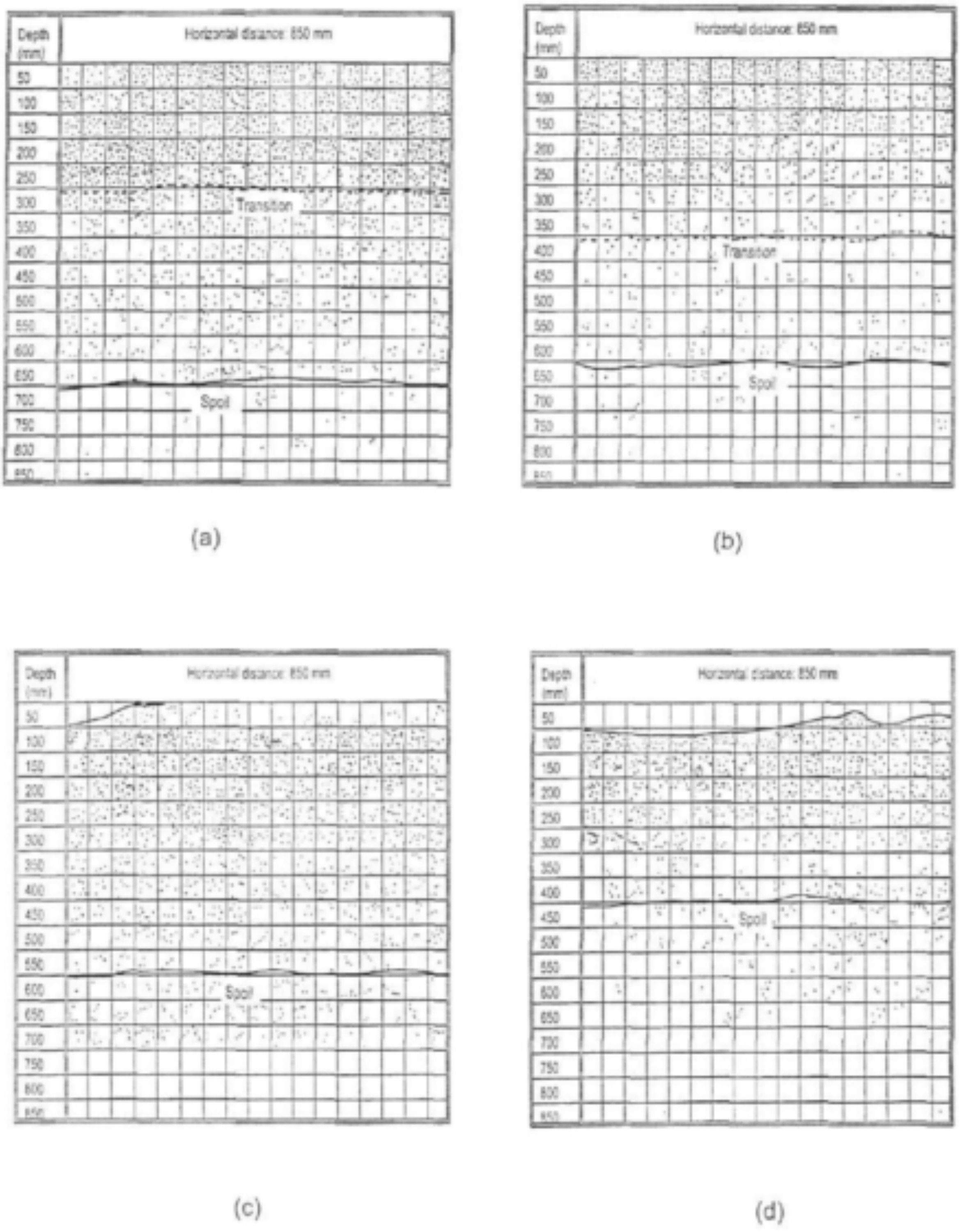


Figure A2.5 Kriel: Root distribution maps (July 1997)

(a)

(b)

(c)

Figure A2.6 Middelburg South A: Root distribution maps (September 1997)

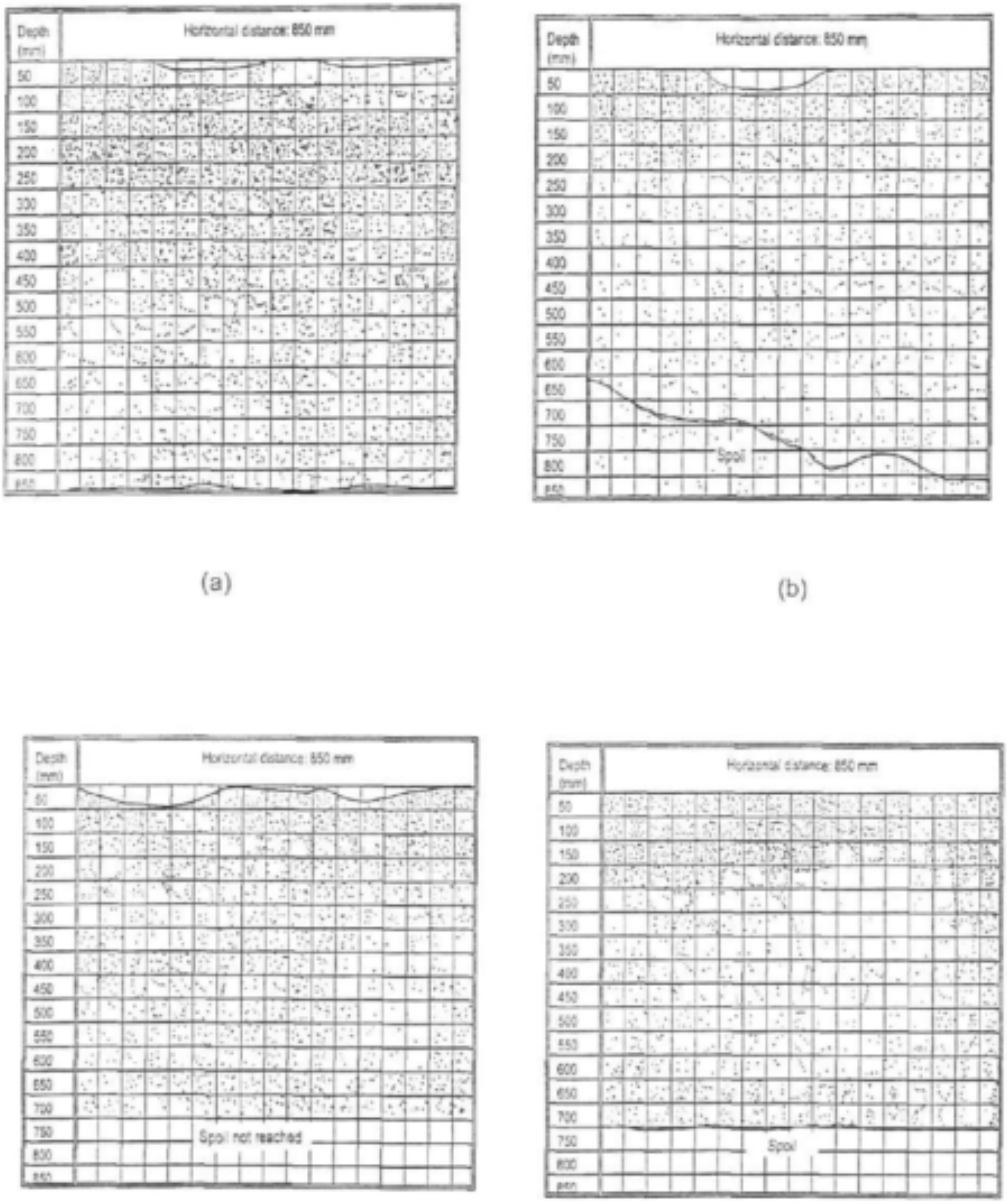


Figure A2.7 Optimum A: Root distribution Maps (August 1997)

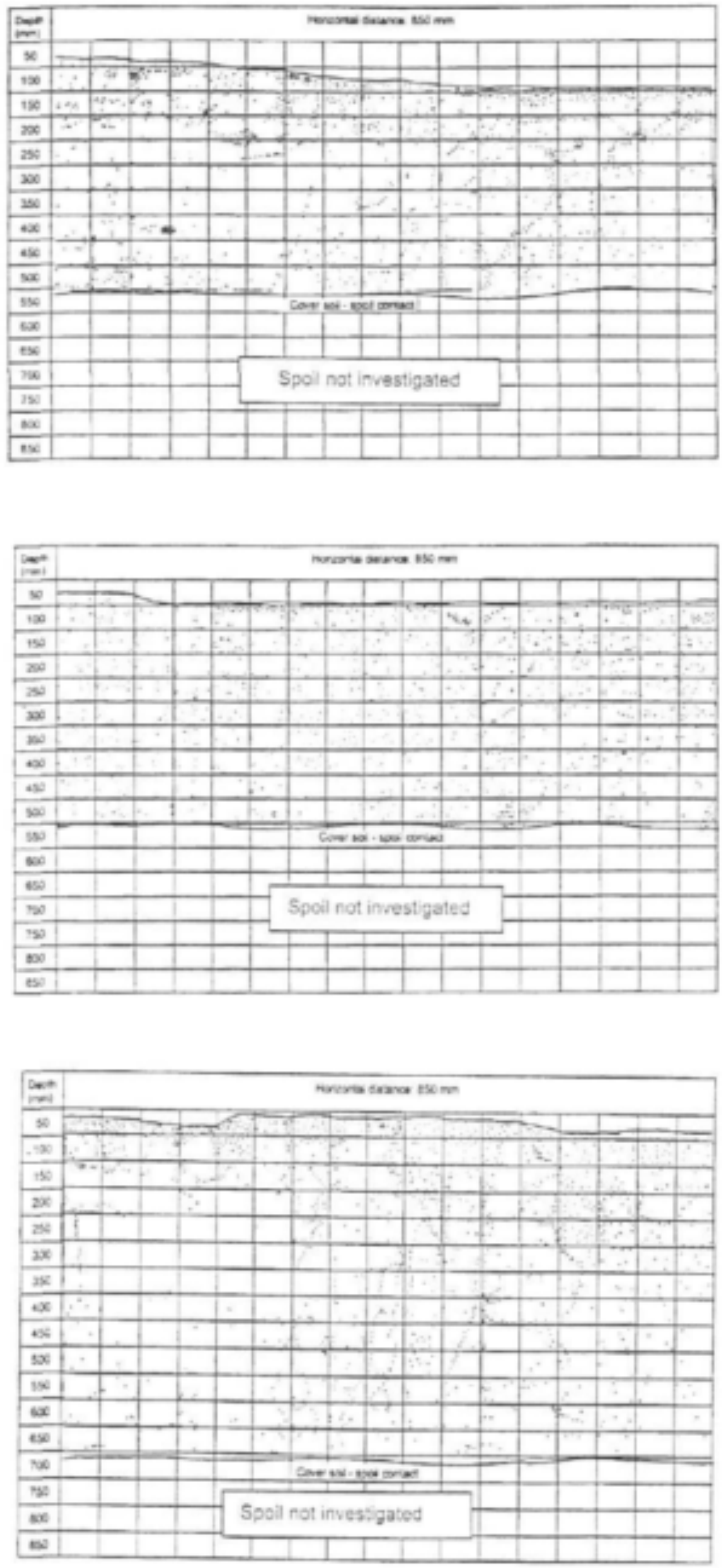


Figure A2.8 Optimum B: Root distribution maps (April 1999)

APPENDIX 3

Appendices to Chapter 3

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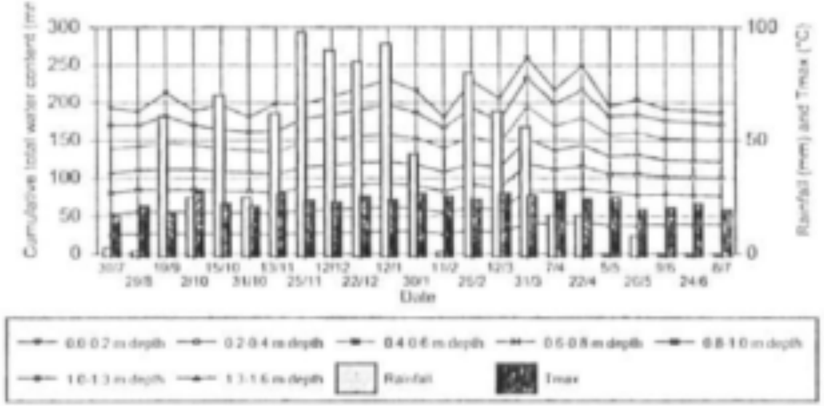
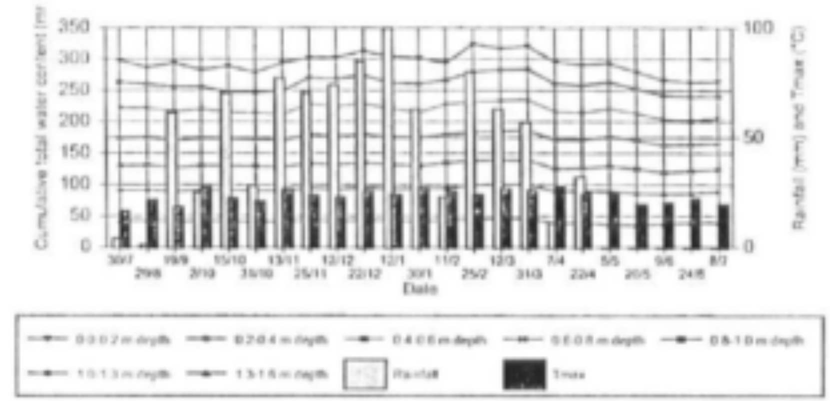


(a) Kriel A
Total water content, rainfall and Tmax



(c) Kriel B
Total water content, rainfall and Tmax

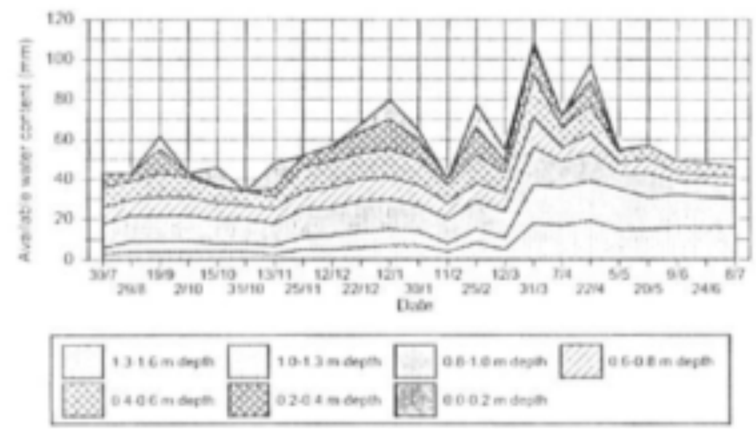
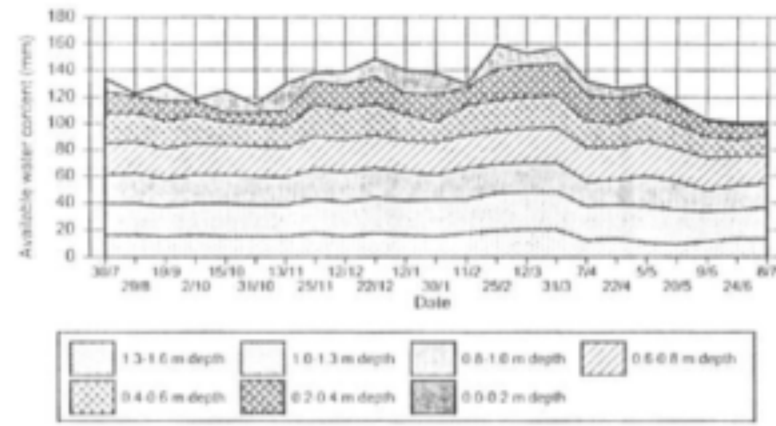


Fig. (b) Kriel A
Available water content



(d) Kriel B
Available water content

Figure A3.1 Total and plant-available water content: Kriel A and B (1997/98 season)

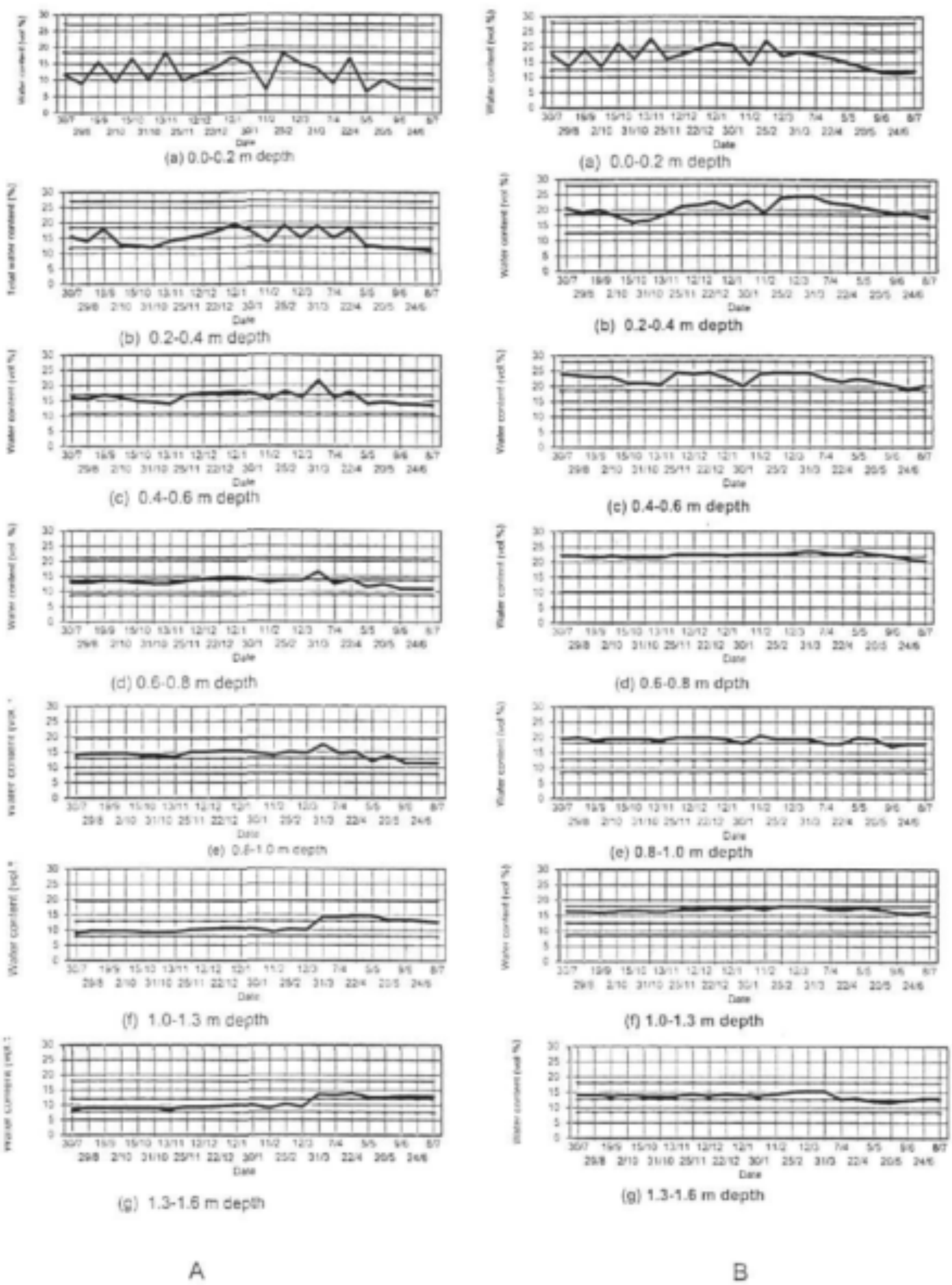


Figure A3.2 Changes in water content: Kriel A and B (1997/98 season). The actual water content is shown in relation to saturation (upper line) DUL (middle line) and LL (lower line)

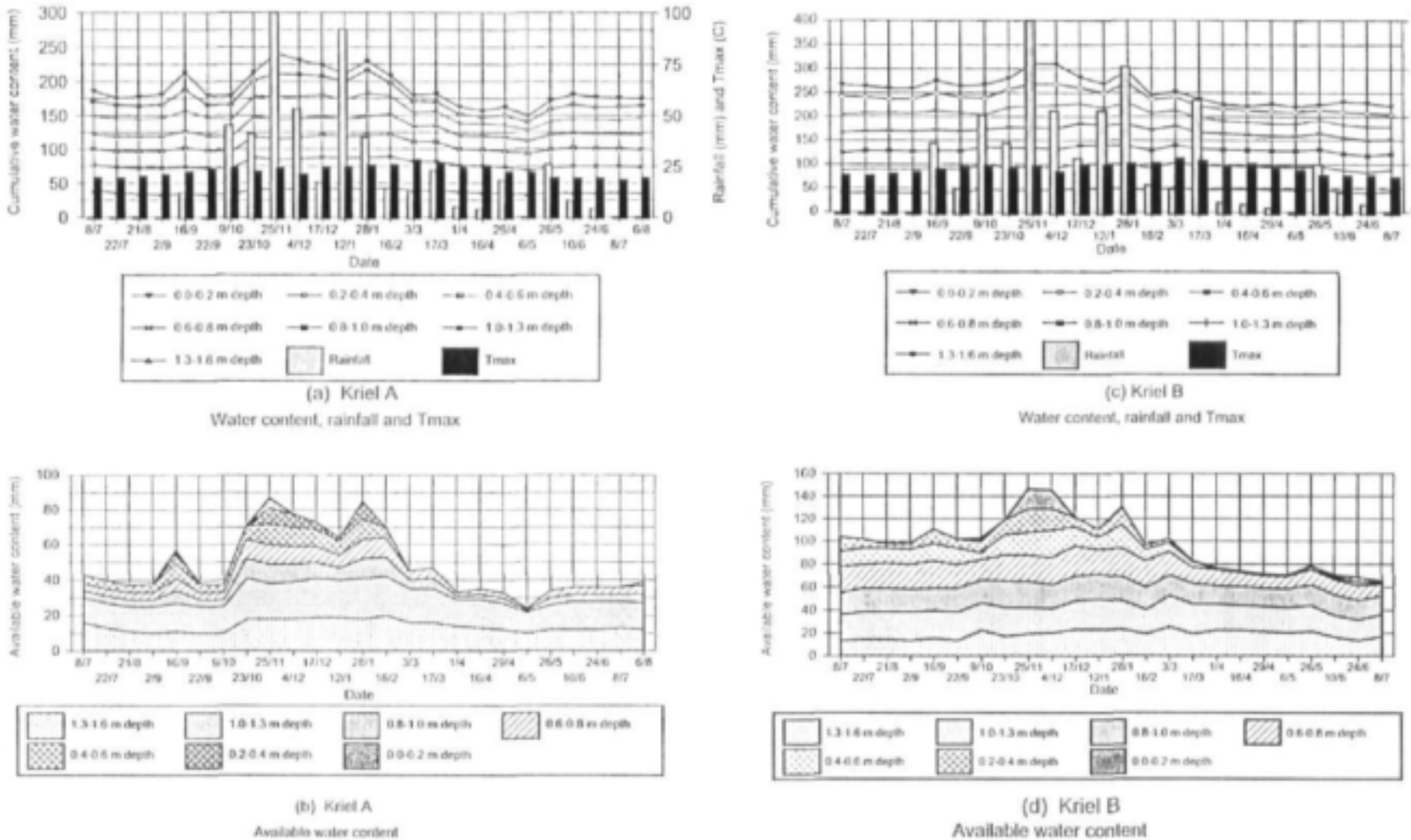


Figure A3.3 Total and plant-available water content: Kriel A and B (1998/99 season)

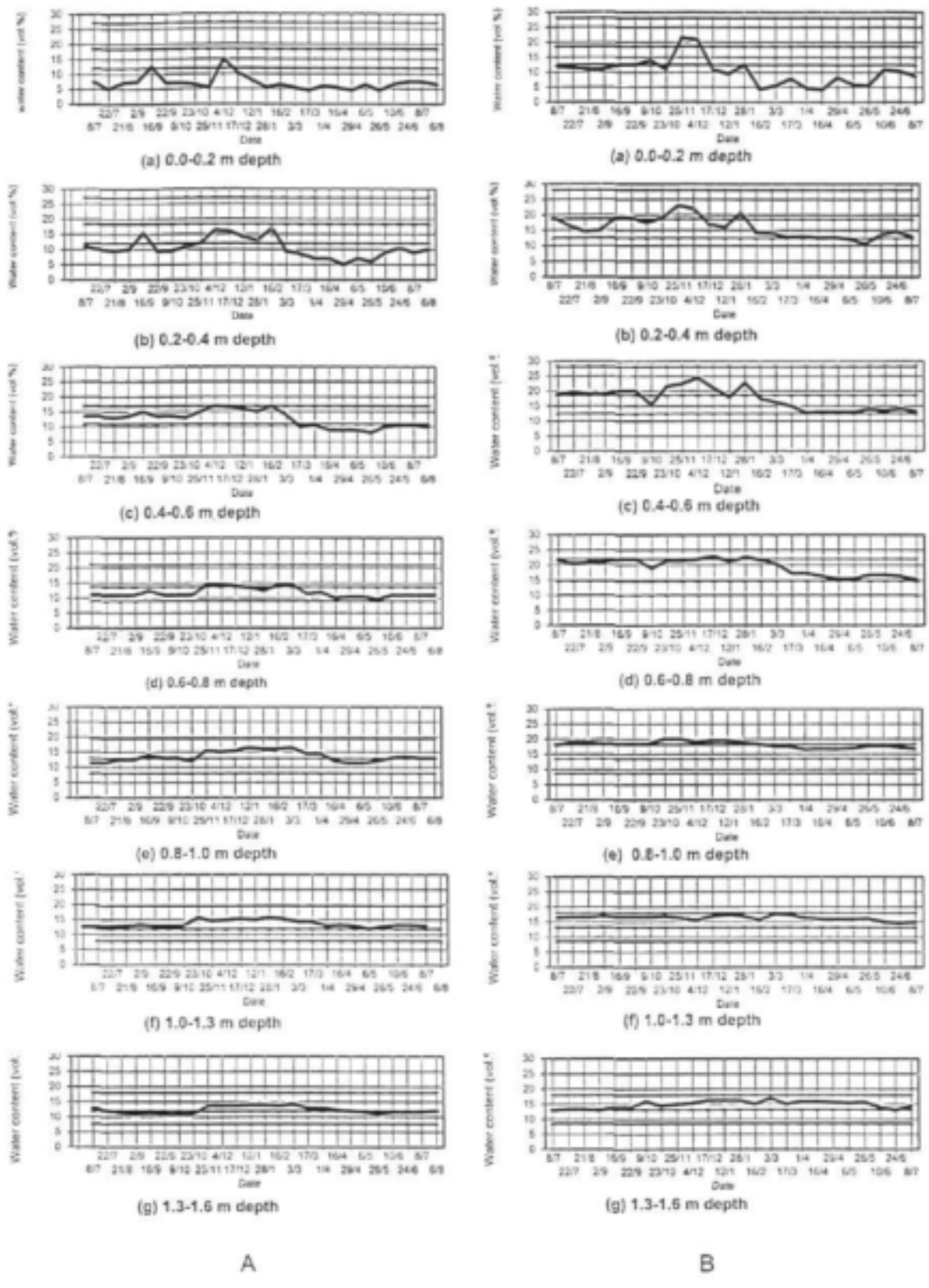


Figure A3.4 Changes in water content: Kriel A and B (1998/99 season). The actual water content is shown in relation to saturation (upper line), DUL (middle line) and LL (lower line)

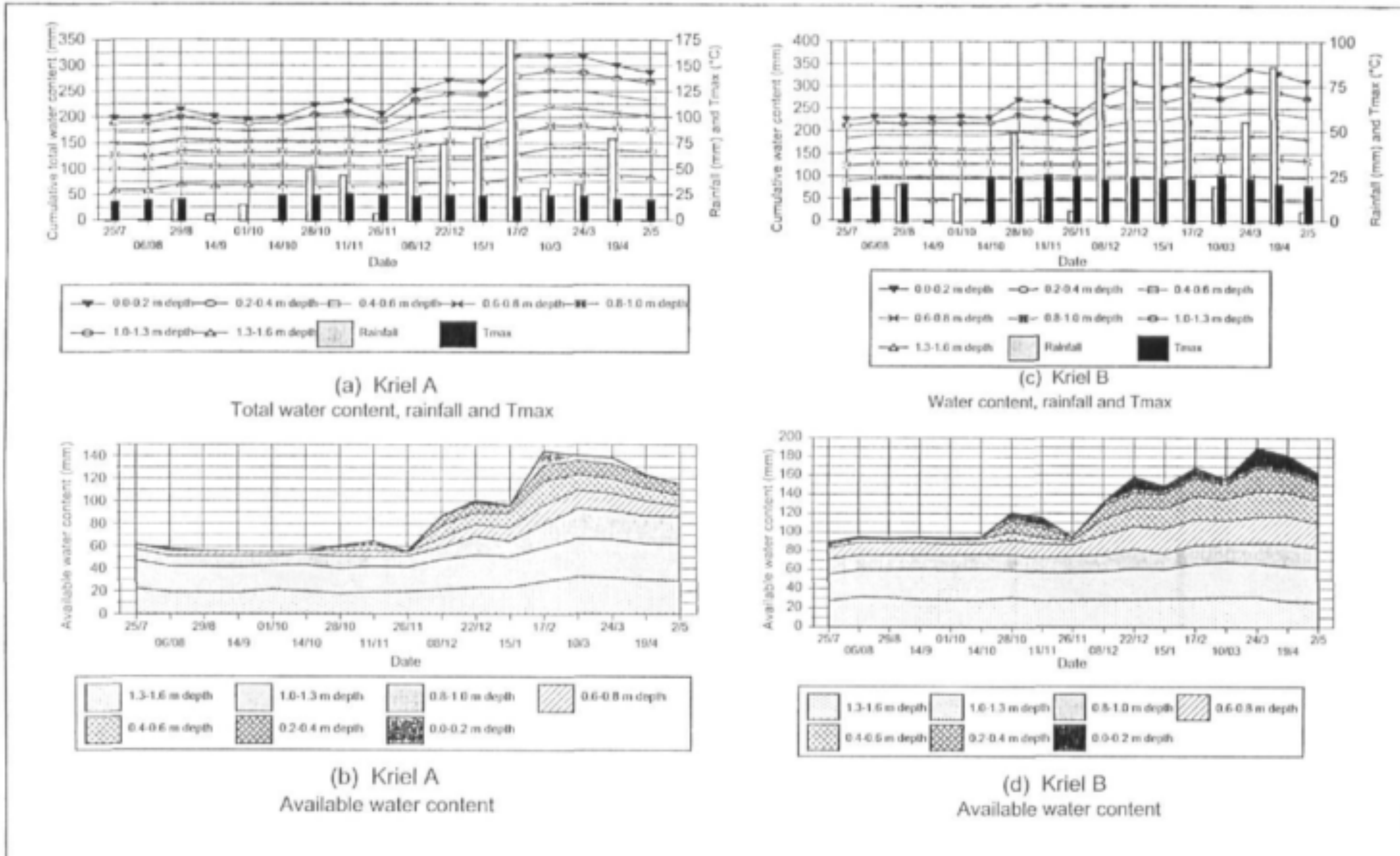


Figure A3.5 Total and plant available water content: Kriel A and B (1999/2000 season)

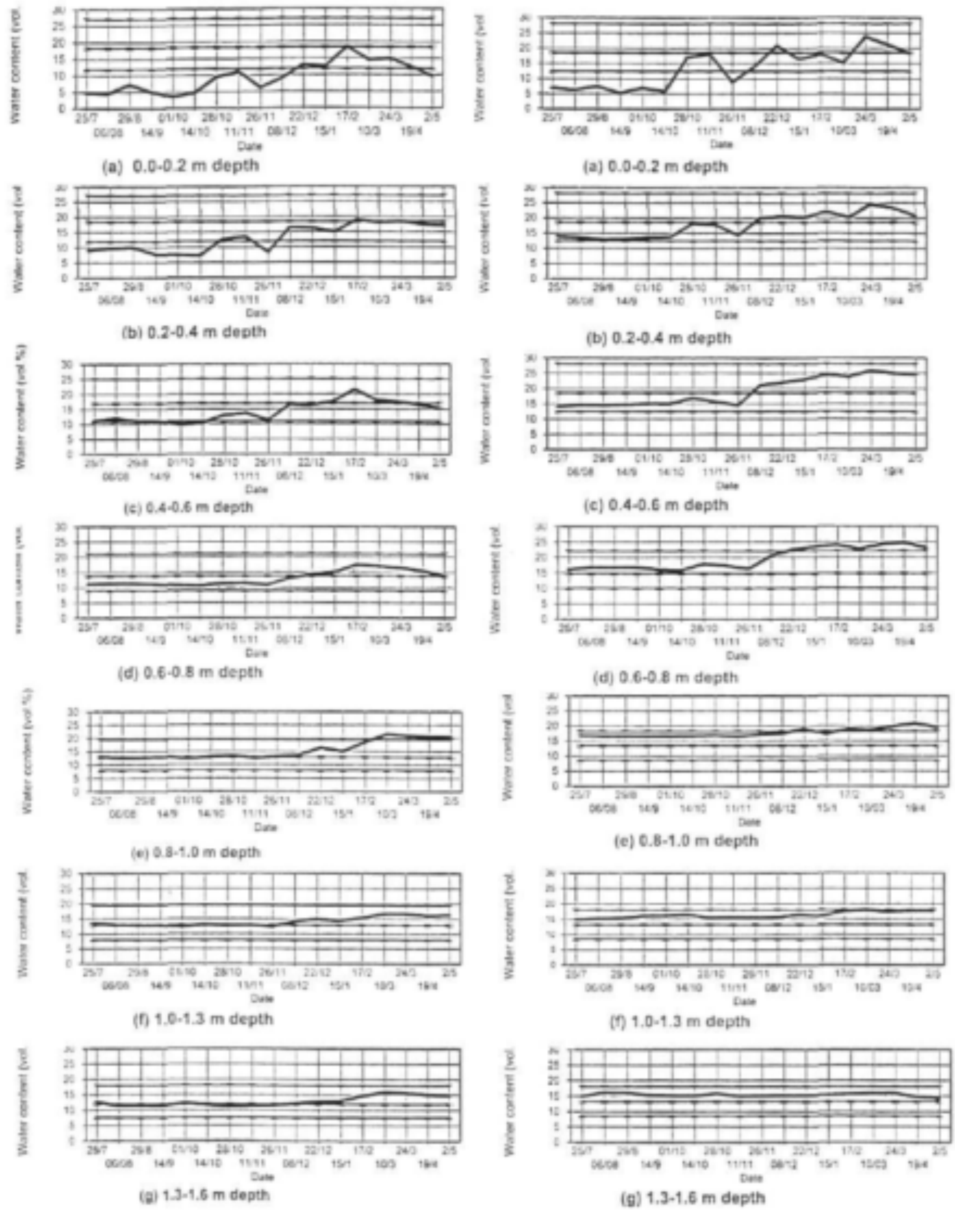


Figure A3.6 Changes in water content: Kriel A and B (1999/2000 season). The actual water content is shown in relation to saturation (upper line), DUL (middle line) and LL (lower line)

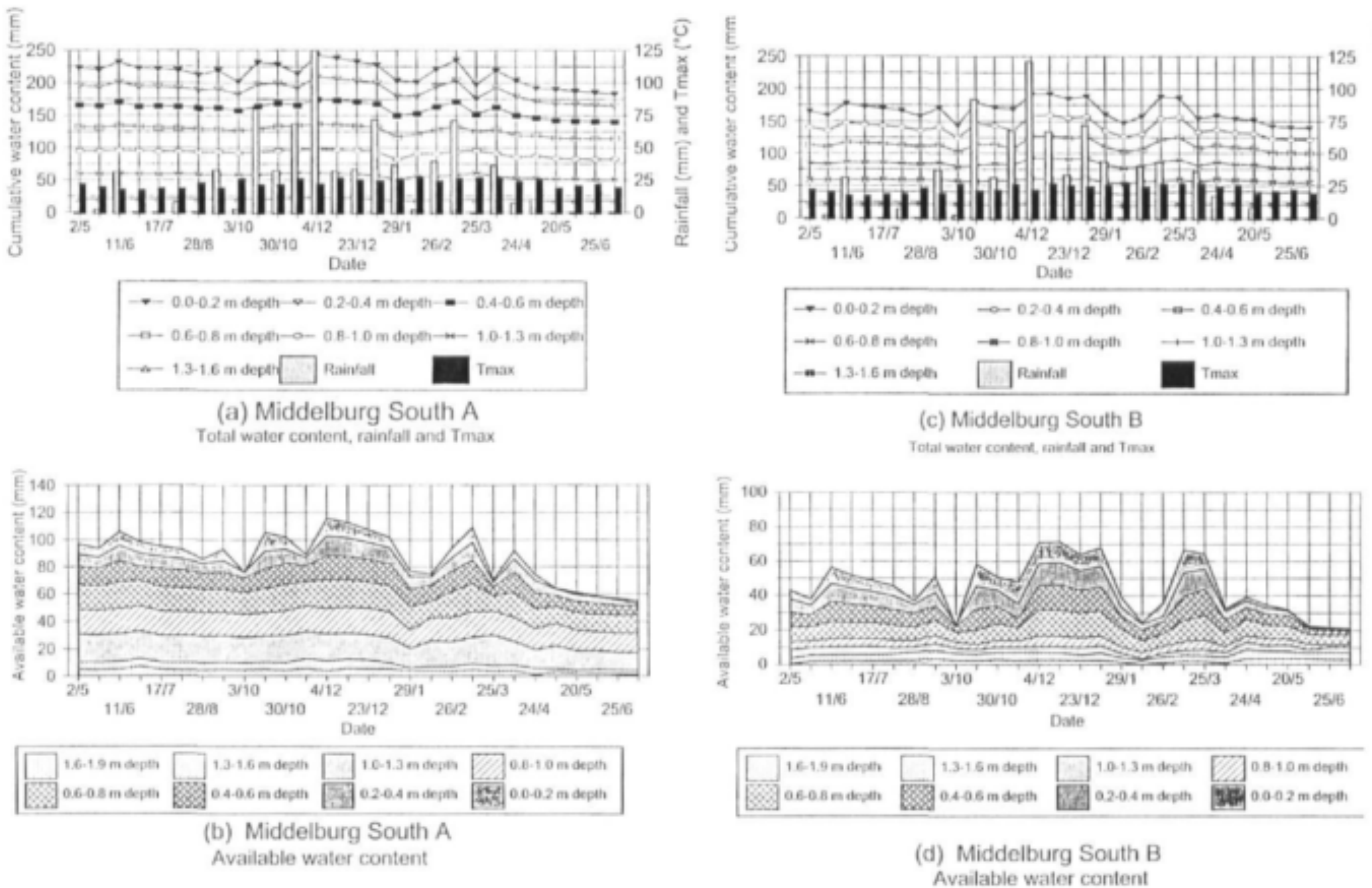


Figure A3.7 Total and plant-available water content: Middelburg South A and B (1997/98)

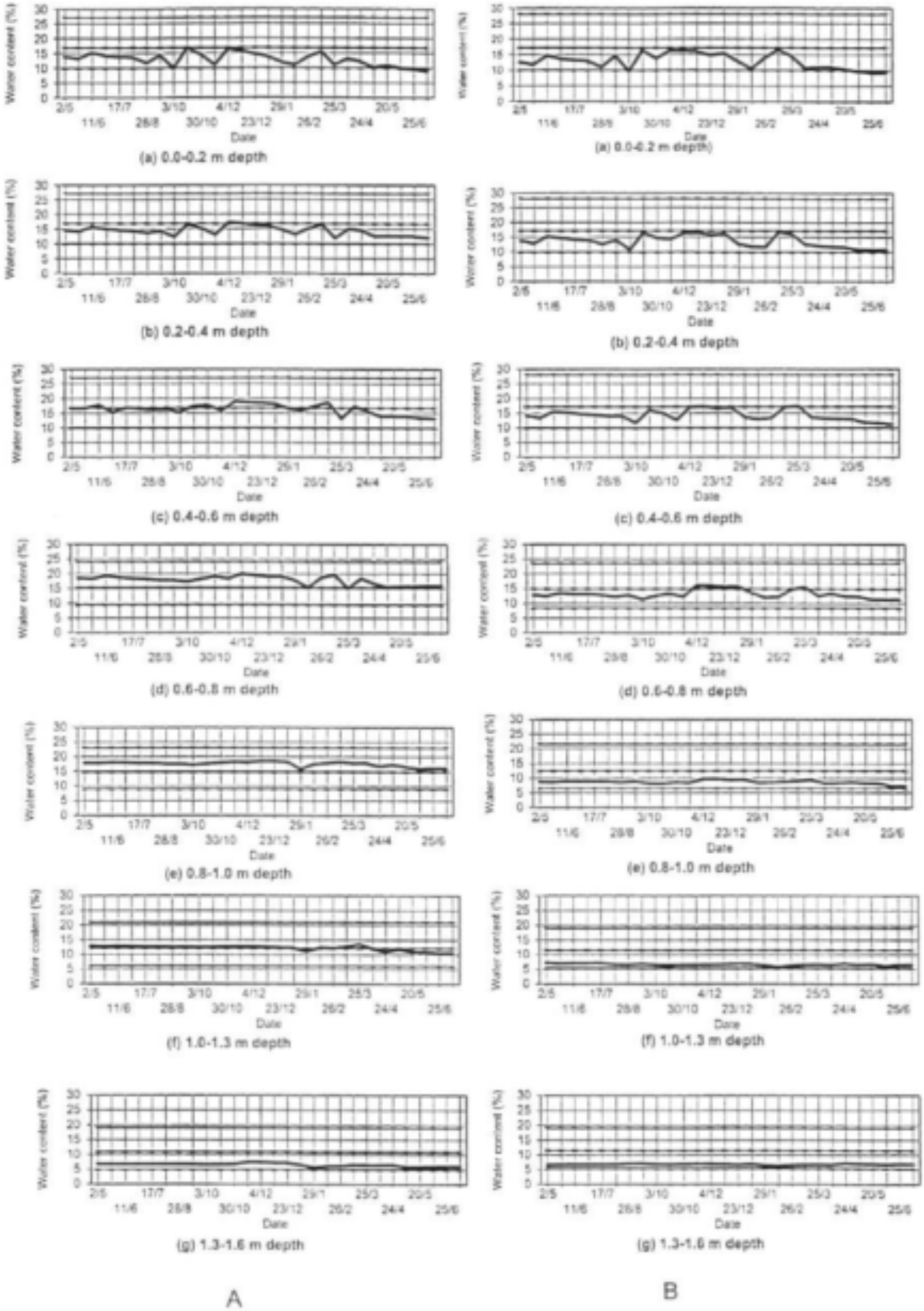


Figure A3.8 Changes in water content: Middelburg South A and B (1997/98).The actual water content is shown in relation to saturation (upper line), DUL (middle line) and LL (lower line)

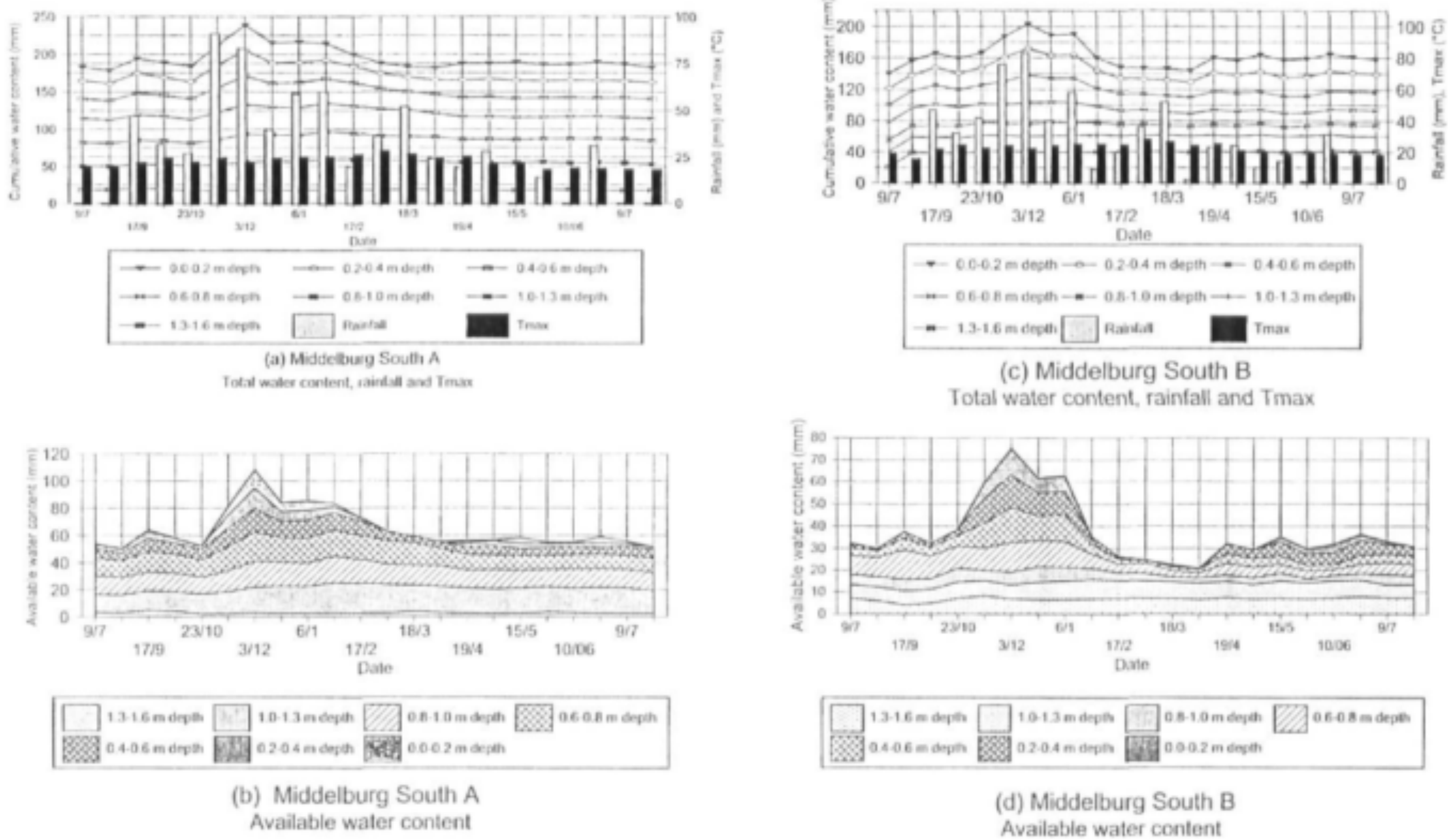


Figure A3.9 Total and plant-available water content: Middelburg South A and B (1998/99)

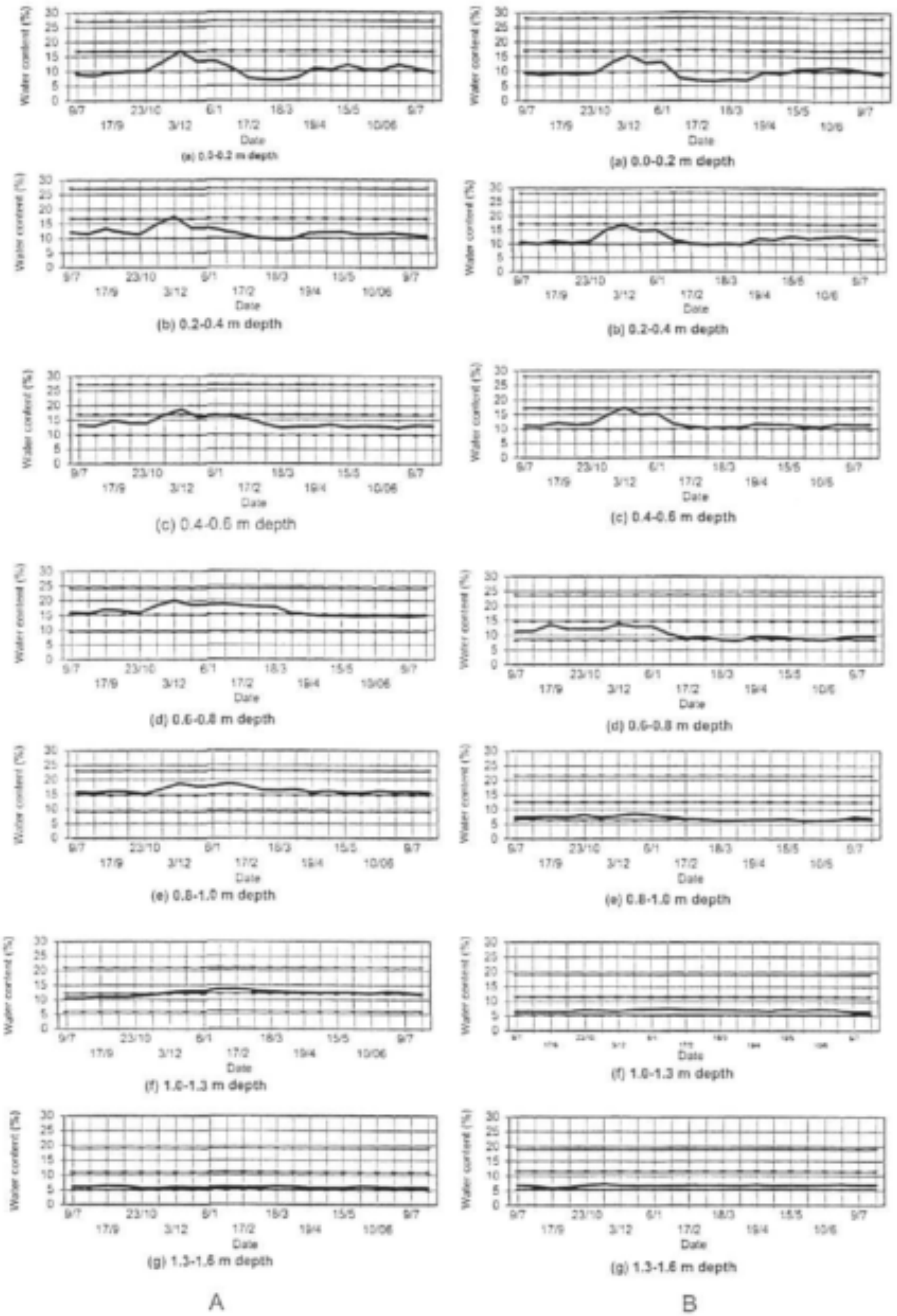
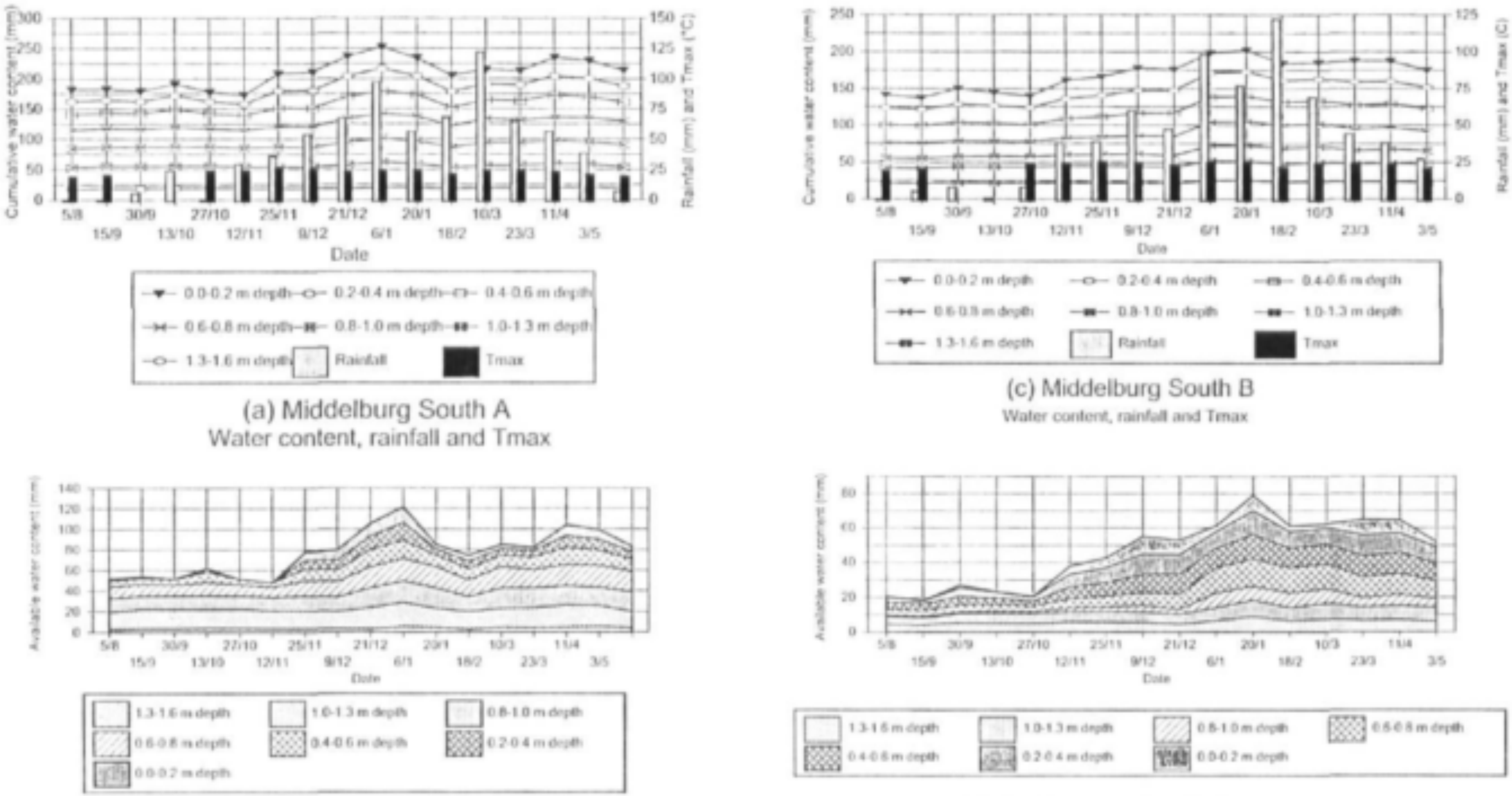


Figure A3.10 Changes in water content: Middelburg South A and B (1998/99). The actual water content is shown in relation to saturation (upper line), DUL (middle line) and LL (lower line)



(a) Middelburg South A
Water content, rainfall and Tmax

(c) Middelburg South B
Water content, rainfall and Tmax

(b) Middelburg South A
Available water content

(d) Middelburg South B
Available water content

Figure A3.11 Total and plant-available water content: Middelburg South A and B (1999/2000)

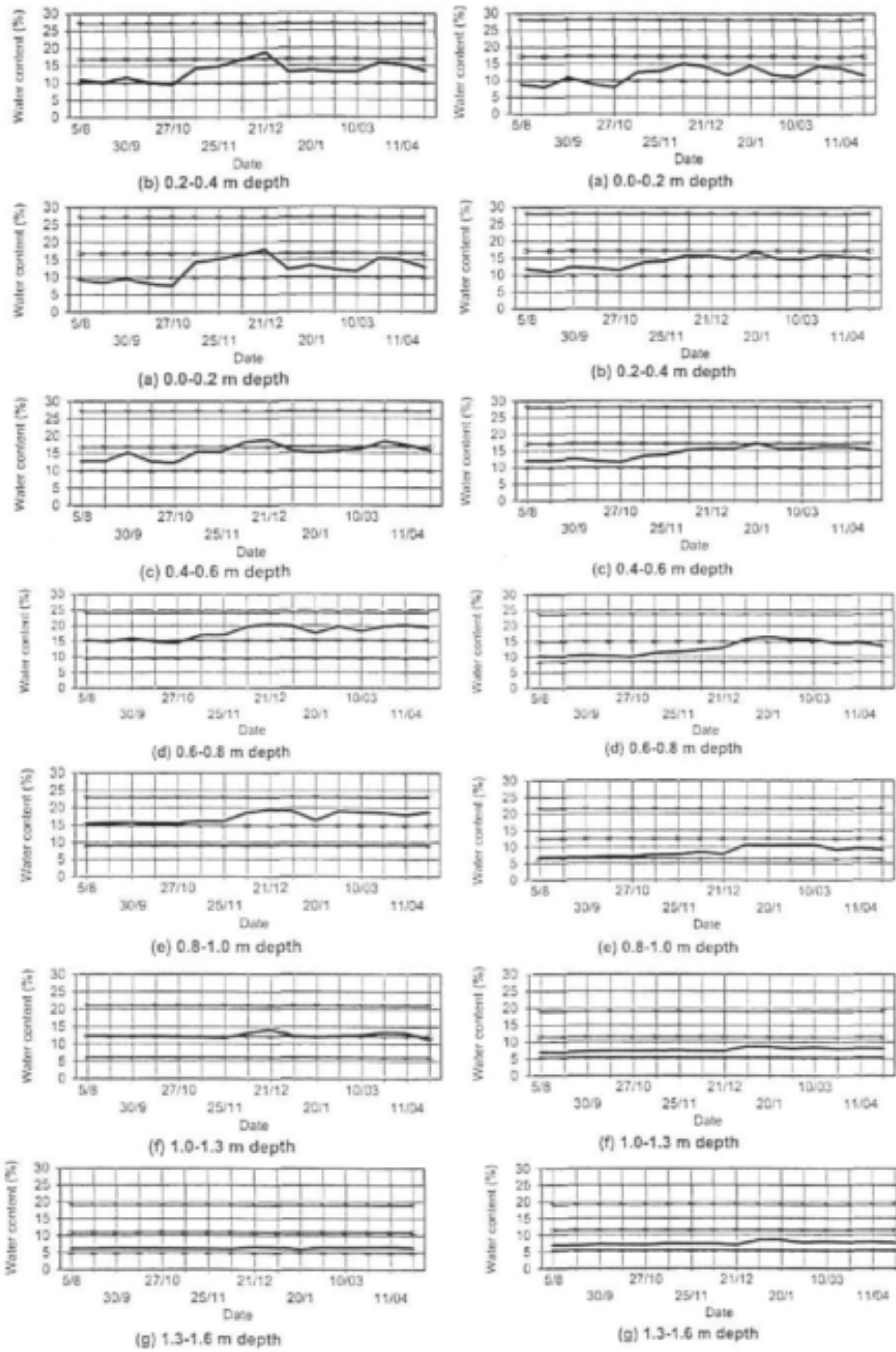
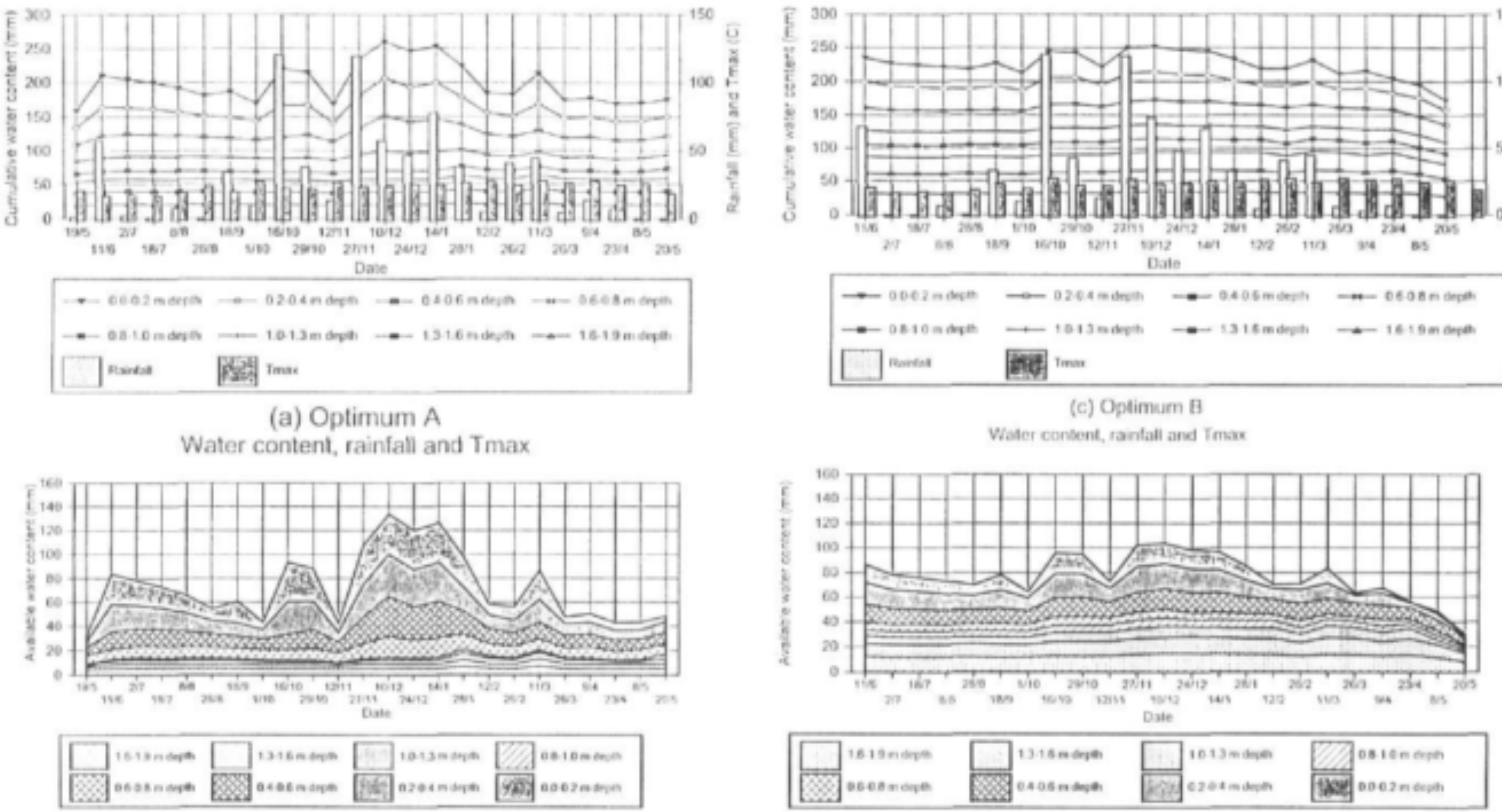


Figure A3.12 Changes in water content: Middelburg South A and B (1999/2000 season). The actual water content is shown in relation to saturation (upper line), DUL, (middle line) and LL (lower line)



(a) Optimum A
Water content, rainfall and Tmax

(c) Optimum B
Water content, rainfall and Tmax

(b) Optimum A
Available water content

(d) Optimum B
Available water content

Figure A3.13 Total and plant-available water content: Optimum A and B (1997/98 season)

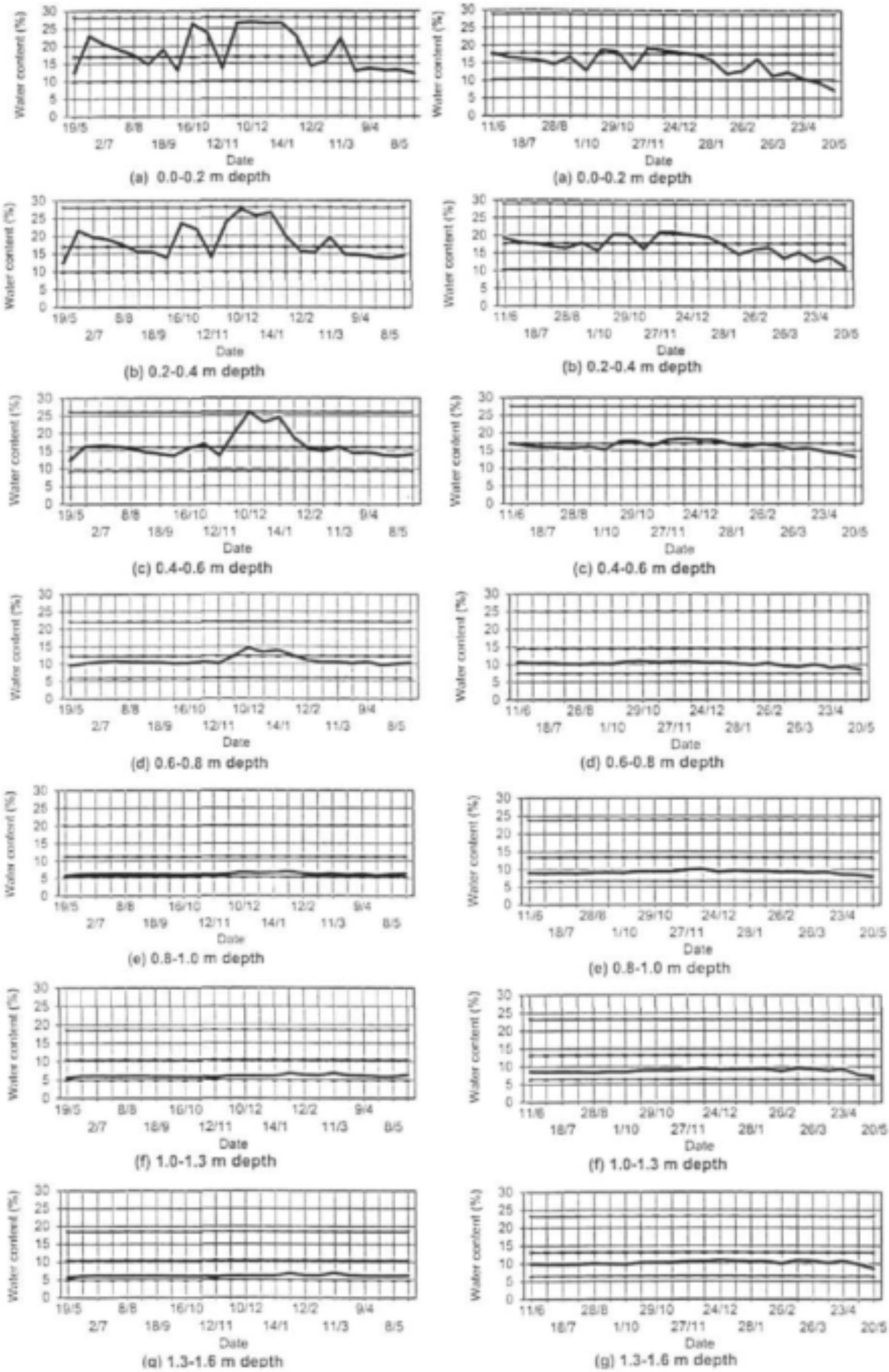
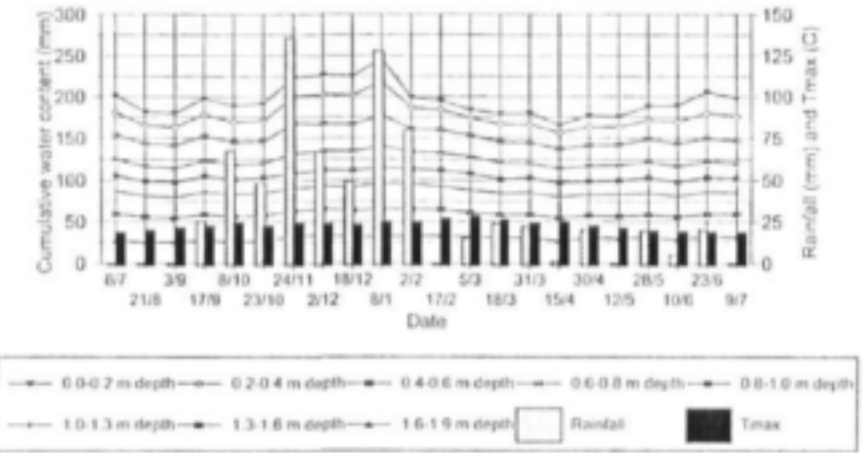
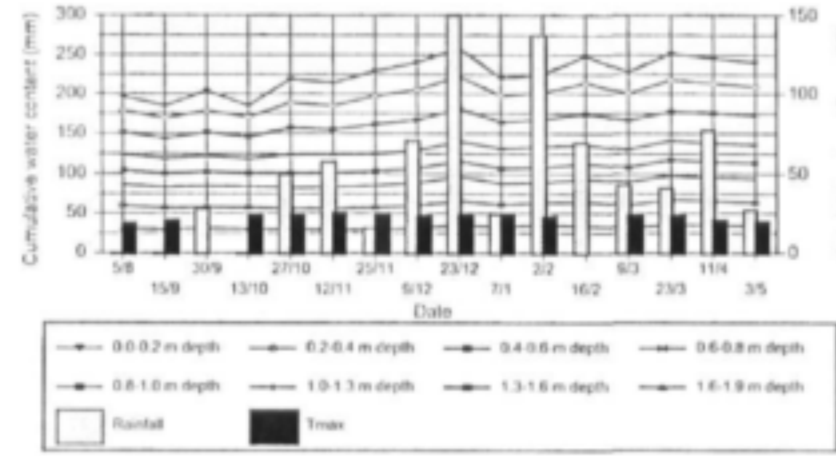


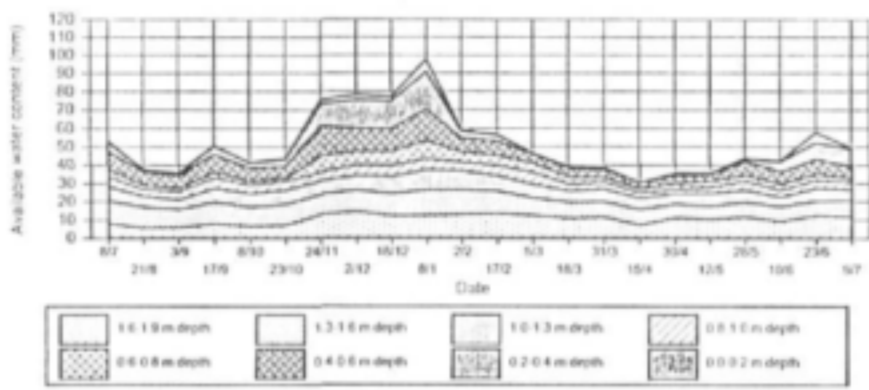
Figure A3.14 Changes in water content: Optimum A and B (1997/98 season). The actual water content is shown in relation to saturation (upper line), DUL (middle line) and LL (lower line)



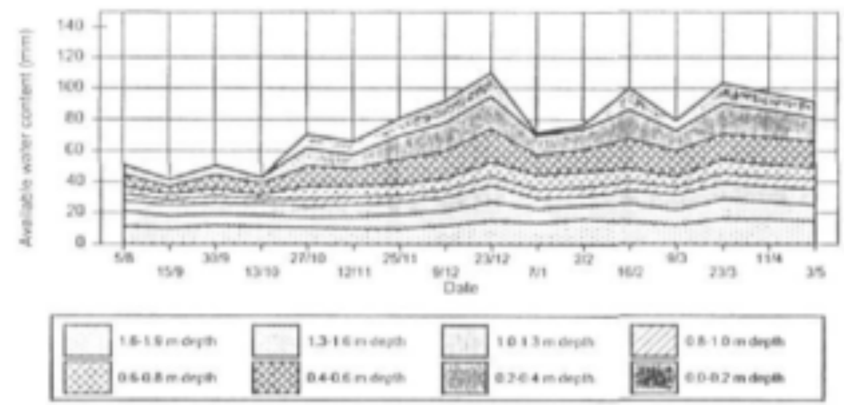
(a) Optimum B (1998/99)
Water content, rainfall and Tmax



(c) Optimum B (99/2000)
Water content, rainfall and Tmax



(b) Optimum B (1998/99)
Available water content



(d) Optimum B (99/2000)
Available water content

Figure A3.15 Total and plant-available water content: Optimum B (1998/99 and 1999/2000 seasons)

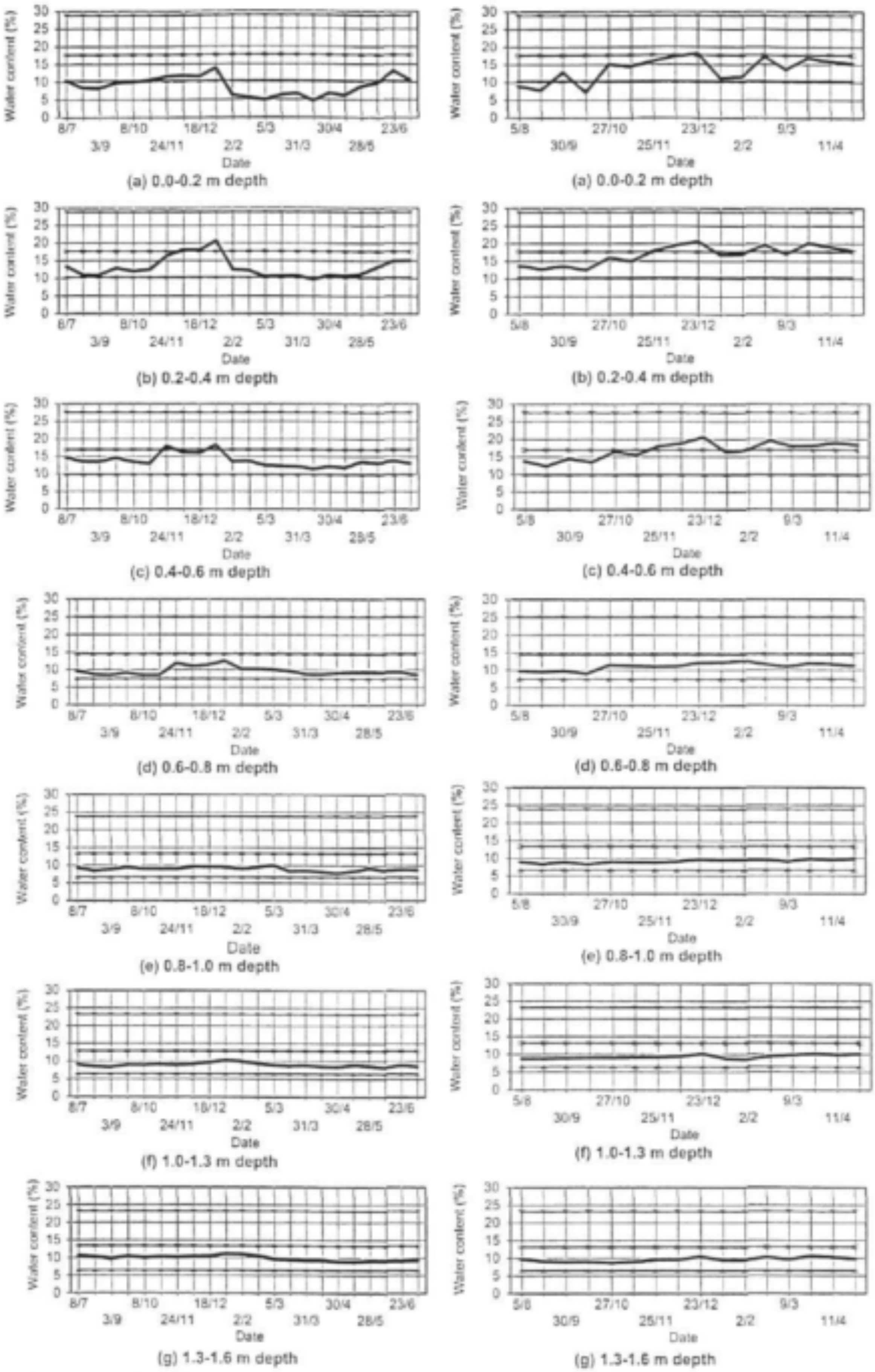


Figure A3.16 Changes in water content: Optimum B (1998/99 and 1999/2000 seasons). The actual water content is shown in relation to saturation (upper line), DUL (middle line) and LL (lower line)

APPENDIX 5

Appendix to Chapter 5

TABLE A5.1 Example illustrating the approach to estimating deep percolation

Period	0-.2	.2-.4	.4-.6	.6-.8	.8-1 (mm)	1-1.3	1.3-1.6	1.6-1.9	P.Root depth (mm)	Cl+Si (%)	a eq.3.36	b' eq.3.35	b eq.3.37	W (mm)	x eq.3.34	DT (mm/d) eq.3.34	DT (mm/h)	Days	D_{per} (mm)	DUL (mm)	O.Sat. (mm) Eq.3.40	lnKPa	KPa	K (mm/d)	D max (mm/d)	D max (mm)	D (DUL) (mm)	D (Bennie) (mm)
Kriel A (1997/98)																												
									a		b	c	d	e	f	g			h	i	j	k		l	m		n	o
30/7	23	31	32	26	28	27	26	20	1100	27	18.84	322.2	354.4	213.0	7.51	0.010	0.000	30	0	272	-59	7.81	2465	0.00	0.4	0	0	0
29/8	18	28	31	26	29	29	27	23	1100	27	18.84	322.2	354.4	211.0	7.61	0.009	0.000	30	0	272	-61	7.09	1200	0.09	0.4	3	0	0
19/9	31	36	34	27	29	29	27	25	1100	27	18.84	322.2	354.4	238.0	6.18	0.039	0.002	22	1	272	-34	6.62	750	0.24	0.4	5	0	1
2/10	19	26	32	27	29	29	27	25	1100	27	18.84	322.2	354.4	214.0	7.45	0.011	0.000	13	0	272	-58	6.62	750	0.24	0.4	3	0	0
15/10	33	25	30	26	28	28	27	25	1100	27	18.84	322.2	354.4	222.0	7.03	0.017	0.001	13	0	272	-50	6.62	750	0.24	0.4	3	0	0
31/10	20	24	29	25	28	28	27	24	1100	27	18.84	322.2	354.4	205.0	7.93	0.007	0.000	16	0	272	-67	6.86	953	0.17	0.4	3	0	0
13/11	37	28	28	25	27	28	26	25	1100	27	18.84	322.2	354.4	224.0	6.92	0.019	0.001	13	0	272	-48	6.62	750	0.24	0.4	3	0	0
25/11	20	30	34	27	30	30	28	26	1100	27	18.84	322.2	354.4	225.0	6.87	0.020	0.001	12	0	272	-47	6.38	590	0.32	0.4	4	0	0
12/12	24	32	35	28	30	31	28	26	1100	27	18.84	322.2	354.4	234.0	6.39	0.032	0.001	17	1	272	-38	6.38	590	0.32	0.4	5	0	1
22/12	28	35	35	29	31	32	29	27	1100	27	18.84	322.2	354.4	246.0	5.75	0.060	0.002	10	1	272	-26	6.15	469	0.40	0.4	4	0	1
12/1	34	39	36	29	31	32	30	29	1100	27	18.84	322.2	354.4	260.0	5.01	0.126	0.005	21	3	272	-12	5.67	290	0.56	0.4	12	0	3
30/1	29	34	35	28	29	31	30	29	1100	27	18.84	322.2	354.4	245.0	5.81	0.057	0.002	18	1	272	-27	5.67	290	0.56	0.4	10	0	1
11/2	14	27	31	26	28	28	27	25	1100	27	18.84	322.2	354.4	206.0	7.88	0.007	0.000	12	0	272	-66	6.62	750	0.24	0.4	3	0	0
25/2	36	38	36	27	30	31	31	25	1100	27	18.84	322.2	354.4	254.0	5.33	0.091	0.004	14	1	272	-18	6.62	750	0.24	0.4	3	0	1
12/3	30	30	32	27	29	30	28	26	1100	27	18.84	322.2	354.4	232.0	6.50	0.028	0.001	15	0	272	-40	6.38	590	0.32	0.4	5	0	0
31/3	27	38	43	33	35	43	41	35	1100	27	18.84	322.2	354.4	295.0	3.15	0.804	0.034	19	15	272	23	4.25	70	1.02	1.3	19	19	15
7/4	18	30	32	25	29	43	40	33	1100	27	18.84	322.2	354.4	250.0	5.54	0.074	0.003	7	1	272	-22	4.72	116	0.87	1.3	6	0	1
22/4	33	36	36	28	30	44	42	33	1100	27	18.84	322.2	354.4	282.0	3.84	0.404	0.017	15	6	272	10	4.72	116	0.87	1.3	13	10	6
5/5	13	25	28	23	24	44	38	27	1100	27	18.84	322.2	354.4	222.0	7.03	0.017	0.001	13	0	272	-50	6.15	469	0.40	1.3	5	0	0
20/5	20	24	29	25	28	40	38	37	1100	27	18.84	322.2	354.4	241.0	6.02	0.046	0.002	15	1	272	-31	3.77	43	1.18	1.3	18	4	1
9/6	15	24	28	22	23	40	39	27	1100	27	18.84	322.2	354.4	218.0	7.24	0.014	0.001	20	0	272	-54	6.15	469	0.40	1.3	8	0	0
24/6	15	23	28	22	23	39	39	27	1100	27	18.84	322.2	354.4	216.0	7.35	0.012	0.001	15	0	272	-56	6.15	469	0.40	1.3	6	0	0
8/7	15	22	27	22	23	38	39	27	1100	27	18.84	322.2	354.4	213.0	7.51	0.010	0.000	14	0	272	-59	6.15	469	0.40	1.3	6	0	0
Total																			32.3								33	31

Note: Equation 3.36 (column b) and others refer to Bennie *et al.* (1998).

Notes to Table A5.1

For notations and equations, refer to Bennie *et al.* (1998).

Column a: Potential rooting depth, used in equation 3.37 to calculate b. A function of soil depth, root penetrating rate and duration of vegetative phases.

Column b: Drainage coefficient a, calculated from equation 3.36.

Column c: Drainage coefficient b', calculated from equation 3.35.

Column d: Drainage coefficient b, calculated from equation 3.37.

Column e: Water content (vol./vol.); sum of 2^{nd} to 8^{th} columns.

Column f, g: Drainage rate in root zone, calculated from equation3.3.4.

Column h: Drainage flux out of the root zone, termed "potential" in this context, as it may be more than can be transmitted through the dense spoil layers.

Column i: The sum of the water-holding capacities of the layers at DUL.

Column j: Drainable water; difference between column e and column i.

Column k, l: Natural logarithm of the matric potential of the lower spoil layers which can retard the drainage flux, derived from relationships established between water content and matric potential (see 5.2, Chapter 5, and Figure 2.3.2, Chapter 2).

Column m: Maximum flux that can pass through the lower spoil layers.

Column n: Drainage, as derived from the availability of water above DUL, where column l (permeability of the lower layers) is greater than the water available for drainage (column j).

Column o: Drainage, as derived from the availability of water as calculated according to Bennie *et al.*, where column l (permeability of the lower layers) is greater than the water available for drainage (column h).

APPENDIX 6 A

Appendices to Chapter 6

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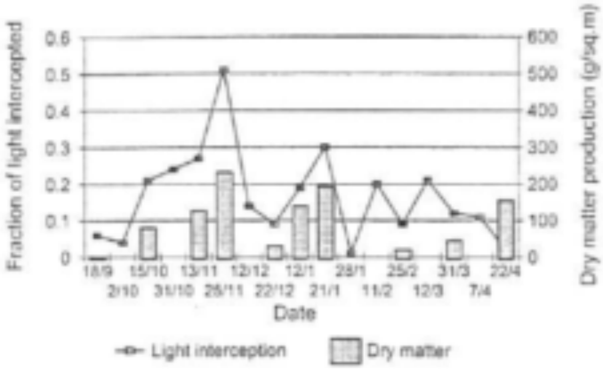
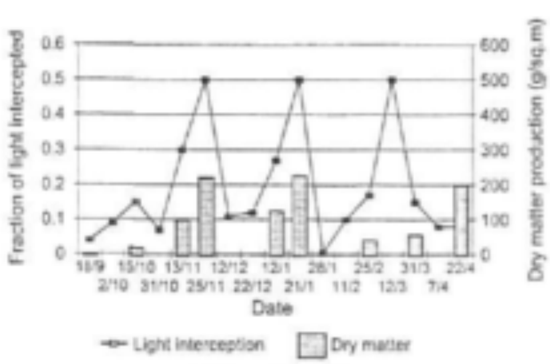
Table A6.1 Effect of fertilizer on dry matter production

Mine	Treatment	Dry matter					
		A Site			B Site		
		Date	g m⁻²	Fraction of optimal level	Date	g m⁻²	Fraction of optimal level
Kriel	No fertilizer	23 April 1998	67.7	0.56	23 April 1998	85.3	0.46
	Optimal -50%		72.6	0.60		152.9	0.82
	Optimal		120.1	1		187.6	1
	Optimal +50%		195.2	1.63		225.2	1.20
	No fertilizer	12 Jan. 1999	121.1	0.40	12 Jan. 1999	96.3	0.28
	Optimal -50%		229.6	0.76		251.3	0.74
	Optimal		302.5	1		339.3	1
	Optimal +50%		378.3	1.25		664.2	1.96
	No fertilizer	6 May 1999	82.7	0.38	6 May 1999	60.8	0.36
	Optimal -50%		195.7	0.89		98.0	0.57
	Optimal		218.95	1		170.7	1
	Optimal +50%		188.7	0.86		292.6	1.71
	No fertilizer	2 Feb. 2000	16.7	0.06	2 Feb. 2000	67.1	0.28
	Optimal -50%		141.6	0.54		175.3	0.74
	Optimal		261.0	1		238.0	1
	Optimal +50%		286.3	1.10		390.5	1.64
	No fertilizer	2 May 2000	75.3	0.36	19 April 2000	53.0	0.65
	Optimal -50%		145.1	0.70		66.8	0.82
	Optimal		208.1	1		81.3	1
	Optimal +50%		249.0	1.20		112.7	1.39
Middelburg South	No fertilizer	6 Jan. 1999	181.9	0.31	23 Dec. 1999	356.6	0.83
	Optimal -50%		501.9	0.85		400.8	0.93
	Optimal		591.5	1		430.5	1
	Optimal +50%		648.5	1.10		500.2	1.16
	No fertilizer	21 Jan. 2000	105.5	0.41	22 Jan. 2000	372.7	0.86
	Optimal -50%		247.8	0.96		420.6	0.97
	Optimal		256.9	1		434.8	1
	Optimal +50%		356.2	1.39		588.7	1.35
	No fertilizer	18 April 2000	73.3	0.72	18 April 2000	173.6	0.72
	Optimal -50%		94.0	0.93		202.2	0.84
	Optimal		101.6	1		241.6	1
	Optimal +50%		105.3	1.04		194.1	0.80
Optimum	No fertilizer	Site unavailable			21 Dec. 1998	79.1	0.27
	Optimal -50%					208.2	0.70
	Optimal					297.8	1
	Optimal +50%					486.4	1.63
	No fertilizer				2 Feb. 2000	26.6	0.12
	Optimal -50%					121.2	0.56
	Optimal					215.8	1
	Optimal +50%					240.8	1.12
	No fertilizer				17 April 2000	46.7	0.37
	Optimal -50%					81.0	0.65
	Optimal					125.5	1
	Optimal +50%					150.0	1.20



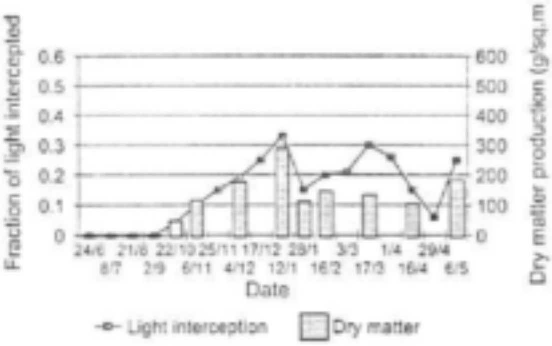
(a) Kriel A (1997/98)

Note: Harvest cuts on 25/11, 21/1 and 22/4; total dry matter: 580 g m^{-2}



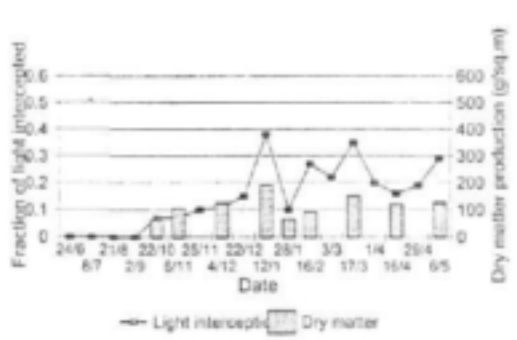
(b) Kriel B (1997/98)

Note: Harvest cuts on 25/11, 21/1 and 22/4; Total dry matter: 644 g m^{-2}



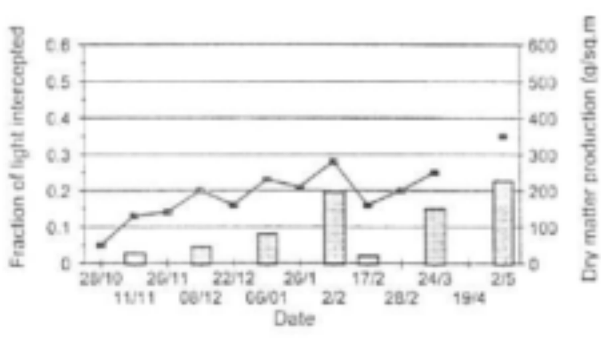
(c) Kriel A (1998/99)

Note: Note: Harvest cuts on 20/1 and 18/4; Total dry matter: 318 g m^{-2}

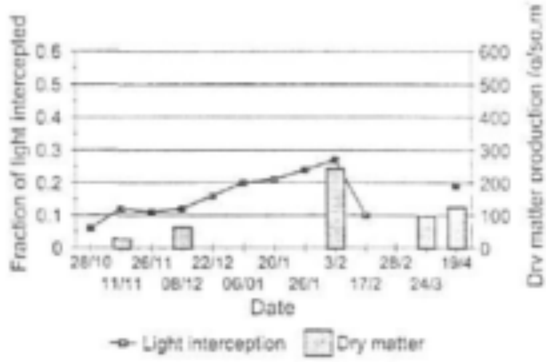


(d) Kriel B (1998/99)

Note: Harvest cuts on 20/1 and 18/4; Total dry matter: 318 g m^{-2}



(e) Kriel A (99/2000)

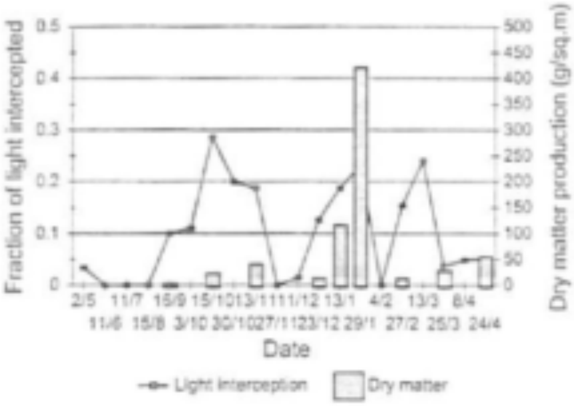


(f) Kriel B (99/2000)

Note: Harvest cuts on 2/2 and 2/5; Total dry matter: 422 g m^{-2}

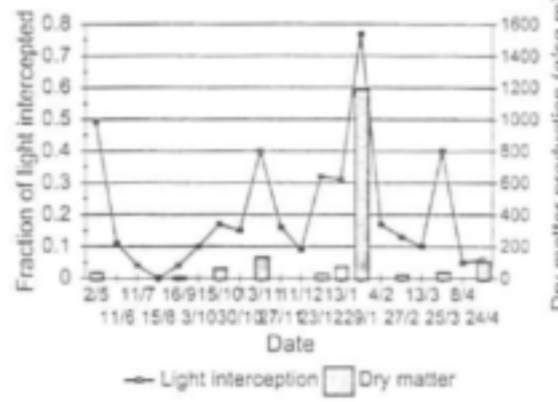
Note: Harvest cuts on 2/2 and 2/5: Total dry matter: 358 g m^{-2}

Figure A6.1 Light interception and dry matter production: Kriel A and B



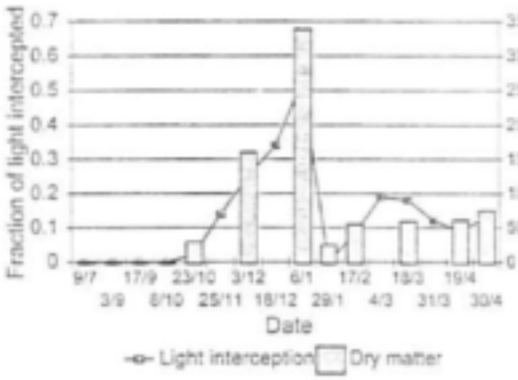
(a) Middelburg South A (1997/98)

Note: Harvest dates 13/11 and 29/1; Total dry matter: 515 g m^{-2}



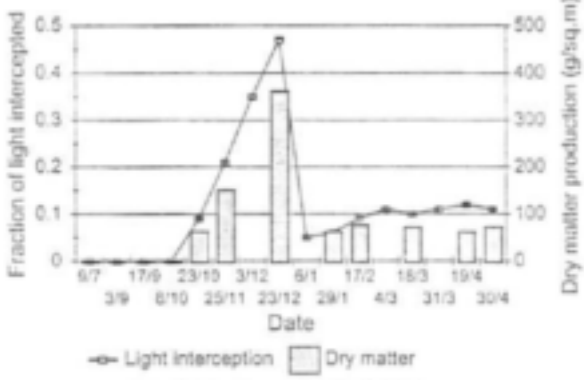
(b) Middelburg South B (1997/98)

Note: Harvest dates: 13/11 and 29/1; Total dry matter: 1420 g m^{-2}



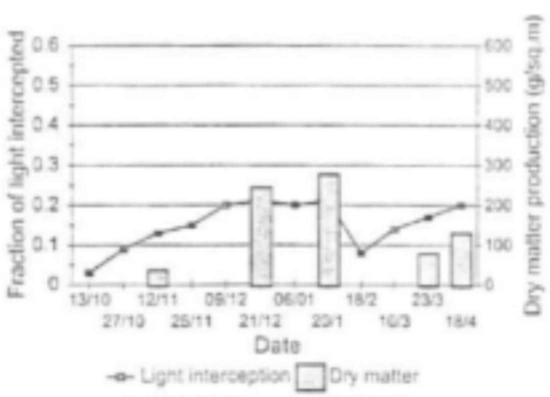
(c) Middelburg A (1998/99)

Note: Harvest date 6/1; thereafter too dry to harvest; total dry matter: 414 g m^{-2}



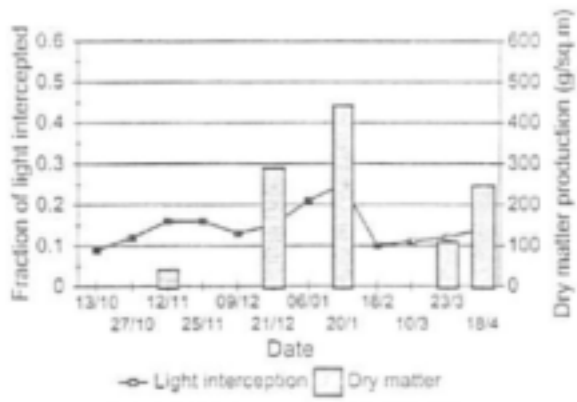
(d) Middelburg B (1998/99)

Note: Harvest date 23/1; thereafter too dry to harvest; total dry matter: 433 g m^{-2}



(e) Middelburg A (99/2000)

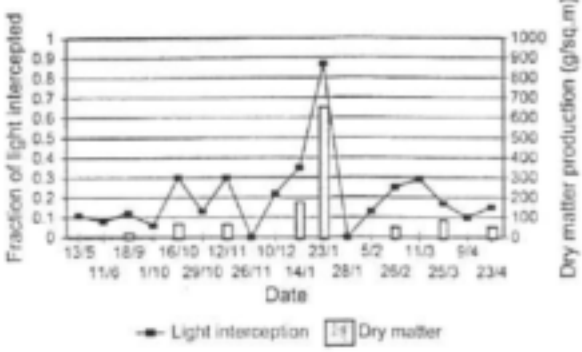
Note: Harvest dates 20/1 and 18/4; Total dry matter: 407 g m^{-2}



(f) Middelburg B (99/2000)

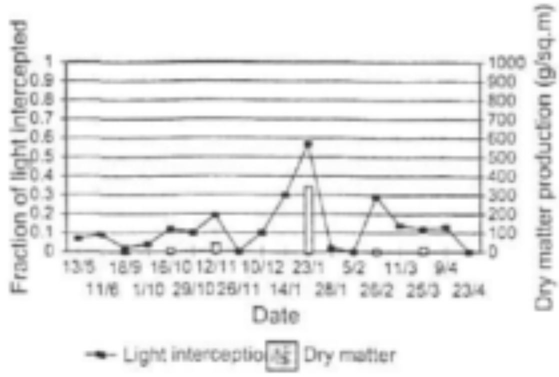
Note: Harvest dates 20/1 and 18/4; Total dry matter: 689 g m^{-2}

Figure A6.2 Light interception and dry matter production: Middelburg South A and B



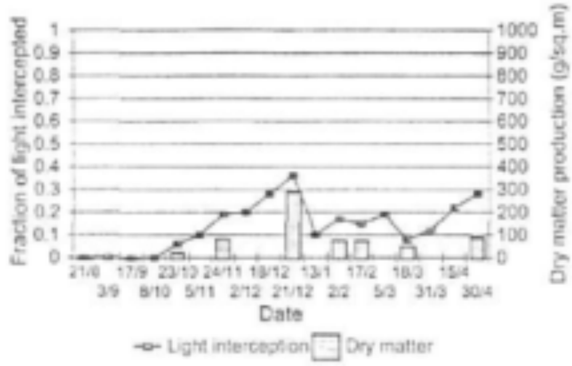
(a) Optimum A (1997/98)

Note: Harvest date 23/1; frosted before second harvest; total dry matter: 704 g m^{-2}



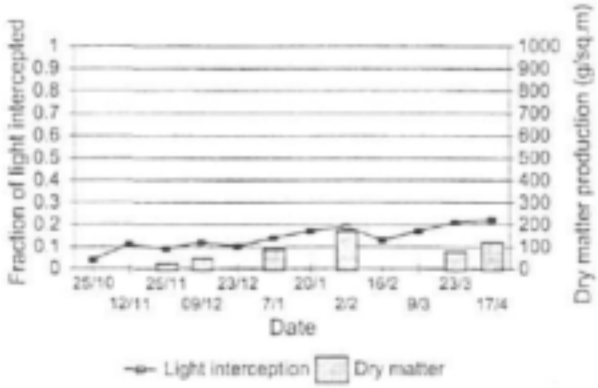
(b) Optimum B (1997/98)

Note: Harvest date 23/1; frosted before second harvest; total dry matter: 344 g m^{-2}



(c) Optimum B (1998/99)

Note: Harvest date 21/12; thereafter too dry to harvest; total dry matter: 378 g m^{-2}



(d) Optimum B (99/2000)

Note: Harvest dates 2/2 and 17/4; total dry matter 291 g m^{-2}

Figure A6.3 Light interception and dry matter production: Optimum A and B

APPENDIX 6 B

Crop simulation study

CROP SIMULATION STUDY

M.D. Howard

1. INTRODUCTION

Climate, and particularly rainfall, plays the most important role in successful plant production systems. Ideally, rainfall and suitable temperatures should occur at the right time, in the right amount and distributed evenly to avoid water stress during critical growth stages. However, this is not always possible due to seasonal variability, resulting in untimely water deficits. Rainfall and the water-holding characteristics of the soil thus largely determine the production capacity of the atmosphere-plant-soil system. Because of large annual fluctuations in the rainfall component, it is necessary to be able to describe how the system functions in the long-term. Application of a reliable model makes it possible to do this.

2. OBJECTIVES

The objectives of this modeling study were as follows:

(a) To obtain reasonable accurate model calibration results for rehabilitated soil sites.
(b) To describe the variation in pasture yield found on rehabilitated mine soils.
(c) To describe the variation in soil water found in rehabilitated soils.
(d) To determine the distribution of production potential and underlying risk found on these rehabilitated soil mines.

3. PROCEDURE

The specific modeling operations undertaken were:

1. Dissemination of long-term climatologically data (supplied by National Department of Agriculture).
2. Computation of model accuracy for the 1998/99 season applied to Optimum, Kriel and Middelburg.
3. Apply the calibrated model to long-term climatological data to produce Cumulative distribution function curves for each site.
4. Interpretation of modeling results.

4. OVERVIEW

Climate is the driving force in the modeling exercise undertaken. For the computation of the Cumulative Distribution Function Curves (CDF), long-term simulation must be carried out. The climatological data were prepared in a format excepted by Putu15. The ARC-Institute for Soil, Climate and Water has not provided the data and format for this exercise. The datasets used here was taken from a project funded by the National department of Agricultural. Verification using the climatological datasets for each location should be carried out, as discrepancies may be found in the climatological data.

5. MODEL SIMULATION AND RESULTS

Models are numerical simulations of natural phenomena. They have to be verified against observable facts. Models are only as good as the "reality checks" they are based on. Fortunately, the reality checks available to modellers are getting better all the time. In recent years, more data has become available to test the models and hypotheses contained in them.

1.5.1 METHODS AND MATERIALS

METHODS

Testing of simulation models consists of two activities: (1) establishing that the source code representing the model performs as intended (verification), and (2) confirming that the simulation models accurately reproduce observed data (validation).

Standard statistical tests as describe by Willmott (1982) were employed. Two methods to quantify goodness of fit of model performance were used. Firstly, the root mean square error and mean absolute error between simulations and measurements were calculated. Secondly, linear regressions were fitted to observe versus predicted data.

The root mean square error allows comparative assessment of how well model components performed. Linear regression measures agreement between model output and measurement (the closer the regression is to the 1:1 line and the closer the intercepts is to zero, the better the model's accuracy).

1.5.2 RESULTS

Model calibration was carried on the 1998/99 growing season (see Figure 6.2.1 in main text). Model calibration produced a correlation coefficient of 92 percent. The mean absolute error was 117 kg ha^{-1} with a root mean square error of 156 kg ha^{-1} (see Table 1.5.2). The scatter diagram (see Figure 1.5.2) clearly indicates under-estimation of high yields.

Table 1.5.2 Statistical results of model calibration for the 1998/99 growing season.

Season	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Inter-cept
1998/99	5	117	156	67	193	0.92	0.97	0.97	173.1

In Table 1.5.2 the number of observations (OBS), the mean absolute error (MAE, kg ha^{-1}), the root mean square error (RMSE, kgha^{-1}), the systematic root mean square error (S.RMSE, kg ha^{-1}), the unsystematic root mean square error (U.RMSE, kg ha^{-1}), the correlation (r^2), the Willmot index of agreement (D), the slope and the intercept are shown.

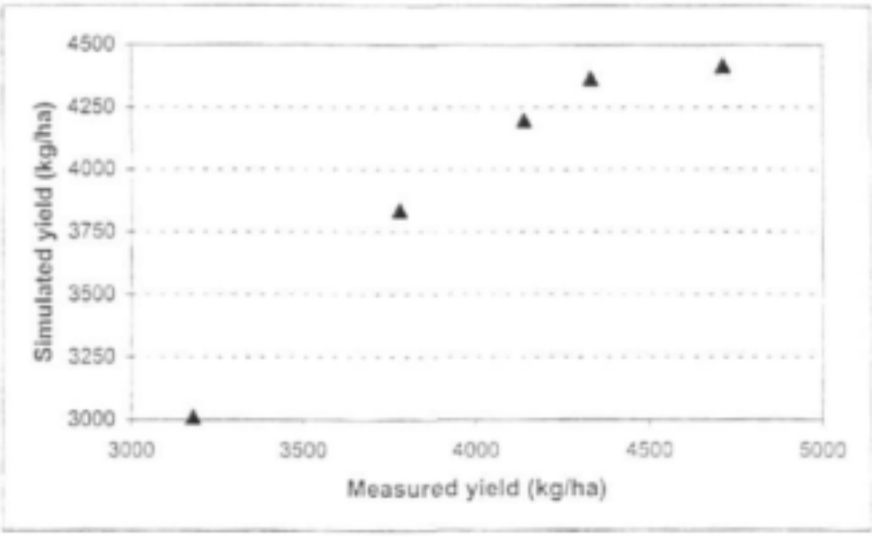


Figure 1.5.2 Scatter plot of measured and simulated yields for the 19998/99 season.

1.5.3 Variation in yield

Long-term simulation was carried out since 1950. A climatological dataset was prepared and used for long-tern simulation of all the sites (Kriel A and B, Middelburg South A and B and Optimum B). Long-term simulation results are shown in Figure 6.2.2 in the main text.

Simulated long-term yields varied between 1500 and 5800 kg/ha. Economic production is most likely to succeed at Kriel, as yields were consistently higher than all the other sites. At Middelburg and Optimum the probabilities of excedance were consistently the same for yields lower than 2800 kg ha^{-1}.

1.5.4 Variation in volumetric soil water content

Putu15 calculates the soil water balance based on the soil water characteristics. The integration step takes place daily. A detailed description of these routines is available (Howard 1997). Simulated soil water content (mm m^{-1}) was plot for each layer (1 though to 7) at all sites in the study undertaken.

Cumulative distribution function for Kriel A and B

The CDF for the rehabilitated mines at Kriel A is given in Figure 1.5.4 and that for Kriel B, in Figure 1.5.5.

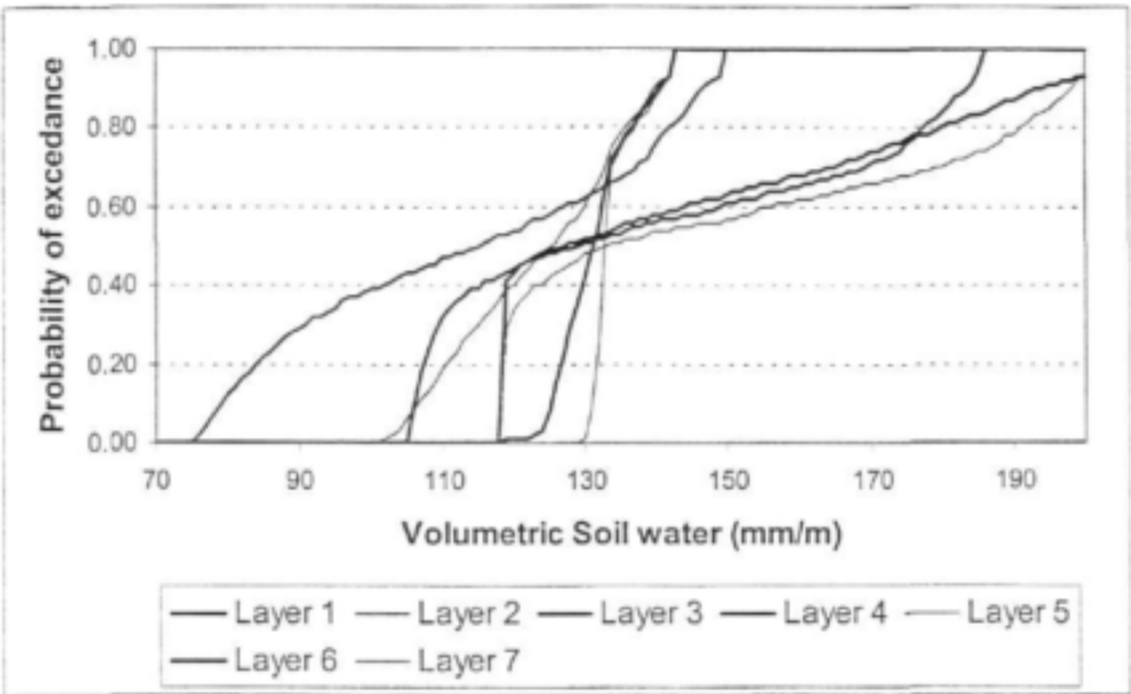


Figure 1.5.4 The cumulative distribution function for soil layers (1 through to 7) at Kriel A.

For soil water levels higher that 130 mm m^{-1} the probability of excedance was consistently lower for soil layer 1 to 3. This may be described to the rainfall patterns found in the Mpumalanga province. The high frequency of thundershowers with high levels of rainfall causes runoff and deep drainage. Also, the soil water characteristic plays an important role in determining the amount of water each soil layer could hold, and amount of excess drainage that could take place.

The importance of available deep drained water is critical to plant production on rehabilitated soil mines. For soil layers exceeding 1000 mm (layers 6 and 7), a rapid increasing level of probability is found for soil moisture level between 115 and 140 mm m^{-1}.

At Kriel B, similar patterns as found at Kriel A emerged (Figure 1.5.5). For soil layers 1, 2 and 3 (less than 600 mm) the probabilities are remarkably the same. This feature is reflected in the soil water characteristics for these layers. High soil moisture content levels are likely to occur in these soil layers over time. For probabilities of 40% and lower, higher soil moisture content are expected in the deeper soil layers (layer 6 and 7) over time.

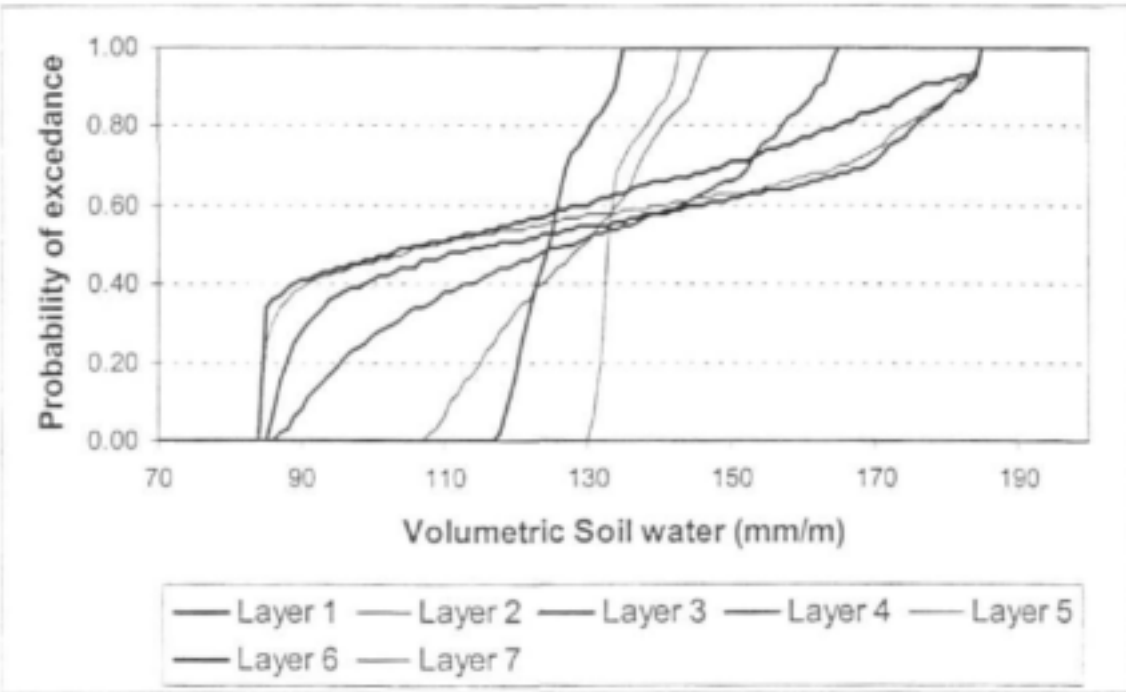


Figure 1.5.5 The cumulative distribution function for soil layers (1 through to 7) at Kriel B.

CUMULATIVE DISTRIBUTION FUNCTION FOR MIDDELBURG SOUTH A AND B

The cumulative distribution function for rehabilitated soil mines at Middelburg South A and B is presented in figures 1.5.6 and 1.5.7 respectively. Low soil moisture content levels are found for soil layers 6 and 7 as depicted from the soil water characteristic (Middelburg A, see Figure 1.5.6). Over time soil plant water extraction is most likely to take place from soil layers 1 through to 3. The consistently higher levels of volumetric soil water content found in layer 5 will (at low probabilities) will provide access to water, particular in dry spells.

Probabilities higher than 50% will yield a volumetric soil water content level of 130 mm m^{-1} and more in layers 1 through to 4. Soil water contents levels less than 90 mm m^{-1} will produce probabilities of 40% and less in soil layers 1, 2 and 3.for Middelburg B (see Figure 1.5.7).

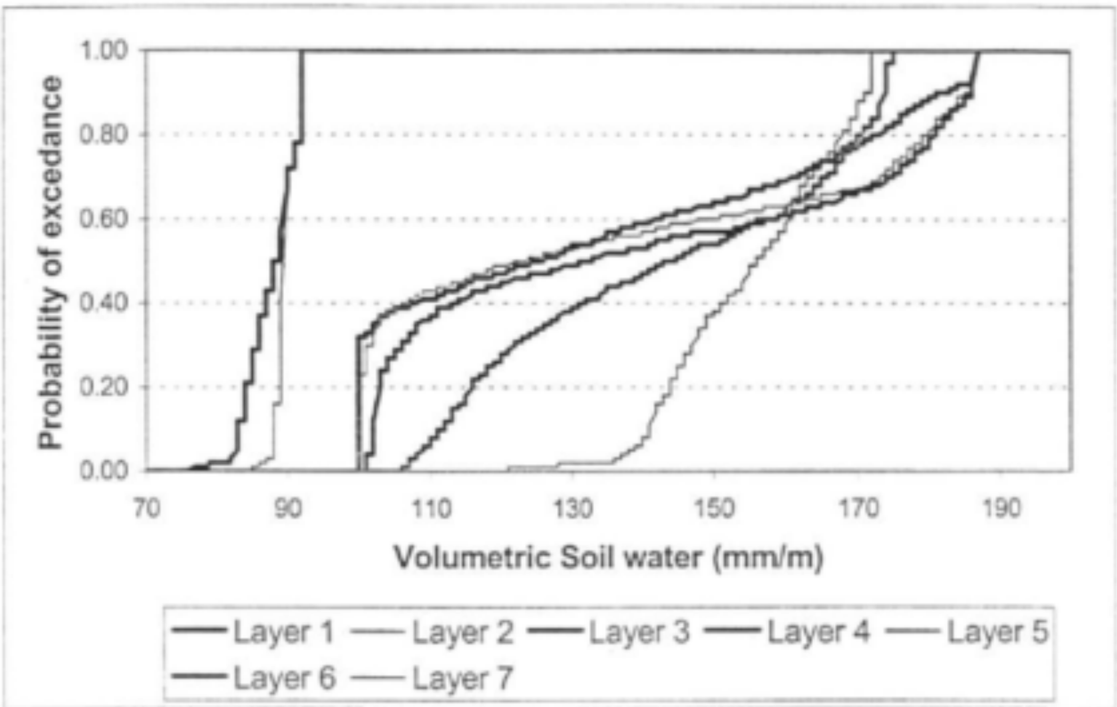


Figure 1.5.6: The cumulative distribution function for soil layers (1 through to 7) at Middelburg South A.

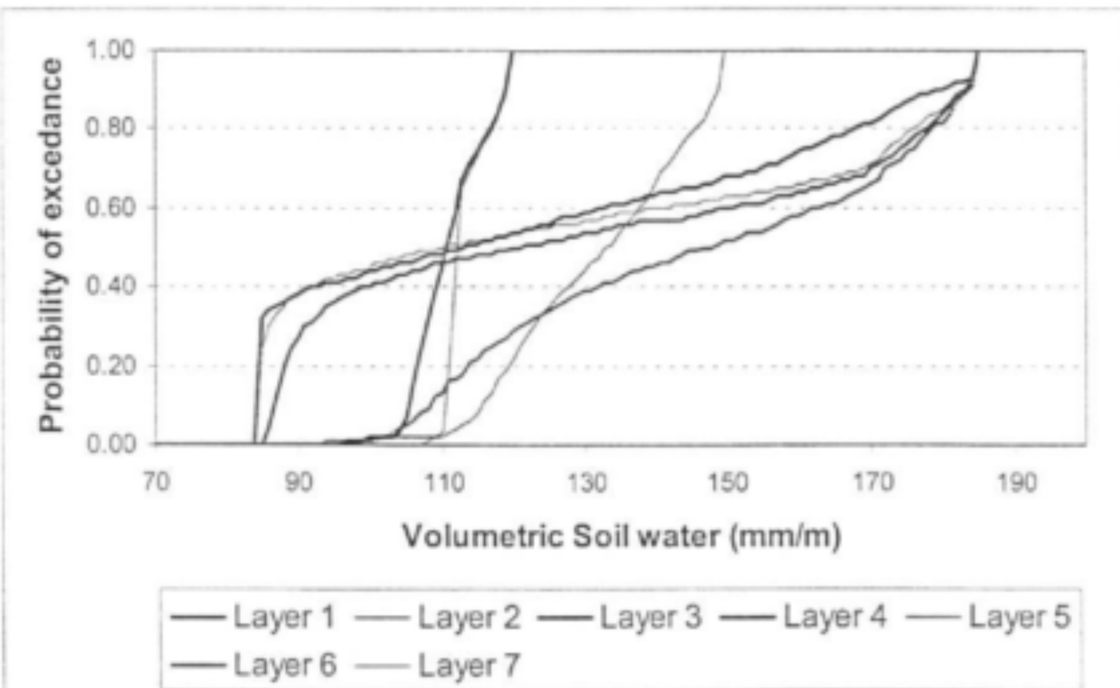


Figure 7: The cumulative distribution function for soil layers (1 through to 7) at Middelburg (B).

CUMULATIVE DISTRIBUTION FUNCTION FOR OPTIMUM B

The relationship between soil moisture content and probability for rehabilitated soil mine Optimum is described in Figure 1.5.8. Plant water extraction is most likely to take place from soil layers 1, 2, 3 and 5. The soil water content for these layers is consistently higher than layer 4.

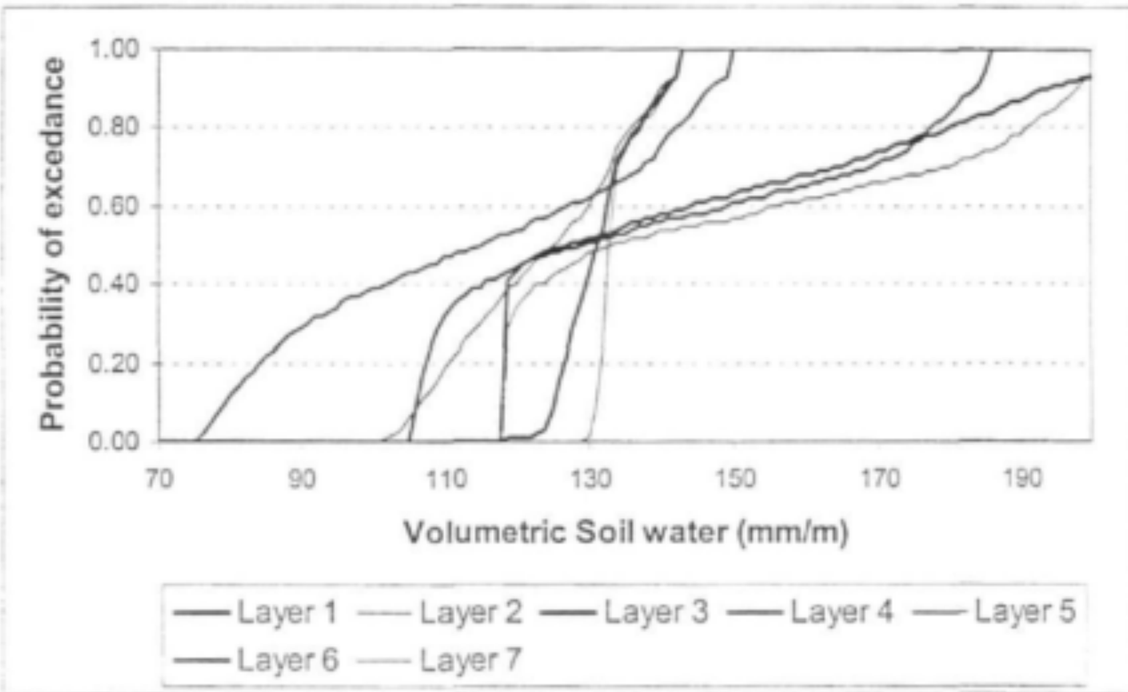


Figure 1.5.8 The cumulative distribution function for soil layers (1 through to 7) at Optimum B

1.6 REMARKS

(a) The modeled soil water characteristic at the experimental sites was derived from the data illustrated in Appendix 3.
(b) The relationships between soil water content and probability of excedance will always be a function of the soil water characteristic for any given soil layer at any give location.

REFERENCE

HOWARD, M.D., 1994. Simulation studies on *Digitaria eriantha* steud. subsp. *Eriantha* at differing soil nitrogen levels. M.Sc. Agric. Thesis, Univ. Free State, Bloemfontein.

APPENDIX 7

Appendices to Chapter 7

LIST OF TABLES

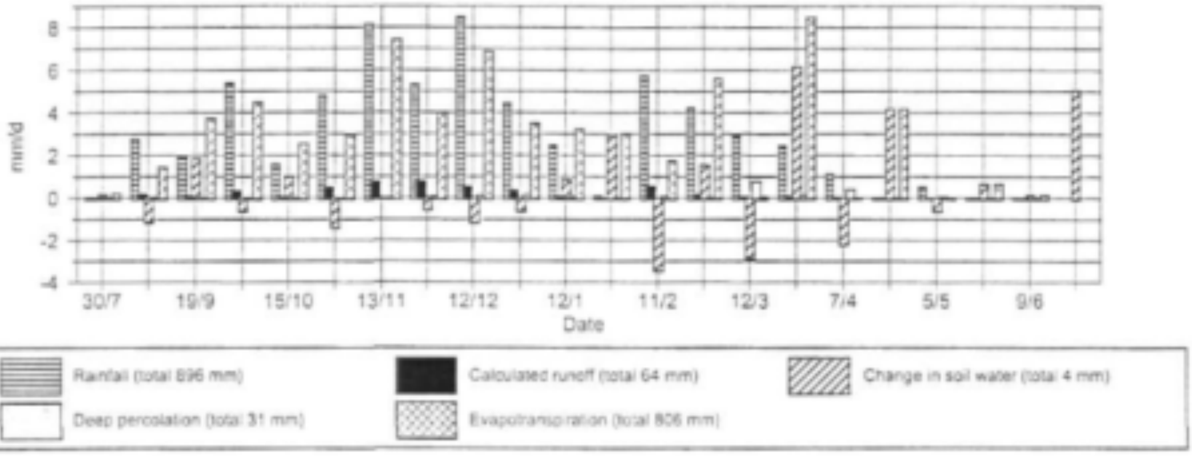
LIST OF FIGURES

Table A7.1 Example of worksheet for calculating evapotranspiration

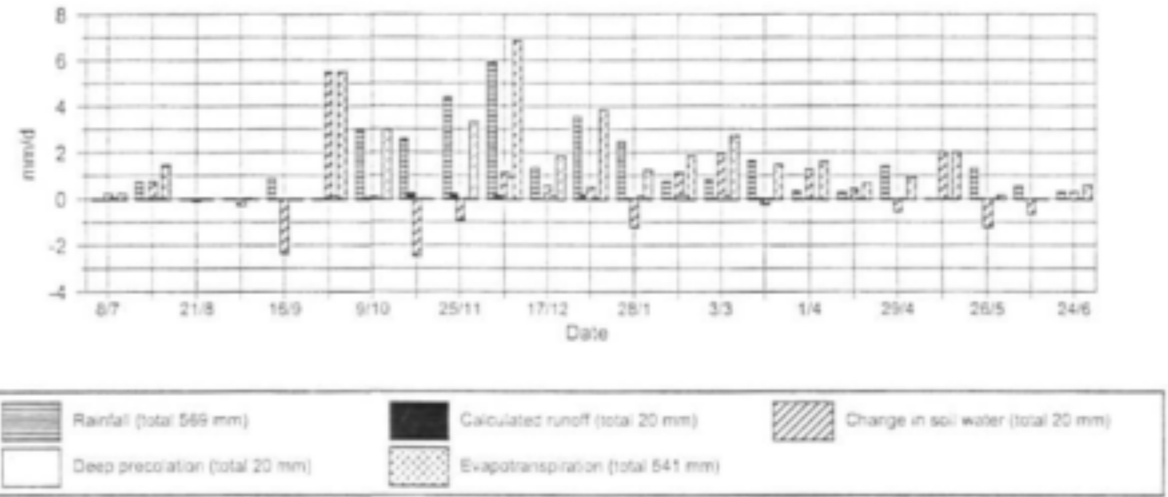
Period	Volumetric water content (mm)							Days	ΔS (mm)									P (mm)		R (mm)		D (mm)		ET	
	0.0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.3	1.3-1.6		0.0-0-.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.3	1.3-1.6	d^{-1}	Total	Total	d^{-1}	Total	d^{-1}	Total	d^{-1}	Total	d^{-1}
	A (see notes on following page)								b											c		d		e	
30/7	23	31	32	26	28	27	26											3							
29/8	18	28	31	26	29	29	27	30	0.17	0.10	0.03	0.00	-0.03	-0.07	-0.03	0.17	5.00	1	0.0	0	0.00	0	0.00	6.1	0.20
19/9	31	36	34	27	29	29	27	22	-0.59	-0.36	-0.14	-0.05	0.00	0.00	0.00	-1.14	-25.00	60	2.7	3.58	0.16	1	0.05	30.8	1.40
2/10	19	26	32	27	29	29	27	13	0.92	0.77	0.15	0.00	0.00	0.00	0.00	1.85	24.00	25	1.9	1.00	0.08	0	0.00	48.0	3.69
15/10	33	25	30	26	28	28	27	13	-1.08	0.08	0.15	0.08	0.08	0.08	0.00	-0.62	-8.00	70	5.4	3.98	0.31	0	0.00	58.0	4.46
31/10	20	24	29	25	28	28	27	16	0.81	0.06	0.06	0.06	0.00	0.00	0.00	1.00	16.00	25	1.6	0.73	0.05	0	0.00	40.3	2.52
13/11	37	28	28	25	27	28	26	13	-1.31	-0.31	0.08	0.00	0.08	0.00	0.08	-1.38	-18.00	62	4.8	6.21	0.48	0	0.00	37.8	2.91
25/11	20	30	34	27	30	30	28	12	1.42	-0.17	-0.50	-0.17	-0.25	-0.17	-0.17	0.00	0.00	98	8.2	9.06	0.76	0	0.00	88.9	7.41
12/12	24	32	35	28	30	31	28	17	-0.24	-0.12	-0.06	-0.06	0.00	-0.06	0.00	-0.53	-9.00	90	5.3	13.10	0.77	1	0.06	66.9	3.94
22/12	28	35	35	29	31	32	29	10	-0.40	-0.30	0.00	-0.10	-0.10	-0.10	-0.10	-1.10	-11.00	85	8.5	5.41	0.54	1	0.10	67.6	6.76
12/1	34	39	36	29	31	32	30	21	-0.29	-0.19	-0.05	0.00	0.00	0.00	-0.05	-0.57	-12.00	93	4.4	7.77	0.37	3	0.14	70.2	3.34
30/1	29	34	35	28	29	31	30	18	0.28	0.28	0.06	0.06	0.11	0.06	0.00	0.83	15.00	44	2.4	1.02	0.06	1	0.06	57.0	3.17
11/2	14	27	31	26	28	28	27	12	1.25	0.58	0.33	0.17	0.08	0.25	0.25	2.92	35.00	1	0.1	0.00	0.00	0	0.00	36.0	3.00
25/2	36	38	36	27	30	31	31	14	-1.57	-0.79	-0.36	-0.07	-0.14	-0.21	-0.29	-3.43	-48.00	80	5.7	7.85	0.56	1	0.07	23.2	1.65
12/3	30	30	32	27	29	30	28	15	0.40	0.53	0.27	0.00	0.07	0.07	0.20	1.53	23.00	63	4.2	2.20	0.15	0	0.00	83.8	5.59
31/3	27	38	43	33	35	43	41	19	0.16	-0.42	-0.58	-0.32	-0.32	-0.68	-0.68	-2.84	-54.00	56	2.9	1.06	0.06	15	0.79	-14.1	0.00
7/4	18	30	32	25	29	43	40	7	1.29	1.14	1.57	1.14	0.86	0.00	0.14	6.14	43.00	17	2.4	0.66	0.09	1	0.14	58.3	8.33
22/4	33	36	36	28	30	44	42	15	-1.00	-0.40	-0.27	-0.20	-0.07	-0.07	-0.13	-2.13	-32.00	17	1.1	0.43	0.03	6	0.40	-21.4	0.00
5/5	13	25	28	23	24	44	38	13	1.54	0.85	0.62	0.38	0.46	0.00	0.31	4.15	54.00	0	0.0	0.00	0.00	0	0.00	54.0	4.15
20/5	20	24	29	25	28	40	38	15	-0.47	0.07	-0.07	-0.13	-0.27	0.27	0.00	-0.60	-9.00	8	0.5	0.00	0.00	1	0.07	0.0	0.00
9/6	15	24	28	22	23	40	39	20	0.25	0.00	0.05	0.15	0.25	0.00	-0.05	0.65	13.00	0	0.0	0.00	0.00	0	0.00	13.0	0.65
24/6	15	23	28	22	23	39	39	15	0.00	0.07	0.00	0.00	0.00	0.07	0.00	0.13	2.00	0	0.0	0.00	0.00	0	0.00	2.0	0.13
Total																	4.0	896		64		31		806	

Notes to Table A7.1

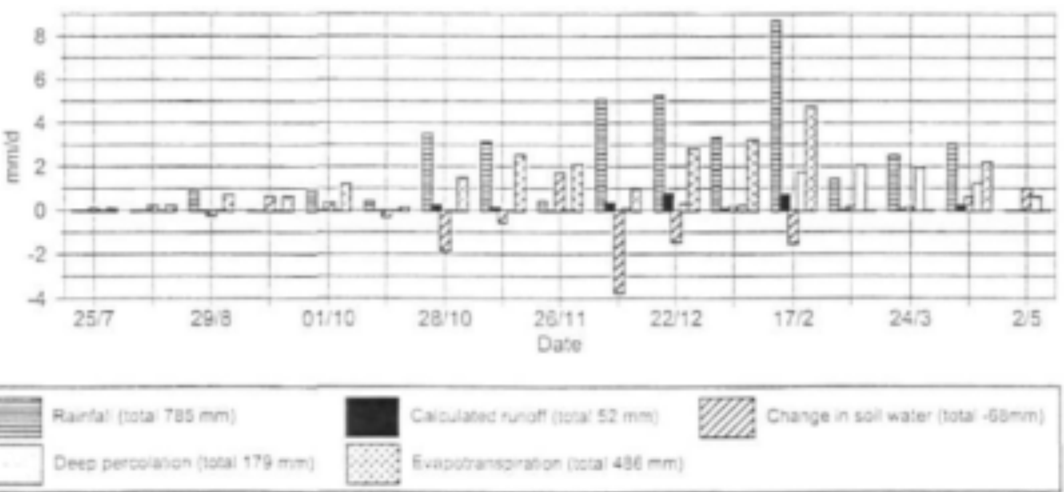
- Columns market (a) show the soil water content during the indicated periods at the soil depths indicated.
- Columns market (b) show the change in soil water content per period and the average per day, for each depth, by subtraction.
- Columns marked (c) show the runoff per period, calculated as set out in Chapter 4, and the average per day.
- Columns marked (d) show deep percolation, as calculated in accordance with Bennie *et al.* (1998) per period, and the average per day.
- Columns marked (e) show values for evapotranspiration, obtained by subtraction, using equation 1, Chapter 7.



1997/98

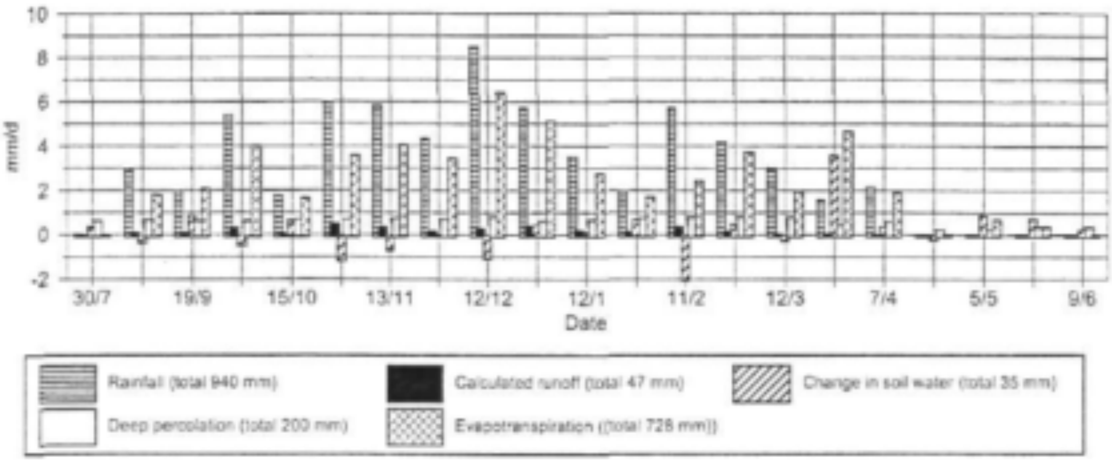


1998/99

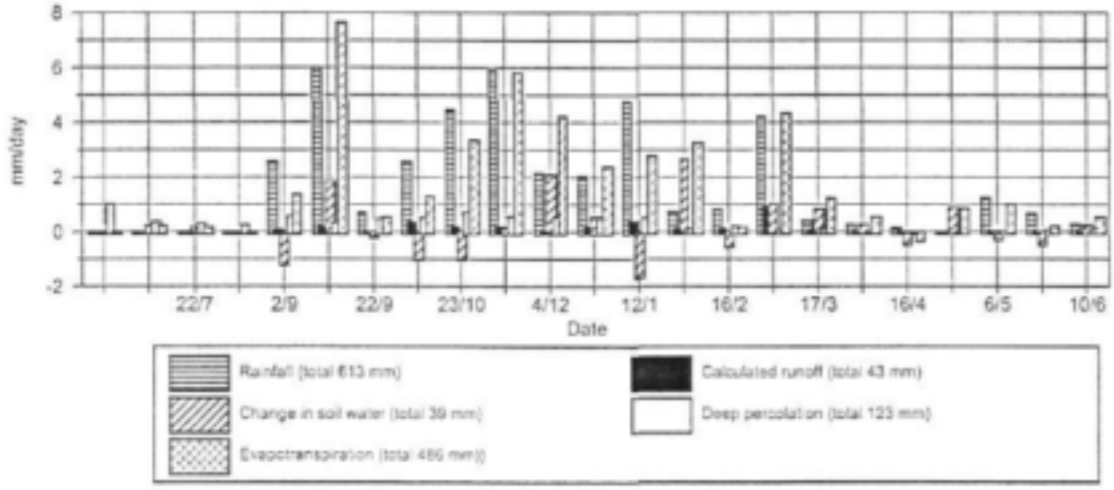


1999/2000

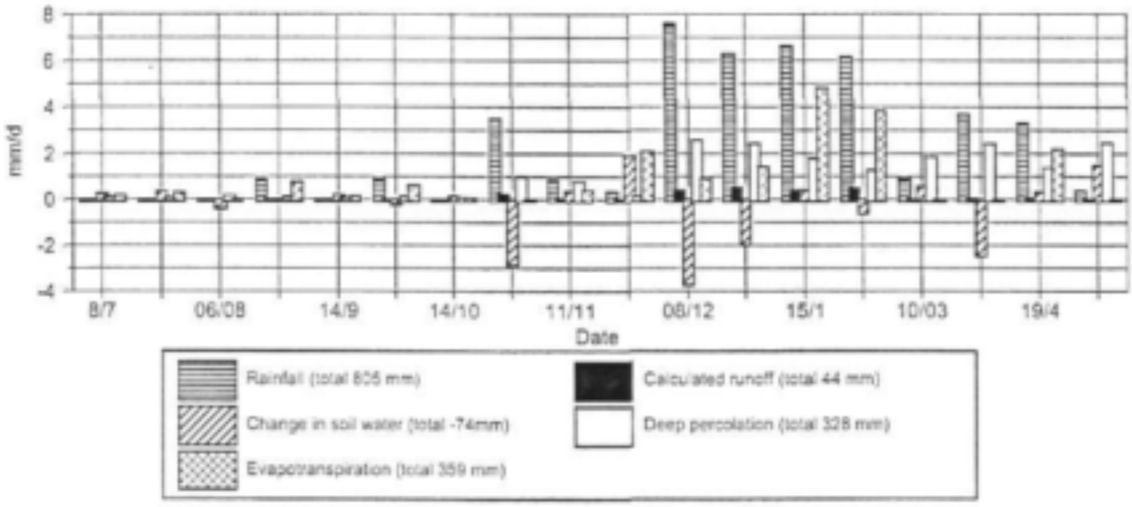
Figure A7.1a Water balance: Kriel A



1997/98

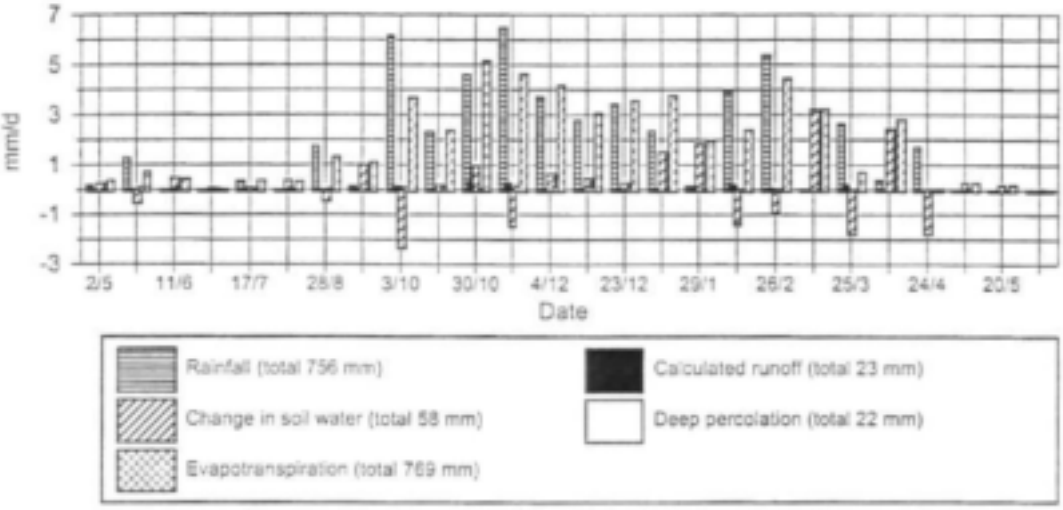


1998/99

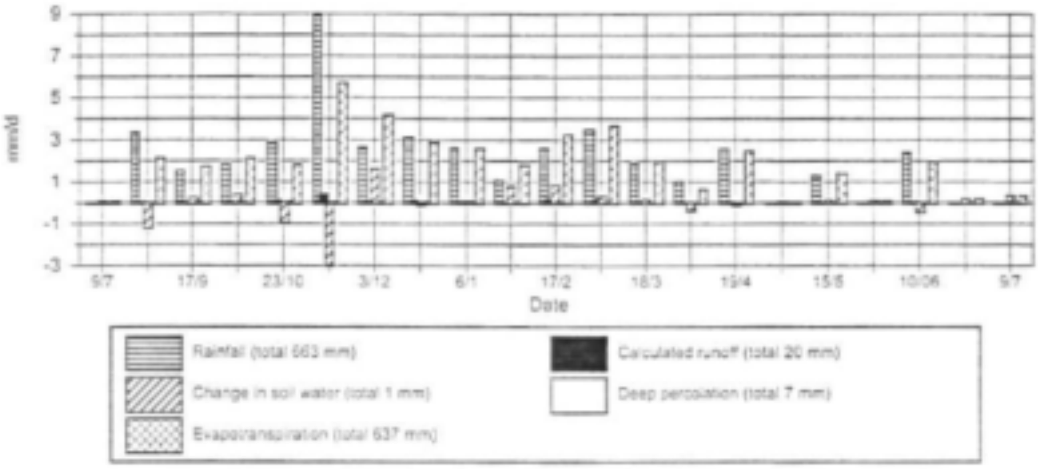


1999/2000

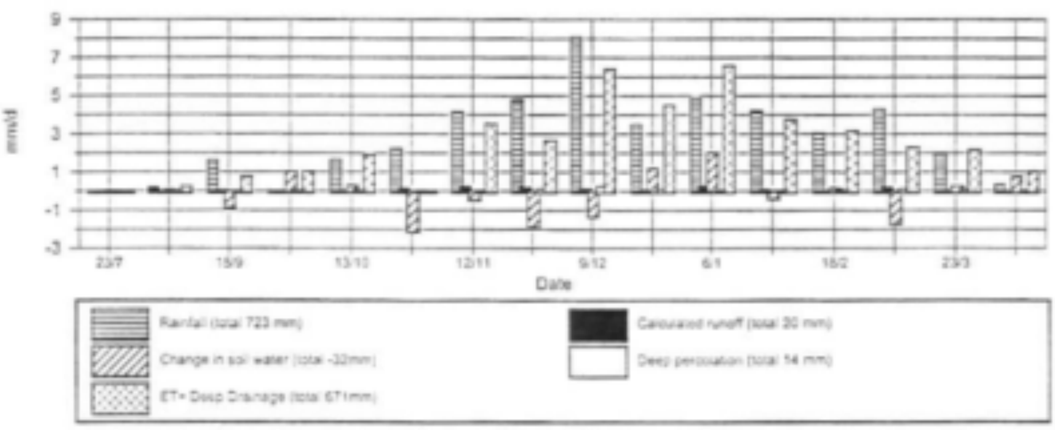
Figure A7.1b Water balance: Kriel B



1997/98

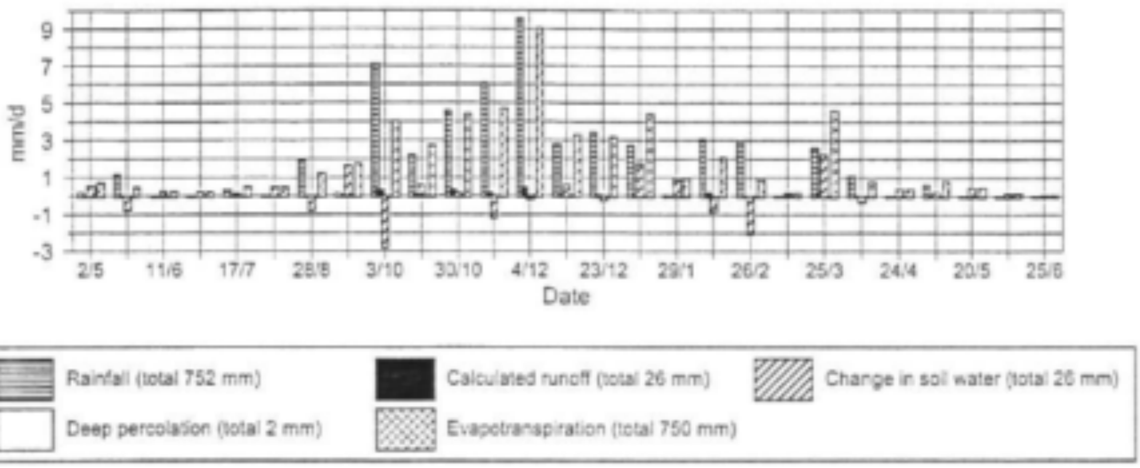


1998/99

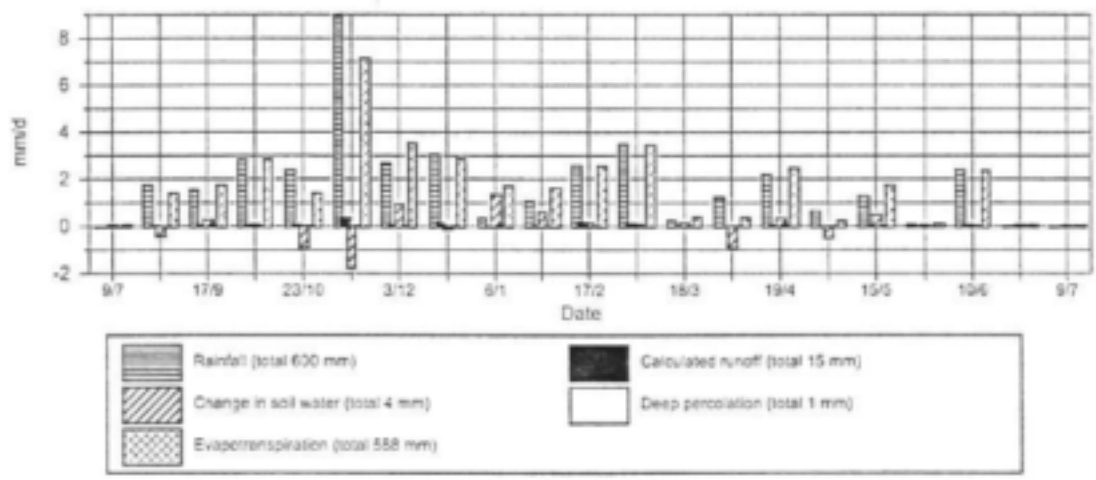


1999/2000

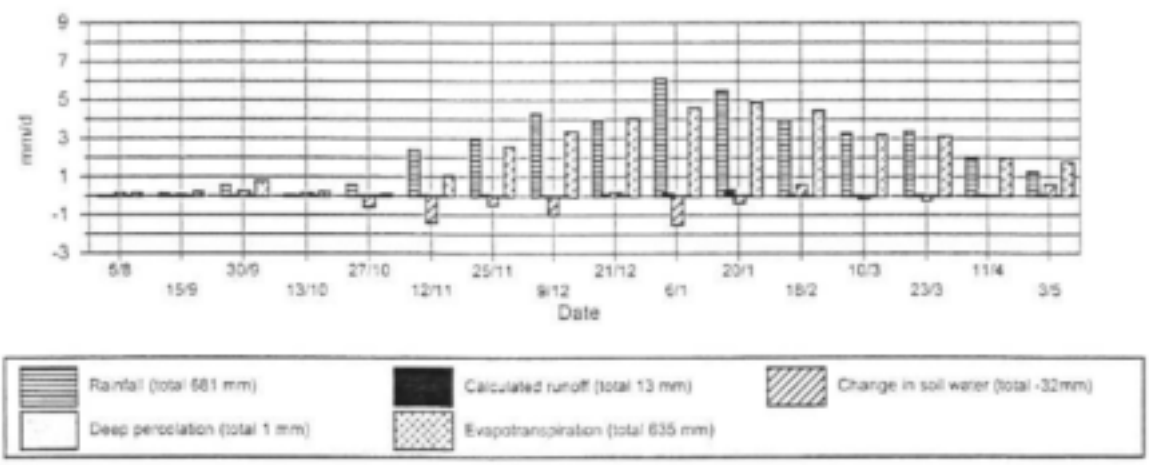
Figure A7.2a Water balance: Middelburg South A



1997/98

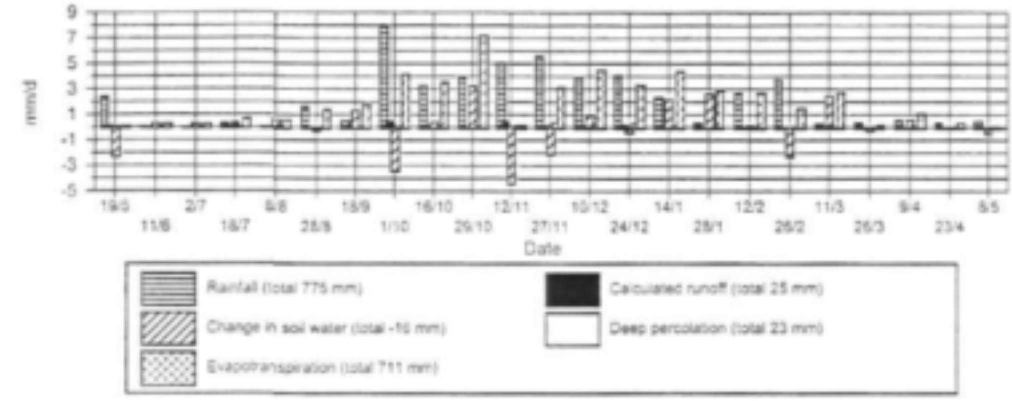


1998/99

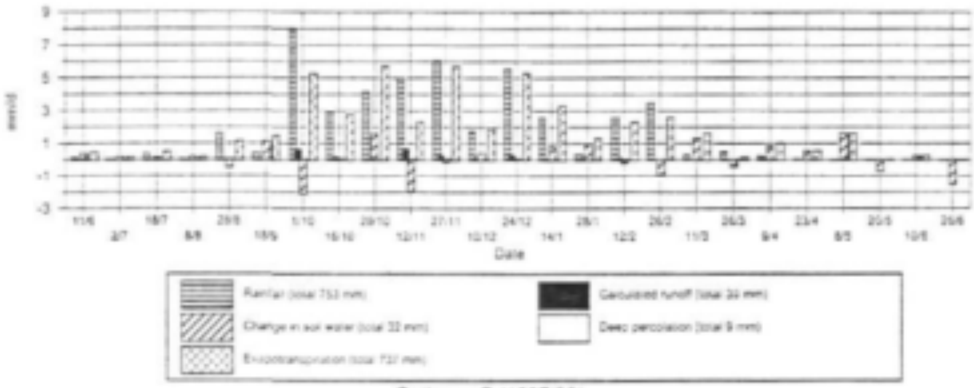


1999/2000

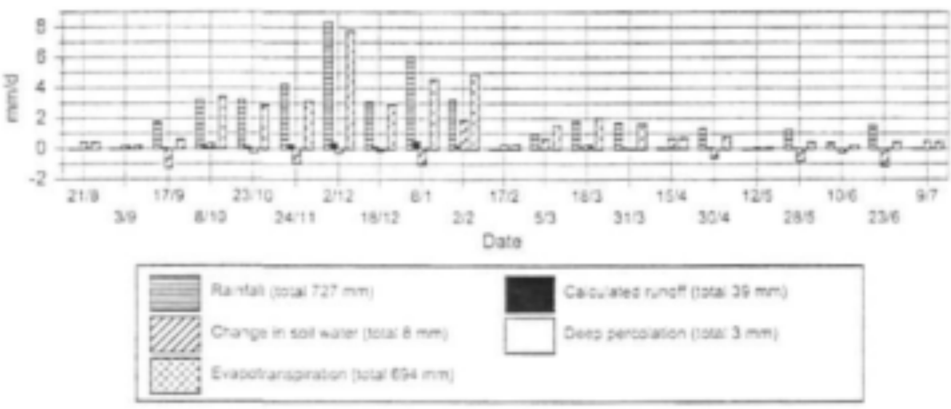
Figure A7.2b Water balance: Middelburg South B



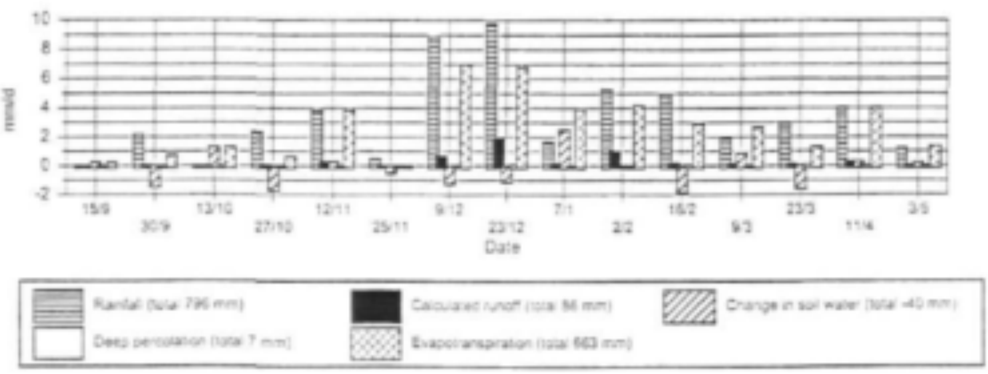
Optimum A (1997/98)



Optimum B (1997/98)



Optimum B (1998/99)



Optimum B (1999/2000)

Figure A7.3 Water balance: Optimum A and B

Other related WRC reports available:

The suitability and Impact of Power Station Fly Ash for water- quality control in coal opencast mine rehabilitation

JJ van den Berg, L Cruywagen, E de Necker and FDI Hodgson

For many years, the option of applying Power Station Fly Ash to prevent, limit or ameliorate acid-mine drainage has been considered. The technique has been introduced at two underground mines, with limited success in terms of mine-water quality management. The scope of these applications was aimed more at stabilising the overlying strata than neutralising mine acidity.

With this background, this project investigated the following:

- To establish possible scenarios for the disposal of Power Station Fly Ash and its utilisation in rehabilitation practices in the coal-mining industry.
- To predict the long-term chemical behaviour of such systems.
- To estimate the long-term local and regional impact of such systems on the environment.

Three possible scenarios of Fly Ash application in opencast mines have been considered. These are: In-pit application below the water table; In-pit application above the water table; Introduction of ash water.

The overall conclusion is that Fly Ash application in opencast mines can be done above the pit water table. Below the pit water table, this should only be done if detailed and site-specific investigations suggest no risk to the environment. This current document provides a sound directive in terms of decision-making and for planning additional experimentation in this regard.

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