Effects of land application of water treatment residue

Report to the Water Research Commission on the Project:
"Development of guidelines for the disposal of water treatment sludges to land"

by

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DEDICATION

We dedicate this report, especially the sections concerned with soil physical aspects, to the late Mike Johnston who passed away in June 2002. His passing left a huge void in many lives and his calm guidance and wisdom across all aspects of soil science was greatly missed by everyone involved in this project.

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EXECUTIVE SUMMARY

1. Introduction

To produce potable water from turbid primary sources it is necessary to remove suspended and dissolved solids, organic matter and other contaminants. Although slight variability exists between the actual methods used in the water treatment process, the underlying principles remain the same. The choice and concentration of chemical(s) and the procedures followed depend largely on the quality of the raw water (turbidity, odour, hardness etc.). Water quality is influenced by factors such as the characteristics of the catchment, seasonal influences and local environmental conditions. Adjusting the dosage levels according to the quality of the water to be treated is therefore necessary. In this regard continuous monitoring of water quality at various stages of the operation process is carried out. Furthermore, economics play a role in the chemicals used, as does availability and accessibility.

The resulting by-product has often been called water treatment 'sludge' – the term in the original title to this report. However, in this report the term 'sludge' is not used as it has too many connotations with sewage sludge (biosolids), a material very different in nature to that produced from water treatment works. These differences have major implications when land disposal is considered and thus this report will use the term "water treatment residue" throughout to avoid any confusion that may occur by using the word 'sludge'. The term "water treatment residue" is similar to the term "water treatment residual" used by some other authors, but the simpler form is preferred here.

The ever-increasing demand for clean water has led to an increase in the number and size of water treatment facilities around the world. A consequence of this is an increase in the production of water treatment residue (WTR), which requires suitable disposal methods. In many parts of the world, including South Africa, WTR has conventionally been disposed of in landfill but due to increased costs land application is becoming the preferred disposal method.

Land disposal is based upon a fundamental tenet that the physical, chemical and biological properties of the soil can be used to digest the applied waste without inducing negative effects on soil quality, groundwater or plant growth. To validate this principle with regard to WTR requires rigorous scientific information since, given the wide variety and thus the different characteristics of residues produced, it is inappropriate and potentially risky to extrapolate across waste disposal systems.

2. Aims and objectives

The project had two major aims as specified in the Terms of Reference (TOR) i.e.,

(i) To produce research data which will assist in the development of environmentally acceptable guidelines for South African conditions for the disposal of water treatment residues to land.

(ii) To study the effect of land disposal of water treatment residues on the physical, chemical and fertility properties of soils and on the chemistry of the local groundwater and nearby surface waters.

Three research products were envisaged in the TOR namely :

(a) A management plan for land disposal of WTR from water treatment works. This product was to be developed specifically for Umgeni Water for their Midmar Water Treatment Works (Hughes *et al*., 2000) although it was anticipated that aspects of the plan could be adapted by other water treatment authorities.

(b) Research data on WTRs (from across South Africa).

(c) Guidelines for the disposal of WTRs (these to be based on data found under field, glasshouse and laboratory conditions).

2.1 Approach

This project is the first to characterise a variety of South African WTRs and to investigate the effects of WTR on the environment and, as stated above, was initially intended to develop guidelines for the land disposal of the wide range of WTRs produced in South Africa. This aim has not been achieved although some widely applicable principles have been established. The study was initially divided into two separate but closely interlinked facets namely the effect of a polymer WTR on soil physical properties; and its effects on soil fertility and soil chemical behaviour. Subsequently, two further facets were added, namely the investigation of the effect of WTRs on the microbial communities present within treated soils and the effect of WTRs on 'poor' soil materials. These facets reflect an investigation of the problems anticipated should land disposal of WTR be undertaken.

2.1.1 Field experiments

The core of the project is centred around two field experiments. The first was established at the land disposal site of Umgeni Water used for the WTR produced at the Midmar Water Treatment Works, near Howick in KwaZulu-Natal (Brookdale Farm). The second, smaller experiment, using the same WTR, was at the University of KwaZulu-Natal's Ukulinga Farm, near Pietermaritzburg, KwaZulu-Natal. The field trials included both grassed and fallow treatments and also compared the effects of WTR with lime, gypsum and polyacrylamide (PAM) – materials whose behaviour in soils is well established. The experiment at Brookdale included both incorporation of the Midmar WTR and mulch treatments; the latter excluded at the Ukulinga. Also at Brookdale Farm two levels of lime (2 and 10 Mg ha^{-1}), gypsum (5 and 10 Mg ha^{-1}) and PAM (15 and 30 kg ha^{-1}) were applied; at Ukulinga only the highest level of each was used. The application rates of WTR were 0, 40, 80, 160, 320, 640 and 1280 Mg ha^{-1} at Brookdale Farm. At Ukulinga only application rates of 0, 80, 320 and 1280 Mg ha^{-1} were used. The Brookdale Farm experiment was on a deep, apedal soil classified as Hutton form, Hayfield family (Soil Classification Working Group, 1991), Typic Haplustult (Soil Survey Staff, 1998), and Kandosol (Isbell, 1996). At Ukulinga the experiment was on a less structurally stable and shallow soil classified as Westleigh form, Helena family (Soil Classification Working Group, 1991), Typic Plinthaquept (Soil Survey Staff, 1998) and Hydrosol (Isbell, 1996).

3. Results and discussion

3.1 Soil physical characteristics

The two field experiments and supporting laboratory experiments were designed to investigate the influence of WTR on soil in terms of water retention, hydraulic conductivity, aeration, aggregation and strength. All treatments of the field experiments used in this study were maintained fallow. The laboratory study included an additional two soils with different physical properties to the Hutton and Westleigh namely a sandy soil classified as Cartref form (Soil Classification Working Group, 1991), Typic Haplaquept (Soil Survey Staff, 1998) and Tenosol (Isbell, 1996), and a typically hard-setting soil of the Valsrivier form (Soil Classification Working Group, 1991), Typic Haplargid (Soil Survey Staff, 1998), Dermosol (Isbell, 1996).

3.1.1 Water retention

Water treatment residue influenced several soil physical properties. Soil bulk density decreased following the addition of WTR to soil. This caused an increase in porosity (particularly macroporosity) and therefore water retained at saturation, but this was only of statistical significance at the 1280 Mg ha^{-1} level. This effect was reduced at Brookdale after about 4 yr, while it was still very evident at Ukulinga Farm after the same period of time. An increase in water retention at wilting point (-1500 kPa matric potential) also occurred, owing to the high microporosity of WTR aggregates. Despite these effects, very little change was measured in either plant available or readily available water content. Neither gypsum nor lime caused any significant change in water retention. A slight improvement was noted on the PAM treatment at Brookdale Farm but this effect did not persist for very long after the trial was established.

3.1.2 Hydraulic conductivity

Although *in situ* field measurements were strongly influenced by natural spatial variability, WTR caused a marked increase in the saturated hydraulic conductivity (K_s). The reasons for this relate to the higher porosity and the inherently stable nature of the WTR aggregates, which imparts a more open structure to the soil and reduces the extent of pore blockage. This finding was corroborated in a laboratory study in which strong positive correlations between WTR content and K_s were found.

3.1.3 Soil aeration

The air-filled porosity at field capacity (-10 kPa matric potential) of the WTR-amended soil remained within a favourable aeration range of 10-15%, suggesting that aeration will not be a limiting factor for plant growth. Initially air permeability improved substantially, but variability in the data masked any subsequent trends.

3.1.4 Aggregation

Attempts at using the size distribution of dry soil aggregates to evaluate the influence of the WTR on aggregation were unsuccessful. Due to the inherent strongly aggregated nature of the Hutton soil at Brookdale, no meaningful change in aggregate stability was measured. Significant improvements in soil stability were, nevertheless,

found when fresh 'wet' WTR was mixed with soil. If complete drying of the WTR is not allowed, the polymers that it contains remain active and available for bonding of the soil particles. Upon drying, these polymers become irreversibly attached to the soil substrate and will not become reactivated even on re-wetting of the soil. This suggests that, although WTR consists of mainly silt and clay, the risk of these particles being released and then clogging water-conductive soil pores is low.

3.1.5 Soil strength

Despite the high strength of the WTR aggregates the penetrometer soil strength (PSS) within the tilled layer was not markedly different from the control treatment. Below the tilled layer, however, the PSS on the WTR-amended treatments was lower mainly as a result of wetter soil conditions, this being especially notable on the Westleigh soil at Ukulinga Farm.

3.2 Characterisation of water treatment residues

3.2.1 Questionnaire

A questionnaire was developed and sent to water treatment authorities across South Africa. Information on the treatment chemicals, dosages, volumes and current disposal practices, and a sample of WTR from each treatment plant were requested. Eleven, of 21 authorities, returned completed questionnaires, representing 37 water treatment facilities. Organic polymers were the most commonly used treatment chemicals, with most plants also using lime. Other less frequently used chemicals and additives were $Al_2(SO_4)_3.14H_2O$, $Fe_2(SO_4)_3$, $FeCl_3$, sodium aluminate, activated silica, activated charcoal, CO_2 and bentonite. Information given regarding residue thickening and disposal was poor, but it is estimated that 5 250 000 m^3 yr^{-1} wet WTR is produced. The most commonly used disposal practices appear to be landfilling, river discharge and on-site disposal lagoons. Samples from Rand Water, Umgeni Water (Midmar), Midvaal Water Company, Amatola Water and the City of Cape Town (Faure) were collected. A second Faure sample (Faure 2) was collected when blue-green algal problems were experienced at the plant.

3.2.2 Laboratory analysis

These samples were analysed for a range of chemical and physical characteristics. These analyses showed that the WTRs had the potential to supply some plant nutrients (Ca, Mg, Fe and S) but that metal toxicity may be a problem, in particular Mn in the Faure WTR, and that P adsorption may be severe. However, the data collected illustrated the range of conditions and types of WTRs produced in South Africa, and that in some instances these residues have favourable characteristics for land application.

3.3 Use of water treatment residues on 'poor' soil materials

3.3.1 Lime water treatment residue and coal mine wastes

A pot experiment tested the growth of *Eragrostis teff* (Zucc.), *Cenchrus ciliaris* L. and *Digitaria eriantha* Steud. in mixtures of Rand WTR and material from a coal mine

and a power plant i.e., a sandy soil material, spoil material and coal combustion ash, at rates of 0, 50, 100, 200 and 400 g kg^{-1} with a uniform fertiliser treatment applied to all mixtures. The grass was harvested on three occasions and the mean total yield (dry mass) determined, as well as nutrient uptake. The pots were leached after each harvest and the pH and electrical conductivity (EC) determined. The soil, spoil and ash were characterised and pH, EC and water retention characteristics of the mixtures determined. Growth of the grasses in the ash treatments was poor and these were terminated. *Eragrostis teff* grown in the soil showed a decrease in mean total yield with increasing WTR application rate, but yield was good up to the 200 g kg^{-1} treatment at the first harvest, declining substantially by the second harvest. In general *C. ciliaris* and *D. eriantha* grown in the soil showed a decrease in mean total yield for all harvests with increasing WTR application. The yield of *E. teff*, grown in the spoil, increased up to 100 g kg^{-1} WTR addition, but decreased thereafter. *Digitaria eriantha* showed a decrease in yield, and *C. ciliaris* an increase, with increasing WTR application rate, but for all treatments the differences were non-significant. The pH and EC of the leachates generally increased with increasing WTR addition. The concentration of nutrients in the grasses did not indicate any deficiencies or toxicities. The use of the Rand WTR showed that it could be applied to the spoil medium at relatively high concentrations without severely negatively impacting on grass growth, but that more caution should be used when applying this material to the soil medium.

3.3.2 Lime water treatment residue and combustion ash

As the growth of grass was poor in the ash treatments, another pot experiment was established to test the growth of two creeping grass species grown in the Rand WTR as a cover over the ash material. *Cynodon dactylon* (L.) Pers. Cv. Seagreen and *Stenotaphrum secundatum* (Walt) O.Ktze. were grown in 20, 40 and 60 mm layers of Rand WTR, with and without a fertiliser treatment. Both species performed best in the 60 mm layer with fertiliser, and *C. dactylon* performed better than *S. secundatum*. The former species was more tolerant of the high pH, but both have potential as cover vegetation on the ash dumps when these are covered with Rand WTR. While the grass did not grow in the ash treatments, it would seem that with suitable species the Rand WTR could be beneficially applied to ash material as a cover layer.

3.3.3 Organic/Fe-polymer water treatment residue and a sandy soil

A further glasshouse study investigated the effect of Faure WTR mixed with a nutrient-poor sandy soil material on the nutrient uptake and seed yield of common dry beans (*Phaseolus vulgaris*). The WTR was added at 0, 50, 100, 200 and 400 g kg^{-1} each with five levels of fertiliser (0, 25, 50, 100 (recommended optimum) and 150%). Bean pods were harvested once the plants had senesced. The number of pods and mass and number of seeds per treatment were determined. The seeds were analysed for nutrient uptake. Interveinal chlorosis and necrotic lesions were evident on cotylendonous and new leaves in the WTR-treated soils and the severity of the symptoms increased with increasing rate of WTR. Additional pots were established at the 400 g kg^{-1} rate (without fertiliser) and leaf material collected for chemical analysis. This showed the cause to be Mn toxicity, with leaf concentrations about 12 times the recommended 100 mg kg^{-1} limit. However, mass of bean seed was highest in the 400 g kg^{-1} Faure WTR treatment with 150% fertiliser. Nutrient translocation to the seed seemed to be relatively consistent regardless of treatment, with little

accumulation of Mn. The use of the Faure WTR on a sandy soil seemed to potentially improve the yield of the indicator crop, but caution should be exercised due to the possibility of Mn toxicity. Much of the Mn is water-soluble and leaching of the pots appeared to reduce the problem and a similar result could be expected under field conditions. The Mn present in the WTR is a contaminant from the brown lime and the $Fe_2(SO_4)_3$ used at the treatment works and the use of 'cleaner' chemicals would remove the problem from the WTR.

3.4 Soil microbiological characteristics

This section of the investigation also utilized both the field sites and additional laboratory studies on the other WTRs discussed above.

3.4.1 Field experiment soils

Sampling of the field plots was carried out in September 2001 and May 2002, and all treatments were investigated under fallow and grassed cultivation. Laboratory measurements used to assess soil quality included pH, EC, organic carbon (OC), and microbial activity using fluorescein diacetate (FDA) hydrolysis.

At both trials in September 2001 WTR-amended plots displayed higher pH in the 0-200 mm soil in comparison to the controls, whereas by May 2002 pH had returned to the condition of the controls. Addition of WTR at Ukulinga resulted in higher OC in September 2001, but in May 2002 this was similar to the controls. However, at Brookdale OC was unaffected by WTR. At Ukulinga and Brookdale the effect of WTR on EC was variable, and microbial activity in the soil profile was unaffected by WTR addition. The field trials thus indicated that long-term effects of land disposal of WTR were not detrimental to the measured indicators of soil quality namely, pH, EC, OC and microbial activity.

3.4.2 Soil respiration as affected by water treatment residues

Observations at Ukulinga and Brookdale reflected long-term changes (3 and 5 yr, respectively) to soil quality following WTR addition. To examine the initial changes in soil quality a laboratory experiment was set up using the field trial soils and the other WTRs from Rand Water, Midvaal Water Company, Amatola Water, and the two samples from Faure. The measurements used to investigate these short-term effects on soil quality were soil pH, EC, and microbial activity as indicated by respiration rate.

Each of the WTRs added to the Hutton and Westleigh soils increased soil pH by varying increments, and the higher the WTR application rate, the higher was the pH produced. With the exception of the Rand and Midmar WTRs that clearly increased soil EC, the effect of the other WTRs on EC was variable. The Faure 1 and Amatola WTRs appeared to have no effect on microbial activity, whereas the Midmar, Rand, Midvaal, and Faure 2 WTRs stimulated microbial activity by Day 2 following the addition of WTR, but this had declined by Day 14. As for pH, higher microbial activity was recorded at higher WTR application rates. This laboratory assessment of the short-term response of the Hutton and Westleigh soil forms to WTR addition

suggested that the tested variables were altered by WTR, but not significantly changed to the detriment of soil quality.

3.4.3 Microbial community structure as affected by water treatment residues

Changes in microbial community structure of the Hutton soil only, following addition of the different WTRs, were examined using denaturing gradient gel electrophoresis (DGGE). Community profiles of the different WTRs proved to be markedly different. However, WTR-amended soil retained banding patterns consistent with the control soil indicating that dominant populations in the Hutton soil had been retained. Microbial community analysis thus indicated that the community structure of the Hutton soil was not significantly altered by WTR amendments.

3.5 Soil chemical and fertility characteristics

Characterisation of the Midmar WTR showed that texturally it is a clay when wet. It contains a high amount of salt extractable cations (when aggregate size is <2 mm), and has a slightly basic pH (between 7 and 8) in both water and KCl. The total concentrations of heavy metals are about 150 mg Cr kg^{-1}, 50 to 60 mg Ni kg^{-1} and about 30 mg Pb kg^{-1}. The environmental and agricultural viability of land disposal of the Midmar WTR was investigated by determining answers to four broad questions:

1. What effects would the application of the WTR have on soil chemical properties?
2. What effects would application of the WTR have on vegetation growing on the treated soils?
3. What effects would the WTR have on the soil solution composition (and by implication the quality of the groundwater)?
4. Could this material be used to reduce solubility of potential pollutants?

3.5.1 Effects of the water treatment residue on some soil chemical properties

3.5.1.1 Pot experiment

In the pot experiment with perennial ryegrass *(Lolium perenne)* as the test crop, topsoils (Soil Classification Working Group, 1991) from two Hutton soils (Hu-M and Hu-T), an Inanda (Ia-C), a Namib (Nb-F) and a Shortlands (Sd) soil were used. In terms of Soil Survey Staff (1998) and Isbell (1996), respectively, these soils are classified as follows: Hu-M (Typic Haplustult; Kandosol); Hu-T (Typic Ustrochrept; Tenosol); Ia-C (Humic, Rhodic, Hapludox; Kandosol); Nb-F (Typic Psammaquent; Rudosol); Sd (Typic Haplustalf; Ferrosol). All samples were fertilised with a basal dressing of N, P, K, Mg and S. Two lime levels were added to the Ia-C and Nb-F soils, the higher calculated to reduce the acid saturation percent to 1%, and the lower being half of that. The WTR was applied at rates 0, 40, 80 and 120 Mg ha^{-1}. All treatments were in triplicate. Eight cuts in all were made of the perennial ryegrass.

Changes in chemical properties included an increase in extractable Ca and pH, and a decrease in extractable acidity. In the Ia-C soil, pH (KCl) increased from 4.25 to 5.37 whilst the acid saturation decreased from 27 to 1% at 120 Mg ha^{-1}. For the Nb-F soil, under the same conditions, the pH increase was from 3.91 to 6.46 and the acid

saturation declined from 37 to 1%. Fractionation of Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn showed that the WTR increased the inactive forms of these elements. The same was established from fractionation of P in the WTR-treated soils.

3.5.1.2 Incubation experiments

Two incubation experiments, both at ambient temperatures, were run separately. In the first the five soils used in the pot experiment plus four more were used. These were another Hutton (Hu-F), another Namib (Nb-A), a Valsrivier (Va) and a Westleigh (We) (Soil Classification Working Group, 1991). The Hu-F and We samples were from the field experiment sites at Brookdale and Ukulinga, respectively (Section 2.1.1), and the Va was that used in the soil physical investigation (Section 3.1). The Nb-A is otherwise classified as a Typic Psammaquent (Soil Survey Staff, 1998) and a Rudosol (Isbell, 1996). Application rates of the WTR were 0, 40, 80, 120, 320 and 1280 Mg ha^{-1}. Samples were incubated for about 3 months. The second experiment involved only two strongly acid soils that were chosen to specifically test the liming effect of the WTR. These were an Avalon; Typic Plinthustult; Hydrosol/Kandosol (Av) and an Inanda; Humic, Rhodic, Kandiudox; Kandosol (Ia-W) (Soil Classification Working Group, 1991; Soil Survey Staff, 1998; Isbell, 1996, respectively). The WTR rates were 0, 20, 40, 60, 80, 100, 120, 320 and 1280 Mg ha^{-1}. Sub-samples were taken during the incubation period for pH analysis and, in the second incubation experiment, acidity analysis. Monitoring of the pH showed that the reaction of the WTR with all the soils was completed within 7 days. Trends in the measured properties were the same as found from the pot experiment.

3.5.1.3 Field experiments

At the field experiments perennial ryegrass was grown at Brookdale Farm from 1998 to 2001, after which the site was re-seeded with Dovey tall fescue. At Ukulinga tall fescue was grown from the outset. Soil samples and grass samples were taken periodically from the two sites and analysed to monitor any effects.

Unlike in the pot and incubation experiments, the WTR in the field did not cause any major changes in pH, Ca, Mg and P levels even in soil samples from the plots with the highest rate of 1280 Mg ha^{-1}. Analysis of Ca and Mg from depth samples taken at 200 mm intervals to 1 200 mm from the Brookdale experiment showed that no migration of these elements had occurred after 3 years following application of the WTR. The same results were noted in depth samples from the Ukulinga site. Except for Mn, exchangeable forms of the eight heavy metals were low or undetectable. Also, there was no indication of redistribution of these metals to lower layers.

3.5.2 Effects of the water treatment residue on plant growth

3.5.2.1 Pot experiment

The dry matter yield (DM) of perennial ryegrass plants grown in the pot experiment increased with the WTR applied in all five soils although the highest increases were in the acidic Ia-C and Nb-F soils (35 and 63%, respectively). For the Hu-M, Hu-T and Sd soils the percentage yield increases from the control treatments recorded in response to the application of the highest rate of WTR were 19, 22 and 18%,

respectively. The fact that the highest yield increases were on the strongly acid soils suggests that the liming effect of the WTR could have contributed, more so considering that lime also increased yields in these soils. It was, however, clear that no one factor was responsible for the increase in yield as the liming effect could not explain the result for the other three soils.

3.5.2.2 Field experiments

In both field experiments and for both grasses a significant increase in yield was not apparent. Importantly, however, from an environmental point of view was that there was no decrease in yield whether the WTR was incorporated or applied as a mulch. The growth on the mulched plots was, however, often observed to be better than any of the other treatments, including the control.

Analysis of the plant material from both pot and field experiments indicated that the WTR did not affect the concentration of the heavy metals in the tissues i.e., no deficiencies were induced and no toxicities created.

3.5.3 Possible effects of the water treatment residue on groundwater pollution

3.5.3.1 Laboratory and glasshouse evidence

Analysis of water extracts from the incubated samples established that the ions that increased with application of the WTR were calcium, chloride and nitrate. Fractionation of heavy metals from the pot experiment and incubated soils showed that application of the WTR increased mostly the immobile forms of the metals. Laboratory and glasshouse experiments therefore indicated that there could be pollution of the groundwater by nitrates.

3.5.3.2 Field evidence

Analysis of saturated pastes from soils at both field experiments showed that although the levels of nitrate were increased by application of the WTR, this effect was only noticeable on the fallow plots. In addition nitrate concentrations tended to decline with depth at both field sites on both fallow and grassed plots.

Nitrate concentrations in the soil water collected by the samplers installed at Ukulinga showed a similar trend to that of the saturated paste data, while phosphate concentrations were below detection. Calcium and Mg concentrations followed a similar trend to that of nitrate. Concentrations of Cd, Co, Cr, Cu, Fe, Mn and Zn were all very low or, as in the case of Ni, below detection.

Analysis of the water from a dam and borehole situated about 400 m downslope from the field site at Brookdale Farm has been undertaken since 1997 by Umgeni Water. Their results show that no leaching of any unwanted elements has occurred as a result of the disposal of the Midmar WTR.

It is clear that no leaching of any potentially toxic heavy elements occurs even under the extremely high rates of WTR applied in the field experiments. This therefore

shows that the danger of groundwater pollution as a result of the land disposal of the Midmar WTR is minimal.

3.5.4 The water treatment residue as a possible pollutant-reducing agent

The effect of the application of the WTR on the sorption of P and heavy metals (Cd, Ni and Zn) was studied in the laboratory. Cadmium was chosen to represent potential phytoxicity and zootoxicity, Ni because it is used as an indicator cation for safe disposal of biosolids, and Zn to represent a nutrient that is often deficient in South African soils. Soils treated with WTR were equilibrated for 6 h in 0.005M $CaCl_2$ solution containing a known concentration of each element. The difference between the initial and final solution concentrations was taken to be the amount sorbed.

3.5.4.1 Phosphorus

Initial P concentrations ranged from 0 to 1 000 mg kg^{-1} for the coarse-textured soils, and from 0 to 1 800 mg kg^{-1} for the clay soils. Treatments of WTR were 0, 80, 320 and 1280 Mg ha^{-1}. The WTR, at high initial P solution concentrations, increased the extent of sorption in the coarser textured soils (Hu-T, Nb-A, Nb-F, Va and We), and decreased it in the highly sorbing Av, Hu-M, Ia-C and Ia-W soils. In the We soil for example, the amount of P sorbed increased from about 250 mg kg^{-1} to around 700 mg kg^{-1} at 1280 Mg ha^{-1}. In the Ia-W soil, application of 1280 Mg ha^{-1} of the WTR reduced the amount of P sorbed from about 1 400 to about 900 mg kg^{-1}. In general though, the WTR greatly reduced soluble P.

3.5.4.2 Heavy metals

For Cd, Ni and Zn only one concentration (50 mg kg^{-1} (2 500 mg L^{-1})), was studied using the incubated soil samples as affected by WTR rates from 0 to 1280 Mg ha^{-1}. For all three metals, the amount sorbed increased with increase in amount of WTR for the seven soils studied, namely the Av, Hu-F, Hu-T, In-W, Nb-F, Va and We. In many cases the sorption was so high that more than 40 mg kg^{-1} of the initial concentration was removed from solution. Even for those soils with high sorption capacity e.g. the Va and We, the WTR still increased sorption by up to an average of more than 25% for Cd and more than 40% for Ni and Zn. Because for the Av and Ia-W soils liming also increased sorption, it could be assumed that the accompanying increase in pH as a result of the addition of WTR promoted precipitation of metals, and/or the resultant increase in negative charge increased their adsorption.

These results show that where excess concentrations of soluble heavy metals may occur and where there is concern about run-off with high P concentrations then polymer WTRs could be considered to immobilise these elements and render them less harmful to the environment.

4. Conclusions

4.1 Soil physical properties

The main reasons for this project were two-fold i.e., there are very few studies on this aspect of WTRs reported in the available international literature and the concern that

should the WTR degrade to its constituent particles (mostly clay and some silt) the effect on soil structure was unknown. By concentrating the disposal of WTR onto a relatively small area of land there may be detrimental effects on soil physical properties due to the blockage of pores with associated problems in terms of changes to hydraulic properties. This project has been able to monitor the effects of the Midmar WTR on the Hutton and Westleigh soils for 5 and 4 yr, respectively. In addition, by laboratory experiments the project was extended to included two other soils with very different properties (a Valsrivier and a Cartref). A wide range of soil physical measurements was taken in the field from all the main applied treatments.

The overwhelming conclusion from all these measurements is that the Midmar WTR actually improved the soil physical properties of both soils shortly after application. With time the soils on the treated plots have gradually reverted to the situation that pertains on the control plots. There is no evidence that even the very high application rate (1280 Mg ha^{-1}) has resulted in any adverse effects on the physical condition of either the structurally stable apedal Hutton or the hard-setting Westleigh soils. Similar conclusions were reached for the Valsrivier and Cartref soils.

4.2 Soil chemical and fertility properties

This project utilized the grassed contours at Brookdale and Ukulinga to follow the effects of the Midmar WTR on a test crop (perennial ryegrass/tall fescue) and on the soil chemical properties. The installation of soil water samplers at Ukulinga, and monitoring of a dam and borehole at Brookdale Farm by Umgeni Water (since 1997) enabled soil water and groundwater data to be collected. In addition, laboratory experiments were conducted using the Midmar WTR and a range of soils.

4.2.1 Chemical analysis

From literature it was clear that three major aspects of WTRs have been most studied i.e., the liming effect, the ability of WTRs to sorb P, and the potential for soil and water pollution by heavy metals within the WTR. The present work has shown that the Midmar WTR does indeed increase soil pH and that this effect is quite long lasting. In addition, the application of WTR increased extractable Ca and Mg, soluble salt content, cation exchange capacity, chloride and nitrate. Agronomically such effects can be considered to be mainly positive although the increase in nitrate may be a cause for some concern. However, the increase was measured in incubated soils in the laboratory experiment. There was some support for these data from the soil water samplers and the saturated paste soil measurements from the field experiments. Elevated nitrate concentrations were measured on the fallow plots of both experimental sites but the grassed plots showed lower concentrations probably because the vegetation extracted the nitrate before it leached through the soil. Groundwater nitrate concentrations were generally all <0.05 mg N L^{-1} in both dam and borehole samples.

4.2.2 Phosphorus

In terms of P sorption, this study has shown that, as found by other authors, WTRs have a high P sorption capacity. This was shown dramatically both in the laboratory and pot experiments. A crucial point, however, is that the grass at both field

experiments never showed any indication of P deficiency, even on the mulched plots at Brookdale where the grass roots were concentrated within the mulched WTR layer. Similarly, the differences in extractable P between the soils on the control plots compared to the WTR-treated plots were small. Thus the work has confirmed that found by other studies i.e., that laboratory estimates of P sorption greatly overestimate the effect when one considers the effect on plants in the field. In addition, the results show that the WTR-treated soils released less P and so this characteristic of the WTR could be used to positive effect in areas where leaching or loss of P into groundwater or surface water bodies is a problem.

4.2.3 Heavy metals

The heavy metal content of the WTR has also been shown not to present any real threat to the environment either by direct leaching (as evidenced by minimal concentrations in the dam and borehole water at Brookdale, and in the soil water collected at Ukulinga) or by uptake by the grass. The study was extended to a range of soils and included an incubation period to estimate the long-term dissolution of the WTR under different soil conditions. Eight metals were analysed and only Mn was measurable in any appreciable quantities. Although the results varied between the soils, overall it seems that application of the Midmar WTR can reduce the amount of soluble metals in soils through sorption and thus lessen the prospect of any pollution danger where this material is land treated.

4.3 Use of water treatment residue on 'poor' soil materials

The WTRs from Rand Water and the City of Cape Town were selected for two main reasons i.e., (i) the size of the producing facilities and (ii) their totally different composition compared to the Midmar WTR. The full characterisation of the materials clearly demonstrates the highly calacareous nature of the Rand WTR and the highly organic composition of that from Cape Town (Faure Water Treatment Plant).

4.3.1 Lime water treatment residue and coal mine wastes

As a result of pre-existing contact between Rand Water and a nearby mine this study was based around the prospects for using the Rand WTR as an aid to rehabilitation of coal mine spoil and combustion ash. The pot experiments showed that the response to the WTR was species specific. It appeared that addition of the Rand WTR to the covering soil should only be at the minimum rate and perhaps even lower than tested in this study. Conversely it could be applied at the maximum rate to the spoil material with no effect on yield. For some of the apparently poor performing treatments, the individual harvests indicated that these grasses had a potential to perform better than suggested by the mean total yield data. The high electrical conductivity (EC) and pH of some treatments may have reduced yield. The yield of the perennial grasses tended to improve as they became established, indicating an increased tolerance to the high EC and pH of some treatments. It is considered unlikely that such high EC and pH would be generated in the field and so in some respects the pot experiment produced a worst-case scenario.

4.3.2 Lime water treatment residue and combustion ash

The combustion ash proved problematic but it was shown that by adding a thick layer of Rand WTR onto the surface it enabled two species of creeping grasses to become established. Additional fertiliser was shown to improve growth of both species probably as a result of improving the supply of P. *Stenotaphrum secundatum* did not grow as well as *Cynodon dactylon* but is likely to aid in stabilising the Rand WTR cap. *Cynodon dactylon* would give better cover and would also further stabilise the material as it produces underground rhizomes in addition to the surface stolons.

4.3.3 Organic/Fe-polymer water treatment residue and a sandy soil

The Faure Water Treatment Plant, near Somerset West, treats raw water mainly to remove colour and odour, in contrast to the other plants that have large sediment loads to flocculate. The resulting WTR is very different to the Rand and Midmar materials but has the same problems of disposal. The Faure plant is in an area of sandy soils and so it is on such areas that disposal would occur should land treatment prove viable. The pot experiments investigated the growth of dry beans as a test crop with different rates of Faure WTR in a sandy soil. The results were generally encouraging although it was clear that Mn toxicity was a potential problem to achieving maximum growth and yield, especially where high rates of WTR were used with no or low additional fertiliser. Leaching decreased the Mn concentrations adequately but such a technique would require careful field management. It is considered that the conditions imposed on the pot experiment exacerbated the release of Mn and it is probable that under field conditions leaching would remove the Mn from the root zone. This coupled with oxidising conditions in the sandy soils that may immobilise the Mn would lessen this element's impact on plant growth.

4.4 Soil microbiological properties

4.4.1 Field experiment soils

The concept of 'soil quality' has become popular in recent years and although the data collected from the previous sub-projects can all be considered to reflect this concept, they do so over the longer term. Soil microorganisms will be immediately affected by any change in soil environment such as may occur with addition of a waste material. This part of the investigation therefore centred on the two field trials examining the microbial activity and related characteristics by thorough sampling of the main WTR-treated soils. Although only two sampling times were possible the results of microbial activity showed that differences between treatments were small. There was a clear trend at both sites for microbial activity to peak at a certain depth below the surface (rather than in the topsoil which might be expected). This trend is almost certainly a result of the extremely dry conditions experienced at both field sites (despite irrigation on the grassed plots) during the latter years of the project. The results also showed that the microbial population in the soils is stable – an indicator of good soil quality.

4.4.2 Soil respiration

To extend the investigation to include the other WTRs that were collected, a laboratory study was undertaken to measure basal respiration when they were added

to the two soils (controls) from the field trial sites. The type of WTR and the application rate greatly affected the basal respiration and, in general, respiration increased with rate of addition of the WTR. The Midmar, Rand, Midvaal and Faure 2 WTRs had the greatest effect on respiration, with the Amatola WTR only having a slight influence on the respiration of the Hutton soil from Brookdale. Increases in respiration became less marked with time. This suggests that such increases will be of short-term duration only and therefore supports the results from the field experiments discussed above. The increase in pH for all treatments due to the lime within all the WTRs is considered to be a positive influence as it is likely to stimulate microbial growth. Although EC tended to increase with WTR addition there was no effect on microbial activity.

4.4.3 Microbial community structure

To look in more detail at the microbial population involved in the respiration and activity measurements, the Hutton soil was mixed with the different WTRs (at 15% m/m) and following incubation the microbial population was examined by denaturing gradient gel electrophoresis (DGGE). Although the results showed changes in the microbial community structure of WTR-amended soils after a period of only 5 days the structure had not drastically changed. The original soil bacterial populations were still present though in lesser amounts. The laboratory investigations provided evidence of the competitive and dominant nature of the soil bacterial species, although these were placed under stress by the addition of the WTR. The observed changes are likely to persist for a short period of time, and are unlikely to pose a problem in the long-term. These results indicate that the tested WTRs can be applied to a Hutton soil at an application rate of at least 15% (300 Mg ha^{-1}) without inducing permanent changes to the soil microbial community structure.

5. Recommendations

5.1 Legislative

5.1.1 Declassification of water treatment residue

This investigation has produced a considerable amount of data on the Midmar WTR and by extension all similarly produced polymer WTRs. However, knowledge of the other WTRs investigated is restricted to the reported laboratory and glasshouse studies. The dangers of extrapolation from these to the field situation are indicated by the phosphate and nitrate behaviour of the Midmar WTR, probably the Mn behaviour of the Faure WTR and the high EC measured in the pot experiment using the Rand WTR. The problems with extrapolation to field situations are compounded for WTRs because they vary both spatially and temporally from the same treatment works. However, it is clear that the laboratory and glasshouse experiments exaggerate the problems and reflect worst-case conditions.

Despite this, it is also clear that all aspects of the work reported reveal a highly consistent result i.e., that land application of WTR is safe and is likely to have no negative impacts on soils, vegetation or groundwater even at very high disposal rates that are unlikely to occur in the field. Indeed, it appears that the land application of WTR can have positive effects such as improving water retention in especially coarse-

textured soils and increasing hydraulic conductivity in fine-textured soils, reducing P sorption in high P sorbing soils and increasing P sorption in sandy soils, increasing the sorption of heavy metals (thereby reducing their pollution threat) and increasing properties such as cation exchange capacity and plant available Ca and Mg.

Notwithstanding the above, there are some aspects that require further investigation before formalised guidelines for the land disposal of WTR can be fully produced and these are outlined in Section 6. However, the positive effects of land disposal of WTR clearly outweigh the assumed negative impacts that were the impetus behind this investigation. Thus, even without formalised guidelines, the results given in this report offer compelling evidence for the Department of Water Affairs and Forestry to consider declassifying WTR in order that land disposal, with minimal regulatory control of the site, may be an approved option for water treatment authorities.

5.1.2 Water treatment residue and biosolids

During the course of this project it became clear that water treatment sludge (as it was originally termed) and wastewater treatment sludge (biosolids) were linked in people's minds. They are, however, completely different materials with drastically different properties with totally different constraints when land application is considered. It was for this reason that the term "water treatment residue" was adopted for this project. It is therefore essential that this term be used in order to distinguish the material from wastewater sludge and that the materials are clearly differentiated in the regulations that govern their disposal.

5.2 General

- In terms of the Midmar WTR the information is extensive and an operational management plan for Brookdale Farm was presented to Umgeni Water in December 2000. This involved land treating the WTR as a slurry at a rate not exceeding 320 Mg ha^{-1} using a muck-spreader. This rate was chosen to be on the conservative side and indications from the field data gathered since that time are that this rate could be safely exceeded. However, given the area available for disposal at Brookdale there is no need to increase the application rate, unless or until the treatment plant increases production.
- This study has also considered in some detail the impact of the Midmar WTR on a wide range of soils under laboratory and glasshouse conditions, which as mentioned earlier give the worst-case outcome. These studies have shown no ill-effects on either soils, vegetation or leachates (and thus groundwater), beyond those that might be expected under the imposed conditions. From literature and the questionnaire, the Midmar WTR is typical of all polymer WTRs which, on the basis of the questionnaire results, are the predominant type produced in South Africa. Therefore land disposal recommendations suitable for the Midmar WTR would apply to all such WTRs across a very wide range of soil types.
- The WTRs from Rand Water, Amatola Water, Midvaal and Faure have no long-term impacts on the microbiological properties of the Hutton and Westleigh soils, despite their very different properties. It is therefore likely that such a conclusion could be extended to other soil types and so by this

measure of soil quality these types of WTR are unlikely to be damaging and thus can be applied to land at rates up to at least 320 Mg ha^{-1}.

- The Rand Water WTR can be used to rehabilitate the coal mine spoil although the application rate will have to be further investigated by trials on-site. Such trials should include other species.
- The Rand material can also be used as a capping material over the combustion ash especially if a thicker layer is used and fertiliser added. Although not tested in this project the effectiveness of the Rand WTR may be improved by the addition of an organic by-product.
- The Faure WTR was problematic in glasshouse pot experiments. The major problem was Mn added during the treatment process as a contaminant in the brown lime and the $Fe_2(SO_4)_3$. As such the obvious solution is for the treatment works to source 'cleaner' additives although the economics of this compared to landfilling the WTR would have to be examined by the plant managers. It is also likely that the Mn would be much less of a cause for concern under field conditions (see Section 6 for further comments).
- Adequate management must be assured for any land disposal scheme for WTR. This would be especially important where the soils may be naturally sensitive e.g. wet soils or those that display vertic properties.

5.3 Techniques

5.3.1 Soil physical properties

Field soil cores would probably be the ideal since water retention, hydraulic conductivity, porosity, air permeability and bulk density can be determined on one soil core. In the absence of field experiments then repacked cores should be used though they tended to overestimate the water holding capacity of WTR-amended soils. Water stable aggregation also proved useful to monitor changes in aggregate size distribution.

5.3.2 Characterisation of water treatment residues

The $SrCl_2$ extraction worked well, but overestimates Ca (and probably Mg) in some WTRs due to dissolution of carbonates in the material. Estimates of P by the AMBIC method were poor and this method needs to be used with caution on these materials.

Physical analyses were difficult due to the high structural stability of some WTRs while others were less structurally stable. Particle size distribution, together with the double pipette method to determine aggregation, may give a reasonable indication of potential breakdown rates.

X-ray fluorescence spectrometry is a rapid indicator of elemental composition, but it will not reflect the true toxicity of the WTR since it is a measure of total elements. The DTPA and TCLP methods gave conflicting results. It appears that TCLP underestimates metal availability and it is also a tedious method. A quicker determination of plant available elements is obtained using DTPA and this seemed to reflect more closely what was observed in the plants. The five-step fractionation procedure gives insight into the distribution of the metals in the sample, which could allow predictions on how they may behave under different land application systems.

Measures of P adsorption by isotherm data appear only to reflect the laboratory environment but do give some idea as to the maximum potential of P sorption by the WTRs. However, all the work in this project has shown that this does not reflect the field environment where the plants showed no indication of P deficiency.

Pot experiments help develop a basic understanding of the behaviour of a WTR when applied to a particular soil or waste for land application purposes. An idea of the parameters that may require further testing can be developed and ultimately a guideline for the establishment of field studies (if needed).

5.3.3 Microbiological properties

A simple measurement of microbial activity such as FDA or respiration appears suitable. For more detailed information the DGGE technique has great potential to give insight into the microbial population, although it is rather costly and time-consuming and requires highly specialised equipment and is thus probably not justified on a routine basis.

5.3.4 Soil chemistry/fertility

The results of this part of the project showed that the Midmar WTR was essentially neutral in its effects on soil properties and plants. This relatively inert behaviour argues in favour of using relatively mild extractants when trying to predict field behaviour. Similar reasoning would apply to other polymer WTRs.

To characterise the Midmar WTR and similar materials that contain reasonable quantities of lime and have a basic pH, the same extractants can be used as for calcareous soils. In terms of predicting the behaviour of WTRs in the field this investigation has only considered the Midmar WTR. However, the similarity between this WTR and others suggests that similar conclusions would apply to many WTRs. To establish the amounts of 'immediately reactive' major cations, a single extraction with 0.1M $BaCl_2$ (unbuffered) is convenient. To estimate the movement of these cations in the field, water extracts would be more advisable. With respect to predicting the movement of heavy metals under field conditions, the use of a weak extractant such as 0.05M $CaCl_2$ is suggested. In the current investigation this extractant was used on soils from a pot experiment and on incubated samples to remove soluble plus exchangeable metals. The results predicted the established mobility of metals at the two field sites with reasonable success.

6. Future research

- As stated above, this investigation has produced a management plan for the land disposal site at Brookdale Farm and has recommended an application rate of 320 Mg ha^{-1} yr^{-1} (Hughes *et al.*, 2000). Since this site is fully monitored by Umgeni Water, further recommendations have not been given. However, all the evidence suggests that the polymer WTR produced at the Midmar Water Treatment Works poses no threat to the environment at such levels of disposal. Given this, only minimal monitoring would appear to be required.

- The only lime WTR produced in any quantity in South Africa is that from Rand Water and their chosen disposal site is a nearby coal mine. Any further work should therefore be directed at field experimentation based on the outcomes of the laboratory and pot experiments already conducted. In addition, different species should be studied in the field and co-disposal with an organic-rich waste could also be a fruitful line of research to improve the effectiveness of the WTR as an aid to rehabilitation.

- The WTR produced at Faure, on the basis of the pot experiment, is also suitable for land disposal with the only problem appearing to be the possibility that Mn may be released and be toxic to plants or contaminate the groundwater. The main source of this Mn is the brown lime used at the treatment plant and from 2004 this is to be replaced with a source of white lime (Mr. P. Flower, pers. comm., 2003). This change will certainly reduce the possible effects of Mn considerably, although it still remains as a contaminant in the $Fe_2(SO_4)_3$ coagulant. In order to investigate the effect of the change of lime further laboratory investigations would be useful. In addition, in order to suggest application rates for land disposal some field experimentation would be required. It is recommended that this could be undertaken at the same time as land disposal of the material, since the likelihood of any adverse effects in the field are minimal.

- Of the common types of WTR the only one not studied in this report is that where alum is a major component. However, such WTR is commonly produced overseas and much of the literature is concerned with its effects when disposed of to land. Therefore much of the required information can be gleaned from the literature. This could then be combined with some laboratory studies, and field experimentation along the same lines as for the organic WTR produced at Faure. Since the other main water treatment plants in Cape Town use alum, it may be possible to run these field investigations concurrently.

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LIST OF SYMBOLS

Symbol	Definition
e_a	Air-filled porosity ($m3\ m^{-3}$) (Section 6.4.2; Equation 6.6)[a]
K_a	Air permeability (μm^2) (Section 6.4.2.2; Equation 6.8)
K_{fs}	Field saturated hydraulic conductivity ($mm\ h^{-1}$) (Section 6.3)
K_s	Saturated hydraulic conductivity ($mm\ h^{-1}$) (Section 6.3)
ρ_b	Bulk density ($kg\ m^{-3}$)

LIST OF ABBREVIATIONS

Abbreviation	Definition
AAS	Atomic absorption spectrophotometry
AMBIC	Ammonium bicarbonate, Na-EDTA and ammonium fluoride at pH 8.0
ANOVA	Analysis of variance
APS	Ammonium persulphate (Appendix 12.1)[a]
Av	Avalon soil from Geluksberg, KwaZulu-Natal (Section 13.3.1)
CCE	Calcium carbonate equivalence (%)
CEC	Cation exchange capacity ($cmol_c\ kg^{-1}$)
Cf	Cartref soil from near Pietermaritzburg (Section 13.3.1)
CV	Coefficient of variation
DAE	Days after establishment
DASD	Dry aggregate size distribution (Section 6.5.2.1)
DGGE	Denaturing gradient gel electrophoresis (Chapter 12)
DM	Dry matter
DTPA	Diethylenetriamine pentaacetic acid (Section 4.2.2)
EC	Electrical conductivity ($mS\ m^{-1}$)
EDTA	Ethylenediaminetetraacetic acid (Appendix 12.1)
FC	Field capacity (Section 6.2.3.5)
FDA	Fluorescein diacetate (Section 10.2.3.4)
FWTR	Faure water treatment residue
GMD	Geometric mean diameter (mm) (Section 6.5.2.1; Equation 6.10)
Hu-F	Hutton soil from Brookdale Farm field experiment (Section 13.3.1)
Hu-M	Hutton soil from near the Midmar Water Treatment Works, Howick, KwaZulu-Natal (Section 13.3.1)
Hu-T	Hutton soil from Mangosuthu Technikon, Durban (Section 13.3.1)
Ia-C	Inanda soil from Cedara Agricultural College, Hilton, KwaZulu-Natal (Section 13.3.1)

Abbreviation	Definition
Ia-W	Inanda soil from World's View, Pietermaritzburg (Section 13.3.1)
Lo	Longlands soil from South African Sugar Experiment Station, Mount Edgecombe, KwaZulu-Natal (Section 9.3.1)
LSD	Least significant difference
m/m	Mass per mass
MOR	Modulus of rupture (Section 6.6.3; Equation 6.12)
MWD	Mean weight diameter (Section 6.5.2.1; Equation 6.9)
Nb-A	Namib soil from Adam's Mission, south of Durban (Section 13.3.1)
Nb-F	Namib soil from a disused mission farm near Durban (Section 13.3.1)
OC	Organic carbon (mg kg^{-1})
PAM	Polyacrylamide (Sections 3.2.6.3 and 5.3.3)
PAW	Plant available water (m^3 m^{-3}) (Section 6.2.3.5)
PCR	Polymerase chain reaction (Section 12.2.3)
PSS	Penetrometer soil strength (kPa) (Section 6.6.2.1)
RAW	Readily available water (m^3 m^{-3}) (Section 6.2.3.5)
RWTR	Rand Water's water treatment residue
SAR	Sodium adsorption ratio (Section 7.3.1.3)
Sd	Shortlands soil from Adam's Mission, south of Durban (Section 13.3.1)
SE	Standard error
TAE	Tris(hydroxymethyl)aminoethane (Section 12.2.2.1; Appendix 12.1)
TCLP	Toxicity characteristic leaching procedure (Section 4.2.2)
TEMED	Tetramethylethylenediamine (Section 12.2.4)
USCP	Unbound silt and clay percentage (Section 6.5.4.2)
UV	Ultra violet
Va	Valsrivier soil from Muden, KwaZulu-Natal (Section 13.3.1)
WASD	Wet aggregate size distribution (Section 6.5.2.2)
We	Westleigh soil from Ukulinga farm field experiment (Section 13.3.1)
WRC	Water retention curve/characteristic (Section 6.2)
WTR	Water treatment residue
XRD	X-ray diffraction (Section 4.2.2)
XRF	X-ray fluorescence spectrometry (Section 4.2.2)

[a] more details are given in the report as indicated in parentheses.

CHAPTER 1

INTRODUCTION

1.1 Terminology

One of the results of the project reported herein that must be brought to the reader's attention at the very beginning is the urgent need to change our terminology regarding the waste material with which this report is concerned. Although the title of the Water Research Commission project refers to "water treatment sludge" it has become clear that this term is too closely associated with 'wastewater treatment sludge' that is otherwise known as 'sewage sludge', and more recently 'biosolids'. The very different nature of water treatment sludge has major implications when land disposal is considered and thus this report will use the term "water treatment residue" throughout to avoid any confusion that may occur by using the word 'sludge'. The term "water treatment residue" is similar to the term 'water treatment residual' used by some other authors, but the simpler form is preferred here.

1.2 Background

This project has its roots in discussions held between the principal investigator and staff of the Water Quality Department at Umgeni Water in 1993. Umgeni Water had recognized that the waste material produced following water treatment was posing a problem as regards disposal due to its classification as an industrial waste and thus it required disposal to landfill – a very expensive undertaking from a number of their treatment plants due to the distances involved.

Numerous discussions followed with the project continuing on a very ad-hoc basis until late 1997 when Umgeni Water approved the terms of reference (TOR) and funding for a project entitled "Investigation of environmental effects resulting from land disposal of sludge from the Midmar Water Treatment Works". This Treatment Works had recently come on-stream and was destined to be the largest plant within the Umgeni catchment area. In order to dispose of the water treatment residue (WTR), Umgeni Water purchased a nearby farm (Brookdale Farm) and requested guidance and advice on how to manage the disposal of the waste. The project thus had two major aims i.e.,

- to produce a management plan for Brookdale Farm to ensure environmentally sustainable land disposal of the Midmar Water Treatment Works WTR; and

- to understand the effects of land disposal of the WTR on (a) soil chemical, fertility and physical properties, (b) vegetation and (c) groundwater and surface water.

In 2000 the Water Research Commission (WRC) agreed to also support the project and this required that the project develop wider, national objectives.

1.3 Objectives

The WRC project had two major aims as specified in the TOR namely :

(i) To produce research data which will assist in the development of environmentally acceptable guidelines for South African conditions for the disposal of water treatment residues to land.

(ii) To study the effect of land disposal of water treatment residues on the physical, chemical and fertility properties of soils and on the chemistry of the local groundwater and nearby surface waters.

Three research products were envisaged in the TOR namely :

(a) A management plan for land disposal of WTR from water treatment works. This product was to be developed specifically for Umgeni Water for their Midmar Water Treatment Works although it was anticipated that aspects of the plan could be adapted by other water treatment authorities. [This management plan was submitted to Umgeni Water (Hughes *et al*., 2000) and details are available from that organisation].

(b) Research data on water treatment residues (from across South Africa).

(c) Guidelines for the disposal of water treatment residues (these to be based on data found under field, glasshouse and laboratory conditions).

It subsequently became clear that the product in (c) above would not be achievable, as it requires the development of a methodology applicable to all WTRs – a task beyond the scope of the project and one that will require a dedicated project. However, the data produced within the present project will assist in this objective and in Chapter 18 some consideration is given to the direction that future work should take, and the methods used in this research that may assist, in developing guidelines in the future.

1.4 Approach, scope and layout of the report

This report presents the results of an investigation that covers over 6 yr of research (Section 1.2) in the field, glasshouse and laboratory. This investigation represents the first study of WTRs in South Africa and because little is known of the types of WTR produced, their properties and their potential for land disposal the work covers a wide variety of aspects. The initial phases were concerned with obtaining information from local water treatment authorities and from the international literature. Chapter 2 outlines the water treatment process, the origin of WTR and some aspects of its disposal. Chapter 3 gives an overview of the international literature on WTRs and other materials relevant to the report and Chapter 4 reports on the characterisation of some South African water treatment residues.

It was anticipated that, as with any waste material, the land disposal of WTR could cause a number of possible problems and therefore the investigation was structured to examine these. Because WTR consists almost entirely of silt- and clay-sized particles, one potential problem is the deterioration of soil physical properties that could occur as WTR breaks down to these constituent size fractions. One major aspect of the

design of the field experiments initiated for Umgeni Water that are described in Chapter 5 was thus to study the long-term impact of the Midmar WTR on soil physical properties. In order to extend this study two further soils with contrasting physical attributes were included in an accompanying laboratory study. This soil physical investigation is reported in Chapter 6.

Following the characterisation of some WTRs an investigation was conducted into the possible use of one WTR (from Rand Water) to ameliorate wastes from a coal mine and a power station (Chapters 7 and 8). In addition, a WTR from Cape Town was tested for its possible disposal onto a sandy, nutrient-poor soil (Chapter 9). These two WTRs were chosen because they have very different properties from the Midmar WTR and are produced by the other two major water treatment authorities in South Africa.

One of the major concerns when disposal of waste to land is considered is the effect on what has been termed 'soil quality'. Although there are many different definitions of what constitutes soil quality and as many suggested ways of measuring it, it is generally accepted that soil microorganisms are sensitive indicators of any adverse changes that may occur as a result of the addition of the waste material. For the long-term management of land disposal of WTR it therefore was essential that this aspect be investigated. The microbiology study combined the use of soil samples from the two field experiments (Chapter 10) with a laboratory study. This latter was divided into two parts. One part measured soil respiration after amendment with a range of different WTRs (Chapter 11); the other characterised the microbial community structure in one of the field soils amended with a range of WTRs using denaturing gradient gel electrophoresis (Chapter 12).

The other effects of wastes on groundwater, soils and soil quality concern the chemical changes that may occur and the impact of the waste on soil fertility, plant uptake and leaching of potentially toxic elements. These aspects were investigated in a number of studies that utilised the field experiments by analysing the soils, grass, soil water and groundwater, as well as a variety of laboratory studies using a wide range of different soils and the Midmar WTR. Chapter 13 reports on the growth of perennial ryegrass in a preliminary pot experiment using low application rates of the WTR, Chapter 14 the results from the two field experiments and Chapter 15 the changes in selected chemical properties of soils in an incubation experiment. Two aspects of WTRs that are commonly mentioned in the literature are their high P sorption capacity and their content of heavy metals, both of which could impact on the feasibility of their land disposal. These aspects were thus studied in some detail and the results are reported in Chapters 16 and 17, respectively.

Finally, Chapter 18 is a summary discussion with recommendations including legislative changes for land disposal of WTRs and possible avenues for future research. A comprehensive reference list is supplied, followed by a list of the publications generated by this research.

CHAPTER 2

THE ORIGIN AND DISPOSAL OF WATER TREATMENT RESIDUE

2.1 The water treatment process and origin of water treatment residue

A fundamental objective in producing potable water from turbid primary sources is the removal of the suspended and dissolved solids, organic matter and other contaminants. Although slight variability exists between the actual methods used in the water treatment process, the underlying principles remain the same. The choice and concentration of chemical(s) and the procedures followed depend largely on the quality of the raw water (turbidity, odour, hardness etc.) (CSIR, 1985). Water quality is influenced by factors such as the characteristics of the catchment, seasonal influences and local environmental conditions. Adjusting the dosage levels according to the quality of the water to be treated is therefore necessary. In this regard continuous monitoring of water quality at various stages of the operation process is carried out. Furthermore, economics play a role in the chemicals used, as does availability and accessibility.

A typical sequence of events leading to the production of drinking water is shown in Figure 2.1.

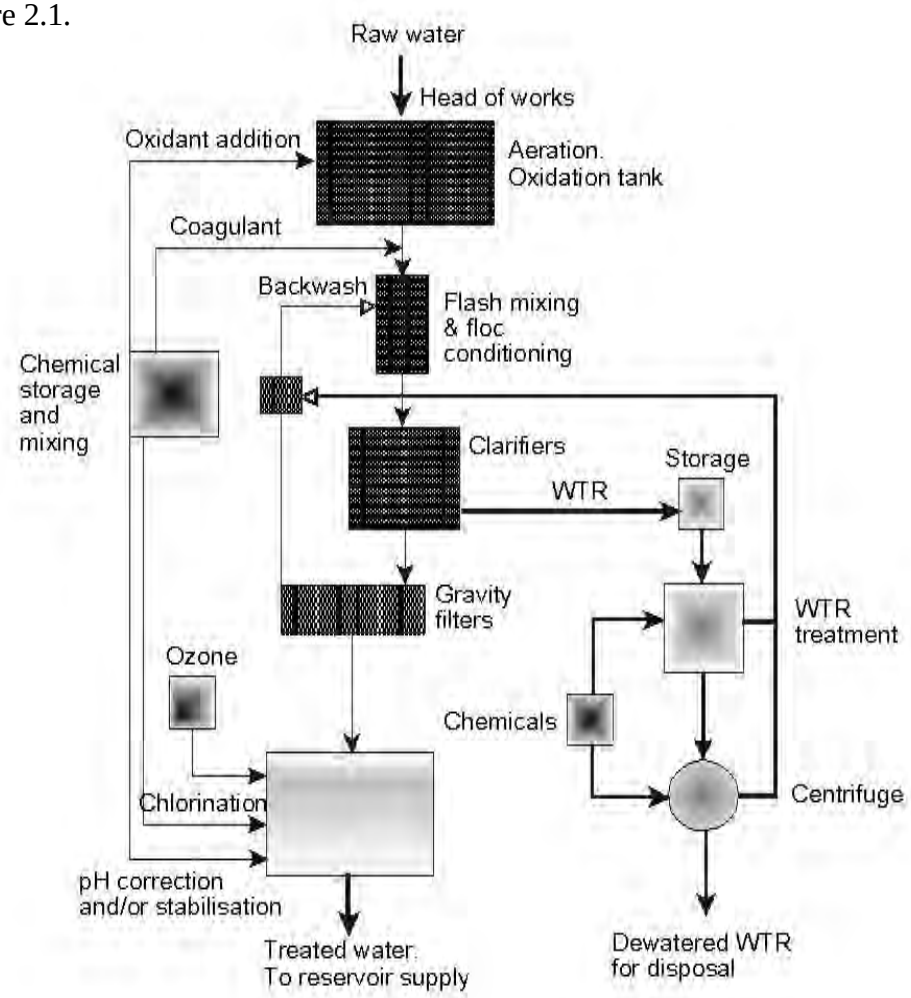


Figure 2.1 Schematic of the drinking water treatment process (after Umgeni Water, 2000).

The turbid water received at the inflow of the works is first passed through a filter screen to remove large objects following which the water is dosed with powdered activated carbon or silica, sodium saturated bentonite and chlorine gas in solution. The purpose of adding these compounds is to reduce the odour and improve the taste of the final product. In addition the sodium ions from the bentonite act as an effective dispersing agent causing aggregates bonded to each other to deflocculate. The dispersed condition is favoured since it is in this state that the external surface area of the suspended particulate matter is at a maximum. Lime and chemical coagulants are then added. Typical coagulants used are aluminium sulfate ($Al_2(SO_4)_3.nH_2O$ [alum]), ferric chloride (Fe_2Cl_3), ferrous sulfate ($Fe_2(SO_4)_3$), and organic polymers. The purpose of the lime (calcitic, slaked and Ca hydroxides) is to raise the pH of the water resulting in the chemical combination of cations with hydroxide ions (OH^-), sulfate ions (SO_4^{2-}) and carbonate ions (CO_3^{2-}) to form insoluble compounds (CSIR, 1985; Tumeo, 1993; Hyde and Morris, 2000). The water is then transferred to flocculation tanks equipped with large mechanical agitators.

Agitation of the water is necessary to increase the number of collisions between the smaller sized particles. Where cationic polymeric compounds are used as the main coagulant the nett positive charges of the polymer compete with the exchangeable cations held by the negative charge on the clay mineral surface. Bonding is therefore electrostatic (coulombic interaction) due to charge neutralisation (Aly and Letey, 1989). The effect of charge neutralisation is to compress the diffuse double layer (termed coagulation by Laird (1997)). In addition, the excess positive charge encourages the formation of cationic bridges which leads to the agglomeration of the mainly silt and clay-sized fraction (Laird, 1997). The relative adsorption of the polycation increases with decreasing valency of the exchangeable cation and decreases with increasing electrolyte concentration of the solution (Gu and Doner, 1992). Because of the aeration process, flocs have a large surface area and can adsorb the dissolved matter from solution (Tebbutt, 1992). This results in the removal of both dissolved colour and colloidal turbidity.

Following the agitation phase of the treatment process, the water is transferred to large settling tanks in which the flocculated material settles out of suspension by gravity. The supernatant is then extracted and passed through sand filters to remove any further particulate matter and to achieve final clarification. To minimise clogging of the sand filters “backwashing” occurs in which water is introduced to the underneath of the filter at a rate much higher than the filtration rate. The rapid upward flow of water expands the filter bed causing the accumulated debris to be scoured from the surface. Water extracted from the settling tanks, although acceptable with regard to its particulate content, may still contain water-borne microorganisms. Consequently the water is disinfected by the addition of chlorine or ozone following which the water is pumped into storage tanks for distribution.

The flocculated material removed from the settling tanks has a solids content of about 2-3% and must be dewatered. Thickening of the WTR is important for two main reasons, first to maximise the rate of water recovery and second to convert the WTR into a manageable form for subsequent handling. To this end the WTR is transferred again to tanks equipped with mechanical agitators after which the solid fraction is passed through a high-speed centrifuge that results in a solids content from 28 to 30%. It is in this form that the WTR is removed from the water treatment facility. The

supernatant is simultaneously returned to the head of the water treatment plant. The WTR that consists primarily of the precipitated hydroxides of the water treatment chemicals along with the material removed from the raw water (sand, silt, clay, humic compounds and dissolved matter) (Elliott *et al*., 1990b) is then ready for disposal.

2.2 Landfill vs. land disposal

Landfill constitutes a closed system where wastes are confined to a specified area by the presence of a barrier (Simon and Tedesco, 1987). However, they are a source of pollution due to the evolution of gases and are often associated with groundwater pollution due to poor site selection and/or poor landfill design (Jarmain *et al.,* 1994). There are also physical problems associated with landfills such as flies, odour, unsightliness, and windblown litter (Ball *et al.,* 1994).

Land disposal or land application of waste, a methodology also known as land treatment, has been described by Overcash and Pal (1979) as "the intimate mixing or dispersion of wastes into the upper zone of the soil-plant system, with the objective of microbial stabilization, adsorption, immobilization, selective dispersion or crop recovery, leading to an environmentally acceptable assimilation of the waste". Therefore, land disposal constitutes an open system offering potential for waste treatment, as opposed to simply waste disposal such as is associated with landfill.

However, this technology is not without potential hazards and associated environmental risks that include reduced soil aeration and reduction of infiltration by the clogging of pores with applied suspended solids. Applied wastes may also cause a build-up of salts leading to salinity problems. There are also concerns regarding heavy metal contamination and associated groundwater pollution (Logan, 1992).

Despite these concerns, researchers have stressed the potential of land disposal as it offers a cost-effective alternative to landfill. Additionally, land disposal has gained in popularity since it offers the added benefit of utilising part or all of the applied waste.

2.3 Past disposal practices and current trends

The ever-increasing demand for clean water has led to an increase in the number and size of water treatment facilities around the world. A consequence of this, however, is an increase in the production of WTRs, which require suitable disposal methods.

Until about 1946, discharge of water purification wastes directly into the nearest drainage course or body of water was the accepted method of disposal in the United States. However, the formation of an investigative committee by the American Water Works Association (AWWA) changed this practice (Proudfit, 1968). Findings from this committee indicated that until about 1946, 96% of water treatment by-products reached streams untreated. Young (1968) reported a similar situation in the United Kingdom, where discharge of WTR into waterways was becoming unacceptable, and that other alternatives were being considered. Both Proudfit (1968) and Young (1968) discuss the advent of residue dewatering practices that are now in common use at water treatment plants. Residue dewatering reduces the volume of material requiring disposal, making the use of drying lagoons more economically feasible. In an AWWA Research Foundation report (AWWARF, 1969) a number of disposal practices were

discussed including lagooning, barging to sea, pipeline to lagoons, sea or sewer, but did not include land disposal. In that report, direct discharge into watercourses was discouraged, although apparently still a frequent occurrence. Albrecht (1972) commented on similar disposal practices for alum WTRs.

Russell (1975) indicated that land application of a 'lime softening' WTR may be an economic and environmentally friendly alternative to direct watercourse discharge or lagooning. It was suggested that this type of WTR be applied to agricultural land using a spreader designed for wastewater disposal, but that tests be conducted to determine optimum application rates. In an AWWARF (1981) committee report, the concept of land application was considered further. The application of a 'lime softening' WTR to agricultural land was based on the premise that the WTR could act as a liming agent and be used in place of conventional liming materials. It was also indicated that there appeared to be little negative impact on the quality of vegetation. Furthermore, it was suggested this type of WTR could be used to reclaim derelict land (e.g. strip-mines) by acid neutralisation.

In many parts of the world, including South Africa, WTR has conventionally been disposed to landfill (Department of Water Affairs and Forestry, 1998). Basta (2000), in a review paper, has indicated that currently landfill is the most commonly used disposal option, but due to increased costs, land application is becoming the preferred disposal method.

A United States Environmental Protection Agency report (USEPA, 1996) discusses some of the more common land disposal practices. These include application to agricultural land either as pure WTR or co-application with fertilisers or co-disposal with sewage sludges, silviculture, land reclamation, dedicated land disposal, turf farms, parks and recreational areas, and construction sites.

In South Africa, the reason for the previous popularity of landfills was that, with environmental concerns being of low priority, landfill constituted a convenient method of waste disposal. Since 1994, however, South Africa has seen the closure of numerous landfill sites for both social and environmental reasons (Department of Water Affairs and Forestry, 2003).

International agreements since 1994 have also put increasing pressure on the South African government to improve environmental policy (Department of Water Affairs and Forestry, 2003). As South Africans become more environmentally aware of the potential hazards of landfills, together with stricter legislation, alternatives for waste disposal are being sought. Land disposal presents an appealing alternative to conventional disposal as it suggests that wastes can be assimilated, without inducing negative effects on soil quality. Indeed, there have also been reports suggesting that land disposal of WTR may improve soil quality (Roy and Couillard, 1998).

2.4 Land disposal of water treatment residue in South Africa: a legal perspective

The responsibility for regulating the final disposal of waste to a landfill site is assigned to the Department of Water Affairs and Forestry (DWAF), in terms of Section 20 of the Environment Conservation Act, 1989 (Act 73 of 1989) (ECA). In

terms of Section 20, no person may dispose of waste unless under the authority of a permit issued in terms of the ECA (Department of Water Affairs and Forestry, 2003).

In terms of the National Water Act (NWA, Act 36 of 1998; Chapter 1, Section 1 (xxiii)), WTR is classified as a waste as follows, " "waste" includes any solid material or material that is suspended, dissolved or transported in water (including sediment) and which is spilled or deposited on land or into a water resource in such volume, composition or manner as to cause, or to be reasonably likely to cause, the water resource to be polluted". Further, in terms of this Act "water use" includes "disposing of waste in a manner which may detrimentally impact on a water resource" (Chapter 4, Section 21(g)).

This implies that for regulation of the substance, a water licence would be needed. This licence would be guided by the Minimum Requirement Series for Waste Disposal, which informs users in terms of waste disposal standards, waste classification and monitoring (Department of Water Affairs and Forestry, 1998). However, the NWA is not only concerned with sacrificial disposal of waste but allows for a "general authorisation" that does not require a licence, but is subject to the relevant regulations under Section 26 and conditions imposed under Section 29. These Sections require *inter alia* that waste standards be prescribed, and that adequate monitoring and analysis be undertaken based on "permissible levels for some or all of its (the waste) chemical and physical components."

However, a major problem is that WTR is currently classified as a "waste" in terms of the definition given above i.e., that it may "cause or be reasonably likely to cause" pollution of a water resource. It is thus considered together with water treatment sludge (biosolids) and thus land disposal would require, at the very least, a general authorisation to be granted. Although the research presented in this report uses the term WTR, in order to stress its very different nature compared to biosolids, South African regulations must also draw this distinction to allow for more effective handling and disposal of WTR.

The work reported here shows that the classification of WTR as a waste material that is "reasonably likely" to pollute water resources should be reconsidered and that its disposal under the "general authorisation" section of the NWA be allowed. This would largely remove the present restrictions on its use and disposal. The results of the research presented in this report show that these materials apparently have no ill-effects on soils, vegetation or groundwater and thus should be able to be disposed of by land application outside of the more strictly controlled conditions imposed by the NWA.

CHAPTER 3

THE EFFECTS OF WATER TREATMENT RESIDUES ON SOIL PROPERTIES AND THEIR USE TO AMELIORATE DEGRADED LAND

3.1 Introduction

Compared to the wealth of information that exists in the literature on wastewater treatment sludges (biosolids) the published research record for water treatment residues can at best be described as sparse because :

- water treatment residue (WTR) was perceived to be relatively innocuous and therefore posed limited risk for adverse environmental effects compared to wastewater treatment sludge (Elliott and Singer, 1988); and

- until recently there was limited legal restriction to water treatment residues being returned to water courses. Consequently alternative forms of waste disposal were not seen as pressing issues deserving of additional research.

3.2 Soil physical properties

The majority of published studies focus on the chemical aspects or uses of WTRs, and few have specifically examined physical characteristics or their effect on soil physical properties.

The earliest published work on the subject is perhaps a study by Rengasamy *et al.* (1980). In this laboratory and pot-based investigation, alum WTR, sampled from a water treatment facility in Adelaide (Australia), was applied to three soil types (a strongly sodic clay, a leached lateritic sand, and a hard-setting red-brown earth) at rates equivalent to 2 and 20 Mg ha^{-1}. The mixtures of WTR and soil were then analysed for a range of soil physical attributes that included dispersion and slaking, particle size distribution, water retention, aggregate strength and modulus of rupture. There were two significant outcomes of the research, namely that WTR has potential application for use as a soil conditioner (since several soil physical properties were improved), and that WTR has a high tendency to adsorb phosphorus (Section 3.3). The study, however, emphasised the importance of extending the work to the field scale and quoted a rate of 2 Mg ha^{-1} as appropriate for testing the research findings presented. The consideration of WTR as a soil conditioner will be looked at in Section 3.2.6.

Subsequently the effect of the land disposal of WTR on soil physical quality, where investigated, has often featured as a secondary research objective despite comments by Skene *et al.* (1995) that as a growth medium the physical properties of the residue are more important than its chemical properties and deserve further investigation.

Bugbee and Frink (1985), however, replaced perlite and peat with alum WTR at varying proportions to test the use of WTR as a potting medium and showed a significant improvement in aeration and available moisture holding capacity of the amended treatments. However, differences in bulk density and total pore space were minimal between treatments.

3.2.1 Water retention

Rengasamy *et al*. (1980) found that water retention was increased by 18%, 85% and 19% for their clay, sand and red-brown earth, respectively, after the addition of 20 Mg ha^{-1} of WTR as a suspension.

The effect of alum WTR on soil water retention has been further addressed by Geertsema *et al*. (1994) and Ahmed *et al*. (1997). In the earlier study, alum WTR was mixed at rates of 0, 1.75, and 2.5% (m/m) with the top 0.15 m of a moderately well-drained, fine, sandy clay loam soil (Table 3.1). They found that alum WTR, and lime (1.21 Mg ha^{-1}) both had a non-significant influence ($p<0.05$) on the soil's water retention.

Table 3.1 The mass water contents (%) recorded in the study by Geertsema *et al*. (1994) 30 months after the trial was established

Soil treatment	Statistic	Matric potential (-kPa)			
		30	100	500	1000
Control	Mean	16	13	9	7
	SD	2	2	1	2
Lime (1.21 Mg ha^{-1})	Mean	17	15	9	7
	SD	2	2	1	1
WTR (2.5% m/m) + lime	Mean	19	14	9	7
	SD	2	2	2	1
All	Mean	18	13	8	7
	SD	2	1	1	2
	$p<0.05$				
	Lime	0.95	0.90	0.93	0.70
	WTR	0.15	0.97	0.77	0.65

In the study by Ahmed *et al*. (1997) the water retention properties for only pure air-dry alum WTR aggregates was studied (Figure 3.1). Although these authors noted a relatively high mass water content at matric potentials of -30 kPa and -1500 kPa, the plant available water (PAW) was calculated to be 0.074 kg kg^{-1}. They attributed this low PAW content to a predominance of fine pores (<10 µm) that characterised the WTR. For this reason they recommended against using pure WTR as a root growth medium. Nevertheless, they concluded that during land disposal, PAW may be controlled more by the aggregate-size distribution of the soil-WTR mixture than by the WTR alone.

Dayton and Basta (2001) examined 17 WTRs from Oklahoma for PAW. They found that the median value of 0.139 kg kg^{-1} was within the typical range for soils (0.063 to 0.300 kg kg^{-1}). They concluded that while some WTRs may have high water holding capacities, PAW may be low, in agreement with Ahmed *et al*. (1997).

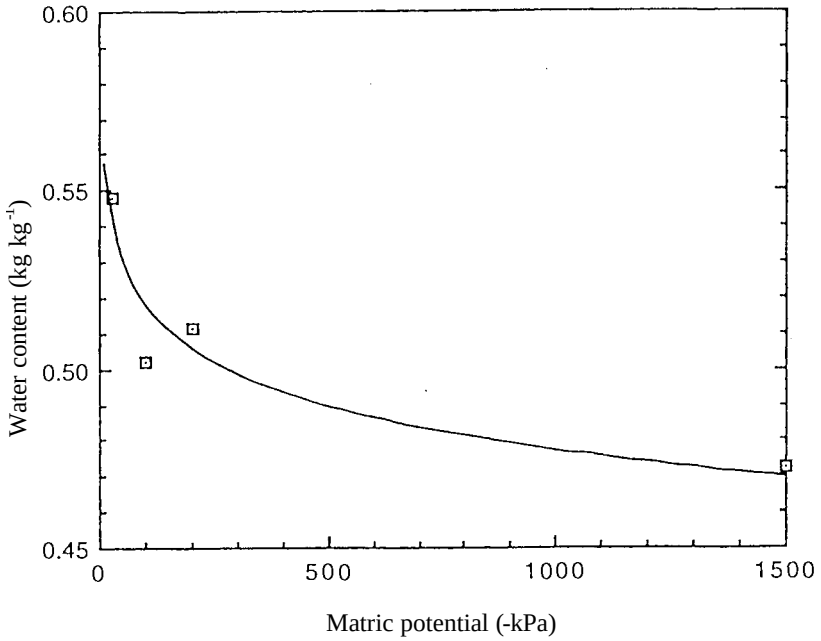


Figure 3.1 A water retention curve of an alum water treatment residue (adapted from Ahmed *et al.*, 1997).

3.2.2 Infiltration, hydraulic conductivity and soil water conservation

The partitioning of rainfall or irrigation at the soil surface is a critical process (Kumke and Mullins, 1997). In terms of the hydrological cycle, rainfall received at the soil surface can infiltrate the soil, contribute directly towards surface runoff or be stored temporarily in soil surface depressions. This temporary storage of water either adds to water infiltrating the soil or is returned to the atmosphere by evaporation. Knowledge of the infiltration process is therefore important in effective soil, water and crop management (Vanderlinden *et al.*, 1998). With WTR-amended soils, the rate of infiltration is of particular concern. If infiltration is reduced after waste addition then the amount of surface runoff will probably be increased and with that an increase in the risk of accelerated soil erosion. On the other hand, if water-soluble pollutants are added with the waste, an increase in the infiltration rate may be detrimental in terms of especially groundwater pollution. One of the few studies that has addressed this issue is that of Ahmed *et al.* (1997) who, in a field trial in Adelaide, Australia, applied alum WTR at rates of 0, 200, 400, 800 and 1600 Mg ha^{-1} to an Urrbrae red-brown earth and found that infiltration rate increased significantly ($p<0.01$).

3.2.3 Soil aeration

The capacity of the soil to maintain gas exchange with the atmosphere is an integral factor in determining the feasibility of land treatment as a waste disposal practice. Adequate aeration is important for the respiration of plant roots and microorganisms (Glinski and Stepniewski, 1985) and for the assimilation of the waste product.

Information regarding the effect of WTR on soil aeration is rare. Ahmed *et al.* (1997) found that bulk density was reduced significantly ($p<0.01$) and total porosity increased significantly ($p<0.01$) with increasing application rate of an alum WTR. However, even at the 1600 Mg ha^{-1} application rate, the mean air-filled porosity (0.25

m^3 m^{-3}) at field capacity was not significantly different ($p<0.05$) from that of the control treatment (0.23 m^3 m^{-3}). Bugbee and Frink (1985) showed, however, that when alum WTR replaced soil in potting media containing originally equal proportions of soil, perlite and peat, macroporosity improved substantially from 0.070 to 0.168 m^3 m^{-3}.

3.2.4 Soil aggregation

For the continued and successful operation of land treatment systems, it is essential that following the disposal of the waste for its assimilation, the soil remains in a well-aggregated state. Deterioration in soil structure or a decrease in its stability may hinder the capacity of the amended soil to support plant growth and maintain adequate levels of soil workability. The influence of WTR on soil stability is therefore important to evaluate the potential of land treatment as a disposal option but there have been limited studies on specifically the influence of WTR on this subject. Rengasamy *et al*. (1980) showed that the alum WTR had a beneficial effect by decreasing clay dispersion and slaking, so improving the stability of soil aggregates against the disruptive forces of water. Despite comments raised by the authors that field studies were a necessary and logical extension of their research, few additional studies have been published on the subject. Skene *et al*. (1995) and Ahmed *et al*. (1997) do, however, refer to the aggregation properties of WTR, but not to their influence when incorporated with mineral soils. Skene *et al.* (1995) examined a polymer WTR and an alum WTR as plant growth media. They reported that when the WTRs were subjected to a few wetting and drying cycles they broke down to a loose granular structure resembling gravel. These aggregates were, however, not prone to slaking during rapid wetting. The gravel texture means that the WTRs were generally very porous and drained well.

3.2.5 Soil strength

The mechanical strength of soil is a useful indicator of soil physical condition (Barzegar *et al.*, 1994). Soil mechanical strength provides anchorage for plants and therefore can have both a direct and indirect influence on crop growth (Young and Mullins, 1991, De Freitas *et al*., 1996). Direct influences relate to root growth and proliferation while indirect effects refer to the timing of land management practices such as tillage or cultivation (Jayawardene and Blackwell, 1990). Since WTRs comprise essentially silt- and clay-sized material, release of this fine fraction due to structural breakdown of the WTR may alter soil strength. Excessive mechanical strength, in particular, is extremely undesirable as it often leads to reduced seedling emergence, poor aeration properties, reduced hydraulic transport and increased risk of sediment scour and entrainment (Mullins *et al.*, 1987, 1990; Proffitt *et al.*, 1995). This factor is of special importance in the successful operation of the land treatment system, since excessive soil strength development could potentially hamper the successful establishment of crops and therefore compromise the viability of the disposal scheme.

The only published study to have directly investigated the influence of WTR on soil strength is that of Rengasamy *et al.* (1980) who reported a decrease in soil strength in response to a maximum WTR application of 20 Mg ha^{-1}. Indirectly, Bugbee and Frink (1985) also alluded to the reduction in soil strength with increased WTR application.

Most of the work concerned with the land disposal of WTRs has been conducted as pot experiments. It is interesting that none of these studies have encountered severe problems with seedling emergence which suggests, albeit qualitatively, that the WTR had limited negative influence on soil strength for the duration of the experiments.

3.2.6 Water treatment residue as a soil conditioner

Wallace and Terry (1998) defined a soil conditioner as any product either synthetic or natural that can improve the physical properties of soil. The practice of soil conditioning is a well-established concept and the literature attests to the vast array of substances tested for their potential use as soil conditioners, perhaps most extensively wastewater sludges (biosolids) (e.g. Khaleel *et al.*, 1981; Metzger and Yaron, 1986; Olness *et al.*, 1998).

In order to investigate the potential of WTRs to act as soil conditioners it is necessary to have some yardstick against which their performance can be measured. Compounds that have been used extremely successfully as soil conditioners for many years are gypsum, lime and polyacrylamide (PAM) and these are included in the experimental design for the present project (Chapter 5).

3.2.6.1 Gypsum

Only a few studies have demonstrated a relationship between gypsum application to soil and water retention. These studies have generally shown that after gypsum application, soil structure was improved and with that an increase in soil macroporosity (Sharma, 1972; Shanmuganathan and Oades, 1983; Chartres *et al.*, 1985; Jayawardene and Blackwell, 1985; 1986). Chartres *et al*. (1985), for example, found that adding gypsum at 5 Mg ha^{-1} and 10 Mg ha^{-1} to a red duplex soil caused an increase in pore space for voids between 300 and 1200 µm in diameter. They attributed this observation to the increased flocculation of the clay particles and therefore the creation of a more open soil structure.

Application of gypsum to structurally unstable soils is a common and well-accepted practice. Gypsum has been shown to improve infiltration, hydraulic conductivity and aeration, and to reduce soil strength, surface sealing and soil erosion (Greene and Wilson, 1984; Frenkel and Fey, 1989; Sumner *et al*., 1990; Agassi and Ben-Hur, 1991; Illyas *et al*., 1993; 1997; Borselli *et al*., 1996). A comprehensive review of the use of gypsum for ameliorating structurally unstable soils is given by Levy and Sumner (1998).

3.2.6.2 Lime

The practice of liming soils specifically as it relates to water retention is poorly reported in the literature. Studies by *inter alia* Baldock *et al*. (1994), Chan and Heenan (1998) and de Castro *et al*. (1999) have all met with conflicting results. A universal comment from these studies, however, is that it is likely that lime does not make a direct contribution towards altering water retention properties but an indirect one, by influencing the aggregation of soils (Collis-George and Figuerora, 1984; Pierson and Mulla, 1989; Mulla *et al*., 1992; Crescimanno *et al*., 1995). The consensus from these investigations is that where aggregation is increased it is likely

that soil water retention is also increased. A recent study by de Castro *et al*. (1999) has shown a statistically significant ($p<0.05$) increase in water retention at matric potentials of -30 and -100 kPa when an acid Oxisol was treated with the equivalent of 3 and 9 Mg ha^{-1} of calcitic and dolomitic lime. They also attributed the increase in water retention to an improvement in soil aggregation.

Lime would normally be applied to acid soils to raise the pH (particularly that of the subsoil) to a target value of around 6.5 to 7 in water (Davies *et al*., 1993). Chan and Heenan (1998) showed that in liming a red earth from Australia (ESP <0.5) at 1.5 Mg ha^{-1} the proportion of water-stable aggregates in the size class >2 mm and <50 µm increased after the third year. de Castro *et al.* (1999) also measured an increase in aggregate stability, 3 years after treating a Brazilian Oxisol with 9 Mg lime ha^{-1}. Both studies ascribed an increase in Ca^{2+} concentrations as the main reason for their observations. According to Norton and Zhang (1998), however, at pH <5, Al^{3+} keeps clay flocculated and aggregates stable. The replacement of Al^{3+} by Ca^{2+} (Al^{3+} will precipitate as insoluble $Al(OH)_3$ as the soil pH increases) can lead to decreased aggregate stability.

Another reason offered for the improvement in soil stability after liming is an increase in organic matter because of the more favourable conditions for crop growth (de Castro *et al.*, 1999). Despite the clearly established benefits of liming soils to crops, the effect on soil stability is less clear and mixed results have been presented in the literature.

3.2.6.3 Polyacrylamide

The effect of commercially derived polymeric compounds on soil properties has, especially in the past decade, received much attention from a variety of perspectives. The major thrust of this work has been to evaluate the effect of polymers, notably PAM, in improving aggregate stability and soil structure. A lesser proportion of interest has been concerned directly with the effect of these products on soil water retention. Of these, two broad classes of polymers have been evaluated for their influence on soil water retention, namely insoluble 'cross-linked' polymers and water-soluble polymers. Cross-linked polymers display a high propensity for swelling and can absorb a substantial quantity of water into their molecular structure (Azzam, 1980). These products do not, however, interact with the soil (Wallace and Wallace, 1990). The influences of these products on water retention have been tested by *inter alia* Al-Darby *et al*. (1990), Verplancke *et al*. (1990), Daneels *et al*. (1992) and Al-Darby (1996). Several of these studies have shown increases in plant available water.

The influence of water-soluble polymers on soil water retention has been investigated by Khoury *et al*. (1978) and Fitch *et al*. (1989). Unlike cross-linked polymers, water-soluble polymers do not have the equivalent capacity for absorbing water into their molecular structure (Wallace and Wallace, 1990). In cases where water-soluble polymers have polar groups as part of their molecular design, some absorption of water is possible since polar groups are hydrophilic. In general, however, as compared with cross-linked polymers, water-soluble polymers are less effective in improving water retention (Bernas *et al*., 1995). Nevertheless, these authors agree that the increase in aggregation and structural stability observed in their respective studies, could lead to favourable responses in water retention.

Many studies have shown improvements in stability following treatment of the soil with polymers, notably PAM. These works are extensively reviewed by Levy (1995) and more recently in Wallace and Terry (1998). The mechanisms by which polymers usually contribute towards soil stability are explained by Theng (1982). The extent to which PAM may increase soil stability is strongly related to its charge (positive, negative or neutral), molecular weight and density of charge (Levy and Agassi, 1995).

Bernas *et al*. (1995) applied polyDADMAC (a positively charged homopolymer of high molecular weight that is used as a flocculant in the water treatment process) at 1% (m/v) to four soil types from Australia. They found that polyDADMAC increased the overall size of water stable aggregates (>2 mm) and decreased the proportion of <0.125 mm aggregates in all four soils.

3.3 Effect of water treatment residue on soil chemical and fertility properties and plant growth

3.3.1 Chemical properties of water treatment residues

Most studies give, at the very least, a basic overview of the chemical properties of the WTR used in any particular study. While this provides a large amount of data on general chemical characteristics, it also makes comparisons difficult due to varying methods of analysis. Basta (2000) presents an outline of the chemical characteristics of a range of WTRs taken from different sources in the USA (Table 3.2).

Schmitt and Hall (1974) examined a sediment basin residue from the Oak-Ridge Water Treatment Plant in Tennessee by spark source mass-spectrographic analysis for 72 elements, including rare earth elements. They found Fe, Si, Al, K, Ca and Ti to be most abundant and in similar ratios as in the Earth's crust.

Dayton and Basta (2001) analysed 17 WTRs for a number of chemical parameters to determine their potential as a soil substitute (Table 3.3). They found that the WTRs showed potential to act as soil substitutes as generally nutrients were within typical soil ranges. Where deficiencies existed, it was suggested that moderate amounts of fertiliser could alleviate the problem.

3.3.2 Heavy metals

Some studies have examined specific aspects of the chemical make-up of WTRs, in particular metal content and fractionation. Elliott *et al*. (1990b) examined the composition and distribution of Cd, Cu, Cr, Ni, Pb and Zn in eight alum and Fe WTRs. A five-step chemical fractionation process was used to determine exchangeable, dilute acid extractable, Fe-Mn bound, organically bound, and residual metal concentrations. Total metal concentrations in these WTRs varied widely and this variability was partly explained by the composition of the added flocculant that exerts an important role in metal contamination of the resulting residue, and to the background concentrations of metals in the coagulated sediments. Except for Cd, 75% or more of the metals were found in the oxide-bound or residual form and held tightly in the WTR matrix. Chromium and Ni levels were higher in the Fe WTRs, and this was attributed to contaminants in the coagulant. Elliott *et al.* (1990b) concluded that provided the pH of the soil was maintained above 6.0 there existed little risk of

leaching and potential groundwater contamination, since the concentrations of all elements, including Cd, were below the permissible maximum levels for land application.

Table 3.2 Typical elemental composition and selected chemical properties of water treatment residues (adapted from Basta, 2000)

Major elements	**g kg^{-1}[a]**
N	0.495 (0.256)
P	0.226 (0.248)
K	1.7 (0.04 - 5)
Ca	2.7 (0.3 - 5)
Mg	0.45 (0.24 - 0.8)
Trace elements	**mg kg^{-1}[a]**
As	14.7
Cd	1.0 (<0.1 - 2)
Cr	187 (40 - 513)
Cu	234 (135 - 485)
Pb	79.9 (100)
Hg	1.5 (2.5)
Mo	9.1 (12.9)
Ni	102 (26 - 218)
Se	3.8 (1.5)
Zn	557 (195 - 865)
Other	**Concentration[a]**
Al (g kg^{-1})	21.2 (2.8 - 30)
Fe (g kg^{-1})	3.2 (1.2 - 6.6)
Si (g kg^{-1})	20
Organic carbon (g kg^{-1})	31 (8.5 - 65)
pH	7.0 (5.1 - 8.0)
Calcium carbonate equivalence (%)	15 (10 - 20)

[a] Values in parentheses indicate ranges or medians.

Elliott and Dempsey (1991) reported that $FeCl_3$ derived from pickle liquor from the steel industry had Ni and Cr contaminants that would lead to elevated Ni and Cr in those particular WTRs. Copper, Cr, Ni, Pb and Zn were predominantly bound within the oxide and silicate components, whereas Cd was found to be largely acid extractable or organically bound. They concluded that if these WTRs were applied to acid soils the potential for Cd mobilisation existed.

Elliott and Taylor (2000) analysed 32 Pennsylvanian WTRs for Mo. The mean Mo concentration was 3.2 mg kg^{-1}, which is below the land application limit of 18.0 mg kg^{-1} in Pennsylvania. This value was, however, higher than the mean reported for soils, but was not considered problematic. They also found that the Cu:Mo ratio was sufficiently high to prevent molybdenosis (Cu deficiency induced by Mo) in grazing livestock. They suggest that where samples had high Mo concentrations these were linked to the type and source of coagulant, and may reflect high geological concentrations in the watershed concerned.

Table 3.3 Some chemical characteristics of 17 water treatment residues and typical soil levels (adapted from Dayton and Basta, 2001)

Constituent	WTR[a]	Soil[b]
pH	5.3 - 7.8 (7.1)	5.0 - 8.0
EC (dS m^{-1})	0.22 - 1.1 (0.5)	<4.0
Cation exchange capacity (cmol kg^{-1})	13.6 - 56.5 (30.0)	3.5 - 35.6
Total N (g kg^{-1})	1.3 - 18.4 (7.0)	0.2 - 5.0
Organic C (g kg^{-1})	17 - 149 (63)	<30
Soluble – P (μg L^{-1})	34 - 576 (98)	50 - 200
Olsen – P (mg kg^{-1})	4 - 49 (13.1)	>12
Mehlich 3 – P (mg kg^{-1})	1.6 - 54.4 (6.8)	32.5
NH_4 – N (mg kg^{-1})	22 - 140 (51)	50 - 200 (Total organic N)
NO_3 –N (mg kg^{-1})	3.5 - 123 (17)	
K (mg kg^{-1})	19 - 278 (109)	125
SO_4 (mg kg^{-1})	12.5 - 453 (138)	14
Mg (mg kg^{-1})	8 - 1231 (117)	50
Fe (mg kg^{-1})	8 - 231 (60.4)	4.5
Zn (mg kg^{-1})	0.12 - 70 (3.0)	0.8
Ca (g kg^{-1})	0.18 - 21 (2.6)	>0.38

[a] The range and median (in parentheses).
[b] Typical soil values obtained from a variety of sources.

3.3.3 Phosphorus studies

Some studies have examined the transformation and mechanisms of P uptake in WTR-amended media. Jonasson (1996) conducted a P fractionation study of WTR treated with additional P. It appeared from this study that a large proportion of the added P was chemisorbed by amorphous and crystalline Al and Fe or bound as Ca-P complexes. Cox *et al*. (1997) conducted a fractionation experiment on alum WTR-treated soil (and fertilised with P) to determine the forms and availability of P in the mixtures. They found that 'loosely bound' or plant available fractions decreased in the mixtures as WTR application rates increased. They also found that Fe, Al and Ca bound fractions increased with increasing WTR application rates. This indicated that P was adsorbed and complexed by these components, making it unavailable for plant uptake. Butkus *et al.* (1998) examined P uptake by metal hydroxides and oxides typically associated with WTRs. They modelled P uptake by hydrous ferric oxide using a diffuse double layer model. From this they found that the amount adsorbed by the hydrous oxide could not account for all P sorbed by WTRs and concluded that a large proportion of the P may also be bound by cationic polymers added during WTR thickening.

3.3.4 Effects on plant growth

In contrast to the literature on soil physical properties, a large proportion of the studies have examined the effects of WTRs on plant growth when incorporated into growing media and soil (Table 3.4).

Table 3.4 Summary of some studies that have examined the effects of water treatment residues on plant growth

Authors	Type of study	Indicator crop	Type of WTR	Application rate
Rengasamy *et al.* (1980)	greenhouse	maize	alum	2 and 20 Mg ha^{-1}
Bugbee and Frink (1985)	greenhouse	lettuce and marigolds	alum	0 - 66%
	forest application	sugar maple	alum	17.5 Mg ha^{-1}
Grabarek and Krug (1987)	forest application	sugar maple	alum	15.5 Mg ha^{-1}
Elliott and Singer (1988)	greenhouse	tomato	iron	20 - 100 g kg^{-1}
Heil and Barbarick (1989)	greenhouse	sorghum-sudangrass	alum, iron, polymer	5 - 25 g kg^{-1}
Geertsema *et al.* (1994)	forest application	pine	alum	0, 6.5 and 9.3 Mg ha^{-1}
Lucas *et al.* (1994)	greenhouse	fescue	alum	0, 1, 2 and 4%
Skene *et al.* (1995)	greenhouse	broadbeans	alum, polymer	2, 4 and 10%
Ahmed *et al.* (1997)	greenhouse	lawngrass	alum	0 - 1 600 Mg ha^{-1}
	field experiment	lawngrass	alum	0 - 1 600 Mg ha^{-1}
Ippolito *et al.* (1999)	greenhouse	blue grama, western wheatgrass	alum– co-applied with biosolids	0 - 250 g kg^{-1}
Basta *et al.* (2000)	greenhouse	bermudagrass	alum	100%
Codling *et al.* (2002)	greenhouse	wheat	alum	0 - 50 g kg^{-1}
Ippolito *et al.* (2002)	greenhouse	blue grama, western wheatgrass	alum, co-applied with biosolids	0 - 10 g kg^{-1}

Rengasamy *et al*. (1980) achieved mixed responses with respect to dry mass (DM) yield. The lower rate (2 Mg ha^{-1}) increased maize yield with respect to the zero application in all three soils irrespective of the form in which the WTR was applied, and whether fertiliser was added or not. This increase in DM yield was most noticeable when the three soils used were fertilised, and in the unfertilised hard-setting red-brown earth compared to the sodic and the podzolic soils. In addition P uptake by the maize increased in almost all soils and treatments at the 2 Mg ha^{-1} application rate. Despite the yields at the higher WTR rate (20 Mg ha^{-1}) being greater than the control, they were lower than those at the 2 Mg ha^{-1} rate except for the fertilised podzol and red-brown earth. Lower uptake of P was observed with this WTR rate compared to the control and the lower rate, this being ascribed to the sorption of this nutrient by disordered aluminium-rich products in the WTR. From these results it appears that a decrease in uptake of P by plants does not necessarily mean a reduction in DM yield, notably where improved soil physical properties (Section 3.2) provide an environment for better plant performance. In addition, less uptake of P does not necessarily translate to a deficiency.

Bugbee and Frink (1985) tested the growth of lettuce (*Lactuca sativa*) and marigolds (*Tagetes* cv. Lemondrop) in WTR-amended potting materials. They found that lettuce showed P deficiencies when grown in WTR-amended material. The marigolds also gave reduced yields at higher rates of WTR. A concurrent study examined the impact

of liquid WTR applied to forested land. While the pH of the soil increased by 0.5 to 1.0 pH unit, no effect was measured on tree growth or nutrient uptake. They concluded that the WTR was not toxic to plants, but may lead to P deficiencies at high application rates under glasshouse conditions.

Elliott and Singer (1988) tested the growth of tomato (*Lycospersicom esculentum*) in an acid silt loam soil treated with an Fe WTR at rates between 0 and 100 g kg^{-1}. They found that the WTR increased soil pH from 5.3 in the control to 8.0 in the highest WTR-amended treatment. This was attributed to the high pH and moderate to high calcium carbonate equivalence (CCE) of the WTR (9.3 and 53.0%, respectively). A positive relationship between dry matter production of tomato shoots and WTR application was found. Although these authors recognised a reduced P availability on the WTR-amended treatments, they concluded that the elevated pH with increased WTR application rate was the primary reason for the relationship observed between biomass production and application rate, together with improved N supply by the WTR. Their results also showed a substantial reduction in metal (Cd, Zn, Cu, Ni) uptake with increased $FeCl_3$ residue application. Explanations offered for this trend were that the WTR had an inherently low concentration of heavy metals, the increase in pH caused by the WTR reduced the availability of these metals to plants, and the precipitation of these metals in the solid phase further decreased uptake by the plant.

Heil and Barbarick (1989) measured the ability of alum, $FeCl_3$ and organic polymer WTRs to 'fix' phosphorus. Each WTR was mixed with each of two soil types at rates of 0, 5, 10, 15, 20 and 25 g kg^{-1}. The test crop, sorghum-sudangrass (*Sorghum bicolor* L. Moench 'NB280S' – *S. sudanese* (Piper) Stapf) showed a significant improvement in dry matter yield but above a WTR application rate of 15 g kg^{-1}, a decline in yield relative to the control was recorded. They explained the reduced yield on the high P adsorption capacity of the WTRs and further showed that this P fixation capacity is similar for the $FeCl_3$ and alum WTR but significantly lower (approximately 1/6) for the organic polymer WTR. The study also showed that at residue application rates <15 g kg^{-1} the metal concentrations were within the acceptable range for forages, but above the 15 g kg^{-1} threshold elevated Cd concentrations were a cause for concern. They also found that Fe deficiencies were corrected when low rates of Fe WTR and higher rates of alum WTR were used on a calcareous soil. Consistent with the earlier findings of Rengasamy *et al.* (1980), Heil and Barbarick (1989) also reported improved physical conditions brought about by WTR and thus an improvement in plant growth.

Lucas *et al*. (1994) found that an alum WTR reduced tall fescue (*Festuca arundinacea*) growth in a greenhouse study. Although they found WTR additions led to P deficiencies, these were overcome by doubling the recommended P fertilisation rate. They also reported that Mn and Cu concentrations were increased in plant tissue at the higher WTR rates, but neither these nor the resulting reduced yield were a cause for concern.

Skene *et al*. (1995) compared the growth and elemental composition of the foliage of broad beans (*Phaseolus vulgaris*) grown in a soil treated with either an alum or a polymer WTR applied at rates of 20, 40 and 100 g kg^{-1}. They concluded that these WTRs may have potential as growth media, but would require fertilisation for optimal plant growth. They found that the polymer WTR supplied some macronutrients and

did not immobilise P as much as the alum WTR. Basta *et al.* (2000) examined P uptake by bermudagrass (*Cynodon dactylon*) grown in three different WTR-amended soils. They found that an addition of 200 mg P kg^{-1} did not increase P availability in the WTRs, but it did increase plant concentrations.

Ahmed *et al.* (1997) conducted laboratory, glasshouse and field studies and found that the alum WTR used had no detrimental impacts on soil properties. Favourable effects found include increased N availability, neutral to alkaline pH, and reasonable CCE. The yield of 'lawngrass' generally increased with WTR application up to rates of 1600 Mg ha^{-1} in both pot and field experiments. They did note, however, that in the pot experiment, a rate of 800 Mg ha^{-1}, and in the field experiment, a rate of 1600 Mg ha^{-1}, inhibited seed germination. This was attributed to the coarse nature of the WTR, but they suggest that the self-mulching nature of the material would cause rapid breakdown into finer particles. This would possibly improve seed contact with the soil and improve germination in agreement with Skene *et al*. (1995). Ahmed *et al.* (1997) also found in the pot experiment that P concentrations in plant tissue decreased with increasing application rate of WTR, but that this was not evident in the field. They concluded that while in the short-term WTR additions could lead to P deficiencies, it does not appear to present any long-term problems in the field. They also report on concerns about Al toxicity, but found that background soil concentrations were above those of the WTR examined. Elliott and Dempsey (1991) suggest that, as soil Al concentrations are typically high, the factors controlling Al solubility (such as pH) will determine potential toxicity. As many WTRs are reported to increase pH in the soil, the potential for Al toxicity is low, and has not been reported in any WTR studies in the literature examined.

Grabarek and Krug (1987) investigated the effect on the nutrient uptake of sugar maple forest stands when an alum WTR was surface applied. They reported that the WTR had a strong P binding capacity, but this was lower than the binding capacity of soils in the area studied and would not cause long-term P deficiencies in the forest trees. Aluminium toxicity and metal leaching were also not problematic. In a similar study, Geertsema *et al.* (1994) examined the effect of an alum WTR applied to pine plantation research plots. They found that it had no effect on soil, groundwater or growth of pine trees 30 months after application, although it was noted that in the short-term (8 months after WTR application) the concentration of N in the groundwater was elevated over the control treatment. They indicate that while short-term concerns regarding P deficiencies are reported, it is unlikely to be problematic in the longer term, especially at the field scale.

Positive plant responses to the addition of WTR in terms of increased foliar mass were also reported by Ippolito *et al.* (1999). Differences between plant species and time of growth was proposed by Ippolito *et al.* (1999) as the possible reasons for a positive response from blue gramma, and an indifferent response from western wheat grass that was grown later. Negative plant responses were found by Cox *et al.* (1997) with wheat, and Wang *et al.* (1998) using barley. Phosphate sorption was given as the reason for the negative results of Cox *et al.* (1997). On the other hand, Wang *et al.* (1998) reported low pH and increased Al activity as the reasons for the inhibited growth of barley they observed with WTR application. This is seen as an isolated case as other workers who have used alum residue have reported contrary results. Heil and Barbarick (1989) used an alum residue of pH 5.1 in a soil of pH 5.2 and got a positive

response (attributed to improved physical conditions). Skene *et al.* (1995) established that both alum and polymer types of WTR resulted in similar Al concentrations in plant tissue that were less than in the control. The results of Ippolito *et al.* (1999) established that Al shoot concentration actually decreased with increase in WTR addition. The anomalous results of Wang *et al.* (1998) could be because of the strongly acidic nature of their WTR's; one had a pH as low as 3.9.

3.3.5 Other uses of water treatment residue

Based on the results of some of the studies in the literature it is possible that the strong binding effect of WTRs for P might be temporary. Thirty months after the residue was applied to soil, Geertsema *et al.* (1994) observed no significant differences in bioavailable and total P between the control and WTR-treated soils in field experiments. These results are partially supported by those of Ahmed *et al.* (1997) who, in some subsequent cuts of lawngrass grown in pot experiments, observed an increase in P uptake per pot at a WTR application rate of 400 Mg ha^{-1}. From this they concluded that with ageing and exposure to wetting and drying this material released more P. They thus proposed that WTR could serve a dual purpose i.e., it could be used to sorb P from polluted waters and then act as a slow release P fertiliser. Essentially the same suggestion was made by Butkus *et al*. (1998), namely that WTR could supply P to soil if amended with it prior to land disposal.

A number of studies have specifically examined the potential of WTR to remove excess nutrients from contaminated land, water and other waste products. Water treatment residues were found to be beneficial in removing excess N and P from land that had received excess nutrients from poultry litter, manure or fertiliser (Dayton, 1995; Peters and Basta, 1996; Gallimore, 1999; Gallimore *et al*., 1999; Haustein *et al*., 2000; Hyde and Morris, 2000; Dayton *et al*., 2001; Callahan *et al*., 2002; Elliott *et al*., 2002). The residue is thus able to prevent or reduce eutrophication. The principle has also been successfully extended to co-application of WTR with biosolids (sewage sludge) with the aim of reducing the high active P concentrations in the sludge (Ippolito *et al*., 1999; 2002).

The success of WTR as a soil substitute appears to be related to the test crop. Basta *et al.* (2000) successfully grew bermudagrass on 100% WTR but Dayton and Basta (2001) experienced poor growth of tomatoes when grown directly on the residue. Dayton and Basta (2001) considered nitrite toxicity and P deficiency to have been the cause for the poor performance but also suggested that low available water and low bulk density of the material might limit its use in this regard. The study by Basta *et al.* (2000), however, indicated that the residue could be used as a soil substitute for revegetation of degraded lands.

Alum WTR has been tested as a possible replacement for wood shavings in broiler litter (Maurice *et al*., 1998). Having used the WTR from when the chicks were one day-old to market age, these workers reported that there were no discernible negative effects with respect to growth, feed conversions, leg scores, liveability and litter characteristics.

3.4 Soil microbiological properties

Soil quality has been defined as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran *et al.*, 1996). Soil quality thus encompasses not only crop productivity and environmental protection, but also food safety, and animal and human health. However, there is much confusion regarding what constitutes 'good' soil quality due, in essence, to the variety of land uses that exist (Kennedy and Papendick, 1995).

Soil quality is frequently measured by indicators that are assumed to reflect changes in soil function that result from management changes. Although physical and chemical indicators of soil quality have been identified, the biological component of soil quality has often been ignored due to the perceived difficulty of analysis or the interpretation thereof. However, soil microorganisms are vital to soil quality, and are potentially one of the most sensitive biological markers available (Turco *et al.*, 1994). A representative species is often selected as an indicator, although many individual organisms or groups of organisms have been used as indicators (Kennedy and Papendick, 1995).

A wide range of microorganisms naturally reside in soil and perform a wide range of functions which are essential for a 'healthy' soil (Sparling, 1997). Additionally, the numbers of organisms and their collective biomass may vary within and between soils (Stotzky and Burns, 1982). It is estimated that <1% of all bacterial species is known, yet the role of microorganisms on soil quality is extensive. Soil microorganisms are responsible for organic matter decomposition, humus formation and nutrient cycling. They are also essential for the formation of soil structure, due to the presence of mucigel from bacteria and fungal hyphae that bind soil particles, that improves water infiltration and assists in maintaining adequate soil aeration (Kennedy and Papendick, 1995).

The role of microorganisms in mediating soil processes, and their relatively high rate of turnover, suggests that the microbial fraction can be a sensitive indicator and an early predictor of changing soil organic matter processes (Sparling, 1997). A soil of high quality is thought of as being biologically active and containing a wide variety of microorganisms. However, the exact role that the biological fraction plays in maintaining soil quality is unclear and this is due to the great magnitude of microorganisms and the complexity of microbial interactions (Turco *et al.*, 1994).

Extensive research has been conducted on microbial biomass as an indicator of soil quality. However, it has also been stated that it is impossible to measure the ecological significance of a microorganism in a given environment simply by measuring the number present (Brookes *et al.*, 1987). Thus, many methods have also been developed to obtain information on microbial activity. More recent advances have recognised that estimation of microbial diversity may provide more useful information because it allows for the study of organisms which cannot be cultured.

Information regarding the effects of WTR on soil microbiological characteristics has proven impossible to find in the published literature and so this project represents the first attempt to investigate this aspect of WTRs.

3.5 Use of water treatment residue on degraded land

The use of industrial by-products to improve the conditions of mine wastes for plant growth and to simultaneously act as a potential disposal option for the by-product have been reported extensively in the literature. Sopper (1992) reviews a number of studies that consider the use of sewage sludge (biosolids) as an ameliorant on mine dumps to improve soil properties and plant growth. Other materials used on mine tailings have included fly ash (Taylor and Schuman, 1988; Welden *et al*., 1999; Bhumbla *et al*., 2000; Seoane and Leiros, 2001); sawdust (Roberts *et al*., 1988); and manures and papermill sludges (Haering *et al*., 2000). Revegetation of coal combustion ash dumps has been reported by Mulhern *et al*. (1989), Carlson and Adriano (1991), and van Rensburg *et al*. (1998).

The only study known to the authors that examines the use of a WTR on mined land is that of van Rensburg and Morgenthal (2003) who investigated the ability of a lime WTR to neutralize acid mine wastes. Dayton and Basta (2001) and Zupancic (1996) considered the use of WTR as a soil substitute, and the potential of WTR to aid in mined land reclamation. However, they did not specifically test the effects of applying WTR to mined land, thus making it difficult to predict how either material would be affected by the other.

3.6 Conclusions

Water treatment residues can be of both agronomic and environmental value if judiciously used. Elliott and Dempsey (1991) state that WTRs have considerably fewer potentially adverse effects on the environment than sewage sludges. The negative results that have been reported were always found in pot experiments where nutrient balancing and unrealistic plant populations tend to be additional problems. The fact that no negative results have been reported in field experiments, either with respect to element uptake, element migration or plant growth suggests the relative safety of land disposal of WTR from an agronomic viewpoint. The rates of application in most published studies have been conservative with amounts up to about 50 Mg ha^{-1} being used. However, some authors have applied much higher rates than this e.g. Ahmed *et al*. (1997) reported positive results up to 1600 Mg ha^{-1}, and Basta *et al*. (2000) successfully used 100% WTR, and so the question of the optimum rate of application remains to be answered.

Most WTRs have a lime component, and thus have a liming potential. This may be beneficial in increasing the pH of acid soils. Most WTRs seem to supply a moderate amount of N, Ca, Mg, and K, and may contain adequate to high concentrations of micronutrients. Frequently where metal concentrations have been noted as elevated, they have still been within typical soil ranges and have not caused aberrations in plant growth. There is also frequent concern over Al toxicity, usually associated with alum WTRs. Generally these concerns have been discredited due to naturally high soil Al concentrations and the alkaline nature of many WTRs (Ahmed *et al*., 1997).

Many studies have indicated that addition of WTRs to soils may lead to P deficiencies of treated soils, or reduce the availability of added fertiliser P, but this appears to be restricted to greenhouse studies. Although only a few field studies have been conducted, they have not indicated any substantial problems with P deficiency,

especially over the long-term (30 months). This has led to the suggestion that the WTRs may act as slow release fertilisers, initially absorbing P and then releasing it again as the WTR degrades (Geertsema *et al*., 1994). The P sorbing capacity of some WTRs has been seen as a potential benefit under conditions of excessive P. Frequent over-fertilisation, excessive use of P-enriched manures and long-term P applications can lead to enriched P run-off and leaching. Due to the P sorbing capacity of WTRs, reported by many authors, they may be beneficially used to reduce these losses.

There is some evidence that suggests that WTR may reduce PAW, although no studies have been found where plant growth has been reduced due to inadequate water availability. This is probably due to the high water holding capacity of the WTRs, and the conditions under which the experiments were conducted. As these studies were generally conducted under controlled environments, there was little chance that plants grown in WTR-treated material would be exposed to wilting point conditions. This would mean that the actual effect on plant growth has not been determined, and it is rather a theoretical or indicator value determined in a laboratory. Improved aeration and water infiltration are also generally reported so that if these WTRs were to be applied to heavy-textured soils these may be considered positive effects.

It is obvious that the nature of WTRs, although they appear to have some properties in common, is variable being related to the quality of the raw water and the treatment process. This makes it difficult to predict the effect of WTRs on soil properties, soil quality, and plant growth when disposed of by land application in areas which themselves will be variable as regards soil and environmental characteristics. The relative paucity of literature available worldwide and the almost complete lack of literature relating to South African conditions does not allow predictions to be made of possible outcomes of applying South African WTRs to local soils. This study is the first investigation of South African WTRs in field, glasshouse and laboratory experiments in order to gauge their impact on soil physical, chemical, and microbiological properties, their effect on plant growth, and to investigate their suitability for amending poor soil substrates.

CHAPTER 4

THE CHARACTERISATION OF SOUTH AFRICAN WATER TREATMENT RESIDUES

4.1 Introduction

Chapter 3 has indicated that although there have been some international studies that focus on water treatment residues (WTRs), little attention has been given to those produced in South Africa. As part of the present project the collection and characterisation of WTRs produced in South Africa was considered important due to the range of water sources and the different treatment processes used to purify raw water (Chapter 2).

The primary objectives of this part of the project were:

- to distribute a questionnaire regarding water treatment processes and current disposal practices of water treatment facilities in South Africa; and
- to collect WTR samples from water treatment facilities for chemical and physical characterisation..

4.2 Materials and methods

4.2.1 Questionnaire

Initially a list was compiled of the potable water producers in South Africa. This was achieved by collating lists obtained from Umgeni Water, Department of Water Affairs and Forestry, Water Research Commission and other sources.

A questionnaire was developed that requested information on the name and location of the treatment facility (or multiple facilities in the case of more than one treatment plant); the source of the raw water; volume of WTR produced seasonally; WTR solids content; coagulants and flocculants used and dosing concentrations; WTR thickening procedures and current disposal practices. Other questions included enquiries about work that may have been conducted on any particular WTR and the amount of interest in the current study by these companies.

The questionnaire (Appendix 4.1) was based on the assumption that the information obtained would reflect the chemicals and dosing practices currently used. It should be noted that some treatment facilities change their treatment processes depending on the quality of the raw water and availability of treatment chemicals. However, it does give an indication of the range of treatment processes used to produce potable water in SA. The treatment facilities were then contacted and arrangements made to send the questionnaire to the relevant persons for completion. The questionnaire was also posted on the project website.

In addition to the questionnaire, a sample of air-dried WTR was requested from each treatment plant for laboratory characterisation. Five WTRs were collected or received for laboratory studies. While the request for residues was poorly met, three of the WTRs were from the largest water suppliers in South Africa i.e., Rand Water, City of

Cape Town – Faure Water Treatment Plant (WTP) (Faure 1), and Umgeni Water – Midmar Water Treatment Works. The other WTRs were from Amatola Water (East London) and Midvaal Water Company (Stilfontein). A second WTR was received from the Faure WTP (Faure 2) to represent a residue produced when a dramatic change in raw water quality led to a change in the water treatment process. Not all analyses were carried out on this second sample from Faure.

4.2.2 Chemical and physical analyses

The air-dry WTRs were milled and passed through a 2 mm sieve. pH was measured in distilled water and 1M KCl using a Radiometer PHM210 pH meter with a standard glass electrode. A soil:solution ratio of 1:2.5 was used (10 g WTR:25 mL solution), and left to stand for about 45 min with occasional stirring using a glass rod. Electrical conductivity (EC) was measured at 25^{o}C using a Radiometer CDM83 electrical conductivity meter in a 1:5 WTR:water solution (United States Salinity Laboratory Staff, 1954). Extractable cations and cation exchange capacity (CEC) were measured by saturating with Sr^{2+} and subsequent replacement with NH_4^+ (Hughes and Girdlestone, 1994).

Nitrogen was determined on <0.5 mm samples by combustion using a LECO Nitrogen Analyser (Discipline of Animal Science, University of KwaZulu-Natal, Pietermaritzburg). Nitrate and ammonia were extracted with 2M KCl (Maynard and Kalra, 1993) and solution concentrations determined colorimetrically using a TRAACS 2000 continuous flow auto analyser. Plant available phosphorus was estimated by extracting with AMBIC (ammonium bicarbonate) solution and P was determined colorimetrically (The Non-Affiliated Soil Analysis Work Committee, 1990) on a Varian Cary 1E UV-Visible spectrophotometer (UV-Vis). Exchangeable acidity and exchangeable Al were measured according to Sims (1996), with Al being measured by atomic absorption spectrophotometry (AAS, Varian SpectraAA-200). Calcium carbonate equivalence (CCE) was measured according to Jackson (1958). Organic carbon (OC) was digested by potassium dichromate oxidation and determined titrimetrically (Walkley, 1947). Total C and S were analysed by combustion using a LECO CNS 2000 auto analyser (Soil Fertility and Analytical Services Laboratory, KwaZulu-Natal Department of Agriculture and Environmental Affairs, Cedara).

Particle size distribution was determined by an adaptation of the pipette method (Gee and Bauder, 1986; Appendix 4.2). Particle density was determined according to the method of Blake and Hartge (1986). Gravimetric water content was determined at -33 kPa and -1500 kPa using pressure plate apparatus. Plant available water (PAW) was considered to be the difference in water content between -33 and -1500 kPa (Dayton and Basta, 2001).

X-ray diffraction analysis on random powders was carried out on a Philips PW1050 diffractometer using monochromated CoKα radiation from 3^{o} to 75^{o} 2θ with a scanning step of 0.02^{o} at 1^{o} min^{-1} counting interval. The diffraction data were captured by a Sietronics 122D automated microprocessor attached to the X-ray diffractometer. The samples were then qualitatively analysed to determine major mineralogical components.

Total elemental concentrations were measured by X-ray fluorescence spectrometry (XRF, Geology Section, University of KwaZulu-Natal, Durban). DTPA extractable (plant available) Cd, Cu, Co, Cr, Mn, Fe, Ni, Pb and Zn were determined by the method of Liang and Karamanos (1993). The toxicity characteristic leaching procedure (TCLP) (USEPA, 1992) was used to determine potential toxic effects of metal leaching. A five-step fractionation procedure was used to determine exchangeable (1M $MgCl_2$), dilute acid extractable (1M NaOAc at pH 5), Fe/Mn bound (0.175M $(NH_4)_2C_2O_4$ and 0.1M $H_2C_2O_4$), organically bound (0.1M $Na_4P_2O_7$) and residual fractions (acid digest, HF, HNO_3 and $HClO_4$) of Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn (Elliott *et al.*, 1990b). Elemental solution concentrations were determined by AAS.

Phosphorus adsorption isotherms were determined for the WTRs. An adaptation of the method presented by Basta *et al.* (2000) was used. Twenty-five mL of a range of P solutions (0, 2, 4, 8, 16 and 32 mg P L^{-1}) were added in a 0.01M $CaCl_2$ matrix to 1 g of material. To give an indication of how the WTR adsorption isotherms may compare to soils, the Hutton and Westleigh topsoils (Soil Classification Working Group, 1991) from the two field experiments (Chapter 5) were similarly treated, with an extra concentration of 1 mg P L^{-1} included. The mixtures were shaken on a reciprocating shaker for 18 h, allowed to settle for a few minutes and the supernatant filtered and analysed for P colorimetrically (The Non-Affiliated Soil Analysis Work Committee, 1990).

4.3 Results and discussion

4.3.1 Questionnaire

4.3.1.1 Response and chemicals used

Responses to questionnaires varied and were disappointing in some instances. Questionnaires were returned by 37 water treatment plants, which represented 11 water treatment authorities (of a possible 21). One water treatment authority (Albany Coast Water) indicated that they operated a desalinisation plant producing saline brine that was returned to the ocean and is therefore not included in this study. Appendix 4.3 gives the complete list of authorities (and treatment plants) that returned questionnaires and some of the responses to the questions. Some questionnaires were incompletely filled out, possibly due to either poor record keeping or poor understanding of the questions asked. Due to this, only the data relating to raw water treatment are reported here (chemicals and dosages used). Where treatment facilities did not give dosing concentrations, they were omitted from the calculations. In most instances, the questionnaires that were returned gave a range of chemical dosing that reflected seasonal changes in raw water quality. A median value was determined from these ranges and used in the summary statistics (Table 4.1).

Lime (or liming agents) was the most commonly used treatment chemical, followed by the use of organic polymers. Lime is used as a conditioning agent to improve the efficacy of the coagulants and flocculants (itself acting as a flocculant under some conditions) and this may account for its common usage. Organic polymers have proven to be efficient and are relatively cost-effective in treating raw water, as well as being used as thickening and dewatering agents. Bentonite is used by some treatment

facilities where raw water turbidity is very low because this reduces the efficacy of the coagulants and flocculant (Mr. F. Ali, pers. comm., 2002). The use of Al and Fe salts was limited and they were frequently used in conjunction with polymers. Of these salts, $Al_2(SO_4)_3.nH_2O$ was the most commonly used followed by $FeCl_3$. The use of $Fe_2(SO_4)_3$ was only reported by two treatment plants. Other chemicals used included carbon dioxide and activated charcoal. Carbon dioxide has been used in place of liming agents and the use of activated charcoal is usually associated with raw water that has odour and colour problems. This was the situation at the Faure WTP (Firgrove, Western Cape), where dissolved organics and algae cause colour and odour problems in the raw water (Mr. D. Smit, pers. comm., 2003).

Table 4.1 Summary data of the types and quantities of water treatment chemicals used by the treatment facilities that returned adequately answered questionnaires

	Chemical or additive[a]								
Statistic	**Lime**	**Ben**	**AlSO**	**FeSO**	**$FeCl_3$**	**LCP**	**ActSi**	**NaAl**	**Other**
n[b]	33	6	8	2	6	30	3	2	4
n[c]	28	6	8	2	5	23	2	2	3
Mean (mg L^{-1})	16.3	2.2	20.7	8.5	6.7	7.5	4.3	2.8	14.4
SE	18.7	0.8	22.5	3.6	6.5	11.6	2.5	0.4	8.5
Median (mg L^{-1})	8.6	2.0	9.0	8.5	4.3	3.8	4.3	2.8	16.0
Range min (mg L^{-1})	2.3	1.5	1.6	5.9	0.8	0.1	2.5	2.5	5.3
Range max (mg L^{-1})	80.0[d]	3.3	65.0	11.0	16.5	57.0	6.1	3.1	22.0

[a] Lime - lime, Ben – bentonite, AlSO - $Al_2(SO_4)_3.nH_2O$, FeSO - $Fe_2(SO_4)_3$, $FeCl_3$ - $FeCl_3$, LCP – long-chain- organic-polymer, ActSi - activated silica, NaAl - sodium aluminate, Other - activated charcoal and CO_2.

[b] Total number of plants that indicated use of a particular chemical, but not all indicating dosages.

[c] Number of plants that indicated the use of a particular chemical and gave dosages. Summary statistics are based on these data.

[d] Rand Water indicated the use of from 60-80 mg L^{-1} CaO, but have been included under conventional lime for convenience.

4.3.1.2 Water treatment residue production and disposal

While many of the questionnaires returned contained information on WTR volumes produced and, in some cases, estimates of the solids content, some did not give this information. In addition, many plants use thickening processes (such as polymer additions and centrifugation), while others discard the material direct from the backwash filters as a slurry. From the records received, WTR solids contents ranged from 0.5 to 30%. Where no records were given of solids content but WTR production volumes were supplied, consideration was given to the thickening process and a solids content estimated from other treatment works using similar chemical dosages. Typically, these undetermined solids contents were of WTRs that were not thickened and a solids content of 1-2% was used to estimate dry WTR production.

Also the units of WTR production given varied considerably between questionnaires. Values were typically given as a mass (tons) or a volume (L or m^3). All data were first converted to m^3. It was assumed that 1 L equaled 1000 cm^3 (0.001 m^3), while a ton

was assumed to be 1 Mg (1000 kg). Assuming a bulk density of 1 Mg m^{-3}, then 1 Mg WTR was the equivalent of 1 m^3. While these assumptions are very unlikely to hold for all WTRs, it does provide a convenient starting point for production estimates.

Thus from the questionnaires with adequate data and using the volumes or masses given and converting these data on the above assumptions, wet WTR production is estimated at about 3 500 000 m^3 yr^{-1}. If it is assumed that the data collected represent about two thirds of the treatment facilities in South Africa, then a total wet volume of about 5 250 000 m^3 yr^{-1} is produced.

To approximate the volume of dry WTR produced, the solids content of the wet material was calculated based on the values supplied by a particular treatment works. Where none was given the abovementioned estimates were used. This results in an approximate value of 270 000 m^3 yr^{-1} and thus a total volume of 405 000 m^3 yr^{-1} is estimated. Using the assumed bulk density, this equates to about 405 000 Mg yr^{-1} of dry WTR production in South Africa.

For comparison, it was estimated (AWWARF, 1969) that WTR dry mass production in the USA was in excess of 1 000 000 tons yr^{-1}. If a solids content of 10% is assumed (almost certainly an overestimate on the basis of the questionnaire) this translates to about 10 000 000 tons wet WTR yr^{-1}.

Details on the disposal of the WTRs tended to be vague, and as for WTR production volumes, often no information was given. It appears that there are essentially six disposal options, linked to volumes of WTR produced and location. Pumping of the WTR directly into the sea was limited (three treatment works) and obviously restricted to those near the coast. Discharge into a sewer was reported on two occasions, and river discharge on five occasions. The use of drying-beds or 'sludge-lagoons' as dedicated on-site disposal was reported by six plants, and nine reported landfill as their disposal practice. Of the latter, six first used drying beds to reduce the volume of the residue before trucking the material to landfill sites. Only three treatment works indicated land treatment. Of these, the Midmar Water Treatment Works (Umgeni Water) is known to have a dedicated land disposal site (Brookdale Farm). The details from the other two treatment works is unclear, but the implication was that the material is applied to areas of land near the plant, perhaps even on-site.

It is difficult to estimate the amount of WTR disposed of in each manner, although from these data the use of landfill, on-site disposal beds (drying beds) and river discharge are the most frequently used options. Where volumes of WTR are small, disposal into the sea, river or sewer discharge are used. As WTR production volumes increase, the use of landfill or dedicated disposal beds are needed; options that while functional in the short-term become expensive and impractical in the long-term.

4.3.2 Chemical characteristics

The pH of the WTRs ranged from 6.19 to 8.66 in KCl and from 6.56 to 9.16 in water (Table 4.2). In most instances, the WTRs were alkaline, with only the Faure 1 WTR having a marginally acidic pH. The pH of these WTRs is similar to the typical range from 5.10 to 8.00 reported by Basta (2000).

Table 4.2 Some chemical properties of the water treatment residues from five of South Africa's water treatment facilities

Property		Rand	Midmar	Midvaal	Amatola	Faure 1	Faure 2
pH	KCl	8.66	7.78	7.66	6.94	6.19	7.23
	H_2O[a]	9.16 (8.50)	8.00 (7.70)	8.36 (7.80)	7.66 (8.10)	6.56 (6.60)	7.84 (7.40)
Electrical conductivity (mS m^{-1})[b]		35.10 (25.80)	71.50 (59.70)	31.27 (24.70)	25.33 (17.10)	16.40 (8.27)	40.50 (41.90)
Total C (g kg^{-1})		82.20	48.80	25.60	23.80	118.90	nd
Organic carbon (g kg^{-1})		8.0	28.0	16.0	19.0	74.0	103.0
Exch. acidity ($cmol_c$ kg^{-1})		0	0.20	0.10	0.10	0.10	nd
Exch. aluminium ($cmol_c$ kg^{-1})		0.07	0.06	0.06	0.07	0.05	nd
Calcium carbonate equivalence (%)		109.06	5.92	4.48	4.09	6.94	nd

[a] Results in brackets determined in 1:2.5 WTR:water after 30 min with occasional stirring.
[b] Results in brackets determined in 1:2.5 WTR:water at 21°C before pH measurement.
nd not determined.

Electrical conductivity ranged from 16.4 to 71.5 mS m^{-1}, suggesting low to moderate water solubility of salts in the WTRs. These ECs should not present a problem for land disposal, as they are low. Dayton and Basta (2001) similarly report a range from 22.0 to 110.0 mS m^{-1} for 17 Oklahoma WTRs. Total C in the materials was generally high. The Faure 1 WTR had the highest C concentration, but this was expected, as the residue was a product of the removal of dissolved organics using activated charcoal and lime. It is likely that the Faure 2 had a higher total C content, but this was not determined. The other residues probably reflected the amount of lime (presence of carbonates) and organic polymer added during water treatment and the amount of organic material removed from the raw water. Organic carbon content ranged from 8.0 to 103.0 g kg^{-1}. The Faure 2 WTR had the highest OC content. Basta (2000) reports values from 8 to 65 g kg^{-1}, whilst Dayton and Basta (2001) report values from 17 to 149 g kg^{-1}. Elliott *et al.* (1990a) report a mean total OC content of 30 g kg^{-1} for WTRs from seven Pennsylvania water treatment facilities. Exchangeable acidity ranged from zero to 0.2 $cmol_c$ kg^{-1} and exchangeable Al from 0.05 to 0.08 $cmol_c$ kg^{-1}. These values suggest very low acid producing potential for these WTRs; a function of the lime components in the residues and their neutral to alkaline pHs. The CCE generally showed low liming potential for the WTRs (all <7%), with the exception of Rand WTR that had a CCE of 109%, due to the high dosing with CaO. The CCE of WTRs examined by Elliott *et al.* (1990a) ranged from 10 to 20%.

4.3.3 Physical characteristics

The particle size distribution of the WTRs was determined on air-dried samples and this greatly affected the results (Table 4.3). Samples that were easily dispersed tended to have high amounts of fine silt and clay (Rand, Midvaal and Faure 2), while the remaining WTRs, that were less easily dispersed, had higher amounts of sand (Faure 1, Amatola and Midmar). The effect of air-drying can be seen by the Midmar WTR results if those in Table 4.3 are compared with the wet WTR analysis given in Section 5.2.

Table 4.3 Some physical properties of the water treatment residues from five of South Africa's water treatment facilities

Property		Rand	Midmar	Midvaal	Amatola	Faure 1	Faure 2
Texture[a]		clay	sand	clay loam	sandy clay loam	sand	silt loam
Particle size distribution (%)	Sand (0.053 - 2 mm)	1.2	91.6	37.5	67.5	91.0	14.4
	Coarse silt (0.02 - 0.053 mm)	1.6	2.4	2.0	1.1	1.3	5.7
	Fine silt (0.002 - 0.02 mm)	34.3	2.5	31.4	2.1	4.3	61.2
	Clay (<0.002mm)	62.9	3.5	29.1	29.3	3.4	18.7
Particle density (g cm^{-3})		2.43	2.23	2.09	2.02	2.02	nd
Plant available water (g kg^{-1})		18.17	53.81	40.46	8.66	29.64	197.72

[a] Soil Classification Working Group (1991).
nd not determined.

There was also a marked difference in the particle size distribution between the two Faure WTRs, due to the change in raw water quality and treatment processes. It might be expected that generally the residues would exhibit high clay and silt fractions. However, the residues are formed by the coagulation of fine particles into larger stable aggregates, and so frequently exhibit a coarse texture.

The particle density ranged from 2.02 to 2.43 g cm^{-3}. Plant available water ranged considerably from 8.66 to 197.72 g kg^{-1} (Table 4.3). Generally all values were low except for the Faure 2 WTR, which was considerably higher than the Faure 1 WTR. Dayton and Basta (2001) similarly report a wide range of values of PAW from 26 to 416 g kg^{-1}.

4.3.4 Nutrient concentrations

Nutrient concentrations were variable (Table 4.4), depending on the source of the residue. Total S was generally quite low, with the Faure 1 showing an elevated concentration, probably mostly due to the addition of $Fe_2(SO_4)_3$ in the treatment process. Nitrate-N ranged from 9.7 to 94.2 mg kg^{-1} and NH_4-N from 32.1 to 358.4 mg kg^{-1}. Total N concentrations ranged from 200 to 5200 mg kg^{-1}. This indicates that a considerable proportion of the N is bound in less soluble (or less available) forms in the WTRs, except in the Rand WTR, where NO_3-N and NH_4-N accounted for about 60% of the total nitrogen, even though the total concentration was low. Although Dayton and Basta (2001) report a much higher range in total N from 1 300 to 18 400 mg kg^{-1}, concentrations of NO_3-N (22- 40 mg kg^{-1}) and NH_4-N (3.5-123.0 mg kg^{-1}) were similarly low. Extractable P (AMBIC) was generally very low, except for the Midvaal and Faure 2 WTR. The CEC of the WTRs ranged from 15.9 to 41.8 $cmol_c$ kg^{-1} and, with the exception of the Rand WTR, all were above 25 $cmol_c$ kg^{-1}. The Rand WTR had a Ca:Mg ratio of about 1:3, whilst the remaining WTRs were 2:1 or 3:1. This indicates that a Ca:Mg imbalance could occur in soils treated with the Rand WTR. Although the Rand WTR had a very high concentration of total Ca (Appendix 4.4), it is clear that this Ca is in an unavailable form. Generally concentrations of Ca and Mg suggest adequate plant availability, but the concentration of K may be too low for satisfactory plant growth.

Table 4.4 Nutrient concentrations of the water treatment residues from five of South Africa's water treatment facilities

Property		Rand	Midmar	Midvaal	Amatola	Faure 1	Faure 2
Total S (mg kg^{-1})		10	210	130	320	1 200	nd
Total N (mg kg^{-1})		200	1 000	2 800	2 600	5 200	4 800
NO_3 – N (mg kg^{-1})		94.23	16.80	12.76	31.80	9.65	11.53
NH_4 – N (mg kg^{-1})		26.33	170.15	358.38	62.40	108.48	32.10
AMBIC P (mg kg^{-1})		4.70	4.46	31.51	0.74	6.33	21.50
Extractable cations ($cmol_c$ kg^{-1})	Ca	4.54	31.01	38.28	28.49	25.29	37.31
	Mg	15.75	9.13	14.33	8.76	13.42	22.12
	Na	1.37	0.52	0.56	0.88	0.66	0.81
	K	0.38	0.51	0.78	0.39	0.30	0.14
Cation exchange capacity ($cmol_c$ kg^{-1})		15.85	26.59	41.81	25.38	33.47	35.79

nd not determined.

4.3.5 Other analyses

X-ray diffraction revealed small amounts of quartz in all samples. While it may be that sand particles are removed from the raw water, the most likely source is the introduction of sand grains to the WTR by backwashing of sand filters during water treatment. Except for the Faure WTRs, all other WTRs had detectable calcite, most notably the Rand WTR. The obvious source is the lime used in the water treatment process, and although Rand Water uses CaO, calcite is formed as a result of the use of CO_2 during water treatment. The apparent lack of calcite in the Faure 1 sample may be due to the slightly acidic nature of this WTR. All the WTRs showed the presence of clays (which was expected), but these were not characterised. The organic nature of the Faure WTRs and the generally poorly crystalline nature of the other WTRs made determination of mineralogical properties by XRD particularly difficult. Rengasamy *et al*. (1980) also found that, apart from small amounts of quartz in their alum residue, the XRD pattern consisted largely of disordered materials, probably amorphous hydrous oxides of Al, Fe and Mn, as well as organic fractions.

The results of total elemental analysis (Appendix 4.4) can be considered to represent the worst case potential for toxicity problems. This would be pertinent if acidic conditions caused dissolution of precipitated elements and mineral particles. As indicated by Schmitt and Hall (1974), who examined a sediment basin residue for 72 elements, Si, Ca, Mg, K, Fe and Ti were generally the most abundant elements in the WTRs. As mentioned earlier, a notable point is the very high total Ca and Mg contents of the Rand WTR when compared to the other WTRs. The Rand WTR also had a relatively low total Al. Similarly, the Faure 1 WTR had a low Al content. This is not surprising considering that this latter residue is a product of the removal of dissolved organics (rather than turbidity removal). Total Cr and Ni were highest in the Midvaal WTR, perhaps a result of contamination from the $FeCl_3$ coagulant (Elliott and Dempsey, 1991).

Plant available metals (DTPA extractable) and TCLP extractable metals (Table 4.5) are possibly better indicators of potential metal mobility, availability and toxicity to plants.

Table 4.5 DTPA and TCLP extractable metals (mg kg^{-1}) from the six water treatment residues

Element	Rand		Midmar		Amatola		Midvaal		Faure 1		Faure 2	
	DTPA	TCLP	DTPA	TCLP	DTPA	TCLP	DTPA	TCLP	DTPA	TCLP	DTPA	TCLP
Cd	0.66	bd	0.42	bd	0.45	bd	0.50	bd	bd	bd	0.30	nd
Co	0.42	bd	0.63	bd	0.70	bd	1.06	bd	1.82	bd	2.59	nd
Cr	1.16	bd	1.18	bd	1.45	bd	1.86	bd	bd	bd	bd	nd
Cu	1.76	bd	5.78	bd	1.39	bd	7.16	bd	0.41	bd	0.29	nd
Fe	48.70	bd	87.70	bd	63.30	bd	246	5.50	65.00	7.90	42.70	nd
Mn	38.80	310	88.90	235	13.23	44.80	22.10	539	725	849	420	nd
Ni	0.56	bd	1.34	bd	0.61	bd	3.39	bd	bd	bd	bd	nd
Pb	0.20	bd	1.07	bd	2.67	bd	1.43	bd	0.79	bd	1.64	nd
Zn	1.48	bd	3.01	bd	2.04	bd	8.64	23.70	10.27	2.51	10.89	nd

bd below detection.
nd not determined.

Generally, DTPA extractable metal concentrations were low, with Fe and Mn being elevated in most of the WTRs. The Faure 1 WTR had exceptionally high Mn values. This was attributed to contaminants in the brown lime and $Fe_2(SO_4)_3$ used to treat the raw water. A sample of the liquid $Fe_2(SO_4)_3$, used by the Faure WTP, was analysed for Mn and found to contain 723 mg Mn L^{-1}. The Faure WTRs also had somewhat elevated concentrations of Zn, possibly also from the coagulant used. Nickel concentrations in the Midvaal WTR were slightly high, possibly due to contamination from the Fe-salt used for water purification. The TCLP extraction gave high concentrations of Mn for all WTRs, while the remaining elements occurred at low concentrations or were below the detection limits. This suggests that these WTRs would not present metal toxicity problems if disposed of to land, possibly with the exception of Mn. This would be particularly true if acid or reducing conditions persisted, releasing unavailable forms of Mn (Adriano, 1986). The alkaline nature of most of the WTRs would aid in immobilising the metals.

In the five-step fractionation extraction (Table 4.6), little was removed as exchangeable, with the Fe concentration of the Midvaal and Faure 1 being notable, probably due to the use of Fe-salts in their treatment processes. Only small amounts of Mn were exchangeable, with the Rand WTR being below detection. As expected, dilute acid extraction removed a greater concentration of metals, with Fe and Mn tending to show the greatest increase in concentration. Also notable was the increase in Zn concentration of the Faure 1 WTR and the Pb concentration of the Rand WTR. This indicates that these elements may become mobile under acid conditions. Gibson and Farmer (1986, cited by Elliott *et al.*, 1990b) indicate that the sum of the exchangeable and dilute acid extractable fractions represent the maximum availability of the metals to plants. On this basis, in the WTRs examined here, the Cd fractions accounted for very small proportions (0 to 8%) of the total Cd concentration. Nickel, however, was more readily removed by these extractants for all the WTRs except the Midmar WTR, and Mn represented about a quarter of the total content for the Rand and Midvaal WTRs. Lead in these two fractions represented a large proportion of the total for the Rand WTR (19.8%). It would appear that under acid conditions, the Rand WTR is likely to release moderate amounts of these metals. This may be due to these

cations being present as carbonate compounds that readily undergo dissolution (releasing the metals) under acid conditions.

Table 4.6 Five-step fractionation of water treatment residues from five of South Africa's water treatment facilities. Results from Elliott *et al*. (1990b) are given for comparison. Concentrations are given in mg kg^{-1}

	Rand						**Midmar**				
	$MgCl_2$	**Weak Acid**	**Fe/Mn bound**	**Organic bound**	**Residual**		**$MgCl_2$**	**Weak Acid**	**Fe/Mn bound**	**Organic bound**	**Residual**
Cd	bd	2.9	0.4	8.20	24.0	Cd	bd	bd	bd	bd	30.0
Co	bd	5.2	bd	bd	47.0	Co	bd	0.3	bd	bd	80.0
Cr	bd	bd	bd	2.60	339.0	Cr	bd	bd	bd	21.4	254.0
Cu	0.1	7.8	9.0	8.80	32.0	Cu	bd	4.5	15.2	0.6	58.0
Fe	bd	62.6	4 908.8	2 004.4	24 743.0	Fe	bd	244.5	14 373.5	4 962.4	5 6450.0
Mn	bd	941.8	1 541.4	141.8	1 057.0	Mn	23.3	1 026.7	6 869.6	1 668.4	528.0
Ni	3.6	13.3	bd	bd	38.0	Ni	1.17	bd	bd	bd	62.0
Pb	bd	84.8	4.0	bd	340.0	Pb	bd	26.4	bd	bd	460.0
Zn	bd	8.9	0.9	bd	87.6	Zn	bd	3.6	bd	bd	129.2
	Amatola						**Midvaal**				
	$MgCl_2$	**Weak Acid**	**Fe/Mn bound**	**Organic bound**	**Residual**		**$MgCl_2$**	**Weak Acid**	**Fe/Mn bound**	**Organic bound**	**Residual**
Cd	0.3	bd	0.2	bd	41.0	Cd	0.2	0.3	bd	bd	57.0
Co	bd	1.3	bd	bd	121.0	Co	bd	1.9	bd	bd	114.0
Cr	bd	bd	bd	26.4	417.0	Cr	bd	bd	20.0	47.4	352.0
Cu	bd	0.3	8.4	bd	41.0	Cu	bd	3.3	21.8	3.6	67.0
Fe	bd	47.5	4 522.2	2 386.8	58 373.0	Fe	245.9	1 062.2	23 998.2	5 889.6	58 378.0
Mn	4.5	36.3	96.0	bd	248.0	Mn	7.1	426.7	854.2	222.8	275.0
Ni	4.5	1.7	bd	bd	63.0	Ni	bd	16.2	37.6	4.6	84.0
Pb	bd	18.4	bd	bd	620.0	Pb	bd	12.0	bd	bd	740.0
Zn	bd	1.3	bd	bd	150.5	Zn	bd	14.2	27.5	6.3	186.5
	Faure 1						**Elliott *et al.* (1990b) [mean values]**				
	$MgCl_2$	**Weak Acid**	**Fe/Mn bound**	**Organic bound**	**Residual**		**$MgCl_2$**	**Weak Acid**	**Fe/Mn bound**	**Organic bound**	**Residual**
Cd	0.1	0.3	1.6	bd	58.0	Cd	5.8	19.0	bd	38.0	38.0
Co	bd	1.8	10.0	5.40	138.0	Co	nd	nd	nd	nd	nd
Cr	bd	bd	16.0	47.4	225.0	Cr	1.0	2.4	38	10.0	49.0
Cu	bd	0.2	7.4	2.6	57.0	Cu	1.0	5.8	32	6.3	55.0
Fe	737.0	1 111.4	91241.8	2 111.6	289850.0	Fe	nd	nd	nd	nd	nd
Mn	5.0	897.1	1 847.0	991.4	3 235.0	Mn	nd	nd	nd	nd	nd
Ni	3.7	6.6	20.6	bd	73.0	Ni	0.6	12.0	31.8	4.5	51.0
Pb	bd	11.2	bd	bd	830.0	Pb	4.2	2.6	8.4	13.0	72.0
Zn	bd	63.3	134.2	44.3	362.8	Zn	0.5	17.0	34	6.0	42.0

bd below detection.
nd not determined.

The chromate extractable (Fe/Mn oxide bound) fractions tended to show high Fe and Mn concentrations, with Zn increasing in concentration for the Faure 1 WTR. For all the WTRs studied Fe concentrations were highest in the chromate extractable fractions (apart from residual concentrations) accounting for between 7 and 27% of the total Fe content. Manganese accounted for a high proportion of the Fe/Mn oxide bound fraction (2 to 68% of the total Mn concentration). The organically bound fraction again showed moderate levels of Mn and Fe. Concentrations of Cr were also notable in the Midmar, Amatola, Midvaal and Faure 1 WTRs. The residual fraction showed sharp increases in all metal concentrations for all WTRs. These metals are considered unavailable, as they are bound in mineral lattices, are not readily released, and, as for the XRF data, represent the worst case.

4.3.6 Phosphorus adsorption

The P adsorption isotherms for the WTRs and the Hutton and Westleigh soils are shown in Figure 4.1. The P requirement value of 0.2 mg L^{-1} (Fox and Kamprath, 1970) is commonly used as the benchmark to determine P sorption potential, but is considered by some authors as being too high (Dayton, 1995).

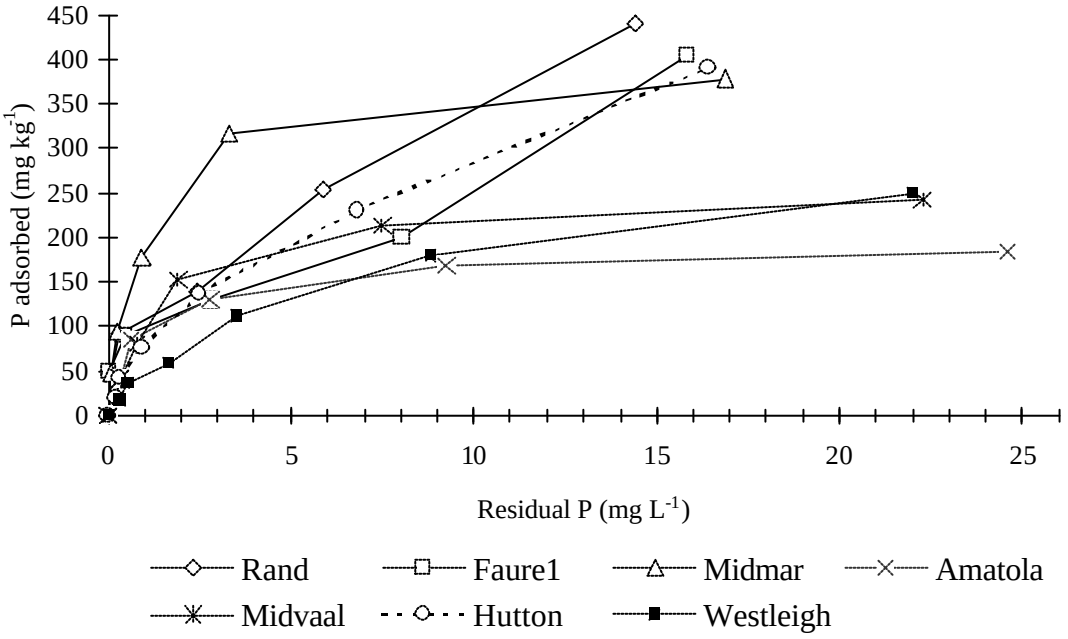


Figure 4.1 Phosphorus adsorption isotherms for the Rand, Midmar, Faure 1, Amatola and Midvaal water treatment residues, and the Hutton and Westleigh soils.

A number of lower values have been proposed that are generally soil and crop specific. For the purposes of this investigation the value of 0.05 mg L^{-1} reported by Zupancic (1996) will also be used. This value was derived for bermudagrass, being an estimate from other similar values for grain crops. In addition, a hypothetical value of 1 mg L^{-1} was also selected for comparative purposes. The amounts of P sorbed to achieve these residual values (taken from Figure 4.1) are given in Table 4.7. The Faure 1 WTR sorbed the most P to achieve a residual concentration of 0.05 mg L^{-1}, while the Midmar WTR sorbed slightly less, but was still moderately high. The Rand

WTR sorbed considerably less, and the Amatola and Midvaal WTRs sorbed very little P. However, all the WTRs were higher than both the Hutton and Westleigh topsoils. To achieve 0.2 mg L^{-1} residual P in solution there were sharp increases in P sorption for all WTRs and soils. The most notable increases were for the Amatola and Midvaal WTRs that showed almost five-fold increases in P sorption, although the Midmar WTR had the highest P sorption at this concentration.

Table 4.7 The amount of P sorbed by the Rand, Faure 1, Midmar, Amatola and Midvaal water treatment residues and Hutton and Westleigh topsoils to achieve residual P concentrations of 0.05, 0.20 and 1.00 mg L^{-1}

Sample	Amount of P sorbed (mg kg^{-1}) to achieve the residual P values (mg L^{-1}) indicated		
	0.05[a]	**0.20[b]**	**1.00[c]**
Rand	25	68	104
Faure 1	50	64	96
Midmar	38	88	180
Amatola	5	24	90
Midvaal	5	24	90
Hutton	5	19	75
Westleigh	3	10	38

[a] Zupancic (1996). [b] Fox and Kamprath (1970). [c] Hypothetical value.

The sorption capacities of the WTRs to achieve 1 mg L^{-1} solution P were similar for the Rand, Faure 1, Amatola and Midvaal, while the Midmar WTR sorbed about double that of the other residues. The Hutton and Westleigh topsoils sorbed less than the WTRs. However, if one considers the trends shown in Figure 4.1, it is clear that the Rand and Faure 1 WTR have not achieved maximum sorption, while the Midmar, Amatola and Midvaal WTR are tending towards some sorption maximum. Zupancic (1996) reports P sorption values of 10, 250 and >800 mg kg^{-1} to achieve a residual P concentration of 0.05 mg L^{-1} for three alum WTRs and so the values reported here (from 5 to 50 mg kg^{-1}) can be considered to be at the low end of the possible range.

As indicated in Section 3.3.5 the P sorbing potential of WTRs has been used to test their ability to remove P from soils, manures and water. Most authors have generally attributed the P sorbing capacity to the presence of amorphous and crystalline oxides and hydroxides of either Al and Fe, or Ca compounds. A number of mechanisms may, however, be responsible for P sorption/precipitation. Dayton *et al*. (2001), however, attribute adsorption to Al and Fe oxides and hydroxides, rather than precipitation reactions, as the primary mechanism for P sorption by the WTRs they studied. They indicated that the formation of Ca-P minerals (other than monetite and brushite) would be too slow for the 15 h batch equilibration they used. Furthermore, they did not observe the concurrent losses of Ca and P from solution that would be necessary for the precipitation of these two minerals.

To determine maximum sorption (including possible precipitation reactions), P was added to the WTRs over a range of 250 to 6 000 mg L^{-1}. Data from this experiment (not shown) indicate that for all the WTRs there are a number of 'steps', until some maximum was reached. As a hypothetical exercise, for demonstrative purposes, a P residual concentration of 3 000 mg L^{-1} was selected and P sorption determined from the sorption curves. At this concentration the amount of P sorbed was 20 000, 12 000, 8 000, 4 000, and 2 000 mg kg^{-1} for the Rand, Faure 1, Midmar, Midvaal and Amatola

WTRs, respectively. While these values have little meaning in practical situations, it does indicate the high P sorbing potential of these residues, suggesting complex interactions with lime, hydrous oxides, organics and clay components of the WTR, leading to multi-layer adsorption and precipitation reactions.

4.4 Conclusions

Although some of the WTRs characterised had low nutrient concentrations, in particular N and P, they may be useful to improve conditions for plant growth in degraded or nutrient-poor soils. The alkaline nature of most of the WTRs (in particular the Rand WTR) would enable them to increase the pH of acid soils. Fertiliser additions may help overcome some of the nutrient deficiencies, possibly with the exception of P. The moderately high P sorbing capacity of these WTRs indicates that large amounts of added P could be removed, but this study has not considered desorption of P from these residues. Desorption and plant growth studies using the Midmar WTR are reported later (Chapters 14 and 17). As indicated earlier (Section 3.3.4) a number of studies have reported on the P sorption capacity of WTRs and how they may reduce P uptake by plants grown in glasshouse. However, field experiments have shown that plant uptake is apparently not affected by additions of WTR (Grabarek and Krug, 1987; Geertsema *et al*., 1994).

In some instances, the high amounts of Mn may lead to toxicity problems (in particular the Faure and Midmar WTRs), especially if used under acid or reducing conditions. It is unlikely that any of the other metals would be problematic. Furthermore, consideration needs to be given to land application rates as well as existing background soil concentrations and characteristics and the intended purpose of the land treated with the WTR (Elliott *et al*., 1990a). These factors will influence the rate and frequency of application.

CHAPTER 5

FIELD EXPERIMENTS

5.1 Introduction

Much of the research reported in the literature concerning the land disposal of water treatment residue (WTR) has been conducted as laboratory and glasshouse studies (Chapter 3). Although these studies assist in understanding the interaction of WTR with soil, extrapolation to the field is problematic. In view of this field trials were a core component of the present project.

An examination of the literature to select WTR rates to be used in this study provided little insight. These studies nevertheless showed that WTRs are far more innocuous than biosolids. It was therefore decided that the maximum permissible rates applicable to the latter could probably be safely exceeded. Ahmed *et al.* (1997) conducted a field experiment using alum WTR at application rates up to 1 600 Mg ha^{-1} on an Urrbrae red-brown earth, and reported some beneficial effects on soil properties, thereby showing that high WTR application rates warranted further research.

5.2 Preparation of the water treatment residue

In March 1998 fresh WTR, with a particle size distribution of 6% sand, 4% coarse silt, 6% fine silt, and 84% clay, was collected from the Midmar Water Treatment Works at Howick, KwaZulu-Natal and transported to a nearby property (Brookdale Farm) owned by Umgeni Water. The wet WTR with a solids content of about 30% by volume was spread out in a layer of approximately 0.30 m to air dry (Plate 5.1).

Plate 5.1 Freshly collected water treatment residue after partial air-drying.

Approximately 6 months was needed for the air-drying and natural breakdown of the WTR into aggregates between 50 and 80 mm in diameter. At the end of this period

(mid-September 1998), all large chunks or blocks of WTR were removed from the material and the remaining WTR reserved for further use.

5.3 Brookdale Farm

5.3.1 Site preparation and selection of treatments

Although several soil types with a range of physical and chemical properties occur at Brookdale Farm, two important criteria governed the selection of the site for the trial. These were that it had to be conducted on the dominant soil type and be close to a source of irrigation water. These two main considerations were met by a gently sloping field (gradient 2^{o}) underlain by a deep, red, kaolinitic, well-drained soil variously classified as Hutton form, Hayfield family (Soil Classification Working Group, 1991; Appendix 5.1), Typic Haplustult (Soil Survey Staff, 1998), and Kandosol (Isbell, 1996). The field, which had been previously cropped to maize, had been under arable production for the past 40 yr (Mr. N. Houston, pers. comm., 1998).

The site of the field trial was first treated with a glyphosphate-based herbicide to destroy the existing vegetation. New vegetation was controlled periodically through re-application of the herbicide. Since unbounded plots were used in the study, five contour embankments spaced approximately 15 m apart were constructed in mid-August 1998 to reduce the risk of sediment wash onto the plots. The four contours were then disced once more in preparation for the treatments (Table 5.1).

Table 5.1 Treatments investigated at the Brookdale Farm trial. The application rates are expressed on an equivalent oven-dry basis

Treatment	Application rate
WTR incorporated into the soil	0, 40, 80, 160, 320, 640, 1280 Mg ha^{-1}
WTR applied on the soil surface (mulch)	320, 640, 1280 Mg ha^{-1}
Gypsum	5, 10 Mg ha^{-1}
Dolomitic lime	2, 10 Mg ha^{-1}
Anionic polyacrylamide	15, 30 kg ha^{-1}

Although disposing of the WTR onto land without any further mechanical incorporation into the soil offers economic advantages, the effect of this mode of disposal on soil properties was uncertain. The mulch treatment (Table 5.1) was therefore included in the experimental design.

In order to allow all aspects of the study to be undertaken it was decided to maximise the number of application rates of the WTR used. This necessitated, given logistical constraints, that each treatment had only two replicates.

The upper two contours were left fallow (used for the soil physical properties investigation reported in Chapter 6) and the lower two were initially planted with ryegrass (*Lolium perenne*) (used for the soil chemistry and soil fertility investigation reported in Chapters 14 to 17). This ryegrass had to be replaced in April 2001 and

Dovey tall fescue (*Festuca arundinaceae*) was planted to be comparable with the second field trial at Ukulinga Farm (Section 5.4). Each of the experimental plots was 6 x 4 m; separated from each other by a 2 m wide buffer strip. Sixteen plots per contour (64 plots in total) were arranged with their longest dimension parallel to the slope of the field. The upslope edge of the plots was situated 1.5 m below the edge of the contour embankments. The layout of the trial is shown in Appendix 5.2. The 16 treatments (each replicated twice), given in Table 5.1, were assigned randomly to the plots located on the upper two contours following which the procedure was repeated for the plots on the lower two contours. This arrangement was necessary in order that the grass (planted on the lower two contours) could be maintained under irrigation.

5.3.2 Application of the residue, gypsum and lime treatments

Owing to the inclusion of the mulched WTR and polyacrylamide (PAM) treatments, the establishment of the trial had to be completed in two stages. In the first stage only the incorporated WTR, gypsum and lime plots were considered. Early attempts to deliver the pre-weighed WTR to the respective plot manually proved too cumbersome (despite the desirability of the process) owing to the large mass of material needed. Consequently a front-end loader, which had the bucket calibrated for the mass of WTR carried, was used. Where the mass of material required was less than a full load, this was added to the plot manually. Caution was exercised to prevent the wheels of the machine entering the plot to avoid soil compaction. Once the delivery of the WTR to the respective plots was completed (end of August 1998), the material was spread evenly across the area of the plot with shovels and then raked over.

To apply the gypsum and lime treatments, the quantity of amendment required per plot was weighed out in the laboratory and then packaged into four equal quantities. The plot to which the amendment was to be applied was subdivided into four equal areas and the contents of each package broadcast by hand across the 6 m^2 subsection.

Immediately after applying the gypsum and lime treatments the contours were disced (early October 1998) to incorporate these products into the top 0.2 m of the soil. During the first run of the disc along the length of the contour, material was dragged laterally across a distance of approximately 0.4 m from the edge of the plot. Consequently the tractor was turned around, and the same transect disced in the opposite direction. This ensured that the material was returned to approximately its original position. Once the entire contour had been disced, the operation was repeated to promote further mixing of the WTR with the soil. Plate 5.2 illustrates the discing operation in progress and Plate 5.3 shows the WTR and soil mixture immediately after discing.

In establishing their trial, Ahmed *et al.* (1997) excavated (using a front-end loader) the top 0.2 m of the soil from each plot, and then mixed in the required quantity of WTR with the excavated soil. The mixtures were then returned to the plots. Although this method is likely to produce a more homogeneous mixture than that followed during the present work, it was an option deemed to be impractical as far as the long-term management of the site by Umgeni Water was concerned.

Plate 5.2 Discing of the incorporated WTR, gypsum and lime treatments at Brookdale Farm in early October 1998.

Plate 5.3 The surface of the 1280 Mg ha^{1} plot immediately after discing. A camera case is shown for scale.

In the second stage, the mulch treatments and the PAM (Section 5.3.3) were applied to the respective plots during the second week of October 1998. For the mulch treatments the procedure followed was exactly as used to prepare the "WTR-incorporated" plots for discing, again ensuring that the front-end loader did not enter any of the plots.

5.3.3 Application of the polyacrylamide treatments

A high molecular weight, medium charge density, anionic PAM (product code G26), was sourced from Floccotan Chemicals in Pietermaritzburg. The mass of polymer

required for the 30 and 15 kg ha^{-1} treatments was 72 and 36 g per plot, respectively. Polymer stock solutions were prepared by dissolving 5 g of the polymer in 5 L of distilled water. As the dry PAM was added, the solution was mixed on a magnetic stirrer to promote dissolution of the granules. The volumes of stock solution thus used for the 30 and 15 kg ha^{-1} treatments were 72 and 36 L per plot, respectively.

To reduce the polymer solution viscosity, the 1 g L^{-1} stock solution was first diluted ten-fold in a 1 m^3 PVC tank. The contents of the tank were then sprayed onto the plot through a 20 mm hosepipe. At the onset of surface runoff, operations were paused until all of the free solution on the soil surface had infiltrated. On average, it took approximately 2 h to apply the equivalent of 15 kg ha^{-1} PAM to a plot. The 30 kg ha^{-1} treated plots were initially sprayed with the equivalent of 15 kg ha^{-1} and allowed to dry for 24 h before applying the remaining dose. Immediately following application of the polymer, each plot was sampled to determine the depth to which the polymer solution had infiltrated. This value ranged between 0.1 and 0.12 m.

All work with regards to establishing the Brookdale Farm trial (Plate 5.4) was completed during mid-October 1998.

Plate 5.4 The Brookdale Farm trial. The grassed plots can be seen in the background and the fallow plots in the foreground.

5.3.4 Climate

Mean monthly rainfall data for the Cedara meteorological site (29°32'S 30°17'E; 1066 m altitude), located approximately 2 km from Brookdale Farm, are given in Table 5.2. The mean annual rainfall is 865.3 mm falling mostly between October and April. Although some of this rainfall is frontal in nature, much of it occurs as high intensity convection thunderstorms and usually during mid- to late-afternoon. Mean annual maximum and minimum temperatures are 22.4 and 9.9°C, respectively. Moderate frosts occur occasionally in winter.

Table 5.2 Mean monthly rainfall (mm) at Brookdale Farm

Month											
Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.
132.9	121.8	111.3	50.5	26.7	15.2	15.3	26.5	42.1	86.4	111.1	125.5

5.4 Ukulinga Farm

5.4.1 Field trial design

This field trial was located at the University of Natal Ukulinga Research Farm in Mkondeni, approximately 10 km from Pietermaritzburg (29°40'S 30°24'E). Compared to the Hutton soil at Brookdale Farm, the site selected for this trial is on a shallow (maximum soil depth ranged between 0.5 and 0.6 m), poorly drained soil underlain by soft plinthite that is prone to hard-setting especially during the dry winter months and classified as Westleigh form, Helena family (Soil Classification Working Group, 1991; Appendix 5.1), Typic Plinthaquept (Soil Survey Staff, 1998) and Hydrosol (Isbell, 1996). The Westleigh soil has inherently poor physical properties (unlike the Hutton at Brookdale Farm), and so any improvement caused by the WTR, could be detected in a shorter time. The site selected had been used previously for forage trials but had been maintained for the previous 3 yr under *Eragrostis curvula*. The field had a slight gradient of approximately 1%. The treatments investigated differed from those at Brookdale Farm by the exclusion of the mulch treatments, a reduction in the number of WTR application rates and only a single rate of application of gypsum, lime and PAM (Table 5.3). All treatments were duplicated. The layout of the trial is given in Appendix 5.3.

Table 5.3 Treatments investigated at the Ukulinga Farm trial. The application rates are expressed on an equivalent oven-dry basis

Treatment	Application Rate
WTR incorporated into the soil	0, 80, 320, 1280 Mg ha^{-1}
Gypsum	10 Mg ha^{-1}
Dolomitic lime	10 Mg ha^{-1}
Anionic polyacrylamide	30 kg ha^{-1}

As at the Brookdale trial the plot size at Ukulinga was 6 x 4 m, with each plot separated from one another by a 2 m wide buffer strip. The procedure adopted at Brookdale Farm to prepare the plots for discing and application of the treatments was followed exactly at Ukulinga. The plots were disced in preparation for the treatments in early October 1999 to a depth of 0.20 m. The WTR, gypsum and lime treatments (Table 5.2) were applied during the third week of October 1999 and the PAM at the end of October 1999.

An adjacent area of the field was used to replicate the same treatments and planted to Dovey tall fescue (*Festuca arundinaceae*) under irrigation. An initial attempt to

establish a crop during mid-November 1999 failed, due to profuse weed growth. Consequently the area was maintained fallow until March 2000 when the grass was successfully established (Plate 5.5).

Plate 5.5 The Ukulinga Farm trial during the winter of 2000. The grassed plots are in the foreground and the fallow plots in the right background.

5.4.2 Climate

Ukulinga Farm has an elevation of 775 m with a mean annual rainfall of 735 mm (Table 5.4). Mean annual maximum and minimum temperatures are 25.7 and 8.9^{o}C, respectively, and light to moderate frosts occur occasionally during winter.

Table 5.4 Mean monthly rainfall (mm) at Ukulinga Farm

Month											
Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.
107.4	101.6	94.5	43.0	27.4	11.9	12.3	23.3	43.0	70.8	92.6	104.8

5.5 Properties of the soils and the Midmar water treatment residue

The properties of the Hutton and Westleigh soils are given in Appendix 5.1 and the laboratory methods used to obtain these data in Section 4.2.2. The major and trace element composition of the Midmar WTR is given in Appendix 4.4. Other chemical and physical properties of the WTR are given in Section 4.3.

5.6 Field experiment maintenance

Routine maintenance of both experiments involved keeping the plots and surrounds weed-free by application of a glyphosphate herbicide (Roundup® and Erase 360S.L.) on the fallow treatments and Basagran on the grassed treatments when necessary, and regular irrigation and mowing (about every 6-8 weeks) of the grassed treatments.

At Brookdale Farm the plots to be seeded with ryegrass (April 1999) were fertilised with 200 kg N ha^{-1}, 30 kg P ha^{-1} and 185 kg K ha^{-1} as limestone ammonium nitrate (LAN), diammonium phosphate (DAP), and potassium chloride (KCl). Subsequently 50 kg N ha^{-1}, 30 kg P ha^{-1} and 50 kg K ha^{-1} were applied in January of each year with an additional 50 kg N ha^{-1} added every 3 months. The same fertiliser scheme, as used in the maintenance applications, was used when the experiment was replanted to tall fescue (March 2001), and this continued until the end of the experiment.

At Ukulinga fertiliser was added at 400 kg N ha^{-1}, 30 kg P ha^{-1} and 150 kg K ha^{-1} prior to seeding with tall fescue (April 2000). Additional N was added every 3 months at 50 kg N ha^{-1}. In February 2001 maintenance fertiliser (50 kg N ha^{-1}, 50 kg K ha^{-1} and 30 kg P ha^{-1}) was added to the lower half of each grassed plot to investigate the effect of additional fertiliser on the grass, compared to that on the unfertilised section of the same plots. After the April 2001 harvest, N fertilisation continued as before over the entire plot. In February 2002 the entire trial was refertilised with the abovementioned maintenance rates. Additional N was added every 3 months, until the completion of the experiment.

5.7 Grass harvesting and analysis

5.7.1 Grass harvesting

Harvesting was done by randomly placing a 0.25 x 0.25 m quadrat in a plot and cutting the grass in the quadrat with a sheep shear to about 200 mm above the soil surface. Three quadrats were harvested in each plot and the material from these quadrats was bulked before being prepared for analysis.

5.7.1.1 Brookdale Farm

The perennial ryegrass was harvested at Brookdale in October 1999, December 1999 and July 2000, and selected treatments were sampled in February 2001. In March 2001 the experiment was replanted to Dovey tall fescue, which, after establishment, was harvested in November 2001, February 2002, October 2002 and February 2003. Initially yield was measured but it became clear that the unfenced plots at Brookdale Farm allowed buck access to the grassed plots so making any measurement of yield meaningless. Therefore, after October 1999 no further yield data was collected.

5.7.1.2 Ukulinga Farm

The grass was harvested at Ukulinga in July 2000, September 2000, February 2001, April 2001 (lower and upper sections of each plot harvested separately; Section 5.6), August 2001, November 2001, February 2002, April 2002, August 2002, November 2002, February 2003 and May 2003. The protection of the site at Ukulinga enabled yield to be monitored throughout the experiment and measurements were made of dry yield mass for most harvests.

5.7.2 Grass chemical analysis

All harvests were analysed for nutrient uptake at the Soil Fertility and Analytical Services Laboratory, KZN Department of Agriculture and Environmental Affairs,

Cedara. Bulked grass samples were dried at 65^{o}C, weighed and then a sub-sample was analysed for Ca, K, Mg, N (in some cases), P, Cu, Mn and Zn (Riekert and Bainbridge, 1998). The procedure was essentially dry digestion followed by dissolving in 1M HCl and analysis by atomic absorption spectrophotometry. For the analysis of Cd, Co, Cr, Ni and Pb the method of Riekert and Bainbridge (1998) was followed with the difference that instead of the 1g of plant material, 5 g were used.

5.8 Soil sampling and analysis

Bulk soil samples (0 - 200, 200 - 400 and 400 - 600 mm depths) were collected at Brookdale Farm from the untreated plots in September 1998, and then from the fallow treatments in February 1999, September 1999, February 2000, February 2001, September 2001, October 2002 and October 2003. At Ukulinga bulk soil samples were collected from the untreated plots in October 1999, and then from the treated plots in April 2000, February 2001, September 2001, October 2002 and October 2003. These were air-dried and stored for any future need that may arise.

In addition samples were taken periodically at selected depths from some of the treatment plots at both field experiments for saturated paste analysis (United States Salinity Laboratory Staff, 1954). Details of these are given in Section 14.4.

5.9 Groundwater sampling and analysis

5.9.1 Soil water collectors

Soil water samplers (Model 1900, Soil Moisture Corporation, CA, USA) were initially installed at Brookdale Farm but due to a combination of low rainfall and logistical problems they were removed and installed at Ukulinga Farm in April 2000. The collectors were placed at a depth of about 450 mm within the upper half of the 0, 320 and 1280 Mg ha^{-1} WTR-treated plots and just outside the lower end of the 1280 Mg ha^{-1} treated plot, to determine whether there was any movement of the solutes out of the plot into the surrounding areas. Both the grassed and fallow plots were studied.

The samplers consist of a porous ceramic cup that is attached via PVC tubing to a pump that is used to create a vacuum within the sampler. The PVC tubing is then closed with a pinch clip. The vacuum causes the soil water to move through the ceramic cup and into the sampler. The amount of water collected is thus a function of the soil water content that in turn depends on sufficient rainfall. Water sampling was carried out whenever soil water conditions were favourable. The samples were analysed for basic chemical properties and metal concentrations (Section 14.2.4).

5.9.2 Dam and borehole sampling at Brookdale Farm

About 400 m downslope from the field experiment at Brookdale Farm is a small dam and adjacent to that a borehole (29^{o}31’20”S; 30^{o}12’50”E). Both of these have been monitored by Umgeni Water since 1997 for a wide range of properties (Appendices 14.1 and 14.2), in order to check that no unacceptable leaching has taken place from the upslope WTR disposal areas.

CHAPTER 6

EFFECT OF A WATER TREATMENT RESIDUE ON SOIL PHYSICAL PROPERTIES

6.1 Introduction

In addition to the soils sampled from the field experiments (Chapter 5) it was considered important to widen the range of soil textures being investigated in the laboratory-based study, and therefore the applicability of the study. Therefore, two additional soils were included, namely a sandy soil classified as Cartref form (Soil Classification Working Group, 1991), Typic Haplaquept (Soil Survey Staff, 1998) and Tenosol (Isbell, 1996), and a typically hard-setting soil of the Valsrivier form (Soil Classification Working Group, 1991), Typic Haplargid (Soil Survey Staff, 1998), Dermosol (Isbell, 1996). The rationale behind selecting the Cartref soil was that if the silt and clay contained in water treatment residue (WTR) disaggregated, then the physical properties of sandy-textured soils could be improved. On the other hand, if the WTR remains as discrete aggregates then the potential exists for it to be used in the amelioration of hard-setting soils such as the Valsrivier. The Cartref was obtained from open grassland near Claridge, approximately 30 km northwest of Pietermaritzburg. The Valsrivier soil was sampled from a field under sugarcane at Muden, KwaZulu-Natal. At both locations only the topsoil (0-0.2 m depth) was collected.

Most of the samples (approximately 300 kg per soil type) were first air-dried and then mechanically crushed to pass a 2 mm sieve. Each soil type was mixed thoroughly before being stored in plastic bins. Air-dried Midmar WTR (the same batch as that used for the Brookdale Farm experiment) was used in the laboratory studies. Due to the strong bonds between the polymer (added during the water treatment process) and the constituent silt and clay fraction, a small rock-crushing plant was needed to pass the WTR through a 2 mm sieve. The WTR was mixed thoroughly and then stored alongside the soils.

6.1.1 Properties of dry water treatment residue and the additional soils studied

Although further details regarding the characteristics of the soils used in subsequent studies are presented in the relevant sections, some basic physical and chemical data for the Valsrivier and Cartref soils and the dry WTR used in the laboratory investigations are given in Table 6.1. Details of the Hutton (from Brookdale Farm) and Westleigh (from Ukulinga Farm) are given in Chapter 5 and more comprehensive details of the Midmar WTR are given in Chapter 4. For the sake of convenience the Midmar WTR will henceforth be referred to as WTR throughout this Chapter.

6.1.2 Preparation of soil-water treatment residue mixtures

In mixing the WTR with soil an important consideration is the depth to which the WTR will be incorporated in the field. This depth is the controlling factor in converting the WTR application rate from a mass per unit area basis (for example Mg ha^{-1}) to a mass of WTR per mass of soil basis. The WTR and soil were mixed at the required application rates on an equivalent oven-dry mass per mass basis, assuming a

maximum depth of incorporation of 0.20 m. The bulk density of the undisturbed soil was used in the calculations (Table 6.2).

Table 6.1 Some basic physical and chemical properties of the Valsrivier and Cartref soils and dry Midmar water treatment residue (WTR)

Property		Valsrivier	Cartref	Dry WTR
Particle size distribution (%)	Soil Texture[a]	Clay loam	Sandy loam	
	Coarse sand (0.50 - 2.0 mm)	5	21	76
	Medium sand (0.25 - 0.50 mm)	8	20	11
	Fine sand (0.15 - 0.25 mm)	29	25	4
	Very fine sand (0.053 - 0.15 mm)	14	11	2
	Coarse silt (0.02 - 0.053 mm)	10	6	2
	Fine silt (0.002 - 0.02 mm)	8	5	2
	Clay (<0.002 mm)	26	12	3
Particle density (Mg m^{-3})		2.68	2.70	2.63
Cation exchange capacity ($cmol_c$ kg^{-1})		10.50	5.27	21.55
Organic carbon (g kg^{-1})		12.7	12.4	47.7
pH (water)		6.81	6.04	7.42
pH (KCl)		5.91	4.98	7.26
Electrical conductivity (mS m^{-1}) 1:5 water extract		45.8	27.1	46.2

[a] Soil Classification Working Group (1991).

Table 6.2 The soil-water treatment residue mixtures used in some of the laboratory-based studies, expressed as the equivalent oven-dry mass of water treatment residue to mass of soil

Soil	Bulk Density (kg m^{-3})	Amount of WTR applied to the soil (kg kg^{-1} soil) corresponding to the field WTR application rates indicated (Mg ha^{-1})					
		0	80	160	320	640	1280
Hutton	1252	0	0.03	0.06	0.13	0.26	0.51
Westleigh	1360	0	0.03	0.06	0.12	0.24	0.47
Cartref	1499	0	0.03	0.05	0.11	0.21	0.43
Valsrivier	1450	0	0.03	0.06	0.11	0.22	0.44

It can be seen from Table 6.2 that the amount of WTR added to the soils ranged from a minimum of 3% (80 Mg ha^{-1}) to a maximum between 43 and 51% (1280 Mg ha^{-1}). All the laboratory studies reported in this Chapter are based on the ratios given in Table 6.2 (unless indicated otherwise).

6.2 Water retention

6.2.1 Introduction

Soil water retention is a basic property of the soil that regulates the storage and movement of water within the soil and ultimately plant growth (Kern, 1995; Chen and Wheater, 1999). It is sensitive to both the inherent properties of the soil and past management practices. Knowing the changes, if any, caused by the land disposal of WTR is important as this will have a bearing on the timing of land management operations and agricultural productivity.

6.2.2 Materials and methods

6.2.2.1 Field sampling

Undisturbed soil cores were collected at various times of the year from the Brookdale and Ukulinga field trials to monitor any changes in water retention properties (Table 6.3).

Table 6.3 Sampling dates at which undisturbed cores were collected from the 0 to 50 mm soil depth at the Brookdale and Ukulinga Farm experiments

Site	Sampling date (month/year)									
Brookdale	02/99	04/99	06/99	11/99	04/00	06/00	02/01	09/01	08/02	06/03
Ukulinga				12/99	04/00	08/00	02/01	09/01	08/02	06/03

At Brookdale, the 0, 80, 320 and 1280 Mg ha^{-1} WTR-incorporated treatments and the high application rates of lime, gypsum and polyacrylamide (PAM) were sampled. Since the breakdown of the WTR was expected to be greatest nearer to the soil surface, cores were obtained from the 0 to 50 mm depth of the plot. Rigid stainless steel sleeves (75 mm i.d. and 50 mm height) were hammered vertically into the plot surface using a core sampler. The cores were then excavated using a small trowel.

Soil cores were collected when the soil was approximately at field capacity to reduce the influence of swelling and shrinkage on the retention curve and to avoid the risk of fracturing the soil core when sampling during drier soil conditions. During winter (June and July) it was necessary to wet the soil 2 days before sampling was undertaken.

Due to the intended long-term duration of the trial it was considered unwise to extract a large number of cores from each plot given the area disturbed in the sampling of even a small sized core. As a result four replicates per treatment were collected during each investigation. These were taken from two separate positions within each of the two replicated plots. The pre-weighed steel cylinders and their contents were excavated from the plot, covered in plastic to reduce evaporative losses and transported to the laboratory.

6.2.2.2 Soil core preparation and treatment

Once in the laboratory, the cores were trimmed flush with the edge of the ring by gradually shaving away the excess soil with a sharp blade. A single layer of pre-weighed cheesecloth, held in place by an elastic band was used to cover the bottom face of the core to retain the soil within the steel sleeve. The cores were then wet from the bottom by placing them in a water bath for 48 h. During the final stages of wetting, water in the bath was raised close to the upper surface of the core. Finally, each core was removed from the water bath and allowed to drain for 10 min before being weighed to determine the saturated water content. The cores were then placed on a sand bath tension table (Smith and Thomasson, 1974). The mass of the core at matric potentials of -1, -2, -3, -4, -5, -6, -8 and -10 kPa was measured after equilibration at each tension for 48 h. Following the -10 kPa setting, the samples were transferred to pressure chambers and equilibrated at -30 and -100 kPa matric potential. Once equilibrated the mass of each core was determined. On average it took approximately 7 days for equilibrium to be reached at each potential. The permeability of air through the core was also measured once equilibration at -100 kPa was obtained (Section 6.3). The cores were then oven-dried at 105^{o}C until they had attained a constant mass (usually in about 2 days). This final mass was used to calculate the mass water content at each matric potential. The bulk density of the core, obtained as the mass of the dry soil divided by its volume, was used to transform the mass water content to an equivalent volumetric water content by the relationship:

$$q_v = q_m \, x \, r_b \, x \, r_w^{-1} \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 6.1}$$

where, θ_v is the volumetric water content (m^3 m^{-3}), θ_m is the mass water content (kg kg^{-1}), ρ_b is the bulk density of the soil (kg m^{-3}) and ρ_w is the density of water (kg m^{-3}).

6.2.2.3 Preparation of repacked soil cores

Without field trials on the Valsrivier and Cartref soils, water retention properties were measured on repacked samples. Studies also included the Hutton and Westleigh soils from the Brookdale and Ukulinga Farm experiments. Air-dried soil and WTR (<2 mm) were first mixed on an oven-dry basis at rates of 0, 80, 320 and 1280 Mg ha^{-1} assuming a soil depth of 200 mm in calculating the mass ratio of WTR to soil (Table 6.2). Each treatment had four replicates. The bulk density obtained in packing an equivalent set of treatments for saturated hydraulic conductivity was chosen for this study (Section 6.3). These bulk densities are presented in Figure 6.21 for the Hutton, Westleigh, Valsrivier and Cartref soils, respectively. The same steel cylinders used for collecting the undisturbed cores were used to retain the samples.

For each WTR-soil mixture the mass of oven-dry material required to obtain the bulk densities shown in Figure 6.21 was calculated according to the relationship:

$$r_b = M \, x \, V^{-1} \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 6.2}$$

where ρ_b is the required bulk density (kg m^{-3}), M is the mass of oven-dry material (kg) and V is the volume of the steel sleeve used to retain the sample (m^3).

The oven-dry mass of each sample was then converted to an air-dry equivalent by correcting for its water content and this mass was used in the packing of the cylinders. Since the cylinders were open at both ends, they were placed on a flat steel plate before packing. Half the required quantity of air-dry material was poured via a funnel loosely into the cylinder. The material was then compacted slightly to a depth of 25 mm using a small hydraulic press, after which the balance of the material was added and re-compacted level with the top face of the cylinder. The ensuing treatment of the repacked cores was exactly as for the undisturbed cores, except that before measuring their water retention properties, two wetting and drying cycles were imposed. In a single cycle the samples were saturated for 24 h and then equilibrated for 48 h at a matric potential of -10 kPa. This technique of wetting and drying repacked soil samples to encourage a final bulk density has been successfully used by *inter alia* Gupta *et al.* (1977) and Wu *et al.* (1990). Limited shrinkage of the samples occurred which implies minimal change in the bulk density. Following the wetting and drying cycles, water retention was measured as for the undisturbed core samples, with the inclusion of -60 kPa matric potential.

6.2.2.4 Measurement at the wilting point (-1500 kPa matric potential)

Soil water retention at the wilting point was determined in triplicate for WTR-soil mixtures (four soil types) of 0, 80, 160, 320, 640 and 1280 Mg ha^{-1}, which were prepared according to Table 6.2. In addition the wilting point for air-dried, <2 mm pure WTR was also measured. A sample of each treatment (three replicates) was poured into pre-weighed rubber rings (52 mm i.d., 9.5 mm height). The samples were capillary saturated for 48 h after which they were desorbed in pressure plate apparatus at a matric potential of –1500 kPa. Equilibration of the samples occurred in approximately 10 days. The mean mass water content and the mean bulk density of the repacked cores were used to obtain the volumetric water content (Equation 6.2).

6.2.3 Results and Discussion

6.2.3.1 Brookdale Farm

Influence of tillage

Loosening of the soil by tillage during the establishment of the field trial in October 1998 had a marked influence on the retention curve (Figure 6.1).

The main effect of tillage, as expected, was a decrease in bulk density and a concomitant increase in the total porosity. Despite the 3 months since the establishment of the trial, the mean total soil porosity recorded during February 1999, which was calculated from both the particle density and the bulk density, was 0.578 $m^3\ m^{-3}$. This corresponds closely with the saturated water content of 0.572 $m^3\ m^{-3}$ obtained from the retention curve (Figure 6.1).

The saturated soil water content for the control treatment in April 1999 was 0.534 $m^3\ m^{-3}$, a decrease of 0.038 $m^3\ m^{-3}$ from February 1999 (Figure 6.1). This finding is consistent with the natural process of consolidation expected during cycles of wetting and drying. By November 1999 consolidation of the tilled soil had advanced to its probable maximum for the control treatment, denoted by the much lower saturated

water content of 0.480 m^3 m^{-3} (Figure 6.1). Since then, deviations from this value occurred which were associated predominantly with the swelling and shrinkage of the soil upon wetting and drying, as well as high variability associated with these types of measurements. However, it should be noted that subsequent measurements rarely exceeded the water contents recorded for the February 1999 sampling, and were only marginally higher than seen for the initial sampling period.

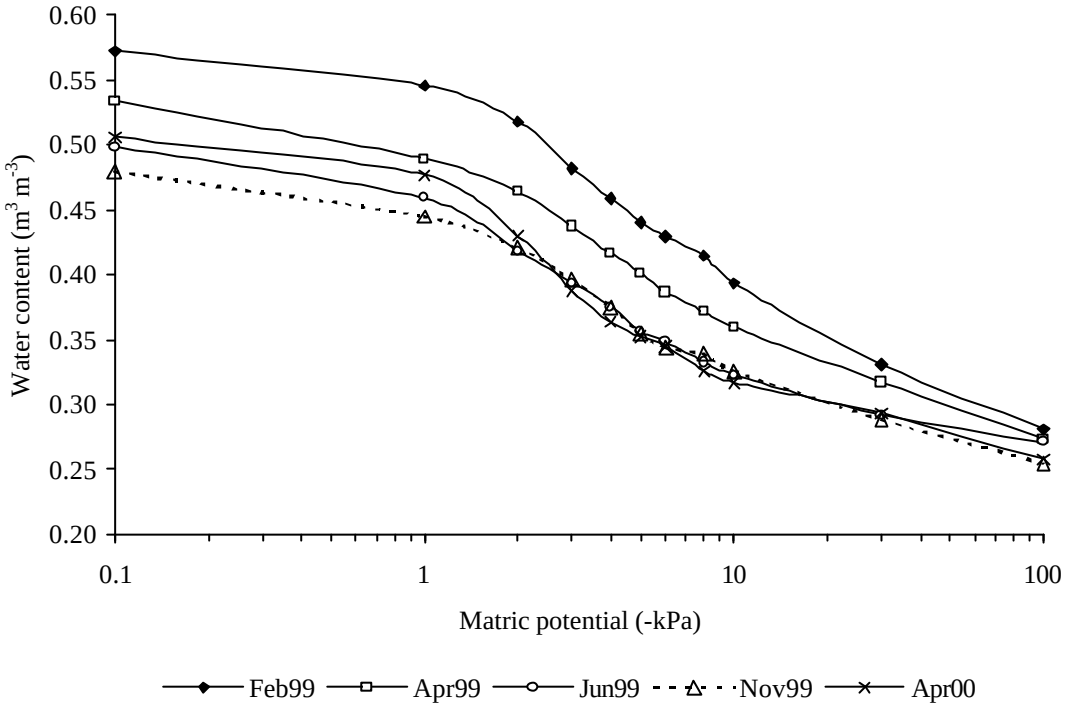


Figure 6.1 The effect of tillage on the water retention curves for the control treatment measured over time (up to April 2000) at Brookdale Farm.

Effect of residue, lime, gypsum and polyacrylamide

No significant differences were found at saturation, -10, -30 and -100 kPa matric potentials for the February 1999 sampling date (Appendix 6.1). This is perhaps a result of the effect of tillage masking any differences that may have been present. The April 1999 sampling showed significant overall differences between treatments at matric potentials of -0, -10 and -100 kPa, with the 1280 Mg ha^{-1} WTR treatment having the highest recorded water content at all matric potentials. The June 1999 sampling was the first to include all treatments, with significant differences between means observed at the saturation matric potential. The highest water contents were recorded for the 320 and 1280 Mg ha^{-1} WTR application rates, although they did not perform significantly different from the 80 Mg ha^{-1} WTR or 10 Mg ha^{-1} lime treatments. Subsequent sampling dates did not show a consistent pattern, although frequently, where overall significant differences were found, the 1280 Mg ha^{-1} WTR treatment was not significantly different from the 320 Mg ha^{-1} WTR or lime treatment. The 1280 Mg ha^{-1} treatment did, however, generally have higher water contents at each matric potential for all sampling periods. The effect of gypsum and PAM was not clear, with no consistent pattern being evident. These data indicate that

the inherently stable structure of the Hutton may not be drastically influenced by the addition of any of the treatments, or that the treatment effects may be of short-term duration. It is likely that the observed differences reflect variability associated with soil moisture (shrink and swell characteristics), faunal influences and sampling.

Readily available water (RAW) content was used as a measure of the change over time for each treatment, as an accurate estimate of plant available water (PAW) for the field treatments was not possible due to the retention curves for the field data only extending to a matric potential of -100 kPa. Nevertheless this showed that for all treatments there were overall significant differences (Appendix 6.2). However, there were no consistent trends for any of the treatments, possibly reflecting variability due to sampling rather than changes caused by any of the treatments.

Water retention curves for selected WTR-incorporated treatments at Brookdale Farm for June 1999, June 2000, September 2001, October 2002 and June 2003 are shown in Figures 6.2 to 6.6, respectively, with the other sampling dates shown in Appendix 6.3. Due to the high levels of variability both within and between the treatments, no clear relationship between WTR content and water retention could be found for the June 1999 sampling, probably due to the effect of tillage, although the 1280 Mg ha^{-1} treatment did show marginally higher water content than the other treatments at saturation and -100 kPa matric potentials (Figure 6.2).

The effect of tillage persisted until November 1999 when, perhaps for the first time, differences in water retention because of the treatments applied were noted (Appendix 6.3). At this time the 1280 Mg ha^{-1} treatment performed significantly better than the other WTR treatments at saturation and the -10 kPa matric potential, while having non-significantly higher water contents at -30 and -100 kPa than the other treatments.

By June 2000 the effect of WTR additions was more evident (Figure 6.3). The general order in water retention (at saturation) between the treatments was 1280 > 320 > 80 > 0 Mg ha^{-1}. This pattern persisted up to the -100 kPa matric potential, where the differences between treatments were less marked, the WTR treatments generally performing significantly better than the gypsum and PAM treatments (Appendix 6.1). Nevertheless, the similarity of the curves representing the 0, 80 and 320 Mg ha^{-1} treatments, especially from a matric potential of -30 kPa downwards, suggests that even at the 320 Mg ha^{-1} level, the WTR did not cause any marked change in water retention. Despite the increase in water retention on the 1280 Mg ha^{-1} treatment, the overall shapes of the retention curves at matric potentials typically greater than -1 kPa are similar to that of the control treatment. The only effect of the WTR seems to have been to shift the retention curve to a higher water content at a given matric potential. The lime treatment showed considerably higher water contents from -2 to -10 kPa matric potentials. No cause could be determined for this pattern and as it only occurred on this occasion it was probably due to sampling variability.

The data for September 2001 showed a similar pattern to earlier samplings (Figure 6.4), with the 1280 Mg ha^{-1} treatment still having a generally higher water content at most matric potentials, although the difference from the other treatments was lower than at June 2000. While the lime treatment performed similarly to the WTR treatments, the gypsum and PAM treatments showed increased water retention in the matric potential range from -1 to -6 kPa. The 1280 Mg ha^{-1} treatment showed a

significantly higher water content at saturation for the October 2002 sampling, this trend persisting for all other matric potentials, although not significantly (Figure 6.5). The 0, 80 and 320 Mg ha^{-1} WTR, lime, gypsum and PAM treatments all behaved similarly.

By June 2003 the 1280 Mg ha^{-1} treatment only showed a significantly higher water content at saturation, when compared to the other WTR treatments, as well as the gypsum and PAM treatments (Appendix 6.1, Figure 6.6). It was not significantly different from the lime treatment.

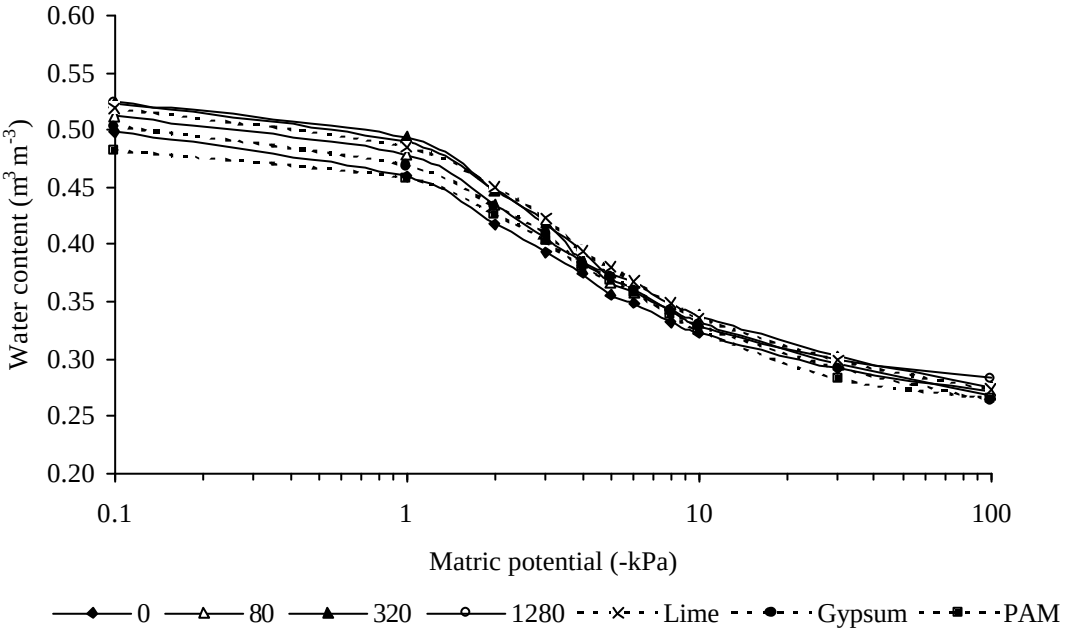


Figure 6.2 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in June 1999 at Brookdale Farm.

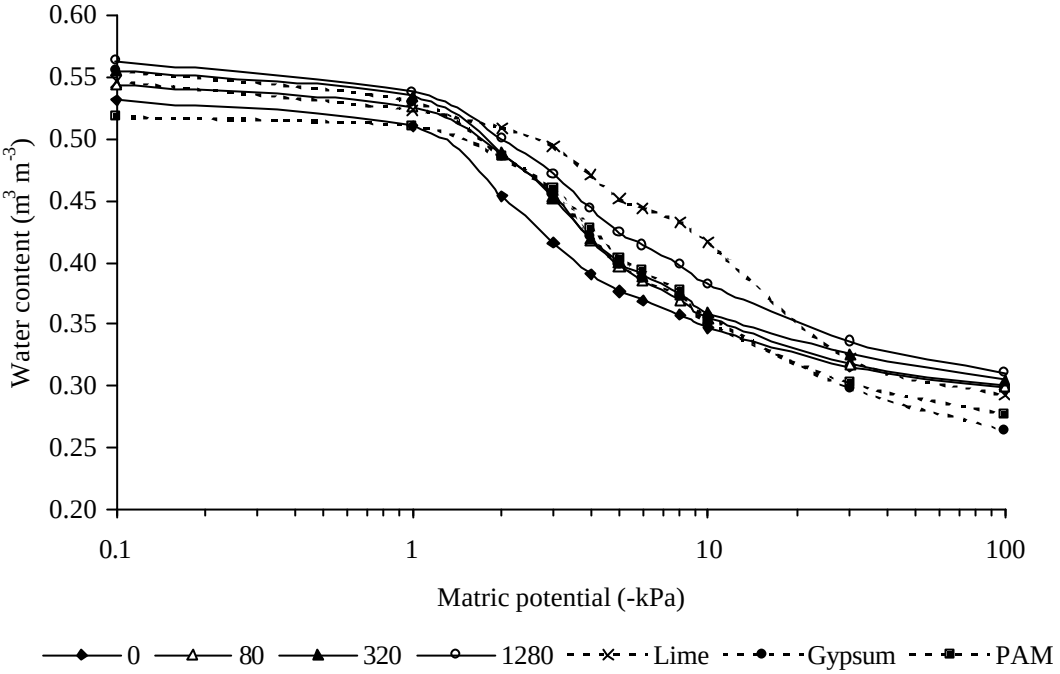


Figure 6.3 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in June 2000 at Brookdale Farm.

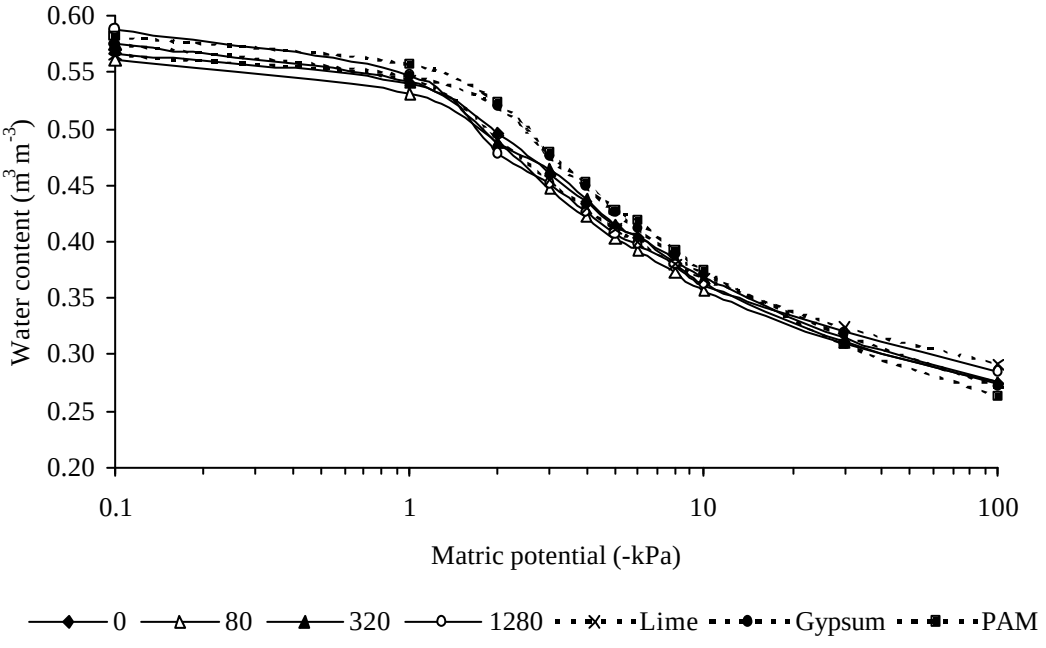


Figure 6.4 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in September 2001 at Brookdale Farm.

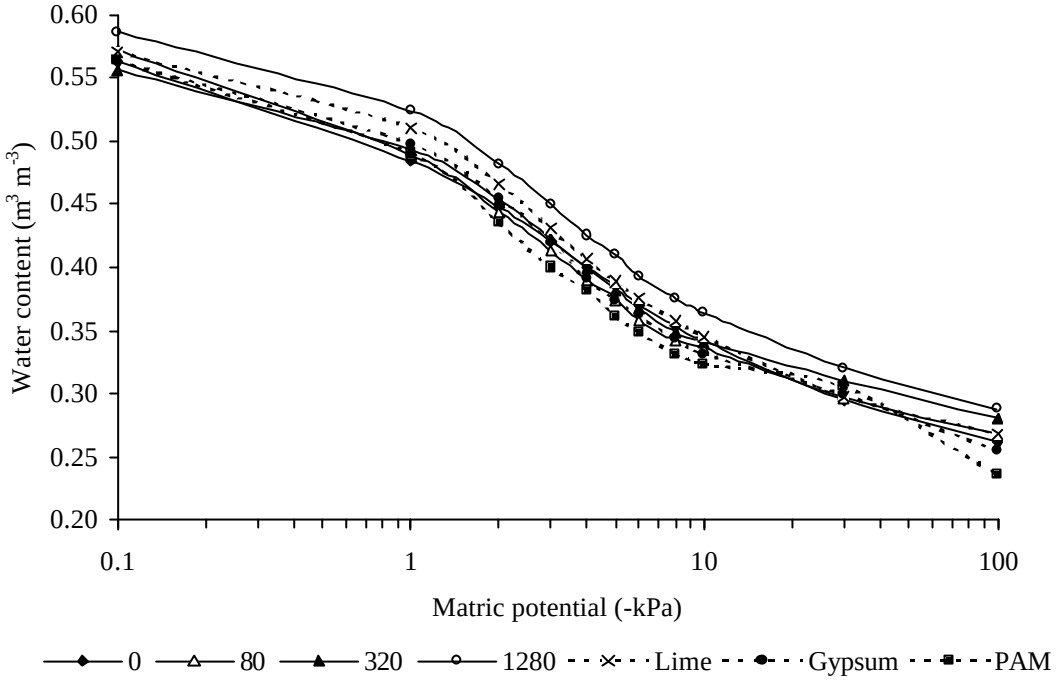


Figure 6.5 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in October 2002 at Brookdale Farm.

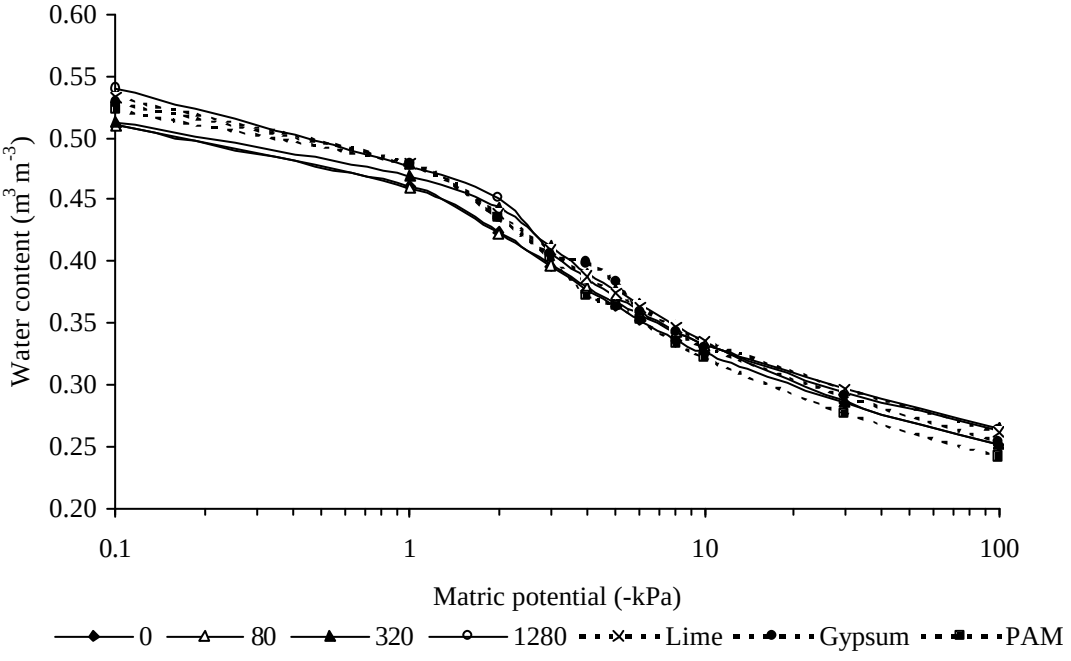


Figure 6.6 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in June 2003 at Brookdale Farm.

6.2.3.2 Ukulinga Farm

Influence of tillage

The effect of tillage at the Ukulinga trial is indicated by the December 1999, April 2000, July 2000 and February 2001 water retention data for the control treatment (Figure 6.7). Tillage of the Westleigh soil at Ukulinga, as at Brookdale Farm, decreased the bulk density by loosening the top 0.2 m of the soil. With time a decrease in the total soil porosity occurred (shown by the decrease in the saturated soil water content) as the bulk density increased due to consolidation of the soil. The collapse of large pores is further shown by the lower volumetric water content held between saturation and -2 kPa matric potential at April 2000 as compared with December 1999 (Figure 6.7).

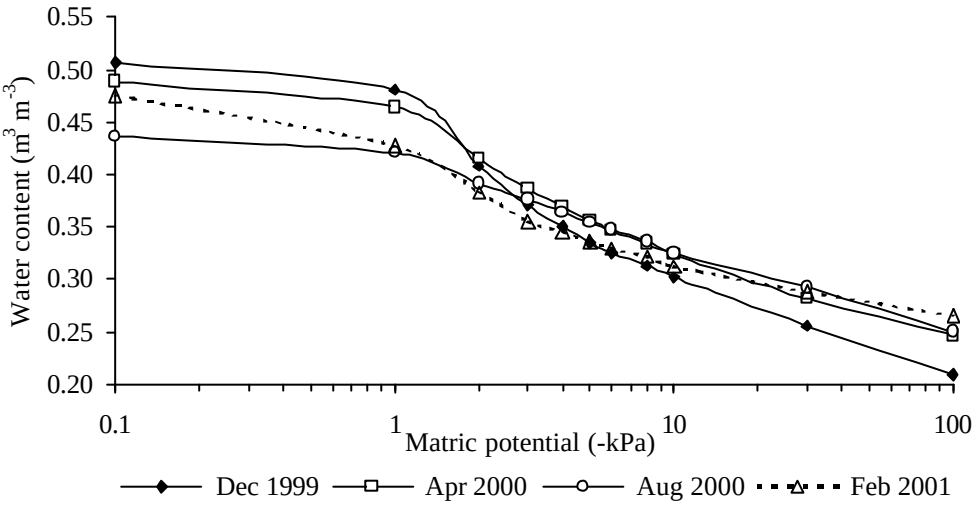


Figure 6.7 Effect of tillage on the water retention curve for the control treatment at Ukulinga Farm.

Effect of residue, lime, gypsum and polyacrylamide

In almost all cases the 1280 Mg ha^{-1} treatment showed significantly higher water contents than the other treatments at saturation, -10, -30 and -100 kPa matric potentials (Appendix 6.4). The 320 Mg ha^{-1} treatment tended to have significantly higher saturated water content when compared to the other treatments, regardless of sampling date. This pattern was not evident for the other matric potentials considered. The 0 and 80 Mg ha^{-1} WTR, and lime, gypsum and PAM treatments tended to be similar at all sampling dates, although some significant differences from the WTR treatments were observed (Appendix 6.4).

A comparison of the RAW contents for each treatment over time (Appendix 6.5) shows that for the 0, 80 and 1280 Mg ha^{-1} WTR treatments, the December 1999 sampling was not significantly different from the April 2000 sampling. However, the RAW contents for the other sampling dates were significantly different from the December 1999 sampling.

The 320 Mg ha^{-1} WTR treatment at December 1999 was significantly different from April 2000, but not at August 2000. For all WTR treatments the minimum RAW content was recorded at February 2001, with an increase subsequently. However, the February 2001 values were generally not significantly different from the subsequent samplings periods. It should also be noted that for all sampling dates the 1280 Mg ha^{-1} treatment had the lowest RAW content when compared to the other WTR treatments. While the gypsum treatments were not included in the December 1999 sampling, the April and August 2000 samplings were not significantly different from one another, although these two dates showed significant differences from the other sampling dates. This pattern was not consistent for the lime treatment, perhaps due to sampling variability. The PAM treatment did not show a clear pattern, but it would appear that generally there was an increase in RAW content over time.

Water retention curves for the treatments being investigated at Ukulinga for December 1999, August 2000, September 2001, October 2002 and June 2003 are shown in Figures 6.8, 6.9, 6.10, 6.11 and 6.12, respectively, with the other sampling dates shown in Appendix 6.6.

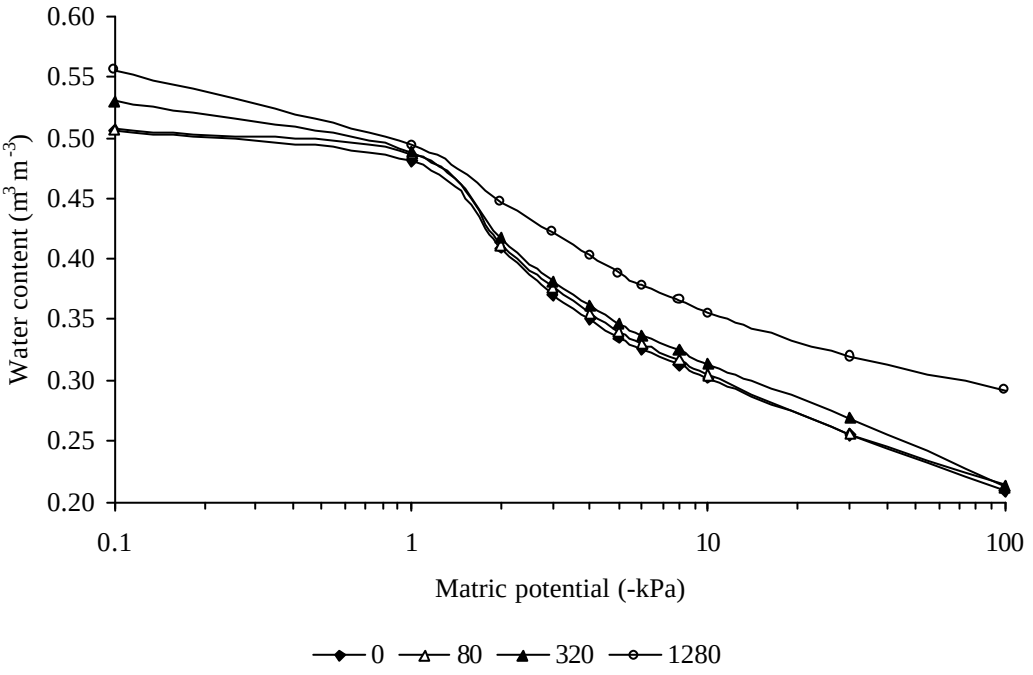


Figure 6.8 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue (0, 80, 320 and 1280, respectively) on water retention measured in December 1999 at Ukulinga Farm.

Three months after the trial was established (December 1999), the retention curves show clearly defined differences between the treatments in spite of the complicating effect of tillage (Figure 6.8). The main reason for such clarity in the results is that between October 1999 and December 1999 rain assisted greatly in the consolidation of the soil and the more rapid reversion of the effects of tillage. The saturated soil water content of the WTR-amended treatments was in the order, 1280 > 320 > 80 = 0 Mg ha^{-1}, which is consistent with relationships measured for the bulk density (Appendix 6.7). The difference in the saturated volumetric water content between the

1280 Mg ha^{-1} WTR-amended soil and the control treatment was 0.049 m^3 m^{-3}. The general shape of the retention curves for the 0, 80 and 320 Mg ha^{-1} treatments is similar from a matric potential of -1 kPa onwards. The 1280 Mg ha^{-1} treatment on the other hand consistently held more water at equivalent matric potentials. For the December 1999 sampling at -10 kPa the difference in water content between the control and the 1280 Mg ha^{-1} treatment was 0.054 m^3 m^{-3}, while at -100 kPa an equivalent value was 0.105 m^3 m^{-3} (Figure 6.8).

The general trend in water retention properties between the treatments recorded in April 2000 (Appendix 6.6) was fairly similar to that measured in December 1999 (Figure 6.8). As found previously, the 1280 Mg ha^{-1} treatment held a greater amount of water compared with the rest of the treatments throughout the range of matric potential investigated. The general trend in the retention curve measured during August 2000 (Figure 6.9) was similar to that in April, although the 320 Mg ha^{-1} treatment showed marginally lower saturated water content than found previously. Similar patterns persisted at all subsequent samplings dates. The saturated water content of the 80 Mg ha^{-1} treatment for the September 2001 sampling was marginally higher than that of the control (Figure 6.10), but returned to a similar water content for the October 2002 (Figure 6.11) and June 2003 (Figure 6.12) sampling periods.

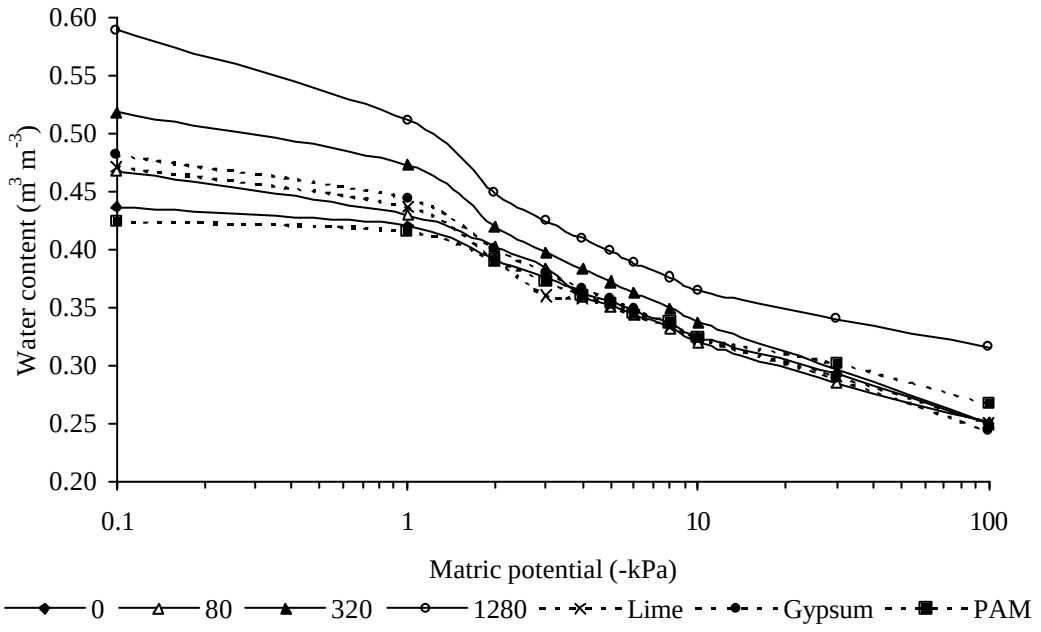


Figure 6.9 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in August 2000 at Ukulinga Farm.

The lime, gypsum and PAM treatments performed similarly to the control and 80 Mg ha^{-1} WTR treatments at most sampling dates. This is confirmed by the generally non-significant differences (Appendix 6.4) seen when these treatments were compared by ANOVA.

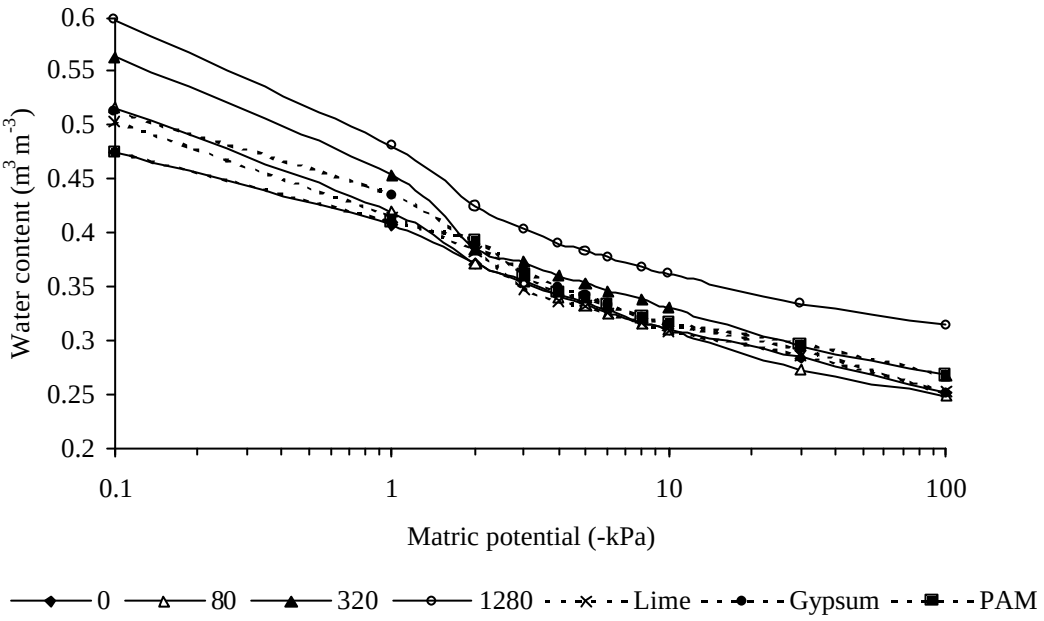


Figure 6.10 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in September 2001 at Ukulinga Farm.

6.2.3.3 Repacked cores

Although the field is the ultimate 'laboratory' there is often a need for laboratory studies, particularly when viewed against the high degree of variability encountered at the Brookdale trial. The objectives in evaluating the influence of WTR on soil water retention using repacked samples of a predefined grade (<2 mm) were to (i) avoid the complicating influence of tillage, (ii) carry out the experiment using accurately controlled ratios of WTR:soil and (iii) extend the study to the investigation of the Valsrivier and Cartref soils. Retention curves for the Hutton, Westleigh, Valsrivier and Cartref soils as obtained from this study are presented in Figures 6.13 to 6.16, respectively.

Many inferences made from the field studies were further substantiated in the laboratory study. The decrease in bulk density of the WTR-amended treatments caused an increase in the amount of water retained at saturation. The difference in total porosity between the 1280 Mg ha^{-1} and the control treatment was 3.9% for the Hutton soil, 5.8% for the Westleigh soil, 8.5% for the Valsrivier soil and 11.4% for the Cartref soil.

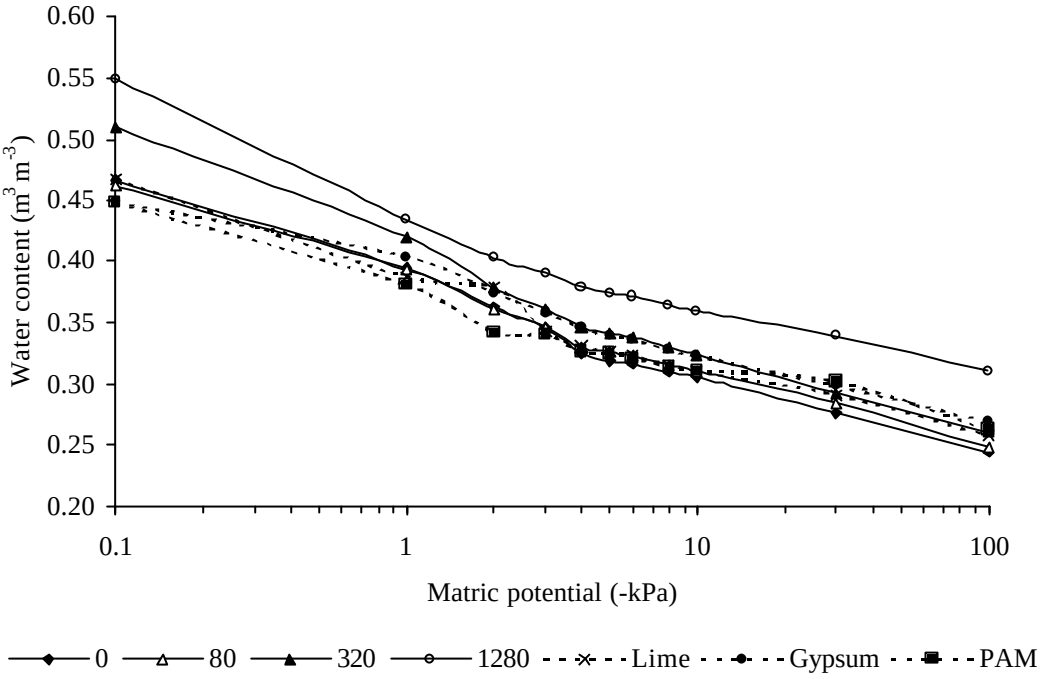


Figure 6.11 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in October 2002 at Ukulinga Farm.

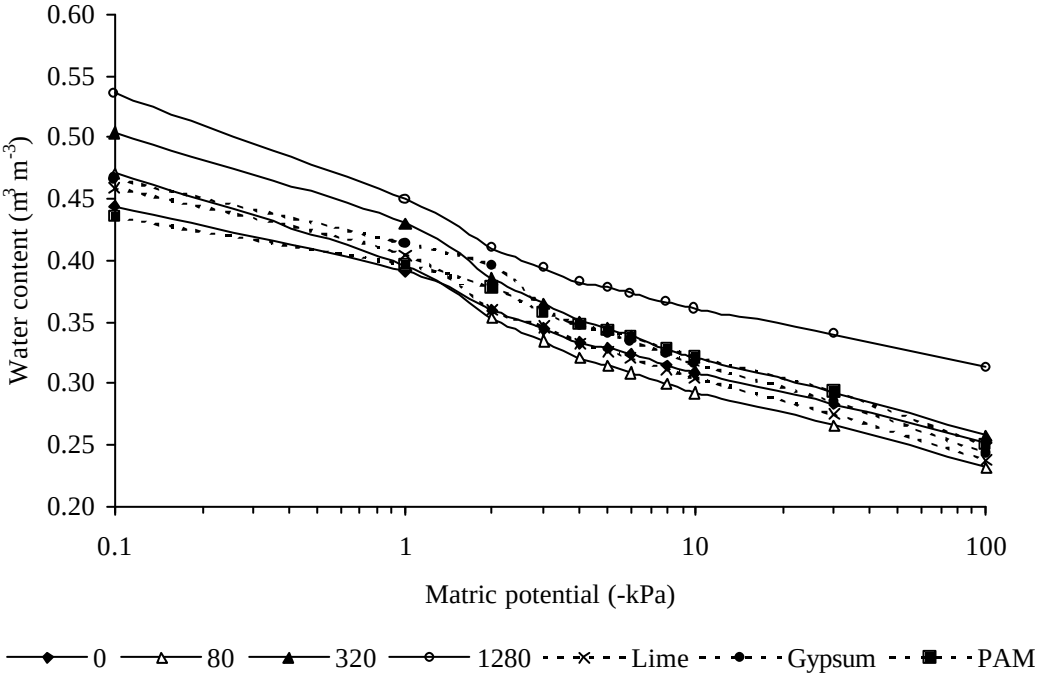


Figure 6.12 The effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (0, 80, 320, 1280, Lime, Gypsum and PAM, respectively) on water retention measured in June 2003 at Ukulinga Farm.

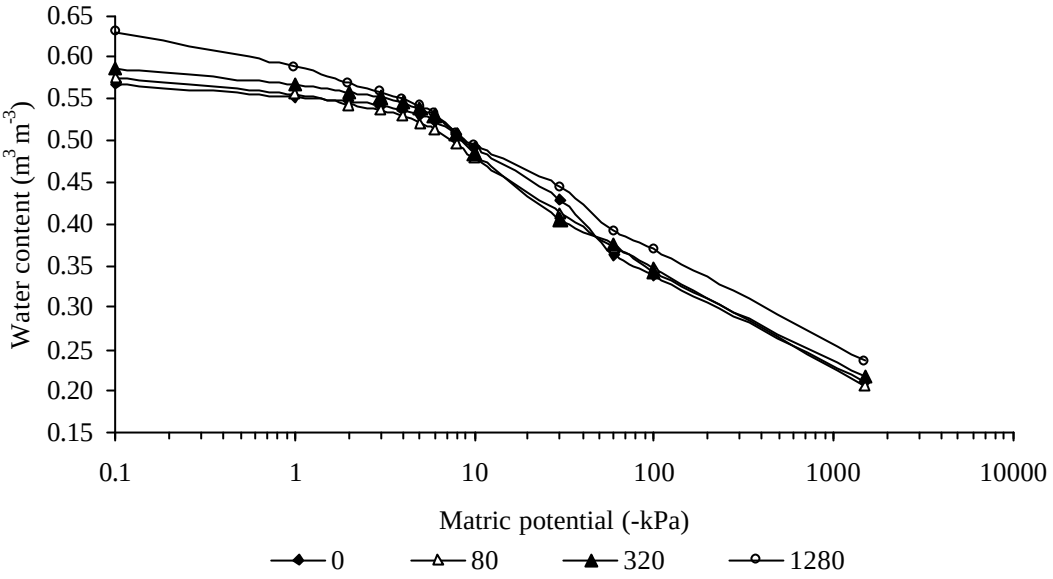


Figure 6.13 Water retention curves of the repacked Hutton soil amended with 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue.

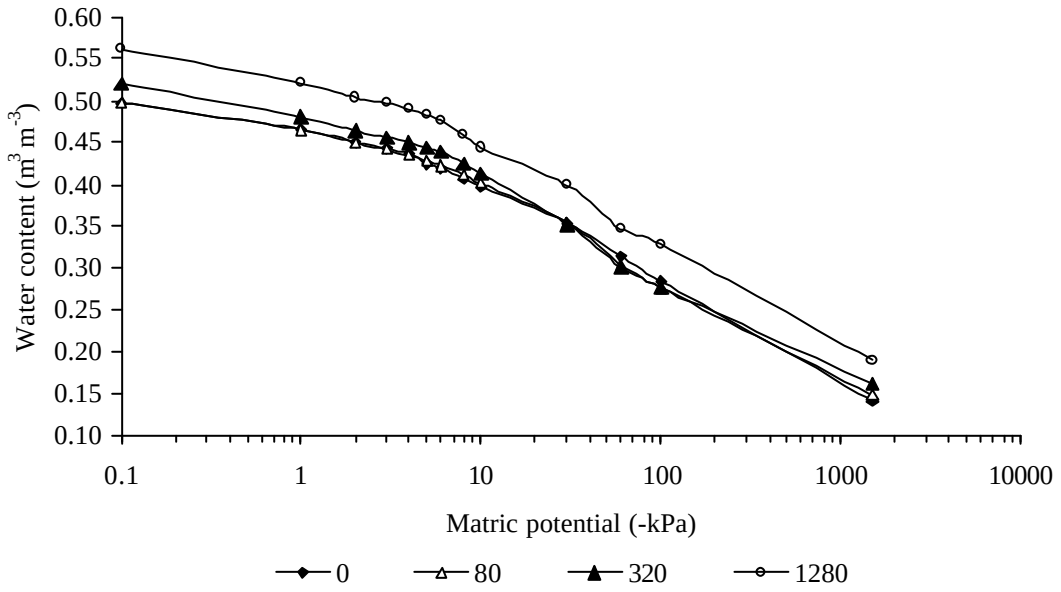


Figure 6.14 Water retention curves of the repacked Westleigh soil amended with 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue.

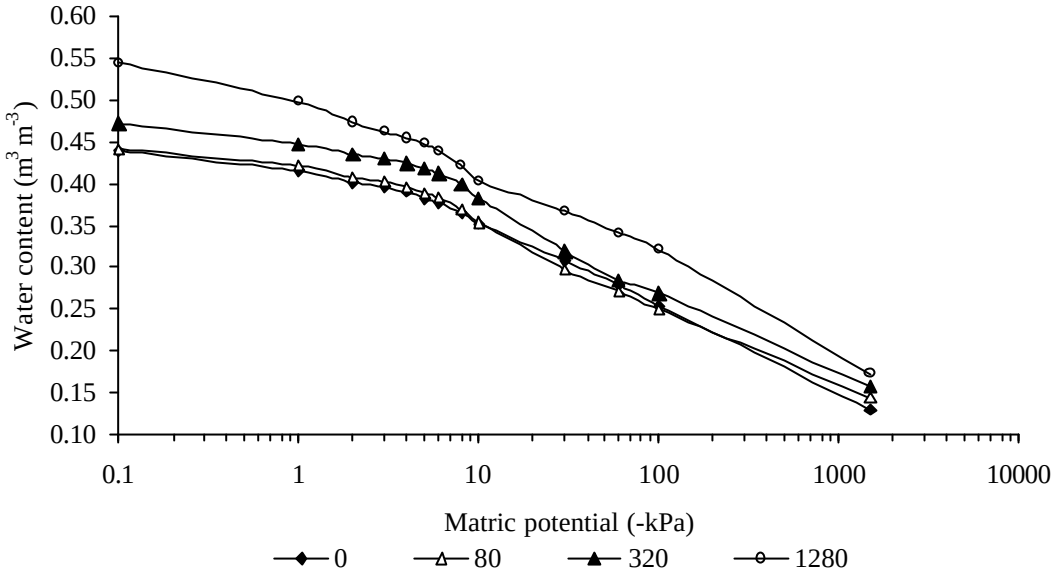


Figure 6.15 Water retention curves of the repacked Valsrivier soil amended with 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue.

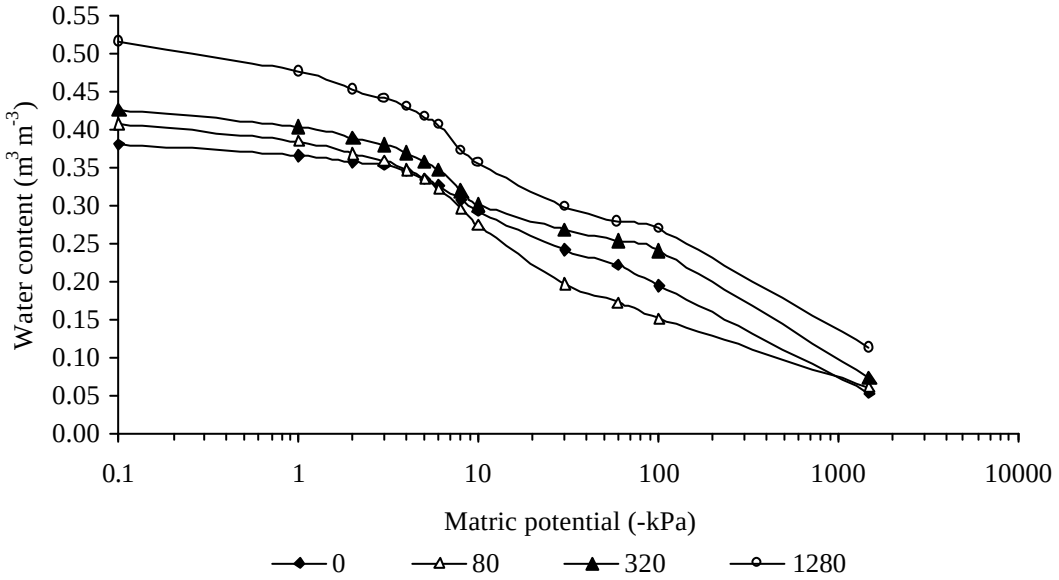


Figure 6.16 Water retention curves of the repacked Cartref soil amended with 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue.

The relationship between water content and matric potential was quite variable between the treatments for the Hutton soil (Figure 6.13). The higher water contents that were measured on the 1280 Mg ha^{-1} treatment at saturation, decreased with decreasing matric potential and at -10 kPa non-significant differences in water content ($p<0.05$) among all treatments were found when subjected to ANOVA ($F_{3,12} = 0.686$;

p = 0.578). At matric potentials lower than -30 kPa, the 1280 Mg ha^{-1} treatment nevertheless shows a higher but non-significantly different ($p<0.05$) mean water content compared with the control treatment. This finding is in strong agreement with the field data despite the complexities of the latter.

In the case of the Westleigh soil, the retention curves for the treatments showed a clear difference between each other (Figure 6.14). The 0, 80 and 320 Mg ha^{-1} treatments show similar characteristics in their water retention properties, although the 320 Mg ha^{-1} treatment had marginally higher water content in the matric potential range from 0 to -10 kPa. At a matric potential of -30 kPa (all pores >9.73 µm in diameter are drained) and -60 kPa, the control treatment shows a marginally greater but non-significantly different water content. For all matric potentials, however, the 1280 Mg ha^{-1} treatment consistently showed a higher water content, but this was found to be only statistically significantly different at a matric potential of -100 kPa ($F_{3,12} = 6.887$; $p = 0.006$).

The general order of water retained between saturation and -10 kPa for the WTR-amended Valsrivier soil was 1280 > 320 > 80 > 0 Mg ha^{-1} although between -3 kPa and -10 kPa the 320 and 1280 Mg ha^{-1} treatments have similar water contents (Figure 6.15). As found for the other soils, the decrease in bulk density with WTR addition caused an increase in the saturated soil water content. Both the 320 and 1280 Mg ha^{-1} WTR treatments were significantly different from the control ($p<0.05$).

The addition of WTR to the Cartref soil had a marked influence on the retention curve (Figure 6.16). The general order of water retained at equal matric potential, in the range from 0 to -100 kPa was 1280 > 320 > 80 > 0 Mg ha^{-1}. The 0 and 80 Mg ha^{-1} treatment, however, showed very similar water contents in the range from -3 to -10 kPa. The addition of 1280 Mg ha^{-1} WTR to this soil resulted in an increase of almost 0.11 m^3 m^{-3} in water retained at saturation compared with the control. This finding is probably related to the strong dilution effect that the WTR had on bulk density when applied to this sandy soil. It is also interesting that at a matric potential of -100 kPa the 1280 Mg ha^{-1} treatment held on average 0.10 m^3 m^{-3} more water than the control treatment.

6.2.3.4 Water retention at wilting point

Water treatment residue

The water retained at the wilting point (-1500 kPa matric potential) for the WTR-amended Hutton, Westleigh, Valsrivier and Cartref soils is presented in Figure 6.17. For clarity the treatments are presented on the basis of mass of WTR per mass of soil (Table 6.2).

The water content of air-dry WTR at the wilting point was about 0.305 m^3 m^{-3}, which is much higher than that measured on the control soils. Consequently, adding WTR to soil led to an increase in water retained at the wilting point. The relationship between the amount of WTR applied and water content was very strong (Figure 6.17). When the water content was converted to a mass basis, to avoid the influence of bulk density, the relationship was also linear.

In the absence of WTR, at the wilting point, the order in water content between the soil types was Hutton > Valsrivier > Westleigh > Cartref. Although the Valsrivier soil is anomalous in this relationship this sequence generally accords with a decrease in the clay percentage. Given the strongly dispersive nature of the Valsrivier soil (Section 6.5) and therefore its poor hydraulic conductivity (Section 6.3) it is possible that adequate equilibration of this soil at -1500 kPa was not fully realised, which would have caused an over-estimation of its water content.

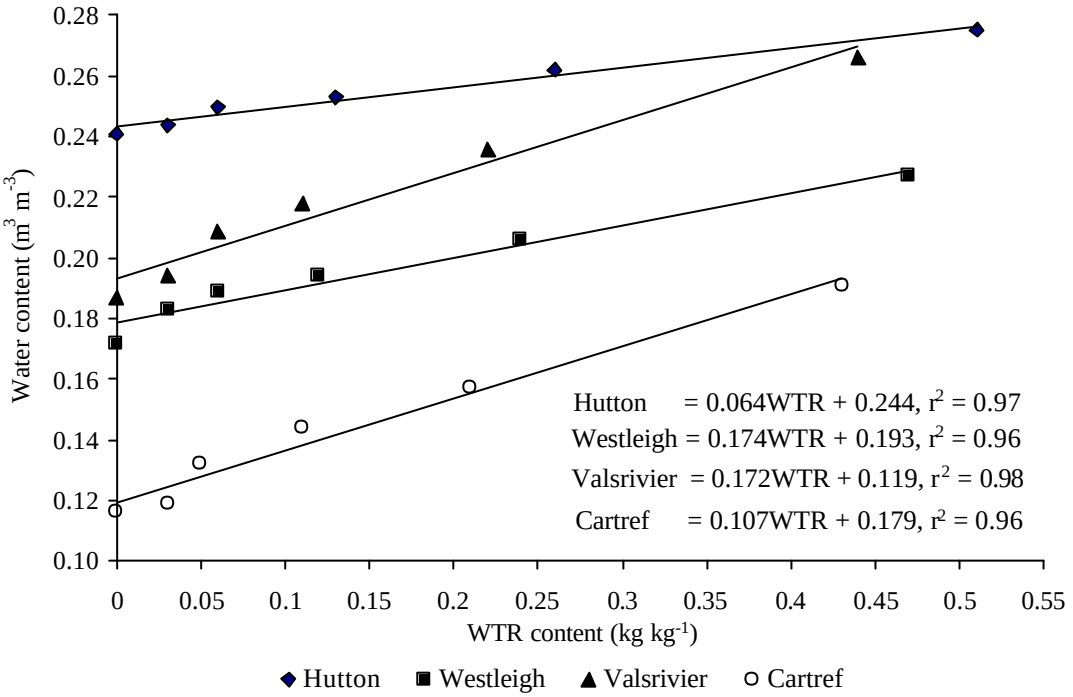


Figure 6.17 The effect of water treatment residue on the water content retained at the wilting point for the four soil types.

Despite the gravelly nature of WTR aggregates, the improvement noted in the water content at wilting point suggests that it contains pores that are dominantly <0.2 µm in diameter. This was confirmed by scanning electron microscopy, which showed that aggregates of WTR are comprised of a network of micropores and fractures. The relative effect of WTR addition on the wilting point was greater for coarser-textured soils than for fine-textured soils, although the Valsrivier soil is again anomalous in this relationship. This can be seen from the slope of the curve that relates water content to WTR content which followed the order Valsrivier > Cartref > Westleigh > Hutton (Figure 6.17).

Lime, gypsum and polyacrylamide

For all soil types gypsum, lime and PAM had a non-significant influence on the water content at the wilting point. Comparing the lower level of each amendment to that of the higher level also showed no significant differences ($p<0.05$) in water content. As compared to adding WTR to soil, there was little instantaneous change to the volume of micropores per unit volume of soil and consequently the water content in the treatments remained fairly similar. These results therefore confirm the findings from the field, and those reported in other studies, that in using these amendments lengthy

periods may be needed to cause any meaningful change in soil structure and therefore water retention at the wilting point.

6.2.3.5 Plant available water and readily available water

The calculation of the RAW and PAW content for the WTR-amended treatments (Tables 6.4 and 6.5) is based on the retention data obtained in the laboratory study. In the strict sense of the definition, the measurement of both the PAW and RAW content is best carried out on undisturbed soil cores. As explained earlier, the purpose behind using repacked samples of a uniform grade (<2 mm) was to compare the effect of the WTR on water retention using accurately controlled WTR:soil ratios. Given the very different soil physical conditions in the field, it is therefore unwise to extrapolate the estimates of PAW and RAW from the laboratory study beyond its intended purpose of facilitating comparisons between the treatments.

It can be clearly seen that even in February 1999 (Brookdale, Appendix 6.2) and December 1999 (Ukulinga; Appendix 6.5), when the RAW contents of the treatments were at a maximum, these values were much lower than measured in the laboratory study (Table 6.4).

Table 6.4 Readily available water (±SE) (m^3 m^{-3}) for the treatments amended with water treatment residue determined from the laboratory study using repacked samples

Soil	WTR application rate (Mg ha^{-1})				$LSD_{5\%}$
	0	80	320	1280	
Hutton	0.154 (0.024)	0.131 (0.025)	0.142 (0.018)	0.124 (0.014)	NS
Westleigh	0.113 (0.015)	0.125 (0.014)	0.137 (0.015)	0.114 (0.012)	NS
Valsrivier	0.098 (0.017)	0.104 (0.014)	0.113 (0.011)	0.083 (0.013)	NS
Cartref	0.096 (0.023)	0.122 (0.017)	0.061 (0.005)	0.086 (0.013)	NS

NS non-significant F-statistic.

The main reason for this discrepancy is that the repacked samples had much higher water contents at -10 kPa (field capacity) compared with the equivalent field samples, despite the much closer agreement in the saturated water content. This suggests that in using repacked samples, there is a tendency to increase the mesoporosity of the soil at the expense of the macroporosity. Moreover, in crushing the material to <2 mm, soil structural influences on water retention are significantly reduced. Similarly the PAW contents of the repacked samples (Table 6.5) would also likely overestimate the field situation, mainly because of the higher than normal water contents measured at -10 kPa matric potential.

Table 6.5 Plant available water (±SE) (m^3 m^{-3}) for the treatments amended with water treatment residue determined from the laboratory study using repacked samples

Soil	WTR application rate (Mg ha^{-1})				$LSD_{5\%}$
	0	80	320	1280	
Hutton	0.251 (0.001)	0.235 (0.009)	0.232 (0.007)	0.219 (0.012)	NS
Westleigh	0.225 (0.004)	0.218 (0.008)	0.219 (0.013)	0.217 (0.010)	NS
Valsrivier	0.210a* (0.016)	0.155b (0.010)	0.158b (0.004)	0.164b (0.016)	0.039
Cartref	0.165 (0.003)	0.160 (0.008)	0.165 (0.007)	0.174 (0.020)	NS

* Letters that are different indicate significant differences between means.
NS non-significant F-statistic.

Despite these complicating influences, using repacked samples offers an insight into the effect of the WTR on water availability to plants, albeit in a purely relative context. Analysis of variance showed that the addition of WTR to the four soil types had a non-significant influence on the RAW content at $p<0.05$ (Table 6.4). With regard to the PAW content, only the Valsrivier soil showed significant differences between the treatments but even so, the 80, 320 and 1280 Mg ha^{-1} treatments were non-significantly different from each other (Table 6.5). Of interest is that despite there being several inconsistencies in relating the WTR application rate to the PAW and RAW, it can be seen that these indices were generally lower at the 1280 Mg ha^{-1} rate than for the control treatment. The main reason for this is that although WTR increased the water content at field capacity, it also had a similar effect at -100 kPa matric potential and at the wilting point (-1500 kPa). The difference in water retained between these matric potentials therefore remained unaltered or even decreased. From a practical perspective this is an important finding as it suggests that although the WTR appears to have a beneficial influence on water retention, such gains may have little additional benefits for crop growth since a portion of this water (especially that held below -1500 kPa) would probably be unavailable for extraction by plant roots.

6.2.4 General discussion and conclusions

The field studies showed that the initial change in water retention properties because of incorporation of WTR had a high degree of variability but as the effects of tillage decreased, differences between the treatments became more defined. At the Brookdale site the variability increased again, reflecting the inherent variability of the measurement. Some key factors that account for this variability are the residual effect of tillage, the varying amount of WTR particles in the samples used for analysis (despite the attempt to achieve a uniform distribution of WTR within the plough layer), the varying degree of structural redevelopment of the soil, and faunal influences.

Although the WTR contains essentially silt- and clay-sized material these are strongly bonded together such that the texture of the material, once air-dried and after a few wetting and drying cycles, resembles that of fine gravel. The major difference,

however, is that individual WTR aggregates are inherently porous, consisting of a network of micropores and channels (typically <0.2 µm).

When WTR is applied to the soil, an immediate effect is a decrease in the bulk density and an associated increase in the total soil porosity. Consequently at saturation the WTR-amended treatments held more water than the control treatment. Since the saturated volumetric water content and the bulk density are related, it follows that where significant changes occurred in the bulk density, so too were significant differences found in the volume of water retained at saturation. The greater amount of water held at saturation on the WTR-amended treatments was rapidly drained and at field capacity a much smaller difference in water content was found between the treatments. At a matric potential of -100 kPa an even smaller difference between the treatments was observed. Nevertheless the WTR-amended treatments held on average more water than the control treatments. Consequently it can be inferred that the addition of WTR to soil had a small effect in increasing the proportion of mesopores within the soil. At the wilting point, however, there was a positive linear relationship between the amount of WTR added and water content mainly because of the contribution by the micropores in the WTR.

From the results presented, despite the variability encountered in the field studies, WTR apparently improved soil water retention, although the improvements were less marked on the Hutton soil. Such increases, which were generally only significant at the 1280 Mg ha^{-1} level, arise from the lower bulk density of the amended treatments and the porous nature of the WTR aggregates. This caused an increase in water retained at both saturation and at the wilting point. Nevertheless the influence on both the PAW and the RAW content is small. Concerning the influence of gypsum and lime on water retention, both products had no significant influence on the water retention properties of either the Hutton or Westleigh soils. Polyacrylamide, on the other hand, caused a marginal increase in water retention shortly after being applied at the 30 kg ha^{-1} level to the Hutton soil at Brookdale Farm. This benefit, however, persisted for only a short period.

6.3 Infiltration and hydraulic conductivity

6.3.1 Introduction

The infiltration of water into soil is a dynamic process (Banton, 1993; Bosch and West, 1998). Initially the rate of infiltration into soil is fast because of a large water potential gradient near the surface, but slows to a nearly constant rate as the potential gradient approaches unity (Radcliffe and Rasmussen, 2000). The final steady state is approximately that of the saturated hydraulic conductivity (K_s) of the soil although Bristow and Savage (1987) caution against the direct acceptance of this apparent steady state as the true K_s of the soil. Entrapped air and the presence of blind-ended pores can influence the complete saturation of the soil and therefore lead to an underestimation of hydraulic conductivity (Bosch and West, 1998). In view of this, the term field-saturated hydraulic conductivity (K_{fs}) is used to refer to this final steady state. By adopting this term the assumption that the entire soil profile is saturated and is therefore contributing towards the flow of water is eliminated (Reynolds *et al.*, 1983; Bosch and West, 1998).

6.3.2 Field-saturated hydraulic conductivity

6.3.2.1 Procedure

Several techniques are discussed in the literature for measuring the infiltration characteristics of soils. Many of these are reviewed in several soil physics texts and so will not be expanded upon here. Of significance among these, are the constant-head well permeameter methods (Reynolds *et al.*, 1983; Amoozegar, 1989; Elrick and Reynolds, 1992), the falling-head lined borehole method (Philip, 1993), the double-ring infiltrometer method and the disk infiltrometer method (Perroux and White, 1988). At present there is no general consensus as to which of these techniques are the preferred options. Since the measurement of infiltration in the field is a time-consuming exercise (Smith, 1999), the best choice of method must draw a balance between the accuracy, speed, simplicity, portability, water use, manpower and costs (Vanderlinden *et al.*, 1998).

At Brookdale Farm the K_{fs} was measured on the WTR-incorporated treatments and all the gypsum, lime and PAM treatments but at Ukulinga Farm, the investigation was confined to the WTR treatments. Given the large number of treatments being evaluated the double-ring infiltrometer method was selected for this study because of the simple set-up of the test and its relatively low cost of operation. Moreover, since the sorptivity component (S) of Equation 6.3 is influenced by the antecedent soil water content, it was desirable that all measurements be completed before any additional rainfall was received at the study site. Since controlling several double-ring infiltrometers at the same time is possible for one person, this method held additional logistical advantages compared with alternative more labour intensive or time-consuming methods.

At Brookdale Farm the investigation was carried out in July 1999 and October 2000 and at Ukulinga Farm in December 1999 and October 2000. The soil surface at two randomly selected positions within each plot was first cleaned of any loose debris with a soft bristle brush. Steel rings were then hammered carefully into the soil to a depth of 0.05 m using a hammer and a block of wood. The diameter of the inner and outer rings (height of 0.25 m) used in this study were 0.3 m and 0.5 m, respectively. The rings were adjusted as necessary to ensure that the inner and outer rings were both level and at the same height to each other. They were then ponded rapidly with water to a depth of 0.2 m. Cumulative infiltration was measured at regular times by noting the depth of water that had infiltrated the soil from the inner ring. Initially, readings were taken every 10 sec but after an elapsed time of 5 min this was increased to every 30 sec.

Once the infiltration rate had tended towards a steady state, readings were taken at 4 min intervals and continued usually for 2-3 h. When necessary, water was added to the outer ring to maintain the same hydraulic head as that of the inner ring. Although maintaining a constant head of water within the rings is theoretically more advantageous, this was not possible given the relatively large size of the rings used in this study.

On average, refilling of the infiltrometers occurred between five and eight times before acceptable final steady state values were obtained. Steady state was assumed

when successive readings of the instantaneous flow rate were within 15% of each other. Due to the constant decrease in the hydraulic head, slight pulsing of flow was noted. To compensate for this in evaluating the steady state, water drained in the first 4 min following the refilling of the infiltrometer was compared with the volume of water infiltrated in the same period during the previous refill, for example by comparing the eighth to the seventh refill cycle. At the end of the measurement a sub-sample of soil was collected by plunging a 15 mm cylindrical corer into the saturated soil surface to a depth of 0.1 m for the apparent saturated soil water content. Although this measurement has no relevance in the calculation of the K_{fs} it nevertheless allowed for comparing the apparent saturated water content between the observations. An approximate analytical equation used to describe the cumulative infiltration of water into the soil as a function of time is that of Philip (1957) which states that

$$\mathbf{I = S\,t^{0.5} + A\,t} \ldots\ldots\ldots \text{Eq 6.3}$$

where I is the cumulative infiltration (a length unit (L)) as a function of time t (a time unit (T)), S is the sorptivity ($LT^{-½}$) and A (LT^{-1}) is approximately equal to the K_s when t is large. For early intervals of time the sorptivity component dominates but at longer time (once a steady rate of flow has been reached) this becomes negligible since the flow of water is driven largely by gravity (Kumke and Mullins, 1997). In differential form Equation 6.3 may be rewritten as

$$\mathbf{dI/dt = S / 2\,t^{0.5} + A} \ldots\ldots\ldots \text{Eq 6.4}$$

A measure of sorptivity is achieved by linearly relating the cumulative infiltration (for early times) to the square root of time and then obtaining the sorptivity as the gradient of the curve. For long times, Equation 6.3 is then solved using the calculated value of S to obtain the approximate K_s (A).

6.3.2.2 Results and discussion

Brookdale Farm

The Hutton soil at Brookdale Farm has an inherently high final infiltration rate in the order of 300 mm h^{-1} (Figure 6.18). This is due to the highly stable nature of the soil aggregates that resisted the tendency to slake or disperse when wet. Nevertheless, adding WTR to this soil further increased the K_{fs}. In June 1999, the 0, 80 and 320 Mg ha^{-1} treatments were not significantly different from each other. The 1280 Mg ha^{-1} treatment on the other hand, showed a significant increase in K_{fs} compared with the control treatment. With regard to the lime, gypsum and PAM treatments, neither lime nor gypsum made any significant difference in K_{fs} compared with the control. It is also interesting that on these treatments, the K_{fs} measured at their high level of WTR application is similar to that measured at their low rate of application. The effect of PAM, however, led to a marked increase in K_{fs} (in the order of 220 mm h^{-1}) especially at the 30 kg ha^{-1} PAM application rate, which was significantly different from the control.

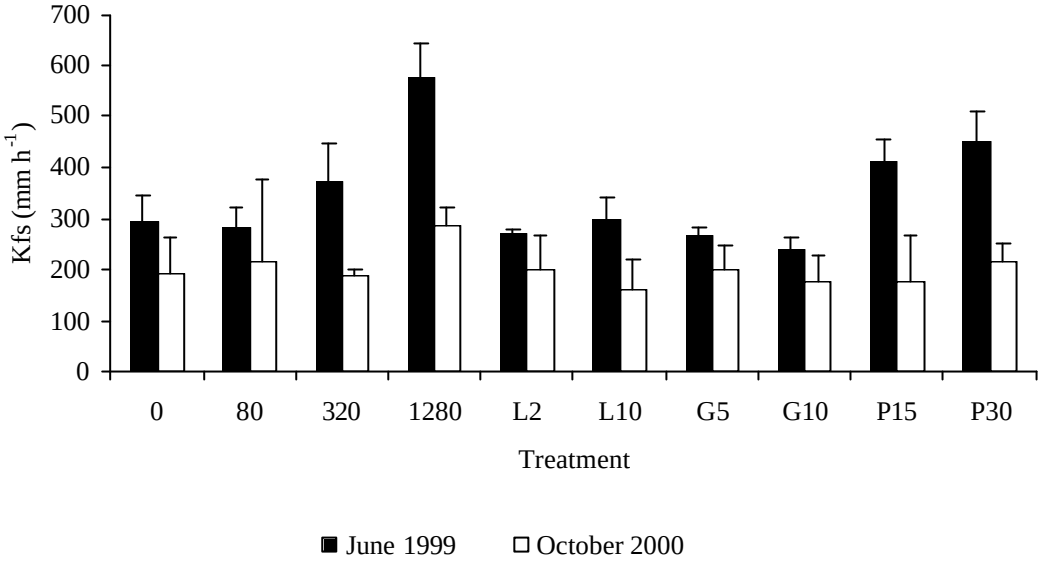


Figure 6.18 Mean (n=4, +SE) K_{fs} measured at Brookdale Farm in June 1999 and October 2000. 0, 80, 320 and 1280 refer to water treatment residue application rates (Mg ha^{-1}). L2, L10, G5, G10, P15 and P30 are treatments of lime at 2 and 10 Mg ha^{-1}, gypsum at 5 and 10 Mg ha^{-1} and polyacrylamide at 15 and 30 kg ha^{-1}, respectively.

The coefficient of variation in K_{fs} for the WTR-amended plots at Brookdale Farm, ranged from 24 to 39%, while the non-WTR treatments showed only marginally lower CV. This level of variability is not unusual and is often encountered in infiltration studies especially using the double ring infiltrometer technique (Scotter *et al.*, 1982; Mohanty *et al.*, 1994). According to Vanderlinden *et al.* (1998) a general remark concerning the coefficient of variation is that besides the variability associated with the measurement technique, it also includes the variation from the measured population. Cracks, holes or large pores in the soil can cause large differences in K_{fs} over a small area and because of this, a high CV does not necessarily imply a poor mean K_{fs} (Vanderlinden *et al.*, 1998). Nevertheless, the trend of increasing K_{fs} with increasing WTR application rate is consistent with the findings of Ahmed *et al.* (1997) who reported an increase in K_{fs} from 398 mm h^{-1} to 1061 mm h^{-1} on an Urrbrae red-brown earth after being treated with 800 Mg ha^{-1} alum WTR.

The order of K_{fs} between the WTR-amended treatments found at the Brookdale trial in October 2000 (Figure 6.18) was 1280 > 80 > 0 > 320 Mg ha^{-1}, but despite this trend such differences were not significant ($p<0.05$) ($F_{9,20} = 0.629$; $p = 0.758$). With regard to the lime, gypsum and PAM treatments, these were also not significantly different from the control. Even the PAM 30 kg ha^{-1} treatment that had shown a marked increase in K_{fs} previously, was only marginally higher than that of the control treatment. Values of K_{fs} across all treatments were also much lower than was recorded during June 1999, due to a decrease in the total porosity of the soil, as the effect of tillage was progressively reduced.

Ukulinga Farm

With regard to the Ukulinga Farm experiment the field estimate of K_{fs} measured during December 1999 was complicated by significant variability and inconsistent relationships both within and between the treatments (results not shown). For the 1280 Mg ha^{-1} treatment, values of K_{fs} greater than 1000 mm h^{-1} were obtained which is clearly an overestimate. The control treatment nevertheless showed K_{fs} values that ranged between 14.7 and 31.3 mm h^{-1}. During December 1999, despite the partial consolidation of the soil profile, the presence of large pores and channels on the WTR-amended treatment surfaces were still clearly visible. During operation of the double-ring infiltrometer water was probably lost rapidly through these channels. Moreover, despite the presence of the outer ring it is also likely that the lateral flow of water was also inadequately contained resulting in the further overestimate of K_{fs}. Repetition of the investigation in October 2000 produced more satisfactory results (Figure 6.19).

The general trend in K_{fs} measured at Ukulinga Farm followed the order 1280 > 320 > 80 > 0 Mg ha^{-1}. Of significance is that a nearly ten-fold difference in K_{fs} was found between the control and the 1280 Mg ha^{-1} WTR treatment. Based on information obtained from undisturbed soil cores (Section 6.3.3), this factor of magnitude is probably an overestimate.

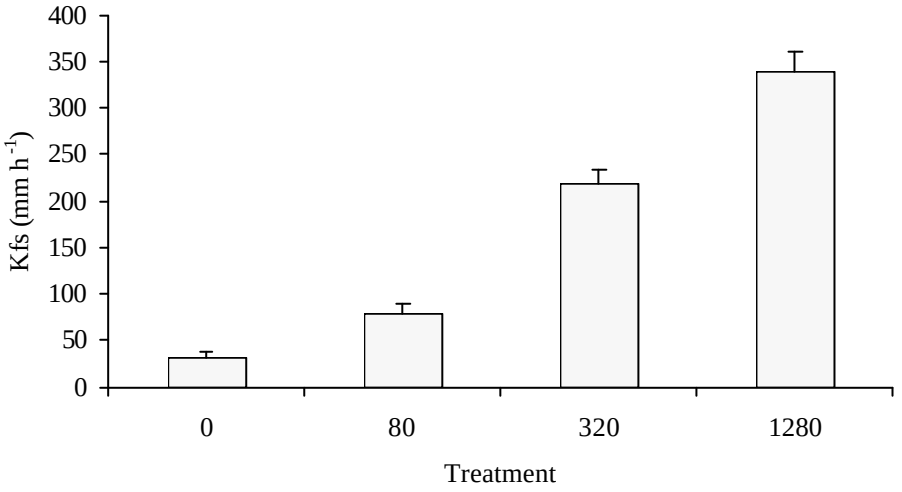


Figure 6.19 Mean (n=4, +SE) K_{fs} measured at Ukulinga Farm in October 2000. 0, 80, 320 and 1280 refer to water treatment residue application rates (Mg ha^{-1}).

A likely reason for this large difference in K_{fs} between the control and the 1280 Mg ha^{-1} WTR treatment is that in the latter, water escaped through large channels rather than through the soil matrix. Nonetheless, compared with equivalent treatments on the Hutton soil, the K_{fs} was much lower. This was expected given that the Westleigh soil has a lower aggregate stability (Section 6.5) compared to the Hutton. Under saturated conditions, the dispersion of clay results in the clogging of water transmitting pores

leading to the decrease in K_{fs} (Curtin *et al.*, 1994). In addition some swelling of this soil probably led to constriction of soil pores and so also caused a decrease in the final infiltration rate (Collis-George and Laryea, 1970).

6.3.3 Saturated hydraulic conductivity of undisturbed soil cores

6.3.3.1 Introduction

Since *in situ* measurements of K_s tends to be time-consuming and often require experienced personnel to carry out the investigation accurately, it was considered important to investigate alternative and more convenient methods of estimating this parameter. The realisation of this objective would have further distinct advantages with regard to the routine monitoring and management of a land treatment system. One such option is to use undisturbed soil cores for the measurement of K_s (Kanwar *et al.*, 1989; Mohanty *et al.*, 1992; Paige and Hillel, 1993).

6.3.3.2 Procedure

At the time of obtaining undisturbed soil cores for the initial water retention study, an additional set of cores (four replicates per treatment) were taken for the measurement of K_s. In April 2000 this procedure was modified in an attempt to reduce any undue disturbance to the plot surface and consequently the same cores used for deriving the water retention curves were also used in the K_s study. This meant that a modification in the treatment of the cores for the water retention study had to be made. By taking a sub-sample of soil during preparation of the cores for determination of mass water content and by determining the mass of the ring, cloth and band beforehand, calculating the bulk density of the core was possible. Once the measurement of K_s was completed, the cores were oven-dried (105^{o}C for 2 days) and the bulk density recalculated using this final mass. In comparing this value with that obtained previously exceptionally good agreement was found, primarily because very little mass was lost from the core during the measurement of K_s. Where differences in bulk density were found, these were in the order of 0.001 Mg m^{-3} and considered negligible.

After equilibration at a matric potential of -100 kPa, the permeability of the core to air was measured (Section 6.4). The steel sleeve retaining the soil was then lengthened by attaching a duplicate sleeve using packaging tape to form a water-tight seal at the joint. The soil was capillary saturated overnight by placing the sleeves in a distilled water bath. These were removed from the water bath and fitted with a plastic funnel containing a wire mesh upon which the bottom edge of the sleeve rested. The K_s of the core was then measured by the constant-head method following the guidelines given by Klute and Dirksen (1986). Briefly it involves maintaining a constant head of water on the soil core and measuring the volume of water transmitted per unit time. This constant head was maintained by way of a mariotte bottle system. Steady state, as defined previously, was assumed to exist when the volume of water per unit time passing through the soil core was approximately constant. In the present study the head of water maintained over the soil was 50 mm.

The K_s of the undisturbed soil cores was calculated from Darcy's Law which states that

$$\mathbf{K_s = V.L / (A.t.}\Delta\mathbf{H)} \text{ .....Eq 6.5}$$

where K_s is the saturated hydraulic conductivity (mm h^{-1}), V is the volume of water (mm^3), L is the length of the soil sample or core (mm), A is the cross sectional area of the sample or core (mm^2), t is the time (h) and ΔH is the hydraulic potential difference between the inflow and outflow boundaries (mm).

6.3.3.3 Results and discussion

Brookdale Farm

The mean K_s (Table 6.6) measured on the June 2000 set of cores was lower than that found for the April 2000 cores. This was expected given the increase in bulk density of the treatments due to the reversion of tillage. This pattern became more variable for subsequent harvests with relatively high levels of variability observed within many of the treatments.

The April and June 2000 data show strong similarity in the overall trend in K_s between the treatments. The 1280 Mg ha^{-1} treatment consistently showed an approximately two-fold increase in K_s compared with the control. The difference was not significant for the April 2000 sampling but was significantly different from all other treatments for the June 2000 sampling (Table 6.6). Concerning the effect of lime, gypsum and PAM on K_s, these treatments were not significantly different to the 0, 80 and 320 Mg ha^{-1} WTR treatments in both instances.

No significant overall differences were found for all subsequent sampling dates (Table 6.6). For the February and September 2001 sampling dates the 1280 Mg ha^{-1} WTR treatment showed the highest K_s, although no consistent pattern was evident for the other treatments. The October 2002 and June 2003 sampling dates showed a considerable degree of variability, with no clear pattern evident. This may reflect variability in sampling rather than the effect of the treatments that were evident at earlier sampling events. As for the water retention characteristics, the data suggest that due to the inherently stable structure of the Hutton soil, the effects of the treatments were relatively short-term. This is probably a combination of the soil characteristics and possibly faunal influences overriding or masking treatment effects.

Ukulinga Farm

The mean K_s of the sampling dates measured at Ukulinga Farm are given in Table 6.7. In general, the results showed strong agreement with the double-ring infiltrometer method, which is encouraging in terms of the potential use of this technique for monitoring a land treatment system.

An increase in the WTR content caused an increase in K_s, which was consistent for all sampling periods (Table 6.7). In almost all cases the 1280 Mg ha^{-1} WTR treatment was significantly higher than all other treatments (Table 6.7), although this treatment did seem to show a high degree of variability over time. The addition of 1280 Mg ha^{-1} WTR to this soil caused an approximately eight to twelve-fold increase in K_s from that of the control for the early sampling periods. This decreased to about a two to five-fold increase from February 2001 onwards. Aggregates of WTR have high

inherent stability and limited potential for swelling. Consequently the flow of water through the WTR-amended treatments was essentially less restricted than in the control treatment, where pore-blockage because of clay slaking and dispersion probably occurred to a greater extent. In addition, the movement of water preferentially through macropores, at the partial expense of the soil matrix could also account for the higher values measured on the WTR-amended treatments.

Table 6.6 Summary ANOVA statistics for K_s (mm h^{-1}) for Brookdale Farm for the different sampling dates

Date	WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-pr
	0	80	320	1280						
April 2000	80.78	91.21	113.43	161.70	118.06	104.41	104.94	NS	1.45	0.243
June 2000	43.91b*	44.14b	53.53b	86.24a	46.09b	50.65b	44.93b	13.26	11.34	<0.001
February 2001	111.83	98.68	103.98	116.92	nd	nd	nd	NS	0.23	0.874
September 2001	77.95	91.53	72.86	101.86	72.15	62.11	84.17	NS	0.54	0.774
October 2002	61.71	160.29	130.27	97.02	90.40	100.22	118.21	NS	1.61	0.195
June 2003	136.09	120.39	121.66	140.20	110.77	117.70	124.35	NS	0.18	0.979

* Letters that are different indicate differences between means within a particular sampling date.
nd not determined.
NS non-significant F-statistic.

Table 6.7 Summary ANOVA statistics for K_s (mm h^{-1}) for Ukulinga Farm for the different sampling dates

Date	WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-pr
	0	80	320	1280						
December 1999	18.39	32.54	71.87	230.20	nd	nd	nd	NS	ND	ND
March 2000	40.74b*	84.20b	78.69b	449.03a	102.28b	136.66b	ND	217.6	4.22	0.010
August 2000	60.67b	126.84b	79.44b	479.01a	48.48b	50.64b	37.35b	119.4	15.22	<0.001
February 2001	63.98bcd	55.70cd	82.34abc	117.14a	106.95ab	16.49d	30.83d	48.57	5.09	0.002
September 2001	64.40b	116.18b	63.27b	280.53a	91.81b	93.23b	65.50b	130.3	3.05	0.026
October 2002	90.06bc	199.90ab	122.57bc	288.60a	113.91bc	44.14c	115.33bc	125.5	3.56	0.014
June 2003	70.48b	92.24b	118.55b	311.52a	85.73b	70.08b	40.46b	135.2	3.91	0.009

* Letters that are different indicate differences between means within a particular sampling date.
nd not determined.
NS non-significant F-statistic.

The lime, gypsum and PAM treatments exhibited a high degree of variability, with no clear patterns for any particular sampling date or over time. However, generally these

treatments did not differ significantly from the 0, 80 and 320 Mg ha^{-1} WTR treatments. Nevertheless, it was noted that the leachate passing through the PAM-amended soil showed lower levels of turbidity than for control treatment. This implies that in the presence of PAM, clay dispersion was reduced.

6.3.4 Saturated hydraulic conductivity of repacked soil cores

In view of the variability encountered in the field studies and the need to extend the study to include the additional soils, namely the Valsrivier and Cartref, K_s was also measured on repacked samples.

6.3.4.1 Materials and methods

In these experiments the <2 mm air-dried fraction of the four soils and the WTR was used. The WTR and soil were mixed at rates of 0, 80, 160, 320, 640 and 1280 Mg ha^{-1} (Table 6.2). Permeameters were constructed from 175 mm long perspex tubing with an internal diameter of 53 mm and a wall thickness of 3 mm. A 10 mm thick perspex base with the same diameter as that of the tube was drilled with 19 holes (8 mm diameter) over which was fitted a plastic mesh with internal openings of 3 mm^2. This plate was then fixed to one end of the tube. A single layer of non-absorbent acrylic material was placed within each permeameter to retain the soil within the column.

Mixtures of WTR and soil were added to each permeameter loosely. A 220 g weight with a slightly smaller external diameter to that of the tube was placed on top of the soil. The soil was then compacted by raising and dropping the permeameter 25 times over a distance of 10 mm. A specially designed apparatus, equipped with a metal cam to control the height from which the permeameter was dropped, was used for this purpose. The height of the compacted material was then measured. By noting the compacted height of two different masses of material added to the permeameter, it was possible to interpolate the amount of material necessary to yield a compacted soil length of 50 mm.

The actual soil column used, however, was 100 mm and so packing of the permeameter was completed in two stages with the second addition of material being compacted on top of the first. This ensured a more uniform distribution in bulk density throughout the length of the soil column. The bulk density (Figure 6.21) was calculated from the equivalent oven-dry mass of soil that was added to each permeameter. Air within the soil column was replaced with carbon dioxide to encourage complete saturation of the soil, as CO_2 has a higher solubility in water. Following this treatment, the soils were capillary saturated by standing in a distilled water bath overnight. A further single layer of acrylic material was placed on the soil surface and the K_s measured as for the undisturbed soil cores using a constant head of 50 mm. The K_s of the repacked treatments was calculated from Equation 6.5.

6.3.4.2 Results and discussion

The K_s reported as the mean of six replicates for the Hutton, Westleigh, Valsrivier and Cartref soils amended with varying rates of WTR is shown in Figure 6.20 and mean bulk density of the treatments in Figure 6.21.

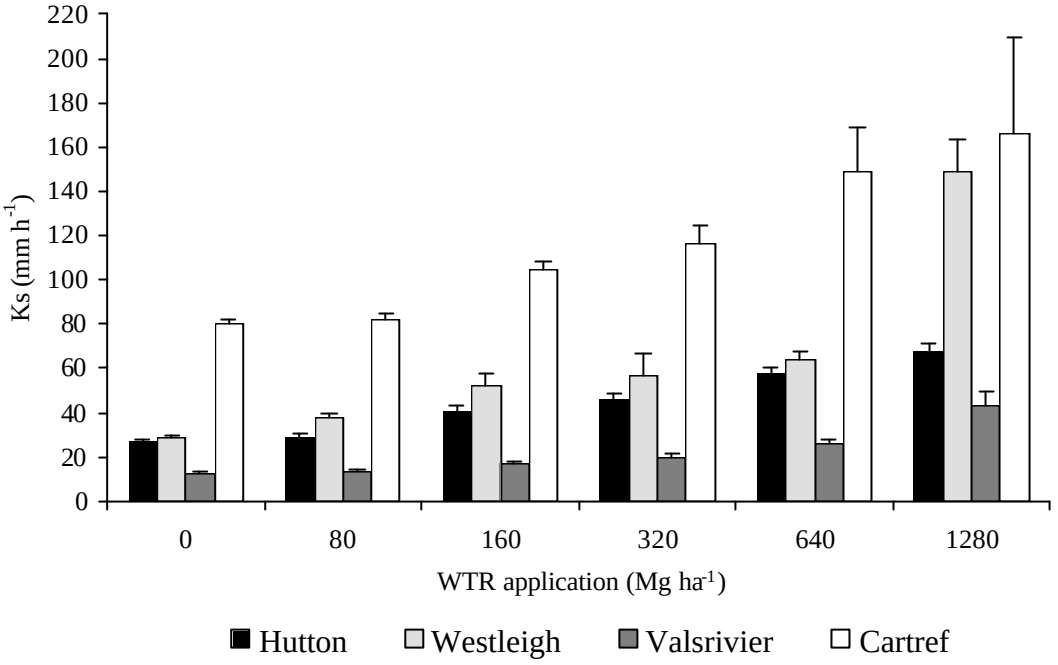


Figure 6.20 Mean saturated hydraulic conductivity (n=6, +SE) of the repacked permeameters for the Hutton, Westleigh, Valsrivier and Cartref soils at equivalent water treatment residue application rates of 0, 80, 160, 320, 640 and 1280 Mg ha^{-1}.

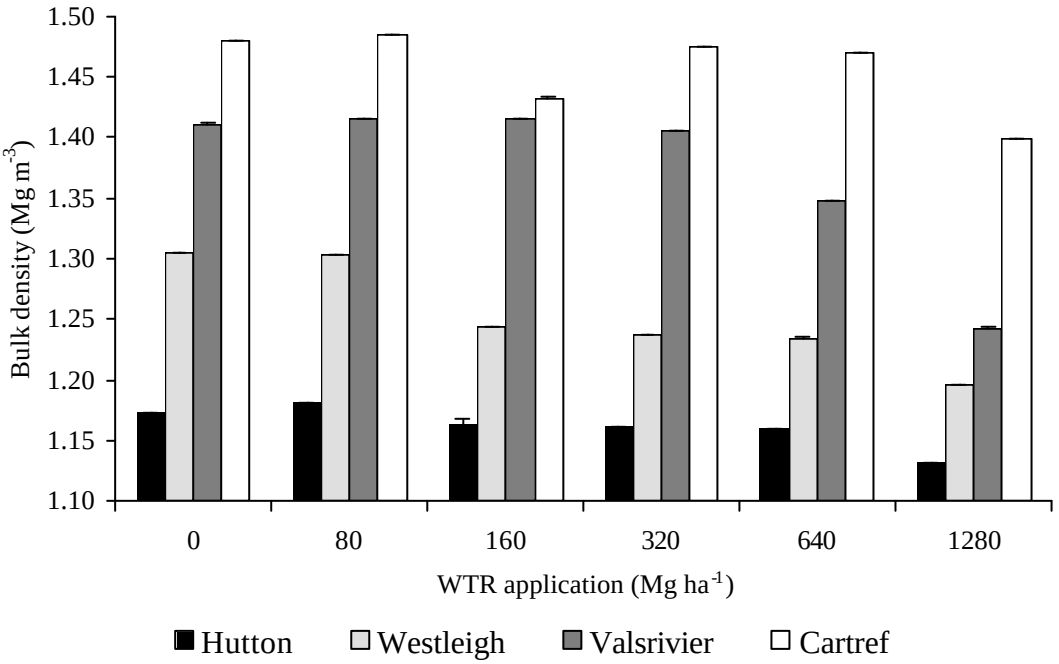


Figure 6.21 Mean bulk densities (n=6, +SE) of the repacked permeameters for the Hutton, Westleigh, Valsrivier and Cartref soils at equivalent water treatment residue application rates of 0, 80, 160, 320, 640 and 1280 Mg ha^{-1}.

Compared to the study where the K_s for each treatment was determined on undisturbed soil cores, the coefficient of variation measured for the repacked samples was much lower, principally because a uniform grade of WTR and soil (<2 mm) was used. It is, however, important to note that while this allowed for improved accuracy in evaluating the influence of the WTR on K_s, this situation will rarely, if ever, be encountered in the field. Consequently the K_s values presented for the repacked samples should therefore be viewed strictly in relative terms.

Pure WTR, measured in the same manner as that for the soils, showed a high mean K_s of 309.5 mm h^{-1}, which is due primarily to the inherently stable nature of the WTR aggregates. When applied to the soil types tested in this study the K_s was consistently found to be higher on the WTR-amended soils than on the control treatment. Analysis of variance showed that in the case of the Westleigh and Hutton soils significant differences in K_s ($p<0.05$) compared to the control treatment were found at WTR application rates of 160 Mg ha^{-1}, while on the Cartref and Valsrivier soils the 640 Mg ha^{-1} level was the minimum at which significant differences were found (Table 6.8). When relating K_s to WTR content by linear regression analysis, high R^2 values were obtained (Table 6.9). In addition the total porosity, which is calculated from the bulk density and particle density, was positively correlated with WTR content, as shown by the high R^2 values of 0.965, 0.818, 0.974 and 0.870 for the Hutton, Westleigh, Valsrivier and Cartref soil forms, respectively.

Table 6.8 Least significant differences comparisons for bulk density (P_b) and saturated hydraulic conductivity (K_s) of repacked permeameters for the Hutton, Westleigh, Valsrivier and Cartref soils

Soil	Parameter	WTR application rate (Mg ha^{-1})					
		0	80	160	320	640	1280
Hutton	K_s	A*	A	A	B	C	D
	P_b	a	a	b	b	b	c
Westleigh	K_s	A	AB	BC	BC	CD	E
	P_b	a	a	b	c	d	e
Valsrivier	K_s	A	A	A	AB	BC	D
	P_b	a	b	b	c	d	e
Cartref	K_s	A	A	AB	ABC	BC	C
	P_b	NS	NS	NS	NS	NS	NS

* Letters that are different indicate significant differences between treatments.
NS non-significant F-statistic.

Table 6.9 Linear regression relationships obtained between K_s (mm h^{-1}) and the rate of water treatment residue (WTR) application (Mg ha^{-1}) for the four soil types

Soil	Regression equation	R^2
Hutton	$K_S = 0.031$ (WTR) + 31.56	0.896
Westleigh	Ks = 0.081 (WTR) + 28.78	0.935
Valsrivier	$K_S = 0.024$ (WTR) + 12.01	0.995
Cartref	$K_S = 0.069$ (WTR) + 88.03	0.896

It is interesting, however, that the factor by which the K_s increased relative to the control, after the addition of 1280 Mg ha^{-1} WTR to the Hutton, Westleigh, Valsrivier and Cartref soils was 2.5, 3.6, 5.2 and 2.1, respectively, i.e., the effect of WTR addition was more marked when added to the poorly permeable soil types compared with the more freely drained soils.

For the control treatment the order of increasing K_s found between the soil types was Cartref > Hutton > Westleigh > Valsrivier which is in accordance with a decrease in the unbound silt and clay percentage (Section 6.5). The influence of improved soil stability following the addition of WTR is demonstrated clearly in the case of the Cartref soil, which showed a substantial increase in K_s despite only a moderate decrease in the bulk density (Figures 6.20 and 6.21). When correlating the unbound silt and clay percentage to K_s for the control treatments (four soils), a moderate negative relationship with an R^2 of 0.66 was found.

Clay that is mobilised when the soil becomes saturated may become trapped in the soil pores. It follows that the greater the degree of blockage of this pore space the greater will be the decrease in K_s. When WTR is added to soils the first and immediate effect is an increase in the total soil porosity (due to a decrease in bulk density). In addition since individual WTR aggregates are highly stable very little dispersible clay is added to the amended soil volume. While some blockage of pores by clay does occur (most of this clay is liberated from the aggregates of soil) the relative significance of this decreases the higher is the WTR content, i.e. per unit volume the dispersive clay percentage will be lower the greater the WTR content.

6.3.5 Conclusions

Field studies showed an increase in the saturated hydraulic conductivity (measured using two different techniques) of the soil after being amended with WTR, but the results showed high levels of variation. This variability stems primarily from natural spatial heterogeneity that exists in the field (despite the assumption that uniform conditions apply). To reduce this influence and to include an assessment for the two additional soils, the influence of the WTR on K_s was measured on repacked samples. The WTR (<2 mm fraction) was mixed with the four soils at six application rates. Although extrapolating the findings of this study to the field is perhaps unwise, it nevertheless confirmed, with far greater clarity, that WTR does in fact increase K_s and that this effect was more pronounced on soils with inherently poor hydraulic properties. The main reason for the increase observed in K_s was the increased porosity, particularly macroporosity, that occurred following the addition of WTR. Consequently the movement of water through these macropores would be more rapid, accounting for the much higher K_s values. The WTR is strongly aggregated because of the cementing effect of the polymer. Consequently, slaking of aggregates and the blockage of water-conductive pores was probably less on the WTR-amended treatments than on the control treatment.

6.4 Soil aeration

6.4.1 Introduction

In soils, diffusion is an important mechanism by which the exchange of air between

the atmosphere and the air-filled pores within the soil matrix takes place. Nevertheless, convective flow also contributes to the exchange of gases especially at shallow depths and in soils with large pores (Hillel, 1998). According to Beven and Germann (1982) and Ball *et al.* (1988), gas exchange in soils is influenced by the size distribution and the continuity of pores. The latter may be even more important than simply the size or number of pores per unit volume of soil. Macropores may contribute towards the rapid transmission of water, by-passing large proportions of the soil volume (Roseberg and McCoy, 1990). In addition, plant roots will favour the path of least resistance and will tend to follow pores their own size or larger, rather than penetrate the soil ped (Roseberg and McCoy, 1992). Root development is therefore strongly influenced by the number and orientation of large pores in the soil. Since the flow of air through soil, unlike that of water, is essentially non-destructive, aeration has also been used as an indicator of the physical condition of soils in relation to its structure and stability (Smith *et al.*, 1998).

6.4.2 Materials and methods

6.4.2.1 Air-filled porosity

The pore space in soil is commonly evaluated from measurements of the total porosity and the pore size distribution. The air-filled porosity was obtained from:

$$\mathbf{e_a = e_t - ?_v} \text{ .....Eq. 6.6}$$

where

$$\mathbf{e_t = 1 - (?_b / ?_s)} \text{.....Eq. 6.7}$$

and e_a is the air-filled porosity ($m^3\ m^{-3}$); e_t is total porosity ($m^3\ m^{-3}$); $?_v$ is the volumetric water content ($m^3\ m^{-3}$); $?_b$ is the bulk density (kg m^{-3}) and $?_s$ is the particle density which is usually assumed to be 2650 kg m^{-3} for most mineral soils. e_a, like $?_v$ is a function of matric potential.

6.4.2.2 Air permeability

For the purposes of this investigation a simplified air-permeameter, based on the design of Corey (1986), was used. The intact soil core bounded by the steel retaining sleeve was placed between two stainless steel chambers with an internal diameter slightly larger than that of the sleeve. Each chamber was fitted with a vented disc upon which the sample face could rest. To improve air-flow, and following the advice of Roseberg and McCoy (1990), spiral grooves were cut on the inside of the chamber wall. A double system of rubber O-rings located within each sample chamber created an air-tight seal between the steel sleeve and its retaining chamber. Air entry and exit through the apparatus was facilitated by drilling a single large bore in each end to the exterior, to which was attached acrylic tubing. The chambers on either end of the sample were fastened to each other by three threaded-rods and winged-bolts.

The air inflow side tube was connected, via an air pressure regulator, to a constant air supply, while the outflow side was discharged to the atmosphere. A flow meter comprising a water manometer plus capillary outflow tube was used to measure the air pressure drop across the core. Air-flow was directed vertically upwards through the sample (Corey, 1986).

Since water content exerts a significant influence on aeration, all samples were equilibrated at a matric potential of -100 kPa before the measurements were made. For each sample three inflow pressures were maintained and the flow rate for each obtained. The air permeability (K_a, in m^2) was then calculated by the equation of Corey (1986):

$$\mathbf{K_a = ?_a\ V\ L\ /\ (A\ ?_m\ g\ h)}\text{.....Eq. 6.8}$$

where $?_a$ is the air viscosity (1.835×10^5 Pa s at 20°C); V is the measured air-flow rate ($m^3\ s^{-1}$); L is the sample height (m); A is the sample cross-sectional area (m^2); $?_m$ is the manometer fluid density (for water this is 998 kg m^{-3} at 20°C); g is the acceleration due to gravity (9.98 m s^{-2}) and h is the pressure drop across the core (Pa). Multiplying the K_a value from Equation 6.8 by 10^{12} converts the units from m^2 to μm^2.

6.4.3 Results and discussion

6.4.3.1 Air-filled porosity

Brookdale Farm

Mean air-filled porosities (e_a) for the -5, -10, -30 and -100 kPa matric potentials for the WTR-amended treatments at Brookdale Farm, calculated according to Equations 6.6 and 6.7, are given in Appendix 6.8. The bulk densities of the treatments from which the total porosities were calculated are given in Appendix 6.7.

The influence of water content on e_a can be seen by comparing the values measured at different matric potentials for the same sample (Appendix 6.8). As expected, e_a increased with decreasing matric potential as progressively smaller pores were drained. For the control treatment there was typically a 10-13% difference in e_a between matric potentials of -5 and -100 kPa (Appendix 6.8), which was also found to be consistent between the sampling sessions, despite the increase in bulk density over time. Generally differences in e_a measured between the WTR-amended treatments for each sampling period were found to be statistically non-significant ($p<0.05$) when tested by analysis of variance (Appendix 6.8). This applied to all of the matric potentials at which the samples were equilibrated. No consistent trend between e_a and WTR content was therefore found. Where significant differences were found (April and June 2000) no clear patterns were evident. The main reason for this is that despite the increase in the total porosity of the soil following the addition of WTR, the water content at the matric potential corresponding to the e_a estimate also increased, leading to negligible influences on e_a.

At field capacity, irrespective of the treatment e_a typically ranged from 21 to 25% (0.21-0.25 $m^3\ m^{-3}$). If the critical soil aeration threshold of 10-15% for optimum soil aeration at field capacity as cited by Ball *et al.* (1988), Blackwell *et al.* (1990) and Carter *et al.* (1998) is accepted, then addition of WTR to this soil, even at the high rate, should not compromise plant growth with regard to soil aeration. Even at a matric potential of -5 kPa when only pores >58.4 µm in diameter are air-filled, the mean e_a values were within the 'optimum aeration' range.

The water retention curve for the lime, gypsum and PAM treatments (at -10 kPa matric potential) showed very similar characteristics to that of the control treatment (Section 6.2). As expected, these treatments also showed non-significant differences for most sampling dates, and as for the WTR-amended treatments, where there were significant differences, these did not show any particular pattern.

Ukulinga Farm

Mean e_a for the -5, -10, -30 and -100 kPa matric potentials for the WTR-amended treatments at Ukulinga Farm (Westleigh soil) are given in Appendix 6.9. The bulk densities for these treatments from which total porosities was calculated are given in Appendix 6.7.

Generally the e_a for the 0 and 80 Mg ha^{-1} WTR treatments were greater in December 1999 than in either April or August 2000. The decrease in e_a with time is probably due to the collapse of large pores during reversion of tillage. In December 1999 for the control treatment the volume of pores >58.4 µm in diameter was on average 22.5%, while in April 2000 it was substantially lower (17.2%) and even less in August 2000 (15.1%). Similarly the e_a of the control treatment at field capacity in December 1999 was about 5.8% greater than it was in April 2000 that, in turn, was 2.3% more than was measured during August 2000. It is interesting that, despite the previous comments, the bulk densities of the treatments were poorly correlated with e_a at field capacity. From February 2001 onward the e_a of the treatments were similar to those reported for the August 2000 sampling period, with some variability being evident. This variability is probably associated with the redevelopment of the soil structure following the earlier tillage, and the natural influence of the soil's shrink-swell characteristics and faunal component.

While significant differences were found between means at most matric potentials for most sampling periods, there was no consistent pattern evident. Generally the WTR-amended treatments were non-significantly different from each other (Appendix 6.9). The lime and gypsum treatments tended to show similar e_a values to those of the WTR treatments, while the PAM treatment tended to show marginally lower values, although this was not consistent.

6.4.3.2 Air permeability

Brookdale Farm

Mean K_a values measured on the undisturbed soil cores are given in Table 6.10. Since the mean K_a values were log-normally distributed, analysis of variance was carried out on log-transformed data (Table 6.10). The log-normal distribution of K_a values has been previously reported by Ball *et al.* (1988), Roseberg and McCoy (1992), Granovsky and McCoy (1997) and Lauren (1997).

Table 6.10 Summary ANOVA statistics for mean (n=4) log-transformed air permeability (K_a) data and untransformed air permeability (±SE), measured at -100 kPa, for undisturbed soil cores collected from Brookdale Farm

Date		WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-Pr
		0	80	320	1280						
April 2000	Log K_a	1.044	1.050	1.166	1.216	0.951	1.498	1.199	NS	1.55	0.211
	K_a	11.194 (1.865)	11.638 (3.872)	17.541 (12.903)	26.083 (21.892)	9.236 (2.672)	34.914 (17.982)	18.727 (12.994)			
June 2000	Log K_a	1.033	1.011	1.130	1.236	0.881	1.328	0.984	NS	1.34	0.286
	K_a	11.228 (3.375)	10.710 (3.276)	15.027 (7.095)	18.998 (10.614)	9.697 (6.562)	30.279 (28.262)	9.837 (2.203			
February 2001	Log K_a	1.264a*	1.165a	1.021b	1.301a	nd	nd	nd	0.190	4.13	0.032
	K_a	18.862 (4.909)	15.863 (8.211)	10.628 (1.833)	20.158 (2.944)	nd	nd	nd			
September 2001	Log K_a	0.822	0.925	0.840	0.797	0.705	0.670	0.885	NS	0.54	0.768
	K_a	7.071 (2.835)	9.415 (4.892)	6.981 (1.042)	7.997 (4.418)	5.199 (1.274)	6.235 (5.836)	7.893 (2.034)			
October 2002	Log K_a	1.510	1.366	1.220	0.755	1.207	1.165	1.416	NS	2.06	0.103
	K_a	40.821 (22.797)	26.812 (8.707)	28.628 (29.468)	6.680 (4.570)	18.980 (10.862)	17.083 (12.006)	27.928 (11.654)			
June 2003	Log K_a	1.253ab	1.141b	1.086b	1.515a	1.196b	1.467a	1.388ab	0.251	3.79	0.010
	K_a	18.936 (7.266)	14.600 (5.393)	12.254 (1.356)	36.132 (17.304)	16.422 (5.163)	31.880 (16.526)	26.013 (11.121)			

* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

The K_a values increased with increasing WTR applications for the April 2000 sampling period (Table 6.10), although there were not any significant differences found for the log-transformed data (Table 6.10). A similar pattern was observed for the June 2000 sampling period, although K_a decreased for the 1280 Mg ha^{-1} WTR treatment. Subsequent sampling periods did not show a clear pattern. High variability was encountered, possibly reflecting variability in the field. While significant differences were found between treatments for the February 2001 and June 2003 sampling periods, the pattern was not consistent and a relationship between WTR application rate and K_a could not be found.

It would appear that the influence of extraneous factors (such as faunal influences) has led to a high degree of variability in the measurement of K_a, leading to no clear trends.

Ukulinga Farm

Mean K_a values measured on the undisturbed soil cores collected from the Ukulinga Farm are given in Table 6.11. As was found for Brookdale Farm, K_a was log-normally distributed so analysis of variance was carried out on log-transformed data (Table 6.11).

Table 6.11 Summary ANOVA statistics for mean (n=4) log-transformed air permeability data and untransformed air permeability (±SE), measured at -100 kPa, for undisturbed soil cores collected from Ukulinga Farm

Date		WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-Pr
		0	80	320	1280						
April 2000	Log K_a	1.292	1.429	1.548	1.780	1.548	1.498	1.516	NS	2.25	0.093
	K_a	20.067 (2.432)	27.166 (2.366)	38.941 (9.088)	59.598 (8.148)	45.356 (17.742)	35.448 (10.381)				
August 2000	Log K_a	1.049	1.035	1.401	1.550	1.425	1.384	1.425	NS	1.06	0.416
	K_a	18.433 (5.815)	17.560 (7.839)	25.183 (0.587)	39.070 (11.136)	26.680 (1.037)	24.273 (1.028)	22.477 (6.454)			
February 2001	Log K_a	1.374	1.691	1.659	1.769	1.550	1.387	1.474	NS	2.26	0.077
	K_a	27.491 (16.518)	49.694 (8.623)	47.575 (15.530)	60.079 (14.594)	35.949 (7.131)	30.125 (22.346)	33.488 (17.242)			
September 2001	Log K_a	1.373	1.358	1.500	1.597	1.467	1.652	1.524	NS	1.14	0.375
	K_a	34.056 (5.803)	23.682 (7.455)	33.871 (13.487)	42.644 (18.073)	30.033 (8.088)	45.257 (6.905)	33.695 (5.087)			
October 2002	Log K_a	1.411	1.470	1.465	1.321	1.492	1.249	1.379	NS	0.73	0.634
	K_a	28.505 (15.574)	30.275 (8.373)	29.348 (3.905)	26.304 (18.174)	35.131 (20.320)	17.793 (1.603)	26.219 (12.743)			
June 2003	Log K_a	1.451ab*	1.637a	1.520a	1.566a	1.569a	1.207bc	1.113c	0.333	3.11	0.024
	K_a	34.138 (27.489)	47.279 (21.511)	33.688 (7.878)	42.910 (26.517)	42.597 (21.934)	16.506 (4.314)	14.151 (6.040)			

* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

For the April 2000, August 2000, February 2001 and September 2001 sampling periods the general order in K_a between the WTR treatments was 1280 > 320 > 80 > 0 Mg ha^{-1} (Table 6.11), although no significant differences between the log-transformed data were found for these sampling periods. It would appear that for the October 2002 and June 2003 sampling periods the WTR treatments showed similar Ka, given the high variability associated with these measurements. The June 2003 sampling did have significant differences between the means of the log-transformed data (Table 6.11), but this was due to the low K_a measured for the gypsum and PAM treatments.

The K_a of the lime treatments was similar to the control, while the K_a of the gypsum and PAM treatments was highly variable with no consistent pattern being shown.

A possible reason for the high variability of the treatments is that during desorption of the sample to -100 kPa, some degree of volumetric shrinkage occurred, leading to the development of several cracks within the soil core. This effect was exacerbated particularly at the high rates of WTR application and so the air-flow rate through these samples was much higher. Nevertheless, considering that the air-filled porosity between the treatments was very similar at a matric potential of -100 kPa, it is likely that an increase in macropore continuity accounts for the higher mean K_a (although statistically non-significant).

6.4.4 Conclusions

Water treatment residue, gypsum, lime and PAM have thus far generally shown a statistically non-significant influence in the field on either the air-filled porosity or air-permeability of the Hutton and Westleigh soils. Air-filled porosities were highly variable both within and between the treatments, but, as explained in Section 6.2, this is perhaps due to the marked influence of tillage during the early phase of the investigation, and natural soil processes once the effects of tillage were no longer present. The variability in the soil can lead to seemingly high variability in the measurements. The presence, for instance, of an ant nest in the area of sampling could increase the number of large, open-ended pores within a single core markedly, leading to an apparently exaggerated measurement of K_a and other measurements. This variability leads to poor statistical relationships, and may mask the true effect of the WTR or other applied treatments. Given that this may be the cause, however, it would then appear that the effect of the applied treatments does not drastically alter the characteristics of the soil.

6.5 Aggregation and soil stability

6.5.1 Introduction

Analysis of the aggregate size distribution of soils has been used successfully in evaluating the effects of various waste products on aggregation. For example, Rasiah *et al.* (1997) showed that when an oily waste residue was applied to soil, a significant increase in the proportion of large aggregates at the expense of smaller aggregates occurred. This effect was linked directly to the effect of the oil in binding smaller soil fragments together. The aggregate size distribution of soils has also been used successfully in evaluating the influence of tillage on soil aggregation (Zobheck and Popham, 1990; Perfect and Kay, 1994).

6.5.2 Materials and methods

Changes occurring in the aggregate size distribution of the WTR-amended treatments at the field trials were measured using a combination of dry- and wet-sieving techniques. For convenience and to ensure that a specific and approximately uniform volume of material was collected from each treatment, samples were collected using a core sampler (Section 6.2). This prevented disturbing large areas of the plot, which was considered unwise especially for continuing measurement of water retention properties. Three cores from each plot (six per treatment) were collected from the 0-50 mm soil depth. The core samples were bulked for each treatment and three sub-samples taken for the measurement of dry aggregate size distribution (DASD). From the DASD sieving, the 2.0-4.75 mm size fraction was used to determine water stable aggregation.

6.5.2.1 Dry aggregate size distribution

The soil samples on which the DASD was measured were first air-dried. They were then sieved through a nest of sieves with apertures of 9.5, 4.75, 2.0, 1.0, 0.5, 0.25, 0.125 and 0.053 mm for 10 min using a mechanical sieve shaker. The mass of the sample retained on each sieve was measured along with the length of the largest

aggregate retained on the uppermost sieve (9.5 mm). Each aggregate size fraction was expressed as the percentage of the original mass of the soil. The mean weight diameter (MWD) was calculated as the sum of the mass fraction of soil remaining on each sieve multiplied by the mean aperture of adjacent sieves i.e.,

$$\mathbf{MWD = ?\ X_i W_i} \text{……... Eq. 6.9}$$

where Xi is the mean diameter of the size class midpoint (mm) and Wi is the proportion of the total sample retained on the sieve.

The aggregate size distribution of most soils follows a log-normal rather than a normal distribution (Kemper and Rosenau, 1986). It is therefore often described by the geometric mean diameter (GMD) that is calculated as:

$$\mathbf{GMD = exp\ (?\ W_i \log X_i\ /\ ?\ W_i\ )} \text{..…….Eq. 6.10}$$

where W_i is the mass of aggregates in the size class i with an average diameter X_i and **?** W_i is the total mass of the sample. From a physical perspective the GMD may be regarded as the sieve size through which 50% of the material would pass.

6.5.2.2 Wet aggregate size distribution

There is divergent opinion presented in the literature on whether aggregates used for wet-sieving should be at their field water content or in their air-dry state. According to Haynes and Swift (1990), aggregate stability as determined by wet-sieving of air-dried aggregates measures both the slaking potential of aggregates and their subsequent breakdown by mechanical action. In addition, for the sake of monitoring the change in aggregation over time, standardising the water content at which the test is carried out was considered important, which in this case is most convenient at the air-dry water content.

Forty grams of the 2.0 to 4.75 mm fraction from DASD was transferred to a wet-sieving apparatus similar to that described by Kemper and Rosenau (1986), which had a nest of sieves of size 2.0, 1.0 and 0.5 mm. The water level was adjusted such that on the upstroke of the machine, the aggregates on the uppermost sieve remained just submerged at the highest point of oscillation. Before operating the machine the sample was first capillary saturated for 10 min after which the sieves were raised and lowered 37 mm at a rate of 29 times min^{-1} for 15 min. The material retained on each sieve was washed into tared 100 mL beakers and dried at 105^{o}C for 24 h, following which the sample was shaken in 0.5% sodium hexametaphosphate for 45 min. This was then washed through the respective sized sieve and that which was retained, transferred once more to tared 100 mL beakers. The water-stable fraction retained on each sieve (WSA_i) was calculated as described by Angers and Mehuys (1993). The results were nevertheless expressed as the MWD calculated according to Equation 6.9. This was replicated three times. In the present context the upper limit of the MWD was 3.375 mm (assuming that the entire sample was retained on the 2.0 mm sieve, with a maximum aggregate size of 4.75 mm). The lower limit was 0.75 mm (assuming that the entire sample passed through the 2.0 mm and 1.0 mm sieves and was retained exclusively on the 0.5 mm sieve).

6.5.3 Results and discussion

6.5.3.1 Dry aggregate size distribution

The mean GMD values for the treatments collected from the Brookdale and Ukulinga trials are given in Tables 6.12 and 6.13, respectively. As expected, good correlation between the MWD and GMD was obtained. The results are therefore discussed only in terms of the GMD. The MWD for the treatments are, nevertheless, presented in Appendix 6.10.

In general, evaluating the influence of WTR on soil aggregation from the DASD at the Brookdale trial was disappointing. Although ANOVA showed significant differences in the GMD between the treatments for February 1999, November 1999 and February 2000, no consistent relationships between the GMD and the application rate of WTR could be found (Table 6.12). Regarding the effect of time on the DASD, inconsistent trends in GMD were also observed and this was independent of the treatment applied.

Table 6.12 Geometric mean diameters (mm) for the treatments investigated at Brookdale Farm

Date	WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-Pr
	0	80	320	1280						
February 1999	1.50ab*	1.11c	1.46ab	1.39ab	1.60a	1.34b	1.09c	0.22	7.34	0.001
September 1999	1.04	1.11	1.21	1.16	1.06	1.19	1.09	NS	0.86	0.547
November 1999	1.62a	1.59a	1.60a	1.59a	1.33b	1.31b	1.15b	0.26	0.26	0.007
February 2000	1.12bc	1.25ab	0.94c	1.41a	1.10bc	1.10bc	1.00c	0.23	4.42	0.010
February 2001	1.04	1.18	1.15	1.14	nd	nd	nd	NS	2.27	0.158
September 2001	0.91	1.05	1.02	1.15	0.93	1.06	1.05	NS	2.07	0.123
October 2002	1.17	1.25	1.14	1.09	1.11	1.11	1.16	NS	0.99	0.469
June 2003	1.18	1.16	1.15	1.17	1.30	1.31	1.00	NS	2.37	0.086

* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

At the Ukulinga field trial, statistically significant differences in the GMD between the treatments were found for all treatments, except the October 2000 and February 2001 sampling periods. As before, there was no consistent trend with WTR content (Table 6.13). Nevertheless, the GMD of the 1280 Mg ha^{-1} treatment was frequently found to be higher than the other treatments. This was due more to the presence of large aggregates of WTR included in the sample than to its interaction with the soil. It is likely that as these aggregates break down into a finer grade, the GMD should decrease in the WTR-amended treatments.

These findings point to the complexities associated with evaluating the aggregation quality of soils from a measure of their DASD and supports similar comments raised by *inter alia* Zobeck and Popham (1990), Skidmore and Layton (1992), Perfect and Kay (1997) and Rasiah *et al.* (1997). Climatic factors, management factors and inherent soil properties can have a strong influence on the DASD. According to Rasiah *et al.* (1997), the log-normal function (from which the GMD is determined) is based on the assumption that the probability of failure of an aggregate does not depend upon its size. This assumption may not be entirely valid, because larger aggregates are likely to fragment more easily than smaller aggregates. In this regard it is felt that as a monitoring index of WTR land disposal systems, a measure of the DASD is of limited value in evaluating the rate of residue breakdown.

Table 6.13 Geometric mean diameters (mm) for the treatments investigated at Ukulinga Farm

Date	WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-Pr
	0	80	320	1280						
November 1999	1.22ab*	1.06b	1.03b	1.39a	1.13b	1.10b	nd	0.18	5.29	0.008
April 2000	1.15b	1.17b	1.24b	1.46a	1.24b	1.17b	nd	0.19	3.32	0.041
October 2000	1.29	1.21	1.16	1.41	1.24	1.15	1.23	NS	1.61	0.217
February 2001	1.29	1.16	1.46	1.36	1.42	1.41	1.36	NS	2.39	0.084
September 2001	1.25bc	1.33ab	1.15c	1.42a	1.46a	1.33ab	1.33ab	0.15	4.57	0.009
October 2002	1.18b	1.29b	1.22b	1.50a	1.18b	1.24b	1.35ab	0.18	3.73	0.020
June 2003	1.41a	1.10c	1.22abc	1.37ab	1.24abc	1.16bc	1.10c	0.22	2.88	0.048

* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

6.5.3.2 Wet aggregate size distribution

The MWD of water stable aggregates for the treatments at Brookdale Farm is given in Table 6.14. Despite a uniform volume of material being collected from each treatment, the results showed high levels of variability, even when comparing the MWD within single treatments. In February 1999, the 1280 Mg ha^{-1} WTR treatment was significantly different from all other treatments that were not significantly different from one another. The WTR has high stability (MWD of 2.35 out of a possible 3.375). When added to soil at 1280 Mg ha^{-1} these aggregates account directly for the increased MWD as much of the material that remained on the sieves at the end of the test was composed of WTR aggregates. The results of the September 1999 and November 1999 sampling periods do not reflect any particular trend, but this may be due to the lack of replication on those occasions.

The results of the study carried out in February 2000 showed statistically non-significant differences in the MWD between the 0, 80 and 320 Mg ha^{-1} WTR treatments, while the 1280 Mg ha^{-1} WTR treatment was not significantly different

from the control, lime, gypsum and PAM treatments. Compared with the results from February 1999, the mean values in February 2000 were much lower. Inspection of the material retained on the 2 mm sieve for the 1280 Mg ha^{-1} treatment showed a far lower proportion of residue particles than was found previously. This was due to the breakdown of these particles over time into a finer grade. From these findings it is apparent that the MWD of the WTR-amended treatments was influenced more strongly by the breakdown of residue particles that to the interaction of the residue in stabilising or destabilising soil aggregates.

The February 2001 sampling showed that the control treatment was significantly lower than the other WTR treatments. However, when compared to previous and subsequent values obtained for the control treatment, it is likely that this was an anomalous estimation on this occasion. Subsequent sampling periods had non-significant differences between means, with no trend evident. This tends to suggest that the effect of WTR was no longer contributing to differences in MWD as the high structural stability of the Hutton was dominating over any treatment effects.

Table 6.14 Mean (n=3, except September and November 1999 where n=1) mean weight diameters (mm) of water-stable aggregates for the treatments measured at Brookdale Farm

Date	WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-Pr
	0	80	320	1280						
February 1999	2.19b*	2.16b	2.14b	2.76a	1.64b	2.06b	nd	0.52	4.54	0.015
September 1999	1.40	2.02	2.20	2.10	1.64	2.00	1.98	nd		
November 1999	1.23	1.48	0.85	0.90	1.25	1.43	1.89	nd		
February 2000	1.40bc	1.35c	1.27d	1.55ab	1.61a	1.63a	1.67a	0.19	6.56	0.002
February 2001	1.17b	1.55a	1.50a	1.70a	nd	nd	nd	0.22	11.32	0.003
September 2001	1.62	1.51	1.55	1.55	1.83	1.56	1.47	NS	0.17	0.980
October 2002	1.50	1.88	1.32	1.32	1.49	2.19	1.85	NS	2.79	0.103
June 2003	1.65	1.77	1.83	1.45	1.56	1.68	1.85	NS	1.67	0.258

* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

With regard to the gypsum, lime and PAM treatments, these products did not cause any meaningful change on the aggregation of the Hutton soil. It is possible that because of the high stability shown by the Hutton soil in its unamended state (MWD in the order of 2 mm), the sensitivity of the wet-sieve method was not sufficient to detect any changes caused by these products on aggregate stability. The marginal decrease in the MWD of the control treatment could be related to a decrease in soil organic matter (considering that the treatments were maintained fallow). Inconclusive evidence was, however, obtained in evaluating the total organic carbon of the samples collected during February 1999 and February 2000. In general the measurement of

water-stable aggregation for evaluating the effects of the WTR, gypsum, lime and PAM on the stability of the Hutton soil at the Brookdale Farm produced unconvincing results. Nevertheless, as the residue breaks down into a more uniform grade, it is expected that the high levels of variability encountered in the findings of this study should decrease.

Compared to the Hutton soil, the Westleigh soil (Ukulinga Farm) is less strongly aggregated, as shown by the MWD in the order of 0.5 mm measured on the control treatment (Table 6.15), although some higher values were recorded on some occasions (September 2001 and June 2003).

Table 6.15 Mean (n=3) mean weight diameters (mm) of water-stable aggregates for the treatments measured at Ukulinga Farm

Date	WTR application rate (Mg ha^{-1})				Lime 10 Mg ha^{-1}	Gypsum 10 Mg ha^{-1}	PAM 30 kg ha^{-1}	$LSD_{5\%}$	VR	F-Pr
	0	80	320	1280						
December 1999	0.52c*	1.04b	1.00b	1.94a	0.74bc	0.73bc	nd	0.39	15.44	<0.001
April 2000	0.62c	0.78bc	0.97b	1.27a	0.89b	0.94b	nd	0.21	9.98	<0.001
October 2000	0.49c	0.56c	0.60bc	0.85a	0.80ab	0.60bc	0.64bc	0.20	3.76	0.019
February 2001	0.49b	0.60b	0.85a	0.78ab	0.65b	0.66b	0.55b	0.18	5.54	0.009
September 2001	0.83	0.55	0.90	0.96	0.85	0.61	0.50	NS	1.81	0.168
October 2002	0.43	0.26	0.58	0.66	0.46	0.68	0.53	NS	1.66	0.260
June 2003	0.86a	0.71b	0.65b	0.85a	0.56c	0.46d	0.33e	0.08	65.66	<0.001

* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

Addition of residue to this soil caused an almost immediate increase in the MWD due to the controlling influence of the highly water-stable residue aggregates. With regard to the WTR treatments, in December 1999, even at the 80 Mg ha^{-1} level the MWD was almost double that of the control. With time, however, as these residue aggregates broke down, less material was retained on the 2 mm sieve and the MWD across all of the treatments decreased. As was found at the Brookdale trial, the largest decrease in the MWD was found on the 1280 Mg ha^{-1} treatment. Nevertheless, in October 2000 (a year after the trial was established), the MWD of the 1280 Mg ha^{-1} treatment was significantly different from that of the control. The 80 and 320 Mg ha^{-1} treatments on the other hand, were non-significantly different from the control and from one another. By September 2001, however, the WTR treatments had generally similar MWDs, even though significant differences existed between some treatments.

With regard to the lime and gypsum treatments, both products caused a similar increase in the MWD, which in April 2000, was in the order of 0.3 mm greater than that of the control. After that a decrease in aggregation seems to have occurred, presumably due to the leaching of the amendment from near the soil surface. Generally these treatments were not significantly different from the control treatment.

The PAM treatment sampled in October 2000 showed a MWD comparable to that of the control treatment, which implies that this product had little influence on improving the aggregation of this soil. There was also an apparent decrease in aggregation for subsequent sampling periods, suggesting that PAM may have negative long-term impacts on soil aggregation. It is more likely, however, that these measurements are anomalous due to high variability.

6.5.4 Effect of 'wet' water treatment residue on soil stability

6.5.4.1 Introduction

In many respects the work reported previously has been concerned largely with the effects of air-dry residue on soil stability. Although this is a convenient reference state, it is also of interest to evaluate the effects of the residue when it is applied in its 'wet state' to soils. In this regard, WTR and soil (four soil types) were incubated at equivalent matric potential for a specified period and the resulting influence on clay dispersion, aggregation and soil strength studied. The discussion of the effects of WTR on soil strength is presented in Section 6.6, although it should be noted that clay dispersion is an integral factor affecting soil strength.

6.5.4.2 Material and methods

The quantity of air-dry soil (<2 mm) to yield an equivalent oven-dry mass of 0.4 kg (by correcting for its water content) was measured out into PVC buckets for the four soil types. Each soil was then brought to matric potentials of 0, -10 and -500 kPa, by adding the appropriate quantity of water to obtain the desired water content as determined from the retention curve. Fresh residue with an initial water content of 6.03 g g^{-1} was equilibrated at matric potentials of 0, -10 and -500 kPa using tension tables and pressure plate apparatus. For each matric potential, the quantity of residue required to obtain an equivalent oven-dry application rate of 0, 80, 320 and 1280 Mg ha^{-1} was then calculated and added to the soil of each matric potential. Incorporation of the residue with the soil was accomplished by churning the mixture with a flat steel bar until it was as homogeneous as possible. Due to the crumbly nature of the soil and residue at -500 kPa, slight kneading of the sample was necessary to obtain an acceptable final condition of the mixture. The buckets were then sealed and shaken end-over-end for 5 min before being stored in a constant temperature room maintained at 23^{o}C for 8 weeks. To prevent the onset of anaerobic conditions during the incubation period, the buckets were removed once a week, shaken for 5 min and the lids left open for an equivalent period before being resealed and returned to the constant temperature facility. During this time, the buckets were also weighed so as to monitor any evaporative losses, which were determined to be negligible, and so no correction for this influence was made.

At the end of the incubation period a sub-sample of material was extracted from the bucket for the measurement of soil strength (Section 6.6). The remaining sample was air-dried and then crushed to pass a 2 mm sieve, after which the aggregation percentage for all samples was calculated according to the United States Salinity Laboratory Staff (1954) as :

$$\frac{\text{(Total silt + clay after complete dispersion - unbound silt and clay) x 100}}{\text{Total silt + clay after complete dispersion}} \quad \text{.....Eq. 6.11}$$

In measuring the unbound silt and clay, 20 g of sample was placed in 1 L sedimentation cylinders to which was added distilled water in such a manner so as to favour wetting by capillarity rather than by flooding. Once the soil was wet the cylinders were brought to volume after which they were shaken end-over-end 20 times over a period of approximately 40 sec. The unbound silt and clay fraction was then measured by the pipette method (Kemper and Rosenau, 1986). The unbound silt and clay percentage for the control treatment incubated at matric potentials of -100 and -500 kPa was not measured.

6.5.4.3 Results and discussion

For easier comparison between the treatments, the influence of WTR content and incubation matric potential on soil aggregation is presented in terms of the unbound silt and clay percentage (USCP) rather than the percentage aggregation (Equation 6.11). One can be derived from the other since they both should sum to 100%. The results of this study for the Hutton, Westleigh, Valsrivier and Cartref soils are presented in Figure 6.22.

For all soil types it can be seen that both the residue content and the incubation matric potential had a marked effect on the USCP. Increasing the content of 'wet residue' caused a decrease in the USCP. Nevertheless, because of the high inherent stability of the Hutton soil, 1280 Mg ha^{-1} residue was needed before any change in the USCP was found. Adding 1280 Mg ha^{-1} residue (under the same conditions) to the Cartref soil reduced the USCP below detectable limits. Because of their much higher USCP in the natural state, the Westleigh and Valsrivier soils were particularly sensitive to the influence of the residue. An approximately 6% decrease in the USCP occurred when the Westleigh soil was incubated (at saturation) with 80 Mg ha^{-1} residue while an equivalent value for the Valsrivier soil was in the order of 8%. Similarly at the 1280 Mg ha^{-1} residue level (incubated at saturation), the USCP for the Westleigh and Valsrivier soils was of the order of 8 and 10% less, respectively, than measured for the control treatment.

Decreasing the incubation matric potential also increased the USCP for equivalent residue content. This relationship was generally more pronounced at the 1280 Mg ha^{-1} level than at the lower residue contents where greater variability in the findings was obtained. When the residue is wet, the polymer that it contains remains active and is therefore capable of binding the constituent silt and clay fractions together.

6.5.5 Conclusions

Attempts at using the dry aggregate size distribution to evaluate aggregate stability produced highly variable results. It is therefore felt that in the present context, the GMD of the DASD is a poor monitoring index of soil quality. At Brookdale Farm the MWD of water-stable aggregates showed high levels of variability that prevented a confident evaluation of the influence of the residue on soil aggregation. At Ukulinga Farm the investigation met with greater success. An increase in the MWD for the residue-amended treatments compared with the control treatment was found. Despite

this apparent improvement in aggregate stability as suggested by these findings much of the material retained on the sieves at the end of the test comprised mainly WTR particles. The increase in the MWD for the residue-amended treatments is linked directly to the inclusion of these particles in the sample, rather than to their effects in stabilising existing soil aggregates.

The hydration state of the WTR exerts a marked influence on soil stability. When the WTR is applied to soil in a fully air-dried state, the polymer that was used to flocculate the suspended material and to thicken the WTR during the water treatment process becomes strongly bonded to its constituent fraction. It is therefore unlikely to become reactivated into solution. Consequently there is little physical binding action between the WTR and soil particles. When the WTR is applied in its wet form, however, some of the polymer in the WTR solution becomes attached to the soil particles, so improving the aggregate stability of the amended soil.

In general, the results obtained in the present study show that WTR has the potential for improving soil aggregation and soil stability and that such effects may be better achieved if the WTR is incorporated with the soil, before being allowed to fully air-dry.

6.6 Soil Strength

6.6.1 Introduction

Soil strength is influenced strongly by water content. As a result, interpretation of data obtained with penetrometers and torvanes are ideally interpreted with a corresponding estimate of soil water content. An unfortunate aspect, however, as explained by Jayawardene and Blackwell (1990) is that non-destructive estimates of water content, such as neutron methods, only provide indicators of soil water content across the total soil volume. Penetrometer soil strength (PSS), however, is influenced by the exact location of the probe in relation to the macropores and the associated wetting patterns. In this regard, PSS should therefore be regarded as a point measurement rather than as a bulk soil measurement (O'Sullivan *et al.*, 1987). Despite the previous comment, these instruments offer useful information on soil strength, especially as a relative comparison between treatments at any given sampling time.

6.6.2 Field soil strength

6.6.2.1 Materials and methods

To avoid complications associated with the effect of soil water content, attempts were made to measure soil strength at or near field capacity, which was assumed to exist approximately 48 h following a rainfall event. The instrument used throughout the investigation was of the constant recording type manufactured and marketed by Geotron Systems, South Africa.

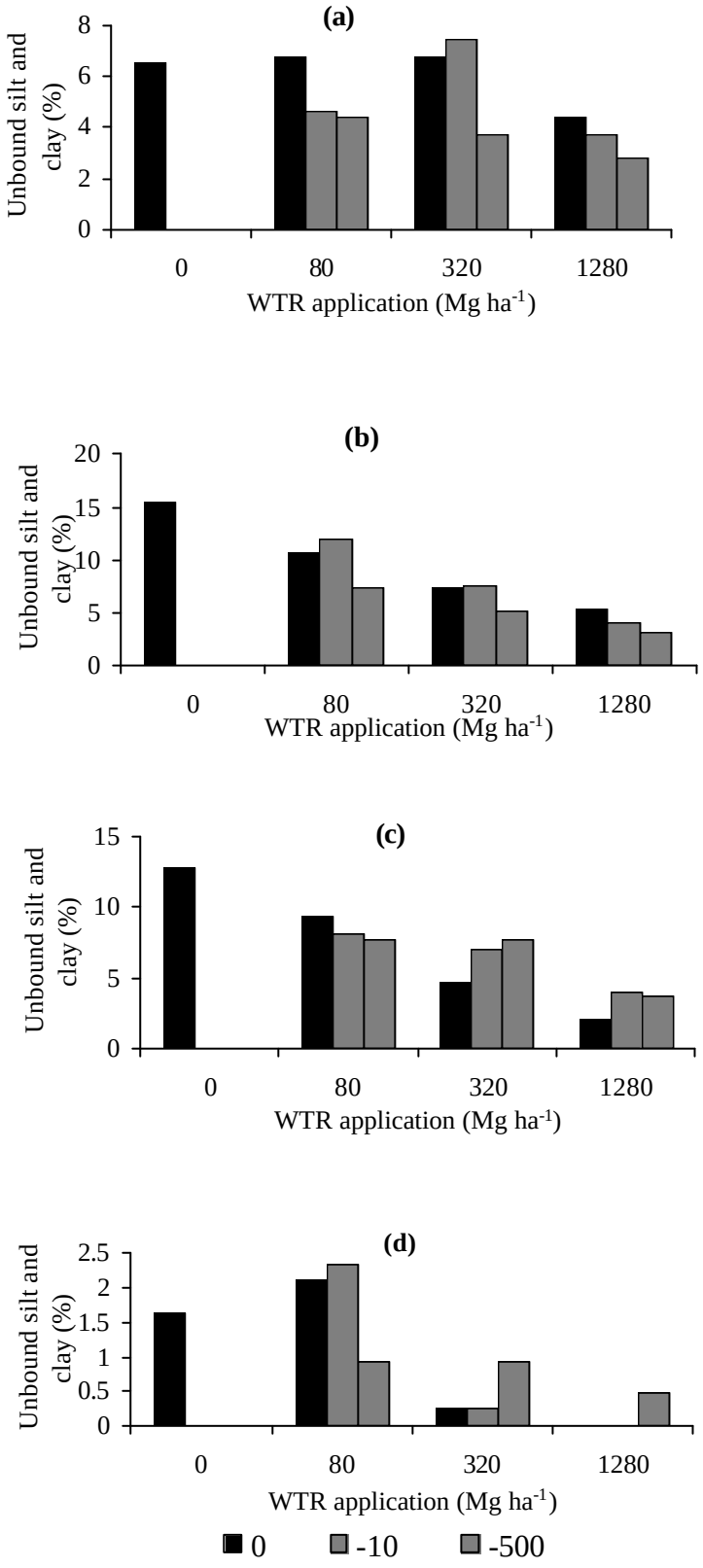


Figure 6.22 Unbound silt and clay percentage of the water treatment residue and soil mixtures for the (a) Hutton, (b) Westleigh, (c) Valsrivier and (d) Cartref soil types after being incubated at selected matric potentials (0, -10 and -500 kPa) for 8 weeks.

The penetrometer is operated by driving a stainless steel cone (apex angle of 30^{o} and a basal area of 130 mm^{2}), mounted at the end of a 0.8 m steel shaft (10 mm diameter) vertically into the soil. Insertion of the probe is eased by a chain-driven gear mechanism (winding ratio 4.8:1) operated by turning two handles at the upper end of the instrument. A footplate ensures stability of the unit during the procedure. The rate of penetration of the probe into the soil is 1 m min^{-1} at 1 sec revolution^{-1}.

A pressure loadcell (type SUB-G-200) attached to the shaft measures the resistance encountered by the probe in kilopascals at 0.01 m depth intervals. The maximum pressure and depth that can be measured are 5 MPa and 0.8 m, respectively. All readings are stored electronically in the memory of the controller unit. In addition, a convenient feature is a digital readout that allows inspection of the results while operating the unit. Customised software is included for the direct downloading of the data from the unit to a personal computer, following which the data can be interrogated using the software supplied or exported to other computer packages.

Six PSS measurements were taken at randomly selected positions within each plot and later combined according to treatment differences. This resulted in 12 penetrometer profiles per treatment. The mulched treatments and the 40, 160 and 640 Mg ha^{-1} WTR-incorporated treatments were excluded from the assessment. Due to poor rainfall in the winter months it was not possible to obtain accurate estimates of soil strength. Consequently much of the investigation was undertaken from early spring to late autumn.

6.6.2.2 Results and discussion

Brookdale Farm

The PSS for the November 1999, February 2000, February 2001, March 2002 and March 2003 are shown Figures 6.23 to 6.27, respectively, while the results for the other sampling periods are shown in Appendix 6.11. These figures show that within the depth of tillage (0 to 0.15 m) the penetrometer profiles for the WTR-amended treatments are similar. From the soil surface to a depth typically around 0.05 m, the PSS increased sharply as greater displacement of the surrounding soil by the conically shaped probe probably occurred. Below this depth and to around 0.15 m the PSS within each treatment was nearly constant. Except during November 1999, where PSS was lower (Figure 6.23), the values ranged between 1.0 and 1.5 MPa regardless of treatment applied.

From a soil depth of 0.15 m downwards (below the tilled layer), as would be expected, the PSS increased sharply but generally remained below 3.5 Mpa. This suggests a moderately compacted subsoil condition. Similar trends to that reported here, where PSS has increased with depth have previously been reported by O'Sullivan *et al.* (1987). The PSS of all the treatments tended to be remarkably similar, with some anomalies. In February 2000 (Figure 6.24) the 1280 Mg ha^{-1} WTR treatment showed a notable increase in PSS below a depth of about 0.25 m. The cause of this is not known. In May 2000 (Appendix 6.11) the 1280 Mg ha^{-1} treatment showed lower PSS than the other WTR treatments at depths greater than 0.05 m. Other anomalous measurements were observed for October 2000 and October 2002 (Appendix 6.11), where some treatments showed erratic PSS from about 0.15 m

depth. Overall the effect of the WTR did not appear to have a marked influence on PSS and no clearly defined trends either within or between the sampling sessions were found.

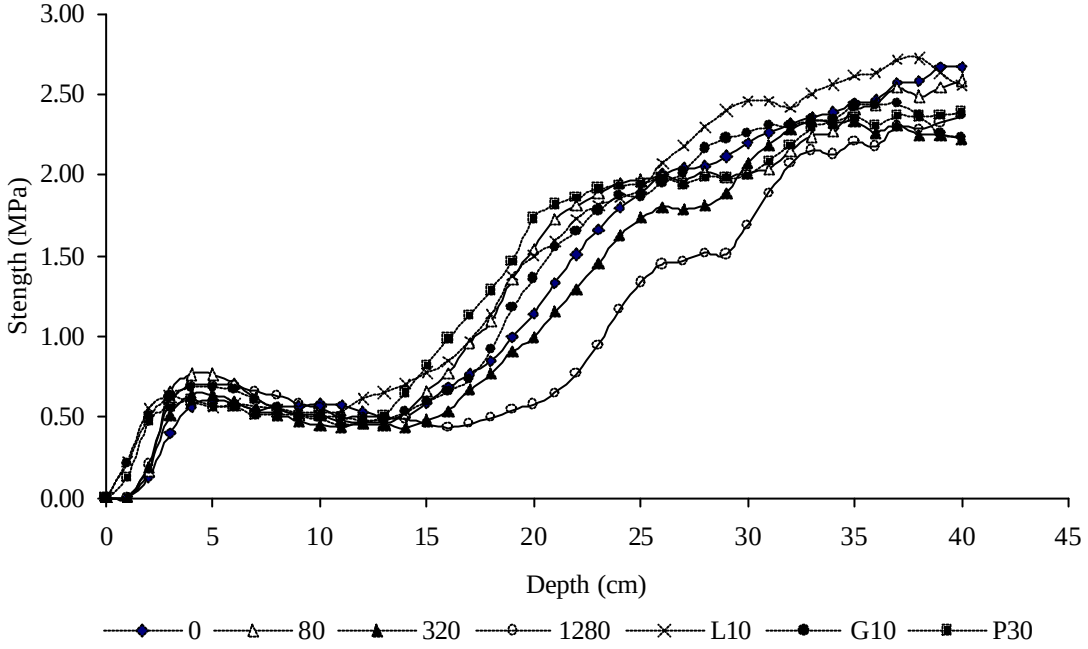


Figure 6.23 Mean (n=12) penetrometer soil strength profiles measured at Brookdale Farm in November 1999. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

The general trend in PSS for the gypsum, lime and PAM treatments was very similar to that of the PSS observed for the WTR treatments. As with the WTR-amended treatments, the PSS for the gypsum, lime and PAM treatments increased sharply to a depth of approximately 0.05 m and then remained nearly constant throughout the remaining depth of the tilled soil (0.15 m). At depths below this the PSS for all of the treatments increased but (as for the WTR-amended treatments) remained below 3.5 MPa.

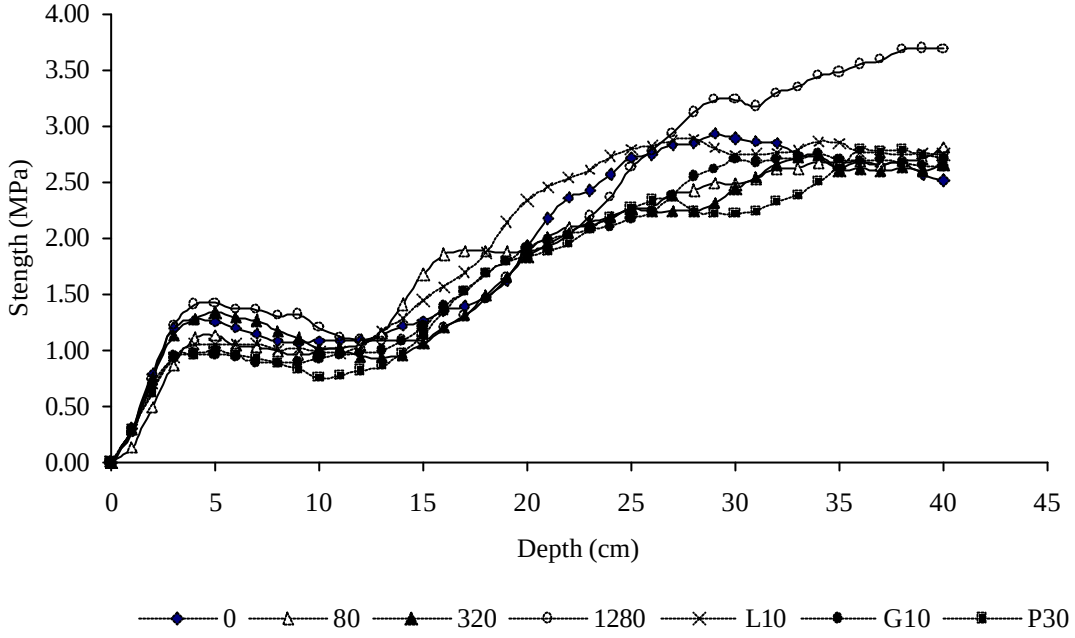


Figure 6.24 Mean (n=12) penetrometer soil strength profiles measured at Brookdale Farm in February 2000. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

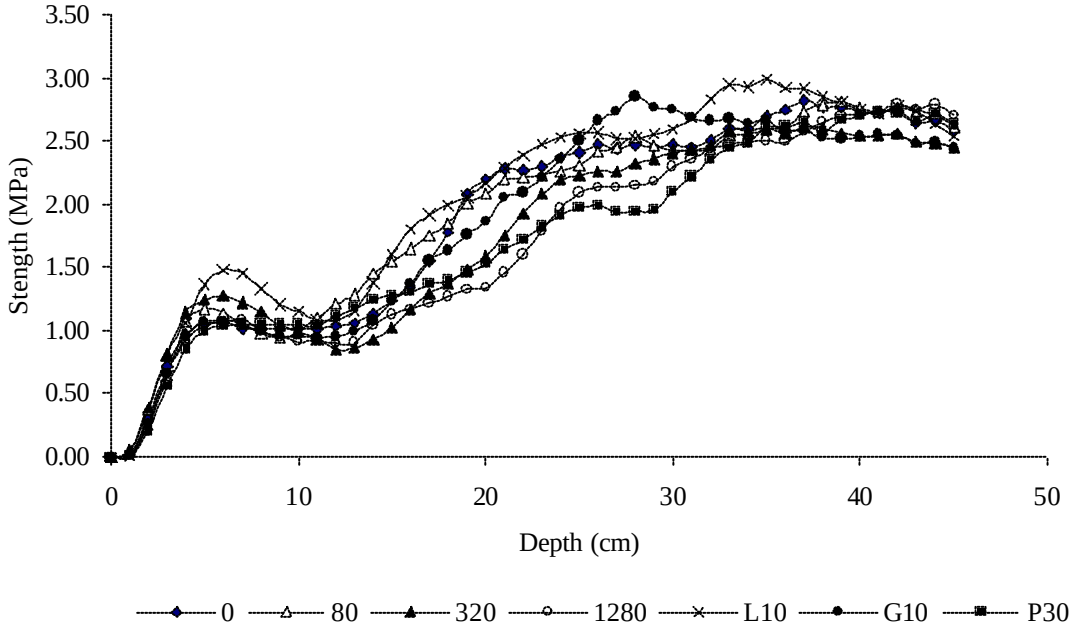


Figure 6.25 Mean (n=12) penetrometer soil strength profiles measured at Brookdale Farm in February 2001. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

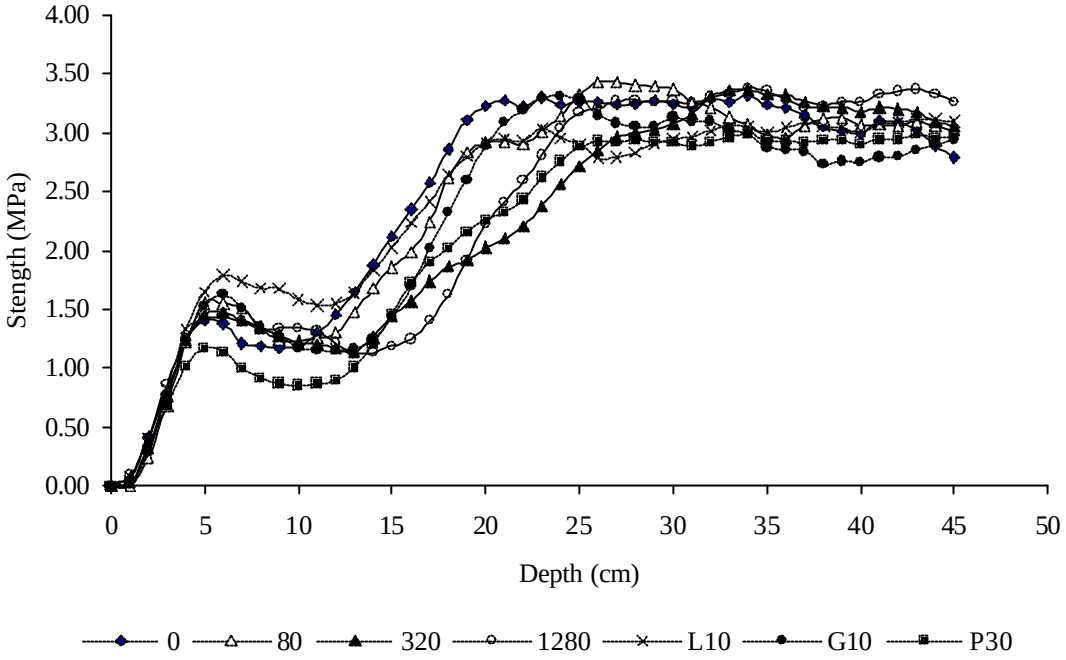


Figure 6.26 Mean (n=12) penetrometer soil strength profiles measured at Brookdale Farm in March 2002. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

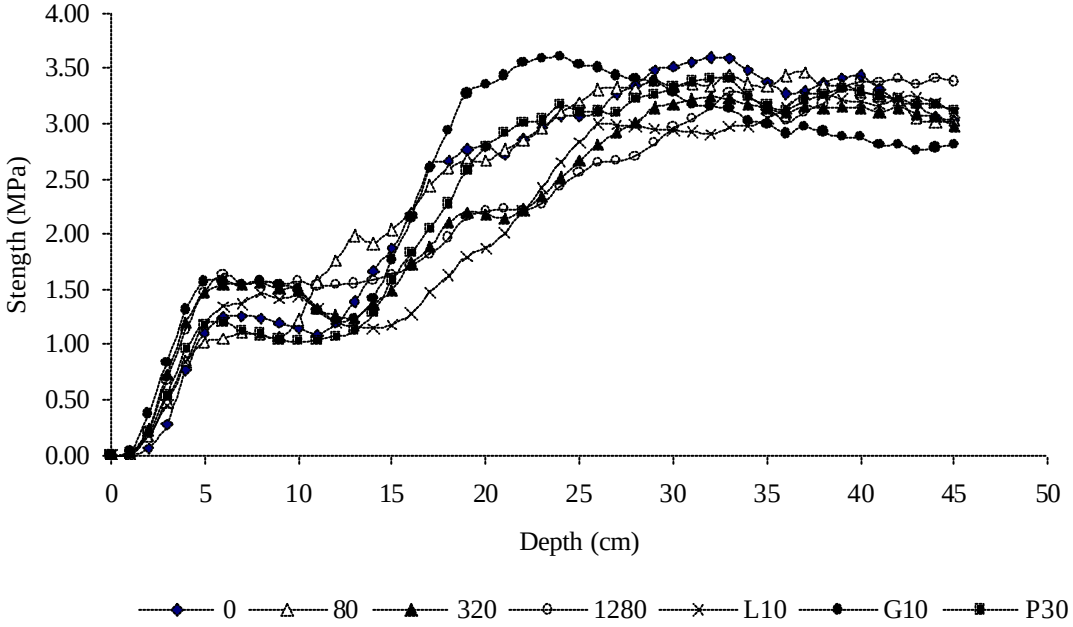


Figure 6.27 Mean (n=12) penetrometer soil strength profiles measured at Brookdale Farm in March 2003. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

Ukulinga Farm

Penetrometer soil strength profiles for the April 2000, February 2001, March 2002 and March 2003 dates are shown in Figures 6.28 to 6.31, respectively, while the other sampling dates are presented in Appendix 6.12. The general trend in PSS with depth shows similarity to the results obtained at Brookdale Farm, despite the difference in soil type and climate.

There was a rapid increase in soil strength that peaked at approximately 1.5 MPa at a depth of about 0.05 m. The PSS remained fairly constant at around 1.2 MPa to a depth of about 0.25 m for the April 2000 and October 2000 samplings, and about 0.3 m depth for the subsequent samplings. At these soil depths the 1280 Mg ha^{-1} WTR treatment consistently showed a lower PSS than the other treatments. Generally at about 0.4 m there was a notable increase in the PSS of the 1280 Mg ha^{-1} WTR treatment. The 320 Mg ha^{-1} WTR treatment tended have a slightly higher PSS than the 1280 Mg ha^{-1} treatment between 0.25 and 0.4 m depth, although this was not consistent. The lower PSS for the 1280 Mg ha^{-1} treatment at greater depth was attributed to a higher water content in the sub-soil layers, due to improved infiltration of water on the plots treated with high rates of WTR, and that the soil depth was effectively increased with the addition of such a large volume of WTR. It would appear that if PSS were measured at a depth beyond that reported here, the values recorded would be similar to those of the other treatments.

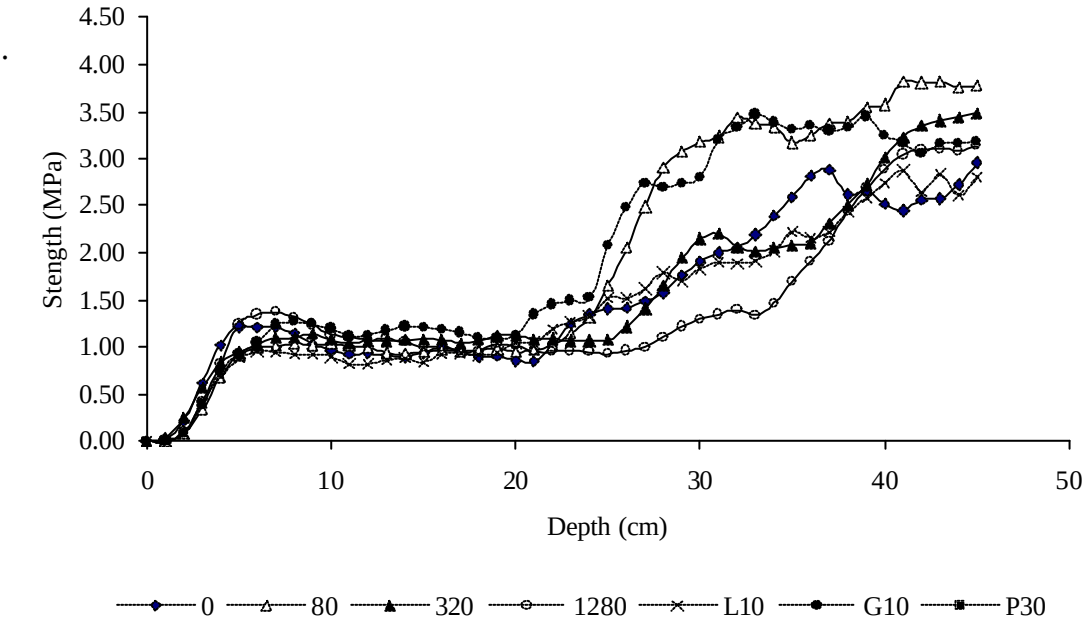


Figure 6.28 Mean (n=12) penetrometer soil strength profiles measured at Ukulinga Farm in April 2000. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

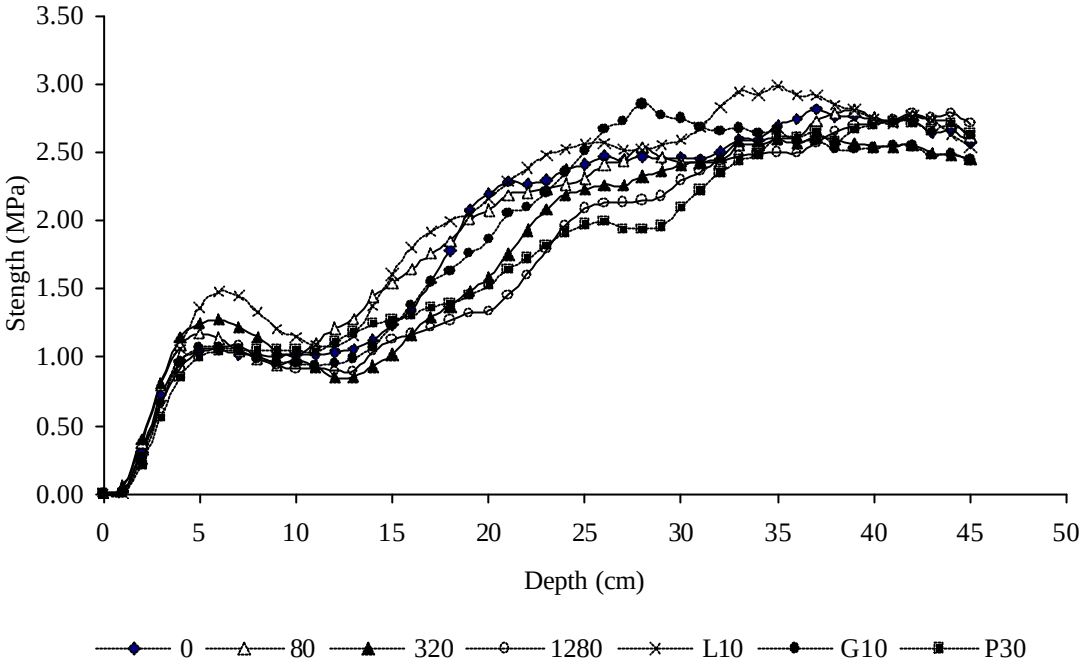


Figure 6.29 Mean (n=12) penetrometer soil strength profiles measured at Ukulinga Farm in February 2001. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

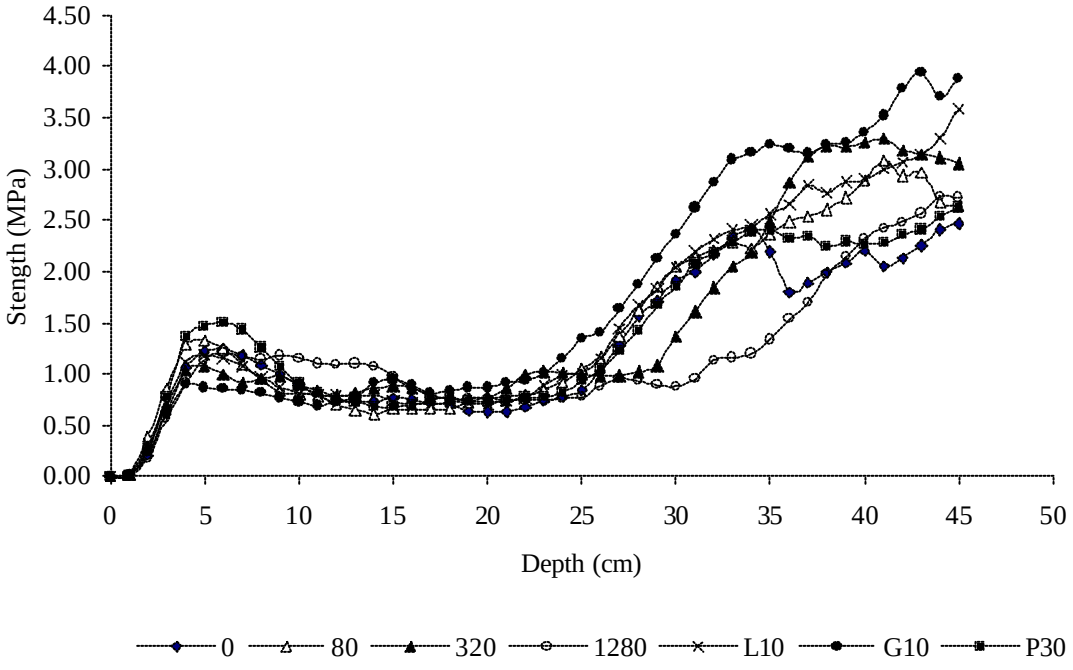


Figure 6.30 Mean (n=12) penetrometer soil strength profiles measured at Ukulinga Farm in March 2001. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

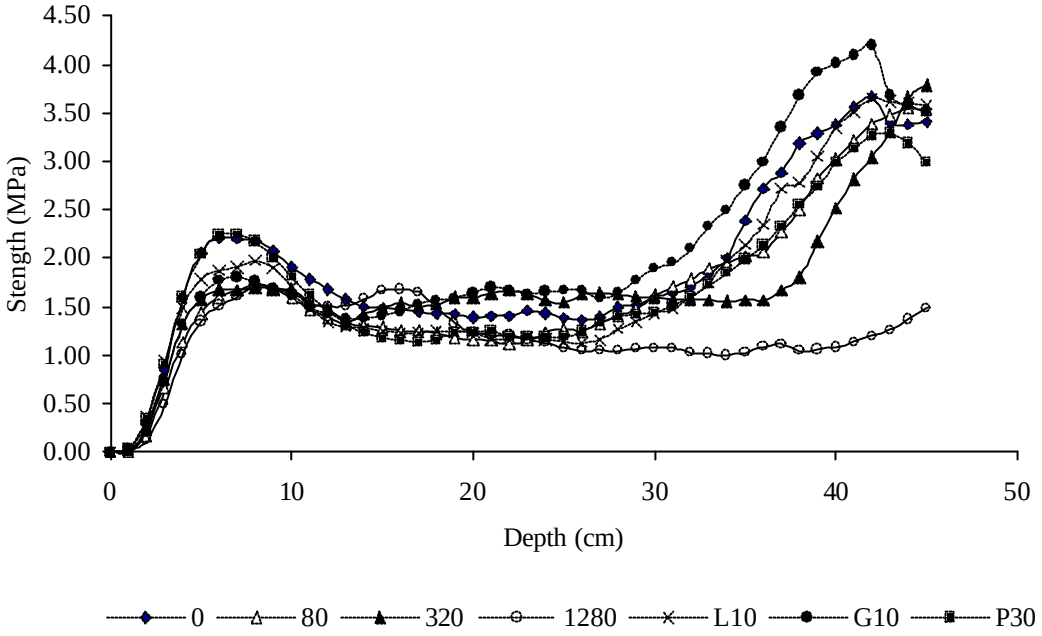


Figure 6.31 Mean (n=12) penetrometer soil strength profiles measured at Ukulinga Farm in March 2003. 0, 80, 320 and 1280 refer to the water treatment residue application rates (Mg ha^{-1}) and L10, G10 and P30 to lime at 10 Mg ha^{-1}, gypsum at 10 Mg ha^{-1} and polyacrylamide at 30 kg ha^{-1}, respectively.

Neither lime nor PAM had any meaningful influence on PSS as shown by the similarity of these curves with that of the control treatment, while the gypsum treatment tended to show slightly higher PSS values at depths greater than 0.25 m. Below this depth, however, PSS values for the gypsum treatment were similar to that of the control. This implies that the differences occurring below the tilled soil, may be due more to natural subsurface variability between the plots than to the treatments.

6.6.3 Modulus of rupture

6.6.3.1 Introduction

The confounding influence of water content on soil strength encountered during the field studies required that an extension of the study under more controlled environmental conditions be carried out. In this regard the influence of WTR on soil strength was further evaluated using a laboratory-based technique, to clarify the previous results. Moreover, this allowed the expansion of the study to include the additional two soil types, namely the Cartref and Valsrivier soils.

6.6.3.2 Materials and methods

Details of the design and execution of the incubation experiment, upon which the results and discussion that follow are based, were presented in Section 6.5.

At the end of the incubation period a sub-sample of material was extracted from the bucket and pressed into rectangular steel moulds (0.0715 m length, 0.0345 m breadth, 0.01 m depth). The remaining sample was air-dried and crushed to pass a 2 mm sieve. The <2 mm fraction was poured gently into an equivalent set of moulds, levelled and saturated overnight following which the excess water was drained. The entire set of briquettes were then air-dried for 5 days at room temperature and then further oven-dried at 50^{o}C for an additional period of 24 h. This initial period of air-drying was necessary as absence of this pre-treatment resulted in severe distortion of the briquettes and unacceptably high levels of cracking. Once dry the dimensions of the briquettes were noted. Where briquettes were formed, these were broken on a beam balance using a briquette-breaking apparatus and closely following the method of the United States Salinity Laboratory Staff (1954), as outlined by Reeve (1965), for measuring the modulus of rupture (MOR). It should, however, be noted that a strict interpretation of the MOR refers essentially to air-dried material passed through a 2 mm sieve. Owing to the limited quantity of samples, only three replicates per treatment were possible.

The MOR was calculated from the following equation:

$$\mathbf{MOR = 3FL/2bd^2} \quad \text{.....Eq. 6.12}$$

where MOR is the modulus of rupture (Pa), F is the breaking force applied at the centre of the beam span (N), L is the length between the briquette end supports (m), b is the width of the briquette (m) and d is depth or thickness of the briquette (m).

6.6.3.3 Results and discussion

Measurements of MOR for the various treatments are given in Table 6.16. Attempts at forming briquettes from the 'wet material' incubated at saturation and at field capacity generally met with good success but similar attempts using material incubated at a matric potential of -500 kPa were less successful. A plausible explanation for this observation was offered by Gusli *et al. (*1994) and Becher *et al*. (1997). These authors commented that where the water content is less than a critical index, (which they termed WCmax) the forces generated by the water menisci are not sufficient to cohere the total soil mass, but only single grains or small aggregates. Below this critical water content the soil tended to break or crumble, as was apparent in the preparation of the briquettes at an incubation matric potential of -500 kPa.

It is further interesting that even without WTR addition, simply remoulding the soils resulted in the formation of briquettes with extremely high soil strengths. Remoulding the Hutton soil, for example, at -10 kPa matric potential increased the MOR from 10.1 kPa, to 1180 kPa. Similar responses to remoulding were observed for the other soil types investigated in this study.

Table 6.16 Modulus of rupture (±SE) (kPa) values for the treatments investigated in the incubation experiment

Soil	Matric potential (-kPa)	WTR application rate (Mg ha^{-1})				Lime application rate (Mg ha^{-1})		Gypsum application rate (Mg ha^{-1})	
		0	80	320	1280	2	10	5	10
Hutton	0	nd	3279 (56)	3133 (86)	5194 (137)	nd	nd	nd	nd
	10	1180 (474)	3498 (18)	3776 (371)	2477 (149)	2812 (59)	2582 (103)	3307 (261)	2756 (50)
	500	nd.	0[a]	0	0	nd	nd	nd	nd
	Air-dry	10.1 (1.6)	8.9 (0.7)	0	0	nd	nd	nd	nd
Westleigh	0	nd	2622 (87)	3434 (241)	4642 (395)	nd	nd	nd	nd
	10	2677 (87)	3540 (191)	2278 (108)	3035 (86)	3975 (154)	3793 (75)	4808 (80)	3259 (76)
	500	nd	0	0	0	nd	nd	nd	nd
	Air-dry	30.0 (2.5)	26.1 (4.8)	18.4 (1.5)	0	nd	nd	nd	nd
Cartref	0	nd	2041 (25)	1423 (56)	2445 (45)	nd	nd	nd	nd
	10	1574 (92)	2928 (153)	1911 (24)	1657 (196)	2797 (169)	3788 (58)	3625 (110)	2844 (96)
	500	nd	0	0	0	nd	nd	nd	nd
	Air-dry	18.6 (2.5)	0	0	0	nd	nd	nd	nd
Valsrivier	0	nd	4052 (50)	2660 (66)	5249 (417)	nd	nd	nd	nd
	10	3358 (95)	3219 (58)	2984 (66)	1780 (81)	4491 (57)	4061 (157)	3613 (280)	3888 (185)
	500	nd	2243 (125)	0	0	nd	nd	nd	nd
	Air-dry	368.8 (40.2)	283.9 (14.6)	153.2 (13.1)	74.7 (19.6)	nd	nd	nd	nd

nd not determined.
[a] Where briquettes could not be formed, MOR is indicated as 0.

The effect of remoulding soils on strength development has been widely investigated in the literature. Several of these studies have shown that with remoulding or reworking of the soil, for example by tillage, clay dispersion increases with a concomitant increase in soil strength (Kay and Dexter, 1992; Barzegar *et al.*, 1994; Harper and Gilkes, 1994; Taboada and Lavado, 1996; Mullins, 1997; Watts and Dexter, 1997).

The main mechanisms proposed to account for the increase in soil strength following remoulding is that the clay particles when mobilised by dispersion and slaking become redistributed upon drying due to the forces exerted by the menisci (Mullins *et al.*, 1987; Kay and Dexter, 1992; Gusli *et al.*, 1994; Becher *et al.*, 1997).

The specific contribution of the WTR to further soil strength development is shown especially clearly for the treatments incubated at saturation. Except for the Cartref soil, the addition of 1280 Mg ha^{-1} WTR resulted in extremely high MOR values of approximately 5 MPa. Equivalent values of soil strength for the incubation undertaken at -10 kPa are, however, smaller.

In sharp contrast to the previous findings, MOR measurements for the <2 mm, air-dried treatments show an inverse relationship between soil strength and WTR addition. For the Cartref soil, briquettes could not be formed for any of the WTR-amended soils, whereas for the Hutton soil only the 0 and 80 Mg ha^{-1} treatments formed briquettes. Greater success in the formation of briquettes was achieved with the Westleigh and Valsrivier soil samples, which have higher soil strength values in their natural state.

In a wet state (high matric potential) the polymer in the WTR acts as a binding agent, which, on drying, results in high soil strength across the entire soil matrix. In crushing these soils, the dispersible clay percentage, which is fundamental for cohesion of the soil matrix is radically reduced and consequently leads to a low MOR. Furthermore, because of the tenacity with which the polymer is adsorbed onto the soil mineral surface, further saturation of the soil did not affect its reactivation.

Regarding the comparative effectiveness of gypsum and lime on soil strength, the results show a high degree of variability. Nevertheless, there are several features of note. For briquettes dried from a matric potential of -10 kPa the higher gypsum application rate (10 Mg ha^{-1}) consistently showed much lower MOR values than the lower rate of gypsum application (5 Mg ha^{-1}) and this applied across all of the soil types. Nevertheless when compared with the equivalent remoulded control sample the final strength of these soils was much higher. During reworking of the soil more negative charges on the clay mineral surface are exposed and on air-drying, bonding is enhanced via exchangeable calcium ions and van der Waals forces (Kay and Dexter, 1992). Similar reasoning applies to the lime-amended treatments, although bonding by exchangeable calcium ions was probably less because of the lower solubility of lime. This hypothesis is partially supported by results for the Hutton and Westleigh soils and to a lesser extent by the Cartref soil which on average showed lower MOR values compared with the gypsum treatments.

6.6.4 Conclusions

Measurements of PSS in the field showed that in general the land disposal of WTR, at an air-dry water content, did not markedly influence PSS at either Brookdale or Uklulinga Farms. Although aggregates of WTR have inherently high strength, this did not compromise the bulk strength of the soil matrix. On the WTR treatments, however, the PSS at Ukulinga Farm below the plough layer was generally lower than found for the control treatment. Since the WTR treatments have a higher final infiltration rate and a lower unsaturated hydraulic conductivity, the soil below the WTR-amended zone was probably wetter than the control treatment. Consequently, the PSS was lower. It is likely that the addition of the high rates of WTR also had a marked influence on soil depth, especially on the shallower Westleigh soil at Ukulinga.

To evaluate the influence on soil strength when wet WTR is mixed with soil, an incubation experiment was designed. The results showed that when wet WTR was applied to soil and the mixtures then air-dried, soil strength increased substantially. This effect was more pronounced at higher matric potentials than for drier conditions since more of the polymer was available for bonding under wetter conditions. When the mixtures were crushed and the strength subsequently evaluated, the reverse trend

was noted. Because of the substantial decrease in the dispersible clay percentage and the extremely poor reactivation of the polymer when re-wetted, binding of individual particles to form larger aggregates was substantially reduced. This caused a decrease in the soil strength.

When fully dry, aggregates of WTR are rigid, but the solid matrix nevertheless contains many micropores and fractures. Under rapid wetting, minute swelling of the WTR aggregate due to cation hydration leads to the brittle failure of these aggregates. There was evidence of this mechanism in the field as only the surface or near surface zone of the mulch layer (at Brookdale Farm) showed notable aggregate breakdown. Below the surface the WTR aggregates showed much higher levels of stability mainly because of shielding from raindrop impact and less rapid wetting and drying cycles and probably more moderate temperature fluctuations.

6.7 General conclusions

In view of the broader objective, the study reported in this Chapter had to serve two interrelated purposes, namely to expand the present body of knowledge that is concerned with the land disposal of WTR on soil physical quality and, based on these findings, to evaluate the feasibility of the land disposal of the WTR produced at the Midmar Water Treatment Works. To reference the effects of WTR on selected soil physical quality indices, more recognised soil conditioners, namely gypsum, lime and PAM were also included in the investigation.

The main findings emanating from this work are as follows:

6.7.1 Water retention

The influence of WTR on water retention was initially difficult to ascertain due to the complicating influence of tillage but as these effects waned over time, clearer relationships between WTR content and water retention properties became apparent. In general the effects of tillage persisted for much longer at the Brookdale Farm experiment (Hutton soil) than was noted at the Ukulinga Farm experiment (Westleigh soil) because of the greater degree of stability of the Hutton soil. Because of the lower bulk density of the WTR compared to the soils to which it was added, an increase in the amount of water retained at saturation was observed. In general, however, such improvement was only of statistical significance at the 1280 Mg ha^{-1} level. From near saturation to typically around -30 kPa matric potential very little difference in the volume of water retained between the treatments was noted, but from a matric potential typically less than -30 kPa, the 1280 Mg ha^{-1} WTR treatment once again retained more water.

With regard to the influence of lime, gypsum and to a lesser extent PAM on water retention, these products generally had no statistically significant influence on either the Hutton or Westleigh soils in the field.

In an attempt to avoid the complicating influence of tillage and to extend the study to include the Cartref and Valsrivier soils, water retention properties were evaluated on repacked samples. The results of this study generally corroborated the results of the field study, although extrapolation of these findings to the field scale should be done

with caution. Nevertheless, the greatest improvement in water retention was observed at saturation which followed the order 1280 > 320 > 80 > 0 Mg ha^{-1}. Below -30 kPa matric potential the WTR-amended treatments held more water than the control, the relative extent of which increased with an increase in WTR content.

Because of the more controlled conditions that were afforded with using repacked samples, an estimate of PAW and RAW content for WTR-amended soils could be made. In general these findings showed that despite the significant improvement that the WTR has on the volume of water retained at the wilting point, both the PAW and RAW contents were statistically not significantly different from that of the control treatment (with the exception of the Valsrivier soil). Since these indices are calculated as the volume of water retained between specific matric potentials, an increase in the volume of water retained at both ends of the matric potential range caused little change in their difference.

6.7.2 Aeration

The advances made in understanding the influence of WTR on water retention allow for some comment to be made with regard to soil aeration. The generally accepted view presented in the literature is that at field capacity, root development only becomes limiting if the air-filled porosity is typically less than about 10 to 15%. Neither the control treatments nor the WTR-amended treatments showed values of air-filled porosity at field capacity below this critical index, which implies that aeration should not be a limiting factor for crop development in WTR-amended soils. When the samples were equilibrated at -10 kPa and -100 kPa matric potential and their permeability to air measured, it was found that increasing the WTR content increased the air permeability, although such differences were statistically non-significant. This increase in air permeability is probably related to an increase in inter-aggregate macroporosity that occurred as a consequence of WTR application.

6.7.3 Aggregation and stability

The WTR is strongly aggregated due to the sustained performance of the polymer in binding the constituent silt- and clay-sized material. This was especially apparent in attempting to fractionate air-dried WTR for measurement of its particle size distribution, since even in the presence of a strong dispersing agent and use of ultrasound, many of the bonds formed by the polymer could not be broken.

Attempts at inferring the influence of the WTR on the aggregation of the soil from its dry aggregate size distribution were unsuccessful although wet-sieving proved to be a more encouraging alternative. Although the MWD of the treatments at both field trials showed an increase with increasing WTR content, much of the material that remained on the sieves at the end of the test was composed primarily of WTR particles. Consequently the improvement in the MWD noted between the WTR-amended treatments was more because of the presence of highly water-stable WTR particles included in the sample than the effect of the WTR in stabilising existing soil aggregates.

To test the influence of wet WTR on aggregation, fresh WTR collected from the treatment plant was equilibrated at selected matric potentials and mixed with soil that

was also maintained at the same matric potential. The samples were incubated for 8 weeks, air-dried and the stability of the aggregates measured once more. The results showed that the incubation water content had a strong influence on the readily dispersible clay percentage. When wet, much of the polymer contained in the WTR is still in an active state and was available for bonding with the soil substrate. When incorporated with soil under drier conditions, less of these bonds remain active and consequently less of a decrease in the readily dispersible clay percentage was noted.

6.7.4 Soil strength

Due to the tenacity with which the polymer binds the constituent silt and clay fractions, aggregates of WTR, although porous, display high strength. Nevertheless, when incorporated with soil in the field the PSS of the WTR-amended treatments, at Brookdale Farm, generally did not show marked differences from the control. At Ukulinga Farm, the 1280 Mg ha^{-1} treatment consistently showed a lower PSS than the other treatments at depth. This was attributed to increased moisture at depth on the plots treated with high rates of WTR and the increase in soil depth due to the addition of high rates of WTR to the shallow Westleigh soil. With regard to the influence of gypsum, lime and PAM, these products generally did not markedly influence PSS, these treatments having similar PSS to the control treatment.

The samples prepared in the incubation study for evaluating the effect of the WTR on soil aggregation were also used to determine the influence of the WTR on soil strength. Briquettes formed from wet material (without prior air-drying) showed a substantial increase in soil strength due to the effect of the polymer in mechanically binding the WTR and soil particles together. An increase in the WTR content caused an increase in the MOR, since more of the polymer in the WTR was available for bonding with the soil. In addition, MOR values were much higher for samples incubated under saturation than under drier conditions. In drying the WTR before its incorporation, a portion of the polymer that would otherwise have been available for bonding becomes irreversibly bonded to the WTR particles and is therefore unavailable for further interaction with the soil. The activation state of the polymer as a fundamental factor regulating the influence of the WTR on soil strength was further seen when briquettes were formed from mixtures that had been fully air-dried and crushed to pass a 2 mm sieve. Even at the 80 Mg ha^{-1} WTR content considerable difficulty was encountered in the formation of briquettes.

6.7.5 Hydraulic conductivity

During the water treatment process it is mainly silt- and clay-sized material that is flocculated out of suspension from the turbid waters. In view of this, one of the main concerns was that in returning this silt and clay to soils, potential problems related to reduced hydraulic conductivity may occur mainly because of the potential of the clay and silt (if mobile) to block water conductive pores. Strong emphasis was therefore placed on the effect of WTR on hydraulic conductivity.

At the field experiments the saturated hydraulic conductivity was measured using double-ring infiltrometers. Undisturbed soil cores were also collected for the measurement of saturated hydraulic conductivity with a view to potentially using this technique for the purpose of monitoring the land treatment scheme. Despite the

significant levels of variation in K_s that were encountered in the field, even within single treatments, the results showed that WTR increased K_s. Although the estimate of K_s for each treatment differed between the use of double-ring infiltrometers and undisturbed cores, in general, the overall trend in K_s found between the treatments as evaluated from both methods showed remarkable similarity.

The findings of the field study were further corroborated when WTR and soil (four types) were mixed at varying proportions and packed into permeameters. The results showed that K_s was positively related to WTR content. Although a slight improvement in K_s on the PAM treatment (30 kg ha^{-1}) was measured, such effects did not persist for very long and in general non-significant differences from the control treatment were found. Neither lime nor gypsum had any statistically significant influence on K_s. At Brookdale Farm this finding is probably related to the inherently high stability of this soil that may have masked any improvement brought about by the addition of these products. On the other hand, on the more poorly structured and less stable Westleigh soil (Ukulinga Farm) it is probable that extraneous influences masked the effects of these treatments.

CHAPTER 7

THE USE OF A LIME WATER TREATMENT RESIDUE TO AMELIORATE SELECTED WASTES FROM A COAL MINE AND POWER PLANT

7.1 Introduction

Two water treatment residues (WTRs) were selected for further investigation of their potential for land application. As the larger study covered in this report uses the Midmar WTR, it was decided that WTRs with different characteristics to the Midmar WTR should be selected and should represent the other two major water suppliers in South Africa, namely Rand Water and the City of Cape Town (Chapter 9).

The Rand Water WTR (RWTR) was chosen for investigations into its use on a coal mine (New Vaal Colliery) near Vereeniging, South Africa. Potential uses of the RWTR included, amongst others, fill material in voids, a liming material, neutralisation of acid hotspots and to improve plant growth. The materials used in the investigations were the sandy soil material (3 to 6 m in depth) removed from the land prior to mining, the overburden material removed from above the coal seams that consisted of shale interspersed with calcareous nodules and coal fragments, and a coal combustion residue (fly ash) from the nearby Lethabo Power Station.

The primary objectives of the study were:

- to characterise the spoil, soil and ash;
- to examine the effect of RWTR on the properties of the spoil, soil and ash;
- to measure the yield response of three grass species grown in mixtures of RWTR and the selected materials; and
- to determine nutrient uptake by the grass species tested.

This was a preliminary investigation into the land disposal of RWTR at this mine and may present Rand Water with a suitable disposal option, reducing the current need to lagoon and store large quantities of waste WTR. The benefit to the mine would be realised if use of the RWTR on their materials proved successful and assisted reclamation efforts.

7.2 Materials and methods

7.2.1 Material collection and preparation

The spoil and soil were collected from storage piles at New Vaal Colliery, ash (few days old) from Lethabo Power Station, and the RWTR (few weeks old, dry material) from Rand Water's disposal site (Panfontein) and air-dried before further handling. The ash, soil and RWTR were mechanically milled and sieved (< 2 mm). The ash and soil material tended to be naturally fine, passing easily through the sieve. The spoil material was collected as large coarse fragments that needed to be milled to a suitable size fraction for the pot experiment. The size chosen (crushed to pass through a 8.5 mm sieve) best represented a compromise between field conditions and a suitable seedbed for plant establishment. It was suggested that the spoil material weathers to a

gravel texture over a few months, when exposed to environmental conditions (Mr. P. Smit, pers. comm., 2002).

7.2.2 Laboratory materials and methods

All laboratory analyses were conducted on <2 mm material. Where required the materials were mixed at the same rates used in the pot experiment (Section 7.2.3.1). For water retention studies, materials of the same size fraction as in the pot experiment were used.

7.2.2.1 Chemical analyses

The methods used for chemical analyses follow those presented in Section 4.2.2. In addition, saturated pastes were made (United States Salinity Laboratory Staff, 1954) and extracted by suction through Buchner funnels connected to a vacuum pump. Extracts were analysed for Ca and Mg by atomic absorption spectrophotometry and Na and K by flame emission (Varian SpectraAA-200), electrical conductivity (EC), nitrate (colorimetric analysis using a TRAACS 2000 Auto Analyser) and phosphate (colorimetric; The Non-Affiliated Soil Analysis Work Committee, 1990) on a Varian Cary 1E UV-Visible spectrophotometer. The pH and EC of mixtures of ash, spoil or soil with RWTR were also determined in a 1:5 material:water extract.

7.2.2.2 Physical analyses

Particle size distribution was determined as in Section 4.2.2. Percent aggregation was measured by the double pipette method (United States Salinity Laboratory Staff, 1954).

7.2.2.3 Water retention studies

As it was not possible to obtain field cores of RWTR and waste mixtures, water retention was measured using soil cores packed with the same mixtures and to the same bulk density used in the pot experiment. The 50 g kg^{-1} treatment was omitted due to equipment constraints. The method used was the same as that for the soil physical investigations given in Section 6.2.3.3 except that the cores were allowed to saturate for 24 h instead of 48 h.

7.2.3 Pot experiment

7.2.3.1 Establishment of the pot experiment

Each pot (200 mm i.d.) had a fine glass-wool membrane placed over the drainage-holes and was lined with a polypropylene bag, which had a few holes punched in the base. Pure ash, soil and spoil were then placed in a pot, lightly tapped a few times and the mass of each material determined. A small space was left at the top of each pot to allow for watering. These masses were then used as the basis for all subsequent calculations, and all pots were filled with mixtures of RWTR and waste to the respective masses of the pure waste material. The rates chosen were 50, 100, 200 and 400 g kg^{-1}, as well as treatments of pure waste material (control pots). Part of the objective was to determine upper limits for land application of RWTR, and this range

was selected to extend from a moderately low to a very high application rate. Previous unpublished work had examined similar rates and shown some success on material from the mine.

Basal fertiliser was applied to each treatment. Current mine practice is to apply 1 Mg ha^{-1} of 2:3:2 (22) (N:P:K) and 1 Mg ha^{-1} of single superphosphate. A fertility analysis indicated that the ash had adequate available P, thus none was added to these treatments. The ash received 0.1973 g N and 0.1973 g K per pot as KNO_3 and $Mg(NO_3)_2.6H_2O$. The soil and spoil treatments received 0.1948 g N, 0.187 g K and 0.618 g P per pot as $NH_4H_2PO_4$ and KH_2PO_4. This approximated the fertiliser additions used by the mine.

The three grass species chosen for the experiment, based on current mine practice, were *Digitaria eriantha* Steud., *Cenchrus ciliaris* L. and *Eragrostis teff* (Zucc.). *Eragrostis teff* is a fast growing annual, whilst *Cenchrus ciliaris* and *D. eriantha* are slower establishing, but more persistent perennial species. The grasses were planted from seed and the pots covered in clear polypropylene sheets until germination. Tap water was used to maintain the pots at or near field capacity. The EC of the tap water ranged from 9.02 to 10.12 mS m^{-1} and pH ranged from 6.8 to 7.7. Plants were thinned to three plants per pot at 20 to 30 mm height. Where germination and initial growth was poor, seedlings (germinated in petri dishes) were planted to ensure the correct number of plants per pot. This was necessary for a number of the ash treatments. The pots were watered every 2 - 3 days to avoid water stress. The frequency of watering was increased as plants grew larger and evapotranspiration increased.

The experiment was arranged in a randomised complete block design (Rayner, 1967) with a single treatment factor (RWTR application rate). Pots were arranged in three blocks (replicates) according to the random design generated by the statistical package Genstat V (Release 4.1, Lawes Agricultural Trust, Rothamsted Experimental Station). Each pot was placed on a collecting tray, to prevent loss of sediment and water. The experiment was started in March 2002. The mean temperature range in the glasshouse was from 14 to 28^{o}C (min = 10^{o}C, max = 31^{o}C) for the duration of the trial.

7.2.3.2 Grass harvest

It quickly became apparent that growth in the ash treatments was very poor, and most plants died within the first few weeks. This aspect of the pot experiment was therefore terminated once it was apparent that the selected plant species would not germinate or develop much beyond the seedling stage. Consequently no harvests or leaching trials were conducted on these treatments. A second pot experiment was then established using the ash material and RWTR (Chapter 8).

The remaining treatments were first harvested 45 days after establishment (DAE). The plants were cut approximately 10 mm above soil level, and the material placed in paper bags and dried at 65^{o}C for 2 days in a forced-draft oven. Dry mass yield was determined for each pot. The pots were then refertilised with the previously described fertiliser applications. Additional fertiliser was added at 80 DAE to correct apparent N and P deficiencies in some treatments. A mixture equivalent to 1 Mg ha^{-1} of 2:3:1 N:P:K fertiliser was added as $(NH_4)_2HPO_4$ and KH_2PO_4. Fertiliser was applied to all

treatments to ensure equal conditions in all treatments. As *E. teff* is an annual it was reseeded after each harvest. The experiment was harvested again at 115 DAE. The pots were refertilised with 2 Mg ha^{-1} of the 2:3:1 fertiliser. *Digitaria eriantha* and *C. ciliaris* were finally harvested at 150 DAE, while the *E. teff* treatments were allowed to continue for an additional 3 weeks due to slower growth. The harvesting times chosen were based largely on the overall performance of the treatments, which led to some variation in growth periods.

Statistical analyses of yield data for each grass species were carried out by one-way ANOVA and where significant F-statistics were found, LSD comparisons were made, at the 5% level of significance, using the software package Genstat V (Release 4.1, Lawes Agricultural Trust, Rothamsted Experimental Station).

Plant material from each harvest was sent for analysis of P, K, Na, Ca, Mg, Cu, Mn, Zn, Fe and B (where sample size permitted) to the Soil Fertility and Analytical Services Laboratory, KwaZulu-Natal Department of Agriculture and Environmental Affairs, Cedara. Due to some treatments having inadequate sample, the replicates were bulked for chemical analysis. This unfortunately negates statistical analysis. No sample of the first harvest was available for *D. eriantha* grown in the soil treated with 400 g kg^{-1} RWTR due to poor growth. The remaining plant material was analysed for total nitrogen by combustion using a LECO Auto Analyser (Discipline of Animal Science, University of KwaZulu-Natal).

7.2.3.3 Leaching experiment

After each harvest, and prior to fertiliser additions, excess water was added to each pot to permit the collection of approximately 100 mL of leachate. Any excess leachate was returned to the surface of the pot. The leachate was analysed for pH and EC. Apart from these leaching events the pots remained unleached.

7.3 Results and discussion

As the characteristics of the RWTR are discussed in Chapter 4, only new data will be presented and discussed here.

7.3.1 Chemical properties

7.3.1.1 General

The soil material was acidic, while the spoil and ash had an alkaline pH (Table 7.1). The ash was the most alkaline. Adriano *et al*. (1980) report pH values of ashes ranging from 5.5 to 12.0, while van Rensburg *et al.* (1998) reported a pH of 9.5 (in water) for a fine coal ash dump in South Africa. Adriano *et al*. (1980) attribute the pH of the ash to the concentrations of S, Ca and Mg in the coal, where high S contents tend to give acidic ash, and high Ca and Mg an alkaline ash. The marginal alkalinity of the spoil was attributed to the presence of calcareous material (Mr. P. Smit, pers. comm., 2002). It was indicated, however, that the mine had nett acid drainage, due to acid hotspots within the spoil deposits. The material collected was considered to be representative of the general spoil conditions.

The EC of the soil was the lowest and the spoil the highest. The ash was marginally lower than the spoil. The EC data suggest that salt leaching would not be a problem. Exchangeable acidity was highest in the spoil, but negligible in the ash and soil, while exchangeable Al was high in the ash and negligible in the spoil and soil. The high exchangeable Al content of the ash may be due to the very high pH, the value representing soluble rather than exchangeable Al.

Table 7.1 Some chemical characteristics of the ash from Lethabo Power Station, and the spoil and soil from New Vaal Colliery

Property		Ash	Spoil	Soil
pH	KCl	9.50	7.48	4.88
	H_2O	9.63	7.63	6.14
Electrical conductivity (mS m^{-1})		32.50	38.20	4.21
Organic carbon (g kg^{-1})		bd	78.7	bd
Exchangeable acidity ($cmol_c$ kg^{-1})		bd	3.26	0.38
Exchangeable aluminium ($cmol_c$ kg^{-1})		7.14	bd	0.08

bd below detection.

The spoil was the only waste that had a notable concentration of organic carbon (OC). This was attributed to the presence of coal fragments in this material. It was not expected that the ash would contain any OC, as this is lost during combustion (Adriano *et al*., 1980). The soil material was a mixture of the topsoil and sub-surface horizons originally over the parent rock that is now the spoil material. The soil material was very uniform in nature and extended down a few metres (Mr. P. Smit, pers. comm., 2002).

7.3.1.2 Nutrient concentrations

Total N was below the detection limit for the ash and soil, and at a low concentration in the spoil (Table 7.2). Low concentrations of NO_3-N and NH_4-N were also found. Extractable P concentrations were low in the soil and spoil, but exceptionally high in the ash. Similar results were found by the original fertility analysis and were supported by XRF data that showed very high total P concentration in the ash (Appendix 4.4). Pathan *et al*. (2003) reported similar findings on a variety of coal combustion ashes. Extractable Ca was moderate in all the materials. The soil and spoil also showed moderate concentrations of extractable Mg, while the ash was considerably lower. All the materials showed slightly elevated Na concentrations, while extractable K was low.

The CEC of the materials was generally low, the soil and spoil being similar. The ash was very low, even though moderate levels of extractable cations were found. It is possible that the method used to estimate extractable cation concentrations also caused dissolution of some of the bound cations, overestimating these values, in particular Ca.

Table 7.2 Some nutrient concentrations of the ash from Lethabo Power Station and the spoil and soil from New Vaal Colliery

Property		Ash	Spoil	Soil
Total nitrogen (mg kg^{-1})		bd	700	bd
NO_3 – N (mg kg^{-1})		9.23	9.15	9.00
NH_4 – N (mg kg^{-1})		2.33	4.16	bd
AMBIC extractable P (mg kg^{-1})		151	4.32	bd
Extractable cations ($cmol_c$ kg^{-1})	Ca	7.76	8.71	5.03
	Mg	1.52	3.25	4.66
	Na	2.18	1.49	1.66
	K	0.28	0.14	0.24
Cation exchange capacity ($cmol_c$ kg^{-1})		5.64	12.91	12.77

bd below detection.

7.3.1.3 Saturated paste

Saturated paste data (Table 7.3) reflect the trends shown for EC (Table 7.1) and extractable cations (Table 7.2), although concentrations were considerably lower.

Table 7.3 Saturated paste analysis of the ash, spoil, soil and the Rand water treatment residue

Property		Ash	Spoil	Soil	RWTR
Saturation %		55.1	45.3	52.3	62.0
EC (mS m^{-1})		238.0	328.0	36.5	146.0
SAR[a]		1.61	1.17	0.25	0.05
NO_3-N ($cmol_c$ L^{-1})		0.06	0.01	0.01	0.98
Cations ($cmol_c$ L^{-1})	Ca	1.49	0.62	0.31	1.06
	Mg	0.15	1.48	0.08	2.82
	Na	1.46	1.20	0.11	0.07
	K	0.06	0.04	0.01	0.06

[a] sodium adsorption ratio = ([Na]/(([Ca+Mg]/2)$^{0.5}$)) (from Levy, 2000).

The 1:5 water extracts tended to suggest that salinity would not be problematic, but the EC of the saturated paste extracts indicate potential salinity problems for the ash and spoil. The United States Salinity Laboratory Staff (1954) indicate that soils with an EC of >400 mS m^{-1}, for the saturated paste extract, may have soil salinity problems. Further weathering of the ash and spoil material may lead to an increase in EC that may become problematic to plant growth. It is, however, unlikely under field conditions where adequate leaching would remove excess salts from the rooting zone. The solubility of the base cations tended to be low. The ash had the highest concentrations of Ca and Na, and the spoil the highest concentrations of Mg and Na. The Na concentration in the saturated paste extract of the spoil is nearly as high as that for extractable Na, indicating that most of the Na is in a readily soluble form. The sodium adsorption ratios (SAR) indicate that sodicity should not be a problem, though the SAR of the ash and spoil were considerably higher than that of the soil. Concentrations of phosphate were below detection and concentrations of NO_3-N were negligible in the saturated paste extracts, for all materials. The Ca and Mg concentrations of the RWTR were moderately high, while Na and K concentrations

were low. The phosphate concentration was below detection and NO_3-N concentration was slightly elevated.

7.3.1.4 Elemental concentrations

X-ray fluorescence data (Appendix 4.4) indicate that the materials consisted mainly of Si and Al, with the ash showing slightly lower concentrations of Si and increased concentrations of Al, when compared to the other materials. Other concentrations of elements were low, except for a high S concentration in the spoil. This suggests that the spoil may have acid-producing potential, especially if this element is in pyritic form (Carrucio *et al*., 1988).

Plant available metals (DTPA extractable) were generally low (Table 7.4), with elevated Cr concentrations in the ash when compared to the other materials. Iron concentrations were highest in the spoil and ash, but lower in the soil. The soil had notably a higher concentration of Mn than the either the spoil or ash. It is, however, unlikely that the concentrations of plant available metals would lead to toxicity problems.

Table 7.4 Plant available metals (DTPA extractable) for the ash from Lethabo Power Station and the spoil and soil from New Vaal Colliery

Material	Cd	Co	Cr	Cu	Fe	Mn	Ni	Zn	Pb
	---------- (mg kg^{-1})----------								
Ash	0.48	0.38	4.12	0.60	24.56	1.39	0.63	1.12	bd
Spoil	0.84	1.01	0.75	2.37	26.28	7.71	1.02	4.01	1.40
Soil	0.53	0.45	0.40	0.30	6.30	25.37	0.44	0.50	bd

bd below detection.

7.3.1.5 pH and electrical conductivity

The pH and EC of the ash decreased with increasing RWTR additions (Table 7.5). The EC decreased notably up to 100 g kg^{-1} of RWTR added, but remained relatively constant thereafter up to the maximum RWTR addition.

The spoil showed an increase in pH and a decrease in EC with increasing RWTR additions. The soil also showed an increase in pH with increasing RWTR additions. It should be noted though that the initial increase with 50 g kg^{-1} RWTR added was dramatic, but then smaller increases in pH occurred up to the maximum RWTR application rate. This was possibly due to a low buffering capacity of the soil. These results suggest that addition of RWTR, even at low rates, leads to a high pH that may induce deficiencies, especially of trace nutrients. These results may not reflect long-term changes, however. Under field conditions the effects of leaching, weathering, fertilisation and plants would influence EC and changes in pH.

Table 7.5 pH and electrical conductivity (mS m^{-1}) of the ash, spoil and soil treated with 0, 50, 100, 200 and 400 g kg^{-1} of Rand water treatment residue

RWTR rate ($g\ kg^{-1}$)	Ash		Spoil		Soil	
	pH	EC	pH	EC	pH	EC
0	9.63	32.5	7.63	38.2	6.14	4.2
50	9.54	27.9	7.73	33.1	7.48	14.3
100	9.48	24.7	7.78	29.8	7.66	14.4
200	9.41	24.0	7.88	28.7	7.83	14.1
400	9.30	24.5	8.01	26.8	8.00	14.3

7.3.1.6 Phosphorus adsorption

Phosphorus adsorption isotherms (Figure 7.1) showed that the ash had an exceptionally high P sorption capacity. To achieve residual P values of 0.05, 0.20 and 1.00 mg L^{-1} (Section 4.3.6) the ash sorbed 12.5, 38.0 and 174.0 mg kg^{-1} P, respectively. Gray and Schwab (1993) found that bottom ash and fly ash showed high P fixing capacities in a laboratory study. They attributed the P sorption to precipitation reactions rather than adsorption reactions due to the presence of soluble Ca oxides, Ca hydroxides and Ca silicates, and high pH. This had the effect of lowering solution P very rapidly, the consequence of which is that added P would not be available for plant growth. It is probable that a similar mechanism is operative for the ash used in this study. The high sorbing capacities of the ash may cause severe P deficiencies, especially if mixed with the RWTR.

The spoil and soil showed moderately low P sorbing capacities, the soil showing a slightly higher P sorbing capacity at low P concentrations. The low sorbing capacity of the spoil may be attributed to the heterogeneous nature of the material, and it is likely that once the spoil has undergone some decomposition the P sorption capacity would increase. Pulford and Duncan (1975) examined P adsorption by coal spoil and concluded that amorphous Fe oxides (formed from pyrite oxidation) were largely responsible for the P sorption, although the presence of Al and Ca compounds were not discounted. They also indicate that, as the material weathers, it is likely that P sorption would increase (as more pyrite and other reactive surfaces are exposed) and that sulphate may compete with phosphate for reactive sites. The spoil sorbed 1.6, 6.5 and 20.0 mg kg^{-1} P and the soil 2.5, 10.5 and 30.0 mg kg^{-1} P to achieve residual P concentrations of 0.05, 0.20 and 1.00 mg L^{-1}, respectively.

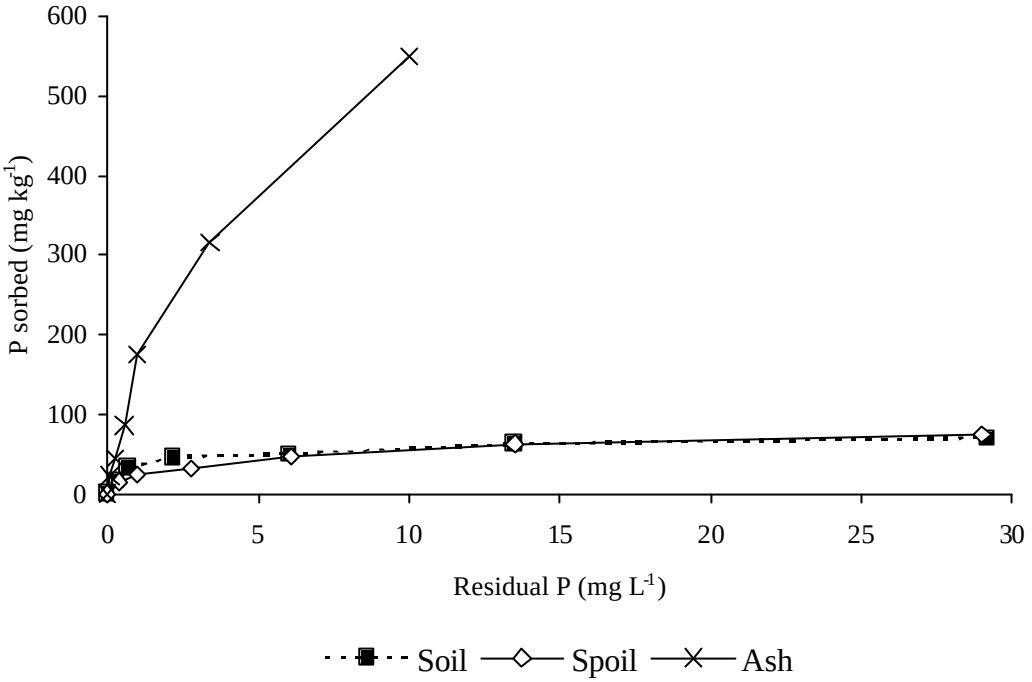


Figure 7.1 Phosphorus adsorption isotherms for the ash, spoil and soil.

7.3.2 Physical properties

Both the soil and spoil had high amounts of sand, and the ash was mainly sand and silt with very little clay (Table 7.6). The particle size distribution of the spoil was expected considering the material was collected as large coarse fragments. Furthermore, as the spoil was only milled to less than 8.5 mm, a large proportion of the material used in the pot experiment was larger than 2.0 mm. Dry sieving showed that 31.13% of material was >4.75 mm, 31.93% was between 2.00 and 4.75 mm, and 36.94% was <2.00 mm. The soil and ash were naturally less coarse. All the materials exhibited a high degree of aggregation, ranging from 56.39 to 65.52%. The RWTR was also very well aggregated (85.19%).

Table 7.6 Some physical properties of the ash from Lethabo Power Station and the spoil and soil from New Vaal Colliery

Property		**Ash**	**Spoil**	**Soil**
Texture[a]		silt loam	sandy loam	sandy clay loam
Particle size distribution (%)	Sand (0.053 - 2 mm)	38.8	75.5	71.9
	Coarse silt (0.02 - 0.053 mm)	16.1	3.1	4.1
	Fine silt (0.002 - 0.02 mm)	39.7	10.2	3.1
	Clay (<0.002mm)	5.4	11.2	20.9
Aggregation (%)		56.39	59.02	65.52

[a] Soil Classification Working Group (1991).

7.3.3 Water retention studies

The water retention curves for the waste and RWTR mixtures (Figure 7.2) indicate that in all cases increasing RWTR addition increased volumetric water content at all matric potentials. It is likely that the lower bulk density of the RWTR led to the increase in water retention. The increase in water retention of the ash due to the addition of RWTR was less noticeable than in the soil and spoil. The effect of RWTR on the ash was only marked at -100 kPa matric potential for the 400 g kg^{-1} RWTR treatment, where water content increased from 0.12 m^3 m^{-3} in the pure ash to 0.27 m^3 m^{-3}. It is possible that the similarities in texture and bulk density of the ash and RWTR led to an apparently reduced effect of the RWTR on the retention characteristics of the ash in the wetter range.

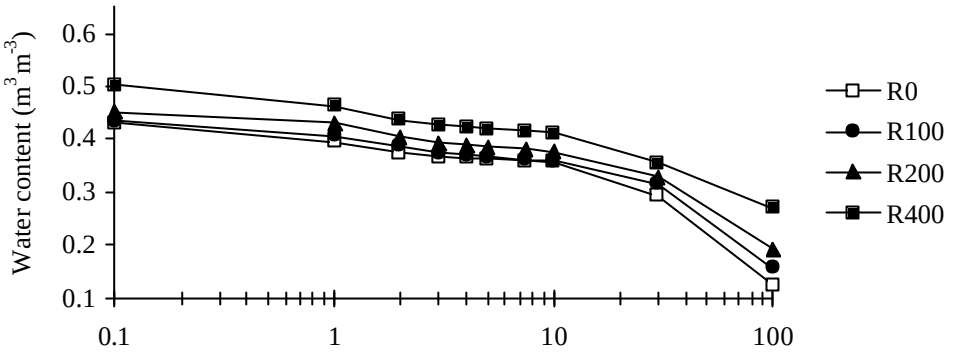
The effect of RWTR on the spoil was more evident. The low saturation value of the pure spoil material was probably due to the coarse nature of the material. The presence of large pores allowed water to drain freely from the core under gravity leading to an apparently low saturation value. This suggests that for this material the 10 min drainage period prior to measurement of saturation mass was too long and so underestimated saturation mass. It does, however, imply that this water would not be available for plant use as it would drain from the rooting zone very readily.

Stewart and Daniels (1992) examined a number of coal refuse properties, including water retention. They too found reduced water holding capacities of the coal refuse when compared to a natural soil. In addition the coarser coal materials had lower water retention capacities than the finer materials, suggesting that water cannot be held in the pores by hydrostatic tension. They also attributed the reduced water holding capacity to the occurrence of hydrophobic carbonaceous material (coal fragments) in the refuse. The sharp increase in water holding capacity of the spoil with RWTR additions, shows that the RWTR dramatically increases water holding capacity.

The soil showed a similar trend to that of the ash. The presence of fine sand and a moderate amount of clay led to moderately high saturation water contents. The addition of RWTR did not increase the saturation water contents dramatically, but a marked increase was noticeable at -30 and -100 kPa. This indicates that RWTR will improve water retention in the drier range, which would be advantageous for soil moisture conservation.

It is clear that additions of RWTR to the waste materials increase their water holding capacity. This is particularly evident in the spoil material, where the greatest benefit could be measured. It should be noted that for the spoil and soil in particular, plant available water (PAW) may not be increased by RWTR additions. It is clear that generally the retention curves run parallel. Although wilting point was not measured here, the data suggest that, if the measured trends continue, PAW will be constant regardless of improvements in water holding capacity at individual matric potentials. This is the same effect as was seen in the repacked cores using the Midmar WTR (Section 6.2.3.3) and for the field soil cores from both Brookdale (Section 6.2.3.1) and Ukulinga (Section 6.2.3.2). Thus despite the Midmar and the Rand WTRs having very different characteristics (Chapter 4) they appear to have a similar effect on the water holding capacity of the materials to which they are added.

(a)



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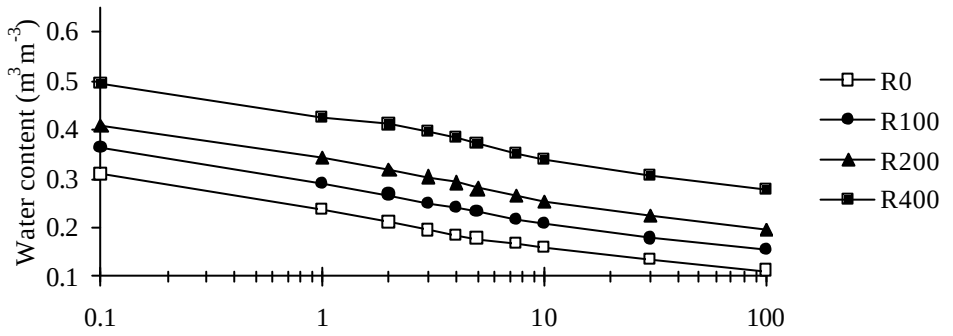


(c)

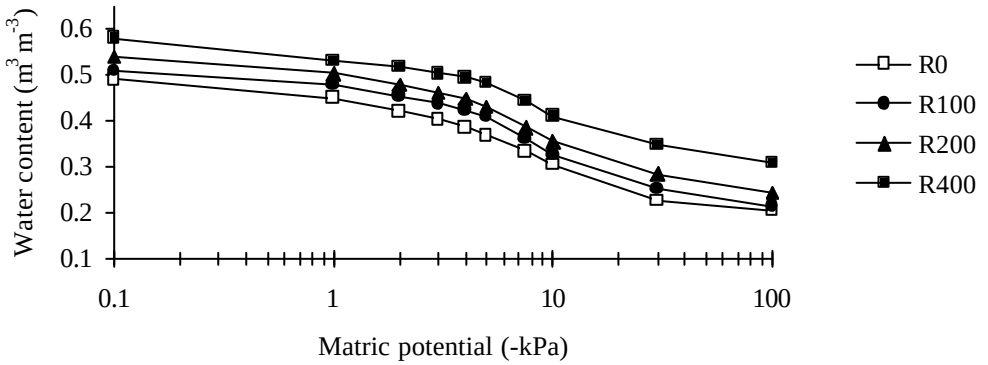


Figure 7.2 Water retention curves for (a) ash, (b) spoil and (c) soil treated with 0, 100, 200 and 400 g kg^{-1} Rand water treatment residue (R0, R100, R200 and R400, respectively).

7.4 Pot experiment

7.4.1 Leaching experiment

Mean EC and pH of the leachates are given in Appendix 7.1. Generally the EC and pH increased with increasing rates of RWTR, although not consistently, and fertiliser additions may also have had an influence. There was also a noticeable increase in EC and pH at each subsequent leaching event for all RWTR treatments. In general the control treatments showed a decrease in pH after each leaching event. This decrease in pH could be attributed to the addition of acidifying fertiliser (NH_4^+), as well as the effect of nutrient uptake by roots, releasing H^+ ions (Tisdale *et al.*, 1993). The pattern measured for EC in the control treatments was more variable. The soil treatments with *E. teff* and *C. ciliaris* and the spoil treatment with *E. teff* tended to show an increase in EC for each subsequent leaching event, while the EC of other treatments tended to decline.

The sharp increase in EC with increasing RWTR additions for all treatments was not considered representative of what may happen on a field scale. The EC frequently exceeded the 400 mS m^{-1} level set by the United States Salinity Laboratory Staff (1954) for saturated paste extracts as the general acceptable tolerance for plants. Under these conditions, it may have been expected that the grasses, especially in the spoil medium, should not have grown as well as was found. The most likely cause for the extreme EC was that the pots were only leached on three occasions with a relatively small quantity of water (when compared to the water holding capacity of the material in the pot). Under these conditions it is probable that salts would collect at the base of the pot during normal watering (no leaching). During a leaching event the leachate collected would mainly represent the soil solution at the base of the pot, which would have a high content of accumulated salts. This effect was then exacerbated as more salts were allowed to collect prior to the following leaching event. In a leaching experiment conducted by Stewart *et al.* (1997), it was found that coal refuse leached in columns had an initial EC of about 200 mS m^{-1}, which is in agreement with the values reported here. They found that EC increased dramatically, peaking at between 1 400 and 1 800 mS m^{-1}. This was attributed to pyrite oxidation and salt dissolution with varying leaching regimes (including a drought cycle in this period). Nonetheless, it indicates the potential for high EC generation in such material. Stewart *et al.* (1997) then report that the EC gradually decreased to similar levels reported for the initial conditions. This supports the notion that under field conditions, with continual removal of oxidation and weathering products, the EC may decrease to acceptable levels.

Decomposition of the RWTR may also have partly attributed to the increase in pH with increasing RWTR additions. The low buffering capacity of the soil led to the high pH of the leachate from the RWTR-treated pots. While the spoil had some acid-generating potential, the presence of calcareous material in the spoil and the strong neutralising potential of the RWTR would have counteracted any acid production. Under field conditions it is unlikely that EC and pH would reach the levels reported here due to regular leaching events (rainfall, irrigation) removing accumulated salts from surface horizons.

7.4.2 Yield

As mentioned earlier (Section 7.2.3.2) the growth of the grasses in the ash material was very poor and this aspect of the study was terminated. Consequently no data were obtained from the ash-based experiments.

There were significant differences in yield for *E. teff, D. eriantha* and *C. ciliaris* when grown in the soil material, but the differences were non-significant when grown in the spoil material (Table 7.7 and Appendix 7.2). A high degree of variability among the replicates of some treatments was evident. This was reflected in the high standard error values and coefficients of variation (CV) for some of the treatments (Table 7.7). A number of trends are evident though and the discussion will focus on these, considering variability and the causes where necessary.

Table 7.7 Summary ANOVA statistics for mean total yield of *Eragrostis teff*, *Digitaria eriantha* and *Cenchrus ciliaris* grown in the soil and spoil material treated with Rand water treatment residue at application rates of 0, 50, 100, 200 and 400 g kg^{-1}

Grass	Waste	F-ratio	d.f.[a]	Probability	CV(%)[b]
E. teff	Soil	26.61	4,8	<0.001	8.7
D. eriantha	Soil	17.72	4,8	<0.001	17.2
C. ciliaris	Soil	8.62	4,8	0.005	4.1
E. teff	Spoil	0.85	4,8	0.534	19.4
D. eriantha	Spoil	1.94	4,8	0.197	8.1
C. ciliaris	Spoil	1.07	4,8	0.430	11.5

[a] degrees of freedom.
[b] coefficient of variation.

Figures 7.3 and 7.4 show the mean total yields for the soil and spoil treatments, respectively. Appendix 7.3 gives the results for each individual harvest.

7.4.2.1 Soil/Rand water treatment residue mixtures

Eragrostis teff decreased in total yield with increasing additions of RWTR, with the control treatment performing significantly better than the RWTR-amended treatments. The highest yields were recorded for the first harvest, with the 0, 50 and 100 g kg^{-1} treatments performing similarly. The control treatment performed significantly better than the 200 and 400 g kg^{-1} RWTR treatments. The second harvest showed a slight increase in yield for the control treatment, but a sharp decrease for the RWTR-treated pots. The yield of the control treatment for the third harvest decreased substantially, while the remaining treatments (except the 100 and 200 g kg^{-1} treatment) also decreased from the second cut. In the third harvest there were no significant differences between the 0, 50, 100 and 200 g kg^{-1} RWTR treatments. The 400 g kg^{-1} RWTR treatment performed very poorly.

This dramatic decline in performance of the RWTR treatments resulted in the overall poor performance seen for total yield. It should also be noted that at the first cut the CV was moderately low, but increased sharply with each subsequent harvest, indicating an increase in the variability of the replicates. The CV for the mean total yield suggests that overall variability was low, however. This general decline in

performance for each subsequent harvest is partly attributable to the increase in EC seen in the leachate data, but may also be due to certain trace nutrients becoming deficient due to the high pH of some treatments, even though no deficiencies were evident. Although these results suggest that RWTR additions have a negative impact on the growth of *E. teff* in the soil, the results from the first harvest indicate that it will grow well up to RWTR additions of 200 g kg^{-1}.

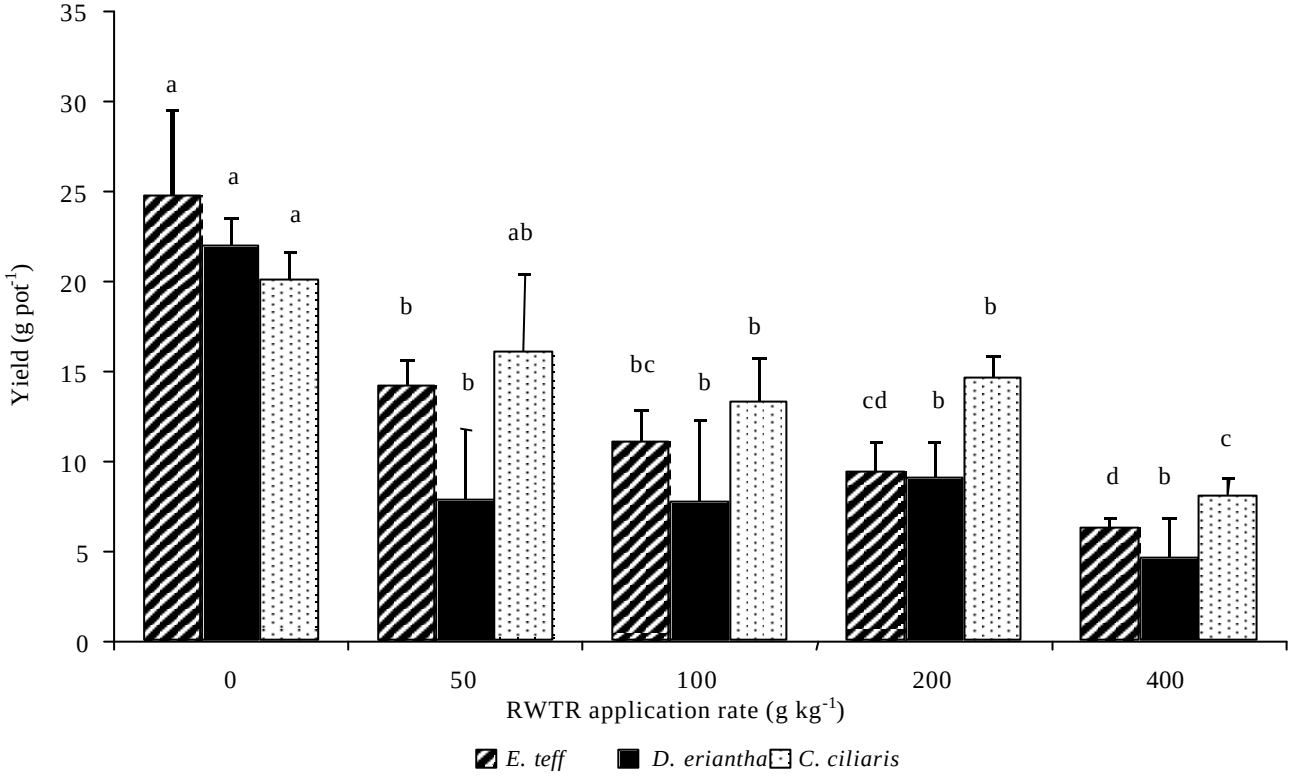


Figure 7.3 Mean total yields (+SE, 3 replicates) for harvests of *Eragrostis teff*, *Digitaria eriantha* and *Cenchrus ciliaris* grown in the soil material treated with Rand water treatment residue at application rates of 0, 50, 100, 200 and 400 g kg^{-1}. Letters that are different indicate significant differences between treatment means within a grass species ($LSD_{5\%}$: *E.teff* 4.5, *D.eriantha* 5.2, *C.ciliaris* 4.9).

Furthermore, *E. teff* is planted as an annual, nurse crop. The principle of using such a crop is to establish rapid cover on the soil surface to afford protection against erosion and, ultimately, to provide a source of organic matter when the plants die (Jones *et al.*, 1975; Wood and Buchanan, 2000). This is considered to aid the establishment of more persistent, but slower growing vegetation (perennial species). It is therefore unlikely that a second crop would be seeded in the field, although it is unlikely to perform as poorly as indicated by the second and third harvests of the pot experiment.

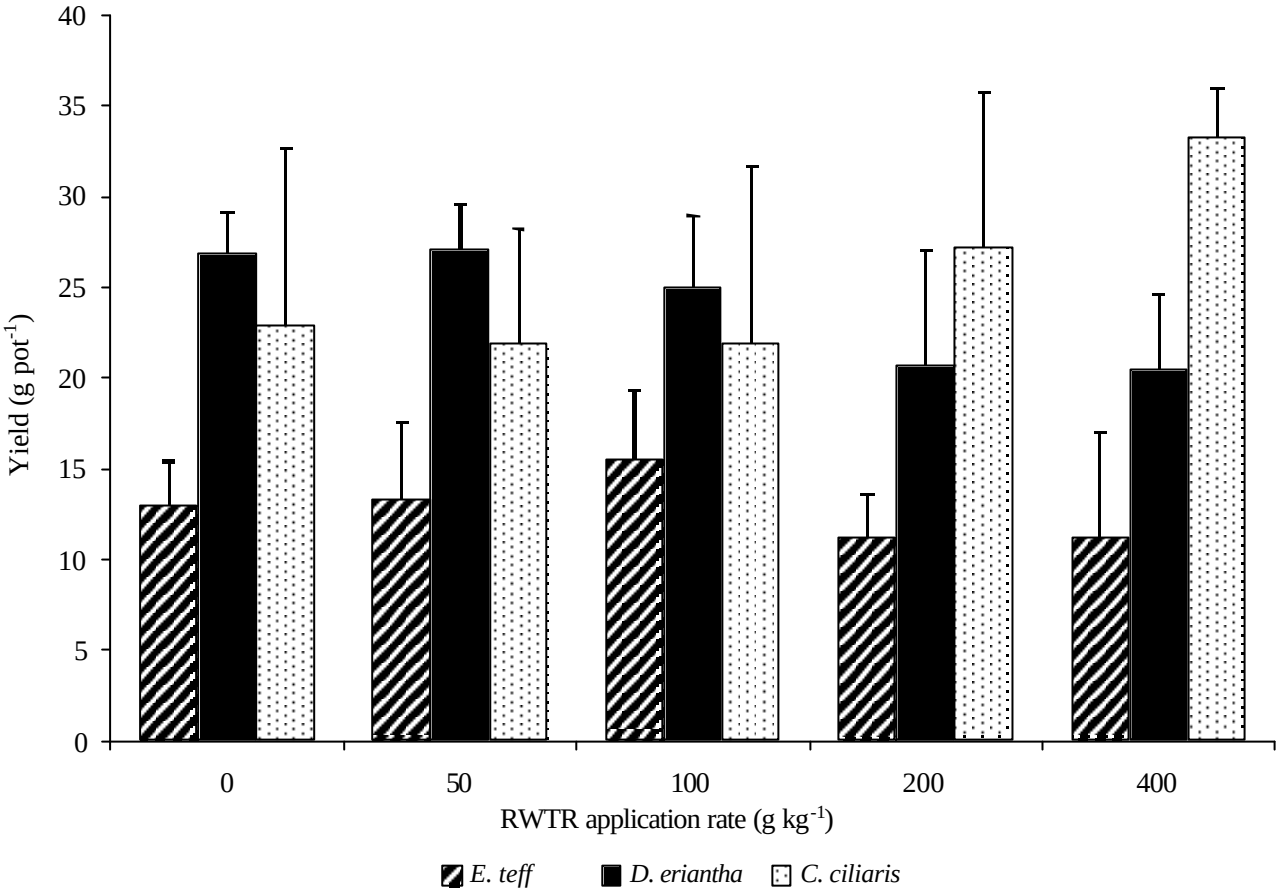


Figure 7.4 Mean total yields (+SE, 3 replicates) for harvests of *Eragrostis teff*, *Digitaria eriantha* and *Cenchrus ciliaris* grown in the spoil material treated with Rand water treatment residue application rates of 0, 50, 100, 200 and 400 g kg^{-1}. There were no significant differences between treatment means within a grass species.

Digitaria eriantha showed a decrease in total yield with increasing RWTR additions. The control treatment had a significantly higher yield than the other treatments. Initially the growth was poor for all treatments, except the control, but improved markedly by the second harvest, decreasing slightly at the third cut. In all instances the control treatment performed significantly better than the RWTR treatments. The decrease in yield with increasing RWTR additions may be because *D. eriantha* is a perennial species. It requires more time to establish, but once established is likely to be more tolerant of changes in growing conditions. The general decrease in yield for the third harvest (compared to the second harvest) was possibly due to an increase in pH to over 8.0 for most treatments and may also be attributable to the relatively short growing period from the previous harvest (35 days compared to 70 days for the second cut). These data suggest that once *D. eriantha* is established it may grow moderately well in the soil with RWTR application rates of up to 200 g kg^{-1}. However, it performed consistently better with no RWTR additions and may not be a suitable species to use under these conditions.

Cenchrus ciliaris decreased in mean total yield. The yield of the control and 50 g kg^{-1} RWTR treatments did not differ significantly from one another, while the yield of the

400 g kg^{-1} RWTR treatment was significantly lower than all other treatments. The decrease in yield with increasing RWTR additions was evident at all harvests. The 400 g kg^{-1} RWTR treatment performed the worst at the first harvest, but did not perform significantly differently from the other treatments at harvests two and three. However, it did perform the poorest in both instances. Although the best yields were generally recorded for the control treatments, good performance was seen at most rates of RWTR, except for the highest application. As with the other two species tested, addition of rates up to 200 g kg^{-1} are likely to give acceptable yields. It should be noted that although the 200 g kg^{-1} RWTR treatment for both harvests two and three had high yields, these are associated with very high standard errors.

7.4.2.2 Spoil/Rand water treatment residue mixtures

Eragrostis teff increased in total yield up to the 100 g kg^{-1} RWTR application rate and then decreased with higher rates, although the differences were not significant. Yield increased as RWTR application rate increased for the first harvest. The second harvest showed increases in yield from the first harvest for each treatment. The 100 g kg^{-1} RWTR treatment yielded the highest. The 200 and 400 g kg^{-1} treatments performed the poorest. The third harvest showed a sharp decrease in yield for all treatments. This decline in yield may be due to the EC increasing to a level where the growth of the seedlings was impaired. As was the case for *E. teff* in the soil, the poor yield from the last harvest skewed the total yield values. This again creates an impression that the RWTR is not a suitable ameliorant at high rates. However, the yields from the first and second harvests suggest that the growth may be satisfactory if one takes into account the typical use of this species as a nurse crop. Under these conditions, medium to high application RWTR rates may be practical. The poor yields of the first harvest, from the control treatment and low RWTR treatments, may have been due to the seedlings not being able to establish easily in the coarse material. The addition of 200 and 400 g kg^{-1} of RWTR may have improved root contact with the soil, due to the addition of finer material, and consequently led to the improved yields of those treatments. Decomposition of the coarse material in the control and low RWTR treatments to a finer grade material may have improved the physical environment, improving root contact by the second harvest, hence the improved yield.

Digitaria eriantha showed a decrease in total yield with increasing RWTR rate, but the differences between treatments were not significant. The yield from the first harvest was very poor for all treatments, but increased markedly for subsequent harvests. The yield of the second harvest did not show much difference between treatments, but by the third harvest substantial improvements in yield were seen for the control, 50 and 100 g kg^{-1} treatments. The general increase in yield was probably due to the plants adapting to the growing conditions. The decrease in yield for the 200 and 400 g kg^{-1} RWTR application rates is possibly due to the high EC and pH as indicated by the leachate data.

Cenchrus ciliaris was the only species that increased in mean total yield as RWTR application rate increased, although the differences between treatments were not significant. The 400 g kg^{-1} treatment performed well. There was a decline in yield for the 400 g kg^{-1} treatment by the third harvest, while, generally, the other treatments showed marginal increases. The 400 g kg^{-1} treatment still had the highest yield, although it was not significantly better than the other treatments.

7.4.3 Effect of pH and electrical conductivity on yield

Initially the poor growth of some treatments was attributed to high EC and pH. However, when yield was plotted against leachate EC or pH, the data showed a high degree of variability and no strong relationships were found, even when the data was transformed (results not shown). It is possible that elevated EC and pH may have influenced yield, but it is questionable considering the favourable performance of some treatments. Generally grass yield declined with increasing RWTR application rates, and this appeared to be associated with an increase in leachate EC and pH. The exception was *C. ciliaris* grown in the spoil treatment, which appeared to show a tolerance of both saline and alkaline conditions. This reinforces the notion that the high EC and pH in the leachate were a result of salt accumulation at the base of the pot, and thus they did not have as direct an influence on plant growth as expected. Where growth of the grass was vigorous it is possible that root development was limited to the upper, less saline, portions of the pots. The poor performance of *E. teff* especially for the last harvest may be due to elevated EC and pH, where growing conditions were unsuitable for seedling establishment and growth. However, it is unlikely that the leachate data give a realistic representation of the entire soil solution EC and pH.

7.4.4 Plant analyses

Appendix 7.4 gives the results of the grass analysis of each harvest and includes typical nutrient concentrations for turf grasses (Bennett, 1993) and *Eragrostis curvula* (Schrad.) and *Festuca arundinacea* (Shreb.) (Miles, undated) for comparison. For the sake of brevity the nutrient uptake will be discussed in brief here, but a more comprehensive overview of possible causes and mechanisms for the patterns of uptake observed are given in Appendix 7.5.

There were no apparent trends for Ca uptake, with values generally being lower than those reported by Bennett (1993), but similar to those reported by Miles (undated). Magnesium concentrations increased with increasing RWTR additions in all grasses and wastes, but this was not unexpected considering the high amounts of available Mg in the RWTR. *Digitaria eriantha* did, however, tend to have higher Mg concentrations than the other two species. The concentrations found here exceed those reported by Bennett (1993) and Miles (undated), perhaps indicating luxury uptake by the plants. Potassium concentrations tended to be high and within typical ranges for grasses, although the pattern of uptake was variable. Uptake of Na showed marginal increases with increasing RWTR additions, but as levels were very low this was not of concern. Phosphorus concentrations showed a decrease in tissue concentration for a number of treatments as RWTR increased, but concentrations remained adequate for plant growth. As P was added to the pots during the experiment, it was unlikely that P deficiencies would occur, even though the RWTR has a potentially high P sorbing capacity (Section 4.3.6). Nitrogen did not show any consistent pattern of uptake, but the second and third harvests did show higher N tissue concentrations. This was probably due to further N applications prior to these harvests. The N concentrations reported for the first harvest were below the sufficiency ranges reported by Bennett (1993) and Miles (undated), but were adequate for the last two harvests.

Trace nutrient uptake was variable. Zinc and Mn uptake tended to increase, while Fe and Cu uptake tended to decrease with increasing RWTR additions. Manganese concentrations frequently exceeded typical ranges for grasses, as given by Pendias and Pendias (1984) who report that world-wide background concentrations for grasses range from 17 to 334 mg kg^{-1} and that, typically, symptoms of toxicity will only be seen at concentrations over 500 mg kg^{-1}. The increase in Fe concentrations was attributed to moderate amounts of available Fe in the RWTR, and in the spoil. While Fe deficiency is typical of calcareous or over-limed media (Mortvedt, 2000), this was not apparent. The Fe concentrations reported here are within or above the typical ranges reported for grasses. Boron uptake was variable, with the concentrations in the soil treatments being below the typical grass ranges. The spoil treatments, however, were considerably higher, this being attributed to high B concentrations in the spoil, although this was not measured.

The concentrations reported here indicate that nutrients were present in sufficient concentrations to support the growth of the plants, although poor growth was observed for a number of treatments. It is possible that other trace nutrients, not measured here, were either at toxic or deficient concentrations. The high pH of many of the treatments may have led to some other trace nutrients becoming unavailable to plants, or weathering of the material may have released some trace elements at toxic concentrations. However, no symptoms of toxicity or deficiency were visually apparent that would have suggested a possible cause of the poor plant growth.

7.5 Conclusions

The high variability in the yield data for almost all treatments makes it difficult to predict how RWTR would affect the growth of these grass species on the materials when used under field conditions. The use of mean yield allowed clarification, but many of the differences were not significant. If one uses mean yield data as a guide for applying RWTR to these materials, then the application of RWTR to the soil should be avoided or used at a minimum application rate, possibly lower than tested here. However, the RWTR can be applied at maximum applications on the spoil material, without apparently causing a significant loss in production of the grasses tested, even though leachate EC and pH seemed excessively high.

If one considers only the trends seen (without statistical support) then it would appear that *C. ciliaris* was the only species to benefit from RWTR additions when grown in the spoil material. This, however, may not be a true reflection of what may occur under field conditions. As the other treatments showed decreases in total yield with increasing RWTR additions, it may indicate that very high applications of RWTR (>200 g kg^{-1}) to these materials would not be suitable for these species. As was noted, however, the variability between replicates was high in some instances which could have skewed the data and led to the decreases seen in total yield. It was also shown that, for a number of the apparently poor performing treatments, the individual harvests indicated that these grasses had a potential to perform better than suggested by the mean total yield data.

It is likely that the high EC and pH of some treatments reduced yield. These high EC and pH values are partly attributable to the design of the experiment. The pots were leached only on three occasions, which led to the accumulation of salts and increased

EC. This could then lead to osmotic imbalances, making it more difficult for plants to take up nutrients and water. This may have led to the newly germinated *E. teff* seedlings not being able to perform as well as when the EC was lower at the earlier harvests. The yield of the perennial grasses tended to improve as they became established, indicating an increased tolerance to the high EC and pH of some treatments. The poorer overall performance of the grasses in the soil material may also be partly explained by poor physical properties for plant growth. As both the RWTR and the soil had moderately high amounts of fine particles, compaction may have created physical barriers to root penetration and, in conjunction with the high pH, have reduced the plants' ability to obtain adequate nutrients for strong growth.

CHAPTER 8

THE USE OF A LIME WATER TREATMENT RESIDUE AS A CAPPING AND GROWTH MEDIUM ON A COAL COMBUSTION ASH

8.1 Introduction

As discussed in Chapter 7 the growth of *Eragrostis teff*, *Digitaria eriantha* and *Cenchrus ciliaris* in mixtures of Rand water treatment residue (RWTR) and the coal combustion ash from Lethabo Power Station was very poor or unsuccessful and so that part of the original pot experiment was abandoned. It was subsequently proposed by representatives from the power station that the RWTR could be used as a growth medium over the ash material. It had been suggested that the ash dumps be capped with a suitable cover material and vegetation established to reduce wind and water erosion. Furthermore, the possibility existed that the ash would be reprocessed in the future to extract certain elements found at elevated concentrations, therefore the surface cover and vegetative layer should be able to be easily removed, and the ash below remain relatively free of other contaminants (such as root material, fertilisers etc.).

A pot experiment was designed to test the potential of the RWTR as a growth medium over the ash material, using two creeping grass species. The objectives of the study were:

- to determine biomass production of grasses growing in RWTR layers over the ash;
- to determine the optimum RWTR layer thickness; and
- to determine if grass performance can be improved with fertiliser application.

8.2 Materials and methods

The same ash and RWTR were used as described in the previous pot experiment (Section 7.2.3.1), but the RWTR was spread over the ash material (rather than incorporated). The size fraction of the RWTR used was slightly larger than previously (<3.5 mm). Three levels of RWTR (thickness) were selected i.e., 20, 40 and 60 mm. A fertilised and unfertilised treatment were tested. The fertiliser treatment consisted of 1 Mg ha^{-1} of the 2:3:2 fertiliser used in the previous experiment (Section 7.2.3.1). This was mixed into the RWTR before being applied over the ash. The two grass species chosen, *Stenotaphrum secundatum* (Walt.) O. Ktze. (coastal buffalo) and *Cynodon dactylon* (L.) Pers. cv. Seagreen (bermudagrass), were selected for their tolerance of alkaline conditions and their creeping growth form (Gallimore, 1999; Prof. A.L.P. Cairns and Mr. J. Klug, pers. comms., 2002). They were planted as seedlings (purchased from a local nursery). The watering of the pot experiment was the same as described for the previous experiment (Section 7.2.3.1). The pots (150 mm i.d.) were arranged in a randomised complete block design (Rayner, 1967) with three replicates (36 pots in total), generated by the statistical package Genstat V (Release 4.1, Lawes Agricultural Trust, Rothamsted Experimental Station).

After 6 weeks the above ground biomass was harvested. Root material was collected from the RWTR and ash layers, by washing and sieving. The vegetative materials were placed in paper bags, dried at 65^{o}C and then weighed to determine dry mass

yield. Statistical comparisons were by two-way ANOVA. If the F-statistic was significant then LSD comparisons of means, at the 5% level of significance, were made (Genstat V, Release 4.1, Lawes Agricultural Trust, Rothamsted Experimental Station).

8.3 Results and discussion

The thicker RWTR layers improved growth of both species (Table 8.1), with a highly significant overall fertiliser by grass interaction ($F_{1,22}$ = 15.98; $p<0.001$) (Appendix 8.1), with *C. dactylon* performing significantly better than the other treatments (Table 8.1). Initially the *C. dactylon* plants showed signs of leaf tip burn (especially in the 20 mm RWTR layers), but this disappeared as they grew larger. The cause of the symptoms were not identified, but could be B toxicity (Bennett, 1993) as this is frequently associated with coal combustion ash (Carlson and Adriano, 1993). *Cynodon dactylon* grown in the unfertilised RWTR performed similarly to *S. secundatum* grown in either fertilised or unfertilised layers. *Stenotaphrum secundatum* showed signs of P deficiency, though the severity appeared less in the fertilised treatments. This may be expected considering the high pH and P sorption capacity of the RWTR. It would appear that *C. dactylon* was more tolerant of low P availability than *S. secundatum*. It is apparent that the fertiliser treatments improved the yield of both grass species, as did using a thicker RWTR layer.

Table 8.1 Mean (±SE, n=3) above ground dry mass yield (g pot^{-1}) for *Cynodon dactylon* and *Stenotaphrum secundatum* grown in three different Rand water treatment residue layers over a coal combustion ash, for both the fertilised and unfertilised treatments. $LSD_{5\%}$ comparisons for mean yield over the different Rand water treatment residue layers are also given

Grass species	Treatment	RWTR thickness (mm)			Mean yield across RWTR thickness[a]
		20	40	60	
Cynodon dactylon	Fertilised	5.87 ±2.72	9.05 ±0.88	11.08 ±2.73	8.67a
	Unfertilised	3.07 ±0.27	4.41 ±1.07	6.29 ±0.68	4.59b
Stenotaphrum secundatum	Fertilised	3.01 ±0.43	4.48 ±2.21	6.92 ±3.05	4.80b
	Unfertilised	3.80 ±1.35	4.43 ±0.62	5.99 ±0.44	4.74b

[a] Letters that are different indicate significant differences ($LSD_{5\%}$ = 1.47).

Basta *et al*. (2000) tested the growth of *C. dactylon* in three alum WTRs with different P fertiliser rates. They found that grass grown in two of the WTRs gave moderate yields that were similar to a comparative soil treatment. Addition of fertiliser P did not significantly improve yield in any of the WTRs tested. Gallimore (1999), in a similar investigation using alum WTRs, found that growth of *C. dactylon* could be supported, and that no addition of P was necessary for satisfactory growth. Even though both of these studies found that addition of P did not improve growth, both report that plant P concentrations were below recommended plant tissue

concentrations for optimal growth, even in fertilised treatments. This supports the current findings that *C. dactylon* may be tolerant of low P availability.

Root biomass (Table 8.2) of *C. dactylon* in the unfertilised RWTR layers did not show a clear pattern, with the 40 mm RWTR layer performing best. In the fertilised treatments the 40 and 60 mm layers showed similar performance, with both being better than the 20 mm RWTR layer. *Stenotaphrum secundatum* root biomass in the RWTR layers showed increases with increasing layer thickness, regardless of fertiliser treatment. The ANOVA (Appendix 8.1) showed that there was a significant grass species by RWTR layer thickness interaction ($F_{2,22} = 5.26$; $p = 0.014$) and that *S. secundatum* performed significantly better than the other treatments (Table 8.3).

Table 8.2 Mean (±SE, n=3) root dry mass yield (g pot^{-1}) for *Cynodon dactylon* and *Stenotaphrum secundatum* grown in three different Rand water treatment residue layers for both fertilised and unfertilised treatments

Grass species	Treatment	RWTR thickness (mm)		
		20	40	60
Cynodon dactylon	Fertilised	1.88 ±0.54	2.43 ±0.34	2.66 ±0.63
	Unfertilised	1.43 ±0.15	2.74 ±0.75	1.60 ±0.32
Stenotaphrum secundatum	Fertilised	1.17 ±0.64	2.05 ±0.73	3.69 ±1.14
	Unfertilised	1.69 ±0.71	2.57 ±0.55	3.03 ±0.44

Table 8.3 Mean root dry mass yield (g pot^{-1}) for *Cynodon dactylon* and *Stenotaphrum secundatum* grown in three different Rand water treatment residue layers over a coal combustion ash

Grass species	RWTR thickness (mm)		
	20	40	60
Cynodon dactylon	1.66c*	2.58b	2.13bc
Stenotaphrum secundatum	1.43c	2.31b	3.36a

* Letters that are different indicate significant differences between treatment means ($LSD_{5\%} = 0.771$).

The root biomass in the ash layers (results not shown) showed no pattern and, as expected, was considerably lower than the root biomass in the RWTR layers. There were no significant overall treatment effects or interactions found (Appendix 8.1). The root biomass in the ash layers of the treatments where little or no root material was initially established (i.e., 40 and 60 mm RWTR layers) was exceptionally low and in some cases no roots were found. The 20 mm RWTR treatments had some root material, but this was as a result of planting in the ash layer. These roots all appeared stunted, with little or no signs of growth. It was clear that the roots did not perform

well and would not grow into this layer. van Rensburg *et al*. (1998) tested the growth of a number of grass species (including *C. dactylon*) on a fine coal-ash dump in South Africa, using various ameliorative treatments. They reported that yield was low in the control treatments, due to the poor physical properties of the ash. The physical characteristics of the ash may also have created a physical barrier to root penetration, and hence the low yield observed in the present study. Furthermore the high exchangeable (soluble) Al concentration of the ash (Table 7.1) may have stunted root growth.

Stenotaphrum secundatum produced a large number of stolons, regardless of treatment. While the performance of this grass was poorer than that of *C. dactylon*, its vigorous creeping habit could be beneficial. The purpose of the grass is to help stabilise the capping material (RWTR) and the rapid spread of the grass would increase the rate at which this may occur. If at each node the plant roots successfully, it will then start producing stolons and spread. Even if the parent plant then dies or shows reduced performance, the ramets (daughter plants) may contribute to creating a vegetative mat over the RWTR. It is possible that under these conditions P uptake by the plants may improve because of a more widespread rooting system. In the pot experiment the roots were confined to a small volume, which needed to supply vigorous stoloniferous growth, and possibly led to the P deficiencies observed. *Cynodon dactylon* also showed prolific stoloniferous growth and, as it appeared more tolerant of the growing conditions, may create a more sustainable cover. This, in addition to a rhizomatous habit (van Rensburg *et al*. 1998; Gallimore, 1999), would offer increased protection against wind and water erosion to the RWTR layers, in turn protecting the ash below.

8.4 Conclusions

Initial indications are that the RWTR may act as a suitable growth medium over the ash material, and that a thicker layer may be more beneficial. It was apparent that additional fertiliser improved the performance of *C. dactylon* significantly, while marginally, but not significantly, improving the performance of *S. secundatum*. This was probably due to partial alleviation of the low P availability in the RWTR layer. *Cynodon dactylon* appeared to be more tolerant of the alkaline conditions, while *S. secundatum* showed P deficiency symptoms. Both species produced a large number of stolons and it is likely that under field conditions they would spread quickly and offer reasonable cover. Even though *S. secundatum* did not perform as well as *C. dactylon*, it is likely to aid in stabilising the RWTR cap. *Cynodon dactylon* would give better cover and would also further stabilise the material as it produces underground rhizomes in addition to the surface stolons. It is also very tolerant of a wide range of growing conditions.

CHAPTER 9

THE USE OF AN ORGANIC/Fe-POLYMER WATER TREATMENT RESIDUE TO AMELIORATE A NUTRIENT-POOR SAND

9.1 Introduction

As mentioned in Chapter 7 the second water treatment residue chosen for investigation was one from the City of Cape Town. Currently the Faure Water Treatment Plant (FWTP) produces between 4 000 Mg (summer) and 11 000 Mg (winter) wet WTR, which is currently landfilled. The cost of disposal of this material is considerable and a more economically viable (as well as environmentally friendly) alternative needs to be found. It is also likely that WTR production will increase substantially in the future as there are plans to double the capacity of the treatment plant (Mr. D. Smit, pers. comm., 2003).

A number of studies report on the potential of some WTRs to supply nutrients (Chapter 3) and the Faure 1 WTR (FWTR) might therefore be beneficially applied to the areas of highly leached sands that are common in the region of the treatment facility. Furthermore, results from earlier work (Section 4.3.2) showed that this WTR was only slightly acid (but did have a lime component), with moderate amounts of organic carbon and a high total C content (Table 4.2). The data also indicated that the FWTR has potential to supply Ca and Mg and a number of trace nutrients (including Fe, S and Zn), and has a moderate amount of total N (Table 4.4). The only concerns were a high Mn concentration and the high P sorbing capacity of the FWTR. However, a potential benefit of the latter, if the FWTR were to be applied to a dystrophic sandy soil, may be to reduce the leaching of P. If the WTR then subsequently decomposes it may release some of this P, essentially acting as a slow release P fertiliser. Geertsema *et al.* (1994) have commented that this may be a likely mechanism of P release from WTR, as only a few studies have shown P deficiencies under field conditions. It does, however, imply that adequate initial P will be added to overcome initially the high P sorption by the WTR.

This study was thus developed with the following objectives:

- to characterise the sandy soil selected for use in this study;
- to test the growth of dry beans in mixtures of FWTR and the nutrient-poor sand;
- to determine a suitable fertiliser application rate for the mixtures; and
- to determine the nutrient and elemental uptake by the seed.

Dry beans were selected as the test crop, as they are a common crop in small-scale agriculture and are easy to cultivate and manage under glasshouse conditions.

9.2 Materials and methods

9.2.1 Material collection and preparation

Water treatment residue was collected and dried at the Faure Water Treatment Plant and delivered to the University of KwaZulu-Natal, Pietermaritzburg. The sandy E horizon material from a Longlands (Lo) soil; Albic Plinthaquept; Hydrosol (Soil

Classification Working Group, 1991; Soil Survey Staff, 1998; Isbell,1996, respectively) was collected from the South African Sugar Association Experimental Station, Mt Edgecombe, KwaZulu-Natal in an area that, although previously cultivated, had been under natural grassland for the past 10 yr. The sand was air-dried and sieved (<2 mm). The FWTR was milled to pass through a 2.8 mm sieve; this size being selected to allow both ease of handling and to be a suitable size for use in the pot experiment.

9.2.2 Laboratory investigations

Basic chemical and physical properties, DTPA extractable metals, total elements (XRF) and P sorption were determined on the Lo sand by methods described in Section 4.2.2. The effect of the FWTR on the pH and EC of the Lo sand and the water retention characteristics of both the Lo sand and the FWTR-treated Lo sand were determined by methods described in Section 7.2.2.

9.2.3 Pot experiment

This essentially followed the method given in Section 7.2.3. The FWTR was added to the soil at the same rates used in the RWTR study (Section 7.2.3) i.e., 0, 50, 100, 200 and 400 g kg^{-1}. Each pot contained 2.6 kg of material, this being determined by the mass of sand a pot could contain. The Lo sand and FWTR were thoroughly mixed at the required rates, and then the fertiliser solution was added and the materials remixed. Four levels of fertiliser were used as well as an unfertilised treatment. The fertiliser requirement was based on levels of 90 kg N ha^{-1}, 60 kg P ha^{-1} and 90 kg K ha^{-1}, which are suggested rates for dry beans grown on a light dystrophic soil (Archer, 1988; Birch *et al*., 1991). The fertiliser was added as a solution of $(NH_4)_2HPO_4$, KNO_3 and NH_4NO_3, to give 100% values of 0.225 g N, 0.150 g P and 0.225 g K. Three other levels were used i.e., 25, 50 and 150%, and a control (0% level). The control treatment had an equivalent amount of distilled water added to maintain the water content of the material the same as those to which fertiliser solutions were added. The mixtures were placed in plastic pots (180 mm i.d.) lined with a polypropylene bag, perforated in the base.

The experiment had 25 treatment combinations, replicated three times and was arranged in a randomized complete block design (Rayner, 1967), generated by the statistical package Genstat V (Release 4.1, Lawes Agricultural Trust, Rothamsted Experimental Station). Six dry bean (*Phaseolus vulgaris*, cv. Ghadra) seeds were planted in each pot in late November 2002. The seedlings were thinned after a week to four plants and again a week later to leave the two healthiest plants. The pots were watered as required to avoid water stress using tap water. The EC of the tap water ranged from 8.78 to 9.97 mS m^{-1} and pH from 6.5 to 7.6. The mean glasshouse temperature ranged from 16 to 38°C (min = 14°C, max = 41°C). Supports for the plants were provided as they grew to prevent the plants lodging.

From an early stage in the experiment the FWTR treatments showed interveinal chlorosis and necrotic lesions on the cotylendonous leaves and subsequently on all new leaves. These chlorotic areas eventually turned a dark brown to black with these leaves dying in some instances (Plate 9.1). The severity of the symptoms increased with increasing FWTR applications and was seemingly not related to fertiliser

application rates. It was suspected that Mn toxicity was the cause and additional bean plants were grown in three additional pots (six plants per pot) of the 400 g kg^{-1} FWTR treatment (unfertilised) to be analysed to determine possible causes. Once sufficient plant growth had occurred, all leaves showing the symptoms were harvested and oven-dried at 65°C for 48 h. This material was sent to the Soil Fertility and Analytical Services Laboratory, KwaZulu-Natal Department of Agriculture and Environmental Affairs, Cedara for fertility (Ca, Mg, K, Na, P, Zn, Cu, Mn, Fe and B) and C, N and S analysis.

9.2.4 Harvesting

The pods were harvested in mid-February 2003 after all the plants had senesced and the pods had dried on the plants. The pods were placed in paper bags and dried at 65°C in a forced draft oven for 48 h. Once dry, the mass of complete pods and the number of pods per pot (two plants) were determined for each treatment. The beans were then removed from the pods and the number and mass of beans recorded for each treatment. The bean seeds were analysed for Ca, Mg, K, Na, P, Zn, Cu, Mn and Fe at the Soil Fertility and Analytical Services Laboratory, KwaZulu-Natal Department of Agriculture and Environmental Affairs, Cedara.

9.3 Results and discussion

9.3.1 General characteristics of the Longlands sand

The sand was acid, with a low electrical conductivity and a moderate organic carbon content (Table 9.1)

Table 9.1 Some chemical and physical properties of the Longlands sand from the South African Sugar Association Experimental Station

Property		Longlands
pH	H_2O	4.94
	KCl	4.64
Electrical conductivity (mS m^{-1})		2.12
Organic carbon (g kg^{-1})		19.9
Exchangeable acidity ($cmol_c$ kg^{-1})		0.19
Exchangeable aluminium ($cmol_c$ kg^{-1})		0.09
Texture[a]		sandy loam
Particle size distribution (%)	Sand (0.053 - 2 mm)	77.2
	Coarse silt (0.02 - 0.053 mm)	4.3
	Fine silt (0.002 - 0.02 mm)	6.4
	Clay (<0.002 mm)	12.1

[a] Soil Classification Working Group (1991).

Extractable acidity and Al were low. Particle size analysis showed that the material was dominantly sand, with about 12% clay, giving it a sandy loam texture. The nutrient concentrations of the Lo sand are given in Table 9.2. Total N was low, as was NO_3-N and NH_4-N. Available P was higher than expected, either due to previous fertilisation of the area or due to the amount of organic carbon. Concentrations of all the extractable bases were low, in particular K, as was the cation exchange capacity.

Plate 9.1 Examples of interveinal chlorosis on leaves of dry beans (*Phaseolus vulgaris*) grown in a Longlands sand treated with 400 g kg^{-1} Faure water treatment residue, 3 weeks after germination.

Table 9.2 Some nutrient concentrations of the untreated Longlands sand

Property		Longlands
Total N (mg kg^{-1})		300
NO_3 – N (mg kg^{-1})		8.03
NH_4 – N (mg kg^{-1})		20.73
AMBIC P (mg kg^{-1})		10.67
Exchangeable cations ($cmol_c$ kg^{-1})	Ca	1.60
	Mg	1.54
	Na	0.39
	K	0.01
Cation exchange capacity ($cmol_c$ kg^{-1})		2.72

Plant available metals (Table 9.3) were mostly low, with only Fe being notably elevated, and Pb and Mn slightly elevated. X-ray fluorescence analysis (Appendix 4.4) showed that the Lo sand was almost entirely Si, which was expected as the soil had a very high sand fraction.

Table 9.3 Plant available metals (DTPA extractable) of the Longlands sand

	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
	----------mg kg^{-1}----------								
Longlands	bd	bd	bd	0.92	82.17	13.96	bd	1.99	1.64

bd below detection.

9.3.2 Phosphorus adsorption of the Longlands sand

The P adsorption isotherm of the Lo sand (Figure 9.1) shows that P sorption was quite low.

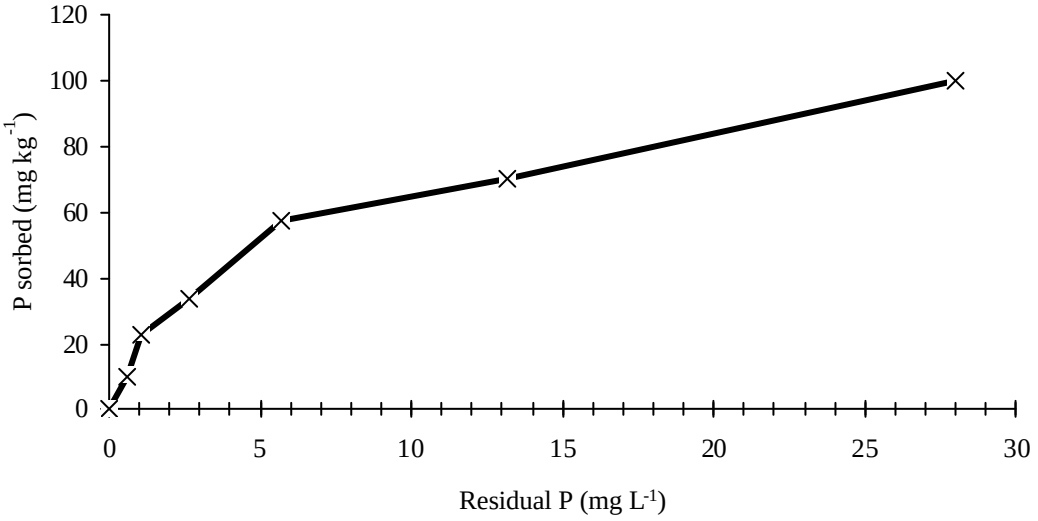


Figure 9.1 Phosphorus adsorption isotherm of the Longlands sand.

At residual P solution concentrations of 0.05, 0.20 and 1.00 mg L^{-1} (Section 4.3.6), the Lo sand sorbed 0.6, 3.0 and 15.0 mg kg^{-1} P, respectively. This was considerably lower than the values given for the FWTR (Section 4.3.6). The low sorption capacity suggests that P is unlikely to be fixed, and may be leached from the plant root zone.

The addition of FWTR to the Lo sand would increase its P sorption capacity, possibly reducing this loss of P.

9.3.3 pH and electrical conductivity

As expected the addition of FWTR increased both the pH and EC of the Lo sand (Table 9.4). The pH increased by 1.33 units from the control to the 400 g kg^{-1} application rate, while the EC showed a more than two-fold increase over the same range, but was still low, however.

Table 9.4 pH and electrical conductivity (EC) of the Longlands sand treated with 0, 50, 100, 200 and 400 g kg^{-1} of Faure water treatment residue

FWTR rate ($g\ kg^{-1}$)	pH	EC ($mS\ m^{-1}$)
Control	4.94	2.17
50	5.29	2.68
100	5.61	3.76
200	5.82	4.72
400	6.27	5.97

9.3.4 Water retention

The effect of increasing FWTR additions to the Lo sand was to increase the volumetric water content at almost all matric potentials (Figure 9.2).

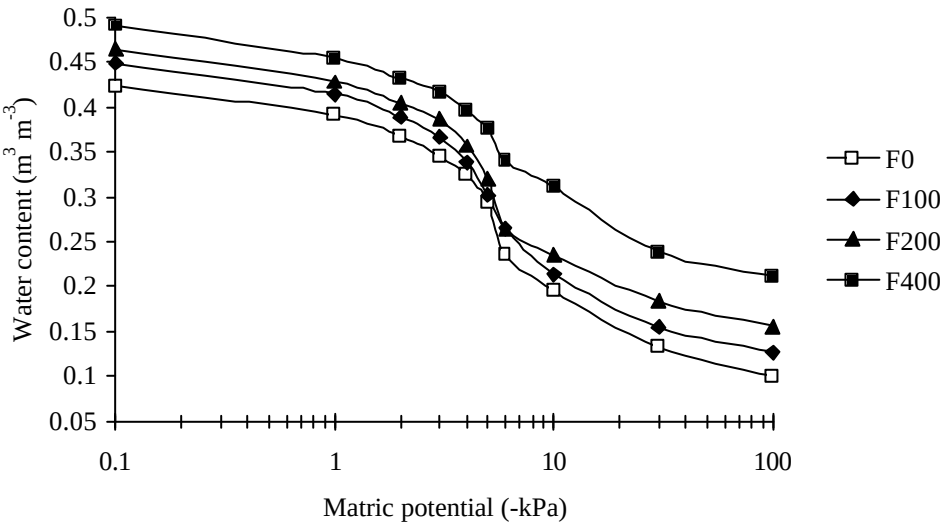


Figure 9.2 Water retention curves for the Longlands sand treated with 0, 100, 200 and 400 g kg^{-1} Faure water treatment residue (F0, F100, F200 and F400, respectively).

At -5 kPa the FWTR added at 100 and 200 g kg^{-1} appeared only to increase water content marginally over the pure Lo sand, but the addition of 400 g kg^{-1} FWTR gave a substantial increase in water content. The difference in water content was most notable at -10, -30 and -100 kPa, suggesting that the FWTR increased the number of fine pores, which led to higher water contents at these matric potentials. As was the

case for the RWTR mixtures (Section 7.3.3) and the data reported in Section 6.2.3, generally the curves run parallel, suggesting that plant available water would not be greatly affected by FWTR additions to this soil.

9.3.5 Pot experiment

9.3.5.1 Leaf analysis

To enable discussion of the yield of the bean plants it is necessary to consider the findings of the nutritional analysis of the bean plants grown in the unfertilised 400 g kg^{-1} treatment to determine causes of the leaf chlorosis symptoms described earlier. Generally the plant nutrients tended to be within the recommended nutrient ranges (Table 9.5).

Leaf tissue P concentration was below the recommended range, perhaps due to dilution because of the high planting density (six plants per pot). Perhaps surprisingly symptoms of P deficiency were not observed, despite the high P sorbing capacity of this WTR and that no fertiliser had been added to the pots. The only element that was considerably over the recommended range was Mn, being some twelve-fold higher than the recommended upper limit of 100 mg kg^{-1}. The symptoms seen on these plants matched some of those described by Bergmann (1992) and Bennett (1993), which may be a combination of actual Mn toxicity and induced deficiencies, due to Mn having antagonistic effects on the uptake of other elements (Mg, Ca, Zn, Cu and Fe). This may indicate that FWTR is not suitable for land application purposes, especially if the land is to be used for crop growth. However, it should be noted that in the case of dry beans, the crop is the seed, and it may be more useful to consider nutrient uptake by the seed as an indicator of potential toxicity problems (Section 9.3.5.3).

Table 9.5 Nutrient concentrations of bean leaves grown in a Longlands sand treated with Faure water treatment residue at a rate of 400 g kg^{-1}, without fertiliser. Recommended nutrient ranges reported by Bennett (1993) and Bergmann (1992) are given for comparison

	N	**S**	**Ca**	**Mg**	**K**	**P**
	(%)					
Leaf sample	3.42	0.25	1.93	0.59	1.96	0.19
Bennett (1993)	4.25-5.50	0.17	0.35-2.00	0.25-1.00	1.70-3.00	0.25-0.60
Bergmann (1992)	3.00-6.00	-	0.50-2.00	0.25-0.70	2.00-3.00	0.25-0.50
	B	**Cu**	**Fe**	**Mn**	**Zn**	
	(mg kg^{-1})					
Leaf sample	61.0	13.7	196.0	1208.0	44.0	
Bennett (1993)	15-50	10-30	50-540	20-100	20-70	
Bergmann (1992)	25-80	7-15	-	40-100	30-70	

Skene *et al*. (1995) tested the growth of beans (*P. vulgaris*) in mixtures of sand and either an alum or polymer WTR. Although nutrient uptake by the seed was not examined, they found no toxicity problems caused by trace nutrients in the foliage of the plants. They did indicate, however, that supplementary fertiliser was needed to realize optimal growth of the plants. Elliott and Singer (1988) reported that uptake of Cd, Zn, Cu and Ni was reduced in tomato shoots grown in a $FeCl_3$ coagulant WTR-amended soil. They also did not report any toxicity problems, but indicated that

supplementary fertiliser would be needed. Lucas *et al*. (1994) tested the growth of tall fescue in an alum WTR-treated soil. They found elevated Mn concentrations in the tall fescue with increasing rates of WTR (0, 10, 20 and 40 g kg^{-1}). However, in a subsequent experiment to test whether Mn was the cause of the decreased yield, they found that, although Mn exceeded recommended levels, plant growth was seemingly unaffected. While the study by Lucas *et al*. (1994) indicates the potential for Mn toxicity, the WTR application rates used were considerably lower than those used in this investigation. As Mn was the likely cause of the chlorotic symptoms seen in this study, attempts to reduce the Mn toxicity were considered and tested in an observational study (Section 9.3.5.4).

9.3.5.2 Yield

Analysis of variance (Appendix 9.1) showed that there were no significant fertiliser by FWTR application rate interactions, for either pod or seed number, but that each treatment factor had a significant individual effect on the measured variables (Table 9.6).

Table 9.6 Summary ANOVA statistics for number of pods and number of seeds for each treatment factor and interactions

Variable	Treatment factor	F-ratio	d.f.[a]	Probability
Number of pods	Fertiliser	35.83	4, 48	<0.001
	FWTR	9.43	4, 48	<0.001
	Fertiliser x FWTR	1.38	4, 48	0.191
Number of seeds	Fertiliser	44.19	4, 48	<0.001
	FWTR	3.14	4, 48	0.022
	Fertiliser x FWTR	1.11	4, 48	0.377

[a] degrees of freedom.

It is apparent that increasing additions of fertiliser with any particular FWTR rate improved pod (Figure 9.3a) and seed (Figure 9.3b) production.

The mean effect of FWTR additions, however, tended to be more variable. The number of pods and seeds tended to increase with increasing rates of FWTR up to 100 g kg^{-1}, but showed marginal decreases with higher rates of FWTR. For both variables, the highest yield was recorded from the 100 g kg^{-1} FWTR treatment with 150% fertiliser application. Comparisons by $LSD_{5\%}$ (Table 9.7) showed that the 150% fertiliser treatment (over mean FWTR application rate) yielded significantly better than the other treatments, while the 50 and 100 g kg^{-1} FWTR rates (over mean fertiliser rate) performed significantly better than the other treatments.

In the case of total number of pods (Table 9.8) the 150% fertiliser treatment (over mean FWTR application rate) yielded significantly better than the other treatments, while the 100 g kg^{-1} FWTR rates (over mean fertiliser rate) performed significantly better than the other treatments, with the 50, 200 and 400 g kg^{-1} FWTR treatments performing similarly.

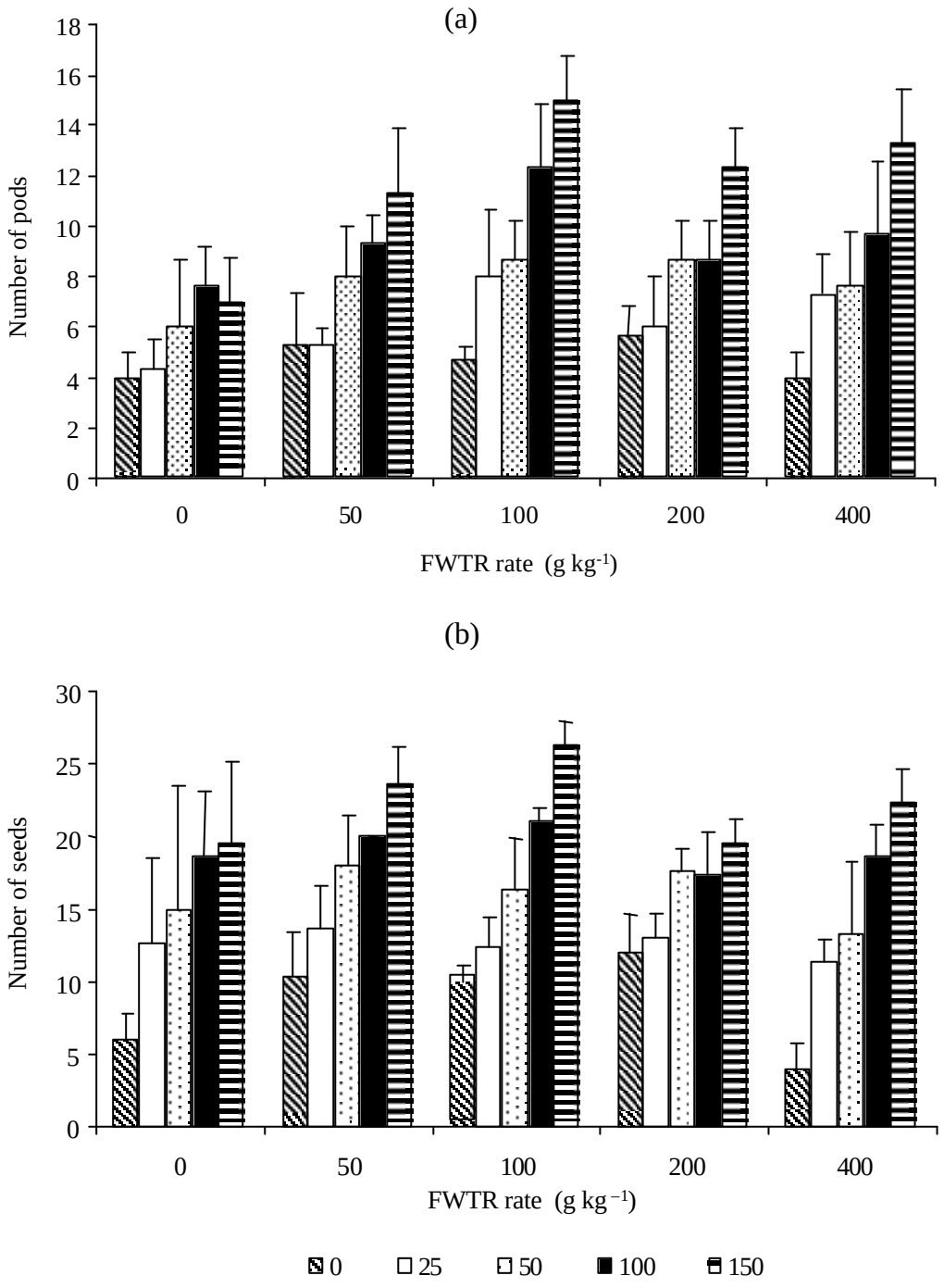


Figure 9.3 Mean (+SE, 3 replicates) number of (a) pods and (b) seeds of beans grown in a Longlands sand with Faure water treatment residue application rates of 0, 50, 100, 200 and 400 g kg^{-1} with fertiliser levels of 0, 25, 50, 100 and 150%, as indicated in the legend.

Table 9.7 $LSD_{5\%}$ comparisons of mean seed mass for each treatment factor for dry beans grown in a Longlands sand treated with 0, 50, 100, 200 and 400 g kg^{-1} Faure water treatment residue with fertiliser applications of 0, 25, 50, 100 and 150%

Fertiliser application rate (%)[a]				
0	25	50	100	150
8.47e*	12.60d	16.07c	19.33b	22.33a
FWTR application rate (g kg^{-1})[b]				
0	50	100	200	400
14.40c*	17.13a	17.20a	15.93b	14.13c

[a] Fertiliser application rate, over mean FWTR application rate.
[b] FWTR application rate, over mean fertiliser application rate.
* Letters that are different indicate significant differences between treatment means for each treatment factor ($LSD_{5\%}$: fertiliser = 1.162; FWTR = 1.162).

Table 9.8 $LSD_{5\%}$ comparisons of mean number of pods for each treatment factor for dry beans grown in a Longlands sand treated with 0, 50, 100, 200 and 400 g kg^{-1} Faure water treatment residue with fertiliser applications of 0, 25, 50, 100 and 150%

Fertiliser application rate (%)[a]				
0	25	50	100	150
4.73e*	6.20d	7.80c	9.53b	11.80a
FWTR application rate (g kg^{-1})[b]				
0	50	100	200	400
5.80c*	7.87b	9.73a	8.27b	8.40b

[a] Fertiliser application rate, over mean FWTR application rate.
[b] FWTR application rate, over mean fertiliser application rate.
* Letters that are different indicate significant differences between treatment means for each treatment factor ($LSD_{5\%}$: fertiliser = 1.317; FWTR = 1.317).

The effect of FWTR on seed mass (Figure 9.4) followed essentially the same trend as described for the seed and pod numbers, although seed mass was highest in the 400 g kg^{-1} FWTR application rate with 150% fertiliser. As before there were no significant interaction effects, but the individual variables had significant effects overall (Appendix 9.1, Table 9.9). Individual seed size (results not given) and mass were not affected by any treatment with all treatments yielding seed of similar mass.

Table 9.9 Summary ANOVA statistics for mass of seeds for each treatment factor and treatment interactions

Variable	**Treatment factor**	**F-ratio**	**d.f.[a]**	**Probability**
Mass of seeds	Fertiliser	52.36	4, 48	<0.001
	FWTR	8.76	4, 48	<0.001
	Fertiliser x FWTR	1.07	4, 48	0.404

[a] degrees of freedom.

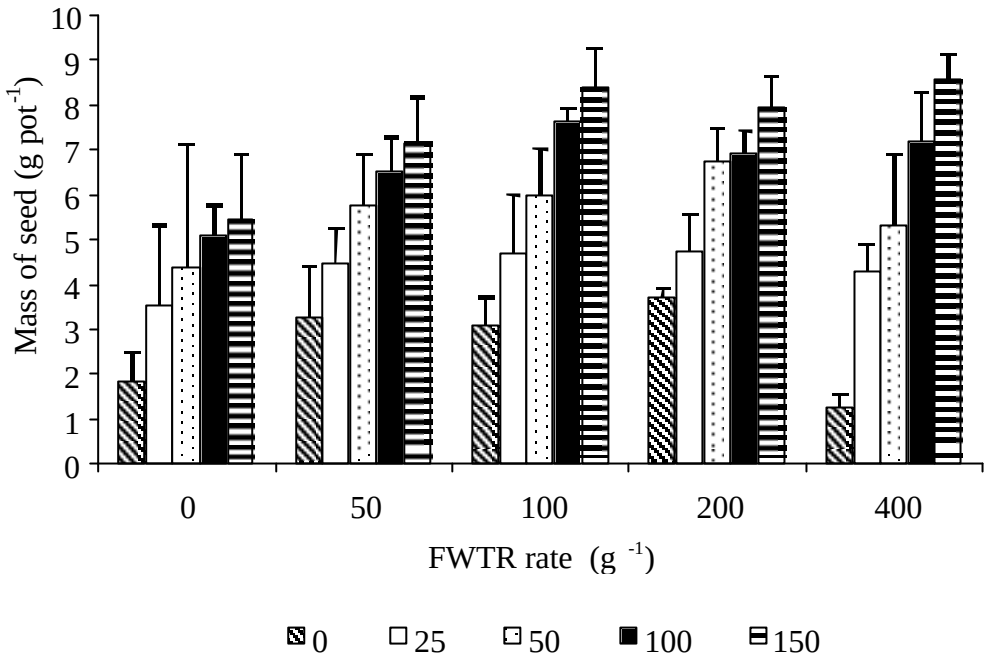


Figure 9.4 Mean (+SE, 3 replicates) mass of bean seeds grown in a Longlands sand with Faure water treatment residue application rates of 0, 50, 100, 200 and 400 g kg^{-1} with fertiliser levels of 0, 25, 50, 100 and 150%, as indicated in the legend.

Comparisons by $LSD_{5\%}$ (Figure 9.5) showed that the 150% fertiliser treatment (over mean FWTR application rate) performed significantly better than the other treatments.

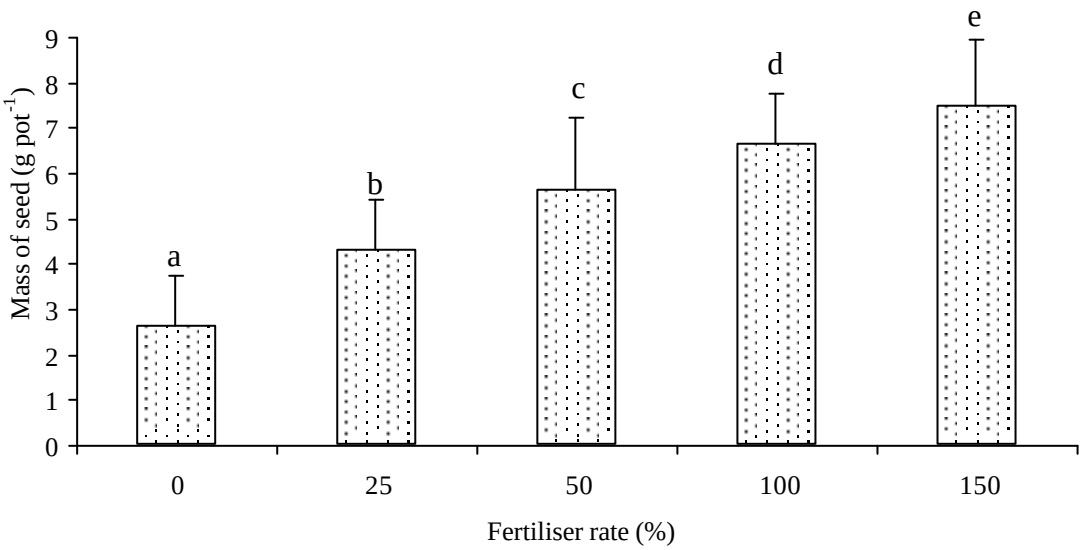


Figure 9.5 Mean (+SE) mass of bean seeds grown in a Longlands sand at fertiliser levels of 0, 25, 50, 100 and 150% over the mean Faure water treatment residue application rates (0, 50, 100, 200 and 400 g kg^{-1}). Letters that are different indicate significant differences between treatment means ($LSD_{5\%}$ = 0.759).

There was an increase in mean seed mass with increasing rates of fertiliser over the FWTR application rates. This suggests that the 100% level was perhaps not the ideal fertiliser application rate under these conditions, with the 150% level performing significantly better. While it was indicated that beans grown in the 400 g kg^{-1} FWTR without fertiliser appeared to have satisfactory foliar nutrient levels (Section 9.3.5.1), it is clear that additional fertiliser improved the mass of seed significantly.

Comparisons by $LSD_{5\%}$ of mean seed mass, for FWTR application rates, showed that the control treatment was significantly lower than the other treatments, which were not significantly different from one another (Figure 9.6). Maximum yield was achieved at the 200 g kg^{-1} FWTR application rate. This suggests that addition of FWTR improves the yield of bean seed in a nutrient-poor sand.

However, from Figure 9.4 it would appear that without fertiliser the 400 g kg^{-1} FWTR application negatively affects seed production in the bean plant, perhaps as a result of Mn toxicity and associated antagonistic effects, or possibly a P deficiency considering the high P sorption capacity of the FWTR (Section 4.3.6). This effect was less obvious for the fertilised treatments, indicating that addition of N, P and K may help overcome the growth-limiting or growth-inhibiting factor.

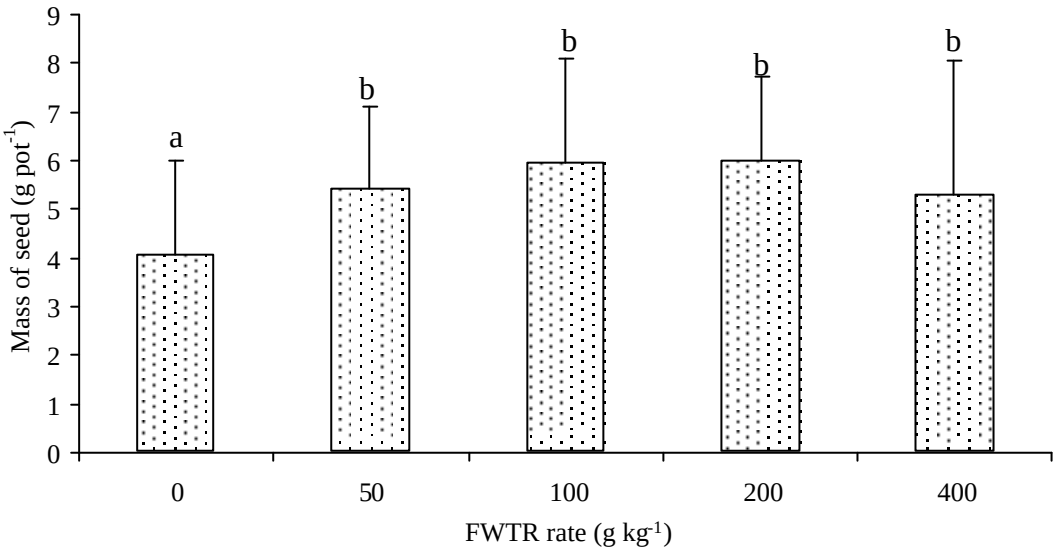


Figure 9.6 Mean (+SE) mass of bean seeds grown in a Longlands sand at Faure water treatment application rates of 0, 50, 100, 200 and 400 g kg^{-1} over the mean fertiliser application rates of 0, 25, 50, 100 and 150%. Letters that are different indicate significant differences between treatment means ($LSD_{5\%}$ = 0.759).

From these data, to achieve maximum yield the recommendation would be to apply the FWTR at 400 g kg^{-1} with 150% fertiliser. This, however, requires that the highest fertilisation rate be used and implies associated costs. To achieve a similar level of production the FWTR can be applied at 400 g kg^{-1} with the 100% fertiliser level, even though this treatment produced 1.39 g pot^{-1} less than the 400 g kg^{-1} FWTR treatment with 150% fertiliser. The cost of fertiliser may require that the lower fertiliser rate be used, but in any event the yield data suggest that the FWTR can be applied at the

maximum rate used here, even though there were indications of Mn toxicity in the foliage. To determine whether this may be detrimental to seed quality one needs to consider nutrient translocation to the seed.

9.3.5.3 Nutrient uptake by bean seed

While no distinguishing patterns of uptake were evident in the bean seeds (Appendix 9.2) for Ca, Mg and Na, there did appear to be small increases in the amounts of P and K with increasing additions of fertiliser. There appeared to be little effect of FWTR additions on the uptake of Ca, Mg, Na, K, or P, however. The FWTR additions appeared to have more effect on trace nutrient uptake, in particular Mn and Fe. Zinc and Cu concentrations were variable, with Zn showing slight increases in concentration with increasing fertiliser additions. Manganese and Fe showed increases in concentration with increasing FWTR, but this was not surprising considering the high concentrations of both these elements in the FWTR. The concentrations, however, were always low. Although there was evidence of Mn toxicity in the foliage of the bean plants, the concentration in the seed indicates that they would be suitable for consumption. However, they may not be usable for propagation (planting), due to physiological damage to the seed testa sometimes associated with toxic levels of certain elements (Dr. A. Modi, and Prof. P. Greenfield, pers. comms., 2003). Furthermore, consideration of fleshy vegetable crops (e.g. tomatoes, lettuce) may also show higher translocation of toxic elements into these portions of the crop, possibly making them unsuitable for consumption. This would require further investigation.

9.3.5.4 Manganese toxicity alleviation

As a result of the chlorosis evident in the leaves of the bean plants, beans were grown in the 400 g kg^{-1} FWTR treatment with a variety of 'ameliorative' treatments applied to try and reduce or alleviate the Mn toxicity. A lime treatment (approximately 2 Mg ha^{-1}) was used to increase the pH, which it was speculated could reduce Mn availability or solubility. Although Mn availability is generally not greatly affected by pH, the nutrient uptake by grasses (Section 7.4.4; Appendix 7.4), suggested that as pH increased Mn availability decreased. The bean plants with this treatment died shortly after the lime additions and it was suspected that the increase in pH over the already suitable level (Table 9.5) led to a reduction in the availability of other essential nutrients and, in conjunction with the Mn toxicity, caused a rapid death of the plants.

As Mn may have severe antagonistic effects on Fe uptake, it was speculated that due to the high Mn availability, the Fe/Mn balance may be causing the symptoms. This was again supported by earlier data (Section 7.4.4; Appendix 7.4), where decreases in Mn concentration coincided with increases in Fe concentration. To determine whether additional Fe would help alleviate this, a commercially available 13% Fe chelate supplement for potted plants was either mixed with the soil and FWTR mixture at the manufacturer's recommended rates or applied as a foliar spray on germinated seedlings. In the incorporated treatment the bean seeds did not germinate, and in the other treatment the seedlings had a strong negative response to the foliar application of Fe, the leaves withering and dying within hours of application.

A 1:5 FWTR:water extract showed that the FWTR had 6.35 mg kg^{-1} water-soluble Mn and so leaching of the mixture to remove some of this excess Mn could possibly

improve bean growth. To test this hypothesis, beans were grown in a 400 g kg^{1} FWTR treatment that was watered excessively. Water was applied to the treatment so that it would drain from the base of the pot. The pot was then only re-watered once the material appeared dry. This was to lessen the possibility of creating reducing conditions in the pot that would lead to Mn reduction and increased availability. Initial indications were that this treatment had the potential to alleviate the Mn toxicity. While previously the Mn toxicity symptoms had been noticed on the cotyledonous leaves and subsequently on the new leaves, this treatment did not show these symptoms. The new leaves also developed a little more before showing the symptoms. It is considered that under the imposed leaching regime, continual removal of the Mn led to increased solubilisation of Mn, or possibly the creation of micro-sites with reducing conditions that may have caused the release of Mn. This was partly confirmed by an increase in the Mn concentration of the leachate collected from this experiment (results not shown). In addition, the continual leaching of this treatment could have caused a loss of other essential nutrients, which may have exacerbated any symptoms seen. However, this observational investigation does suggest that under field conditions adequate leaching and a suitable fertiliser regime may satisfactorily remedy the problem, but this will require further investigation.

9.4 Conclusions

While there was concern that Mn toxicity would be a problem for seed production, it would appear that this was limited to the higher FWTR application rates with low fertiliser additions. As it would appear that the sources of the Mn were the lime and the coagulant salt used to treat the raw water, the problem may be entirely overcome by using 'cleaner' materials. It is possible, however, that such a change would increase the cost of treatment due to the increased cost of purchasing materials with less Mn.

It must also be realized that the pot experiment would have had a higher water content than would be experienced under field conditions and, despite attempts to ensure that the pots were never waterlogged, it is highly probable that reducing conditions prevailed at times, even if only at micro-sites within the pot. Such conditions would have increased the solubility, and hence availability, of Mn. In the field more oxidizing conditions would be likely to exist thus lessening Mn solubility.

It is suggested that leaching will decrease Mn concentrations adequately to lessen or prevent toxicity, but this would require careful management, to ensure that other mobile nutrients were not lost in excessive quantities, leading to other negative impacts on plant growth.

The effect of the FWTR was only tested on a single crop species in this investigation and further investigation using other crop species would be essential if the material was to be applied to areas where the land is to be used for food crops. The decomposition rate of the FWTR is not known and this would also require further investigation to ascertain whether multiple applications are possible on the same area, and at what frequency these applications could occur.

CHAPTER 10

MICROBIAL ACTIVITY AND RELATED CHEMICAL PROPERTIES OF THE SOILS FROM UKULINGA AND BROOKDALE FARM FIELD EXPERIMENTS

10.1 Introduction

Because studies on the effects of water treatment residue (WTR) on soil microbial parameters are rare, the present research protocol adopted a broad-scale approach. The research concentrated initially on selected soil chemical and microbial parameters at the sites of the two field experiments (Chapter 5). Due to the large number of samples that needed to be processed, the field trials were only sampled twice and hence these results give a 'snapshot' of the conditions at the given sampling time. As this only allowed for the assessment of the long-term effects of the WTR from the Midmar Water Treatments Works, this WTR and others from elsewhere in South Africa were investigated in short-term laboratory studies (Chapter 11). In addition an investigation of the effect of some WTRs on the microbial community structure of the soil from the Brookdale farm experimental site was also undertaken (Chapter 12).

The data gathered from the field trials at Brookdale and Ukulinga Farms enabled an evaluation of the effect of the Midmar WTR :

- on the microbial activity with depth in the soil and at the different application rates of WTR; and
- on selected soil chemical parameters, namely, soil organic carbon (OC), pH, and electrical conductivity (EC) with depth and at the different application rates of WTR.

Soil organic carbon was measured since microbial activity generally increases with increasing soil organic matter (or organic carbon). However, an interplay of a wide range of factors affects activity including soil pH, the ionic strength of the soil solution, and redox potential (Schnurer and Rosswall, 1982; Smith *et al.,* 2000). Thus pH and electrical conductivity (simple and commonly determined soil parameters) were also measured to investigate their effect on microbial activity.

10.2 Materials and methods

10.2.1 Water treatment residue

The physical and chemical characteristics of the Midmar WTR are given in Chapter 4 and descriptions of the field experiments in Chapter 5. A sample of the WTR was analyzed at Umgeni Water (Pietermaritzburg) for the presence of pathogenic microorganisms. It tested negative for the presence of both *Salmonella* species and *Escherichia coli.*

10.2.2 Soil sampling

Sampling of grassed and fallow treatments was carried out in September 2001 and May 2002. At Ukulinga Farm the WTR treatments at rates of 0, 80, 320 and 1280 Mg

ha^{-1} were sampled. To be consistent and in order to reduce the number of samples that needed processing, only these WTR-incorporated treatments were sampled at Brookdale Farm. Additionally, at Brookdale the mulched treatments at rates of 320 and 1280 Mg ha^{-1} were sampled.

Triplicate soil samples were taken using an enclosed bucket auger from each treatment. Analyses were carried out on individual soil samples i.e., no compositing (n=6 per treatment). At Ukulinga Farm, soil was sampled at 100 mm intervals to a depth of 500 mm. At Brookdale Farm samples were taken at 100 mm intervals to a depth of 400 mm, and subsequently at 200 mm intervals to a depth of 1200 mm.

The field-moist samples were divided into two sub-samples. For biological analyses, one sub-sample was sieved (<2 mm), placed into plastic bags and stored at 4°C. For chemical analyses, the other sub-sample was air-dried and stored in sealed containers at room temperature.

10.2.3 Laboratory analyses

10.2.3.1 pH

pH was measured, after standing for 30 min with occasional stirring, in a 1:2.5 soil:water extract using a calomel combined electrode attached to a Radiometer PHM 210 standard pH meter.

10.2.3.2 Organic carbon

Air-dried soil was milled (<500 µm) and then 0.5 g was weighed into 500 mL Erlenmeyer flasks. Potassium dichromate was added (10 mL), and mixed for 1 min. Thereafter, 20 mL concentrated sulphuric acid was added and swirled in the flask for 1 min. Samples were allowed to stand for 20 min, following which 170 mL distilled water, 10 mL of an 85% phosphoric acid solution, and 0.5 g sodium fluoride were added. Ferroin indicator (5 drops) was added and samples titrated with Mohrs solution to the brownish-black end point (Blakemore *et al*., 1972).

10.2.3.3 Electrical conductivity

Electrical conductivity was measured at 21^{o}C immediately prior to pH in the 1:2.5 soil:water extract using a Radiometer CDM 83 conductivity meter.

10.2.3.4 Microbial activity

Microbial activity was estimated using a modified fluorescein diacetate (FDA) hydrolysis method described by Perucci (1992). Twenty four hours before analysis, samples were removed from cold storage (4°C) and kept at room temperature. A 2.5 g moist soil sample was weighed into a 100 mL Erlenmeyer flask, and 400 µL of a solution of FDA (20 000 mg L^{-1}), made up with acetone, and 20 mL of 0.6M sodium phosphate buffer (pH 7.6) were added.

Samples were shaken in a controlled environment shaker-incubator (IncoShake-Labotec) set at 30°C and 150 rpm for 1 h. Following incubation, 20 mL acetone were

added to stop the reaction. Samples were filtered through Whatman No. 1 filter paper. The filtrate was diluted ten-fold with distilled water and the absorbence read at 490 nm on a Cary 1E UV-Visible spectrophotometer (Varian).

A standard curve was constructed using 0, 1.75, 2.5, 3.75 and 5 mg L^{-1} fluorescein in 20 mL of phosphate buffer and 20 mL acetone. Data were calculated as µMol product (fluorescein) formed g^{-1} oven-dry soil h^{-1}.

10.2.4 Statistical analyses

Statistical analysis was carried out using Genstat (Release 6.1, Lawes Agricultural Trust, Rothamsted Experimental Station). Analysis of variance (ANOVA) was carried out with data treated as a split-split-split plot design. Separation of means was based on the principle of least significant difference (LSD) at the 5% level of significance.

For each measured variable (OC, pH, EC and microbial activity) the ANOVA indicates two main effects i.e., WTR and depth. The WTR effect is determined by exclusion of the depth effect, while the depth effect was determined by exclusion of the treatment effect. For example, when looking at the effect of WTR on a measured variable (OC, pH, EC or microbial activity), data pertaining to each WTR application rate are grouped to obtain a single mean value for each WTR application rate.

All the graphs plotted in the following section are based on the mean data obtained by the above-mentioned grouping of data. While a graphical representation of the main effects provides a useful indication of general trends, it is recognised that an interplay of factors is more likely to affect the measured variables. Thus, the interaction effects provide more useful information. As with main effects, in some cases where the ANOVA showed significant interaction effects the mean data are plotted to provide a clearer indication of the trend.

10.3 Results and discussion

10.3.1 Organic carbon

At both Brookdale and Ukulinga Farms, the change in organic carbon (OC) with depth was significant in September 2001 and May 2002. Further, at Ukulinga Farm the change in OC with the different application rates of WTR was significant at both sampling times. However, at Brookdale Farm changes in OC with the different application rates of WTR were non-significant at September 2001, but significant at May 2002 (Appendix 10.1). As expected at both trials there was a decline in OC with increasing soil depth. The mean quantity of OC recorded at Ukulinga and Brookdale Farms at both sampling times is given in Appendix 10.2 and 10.3, respectively. At both trials, differences in OC content were more pronounced with depth than with WTR application.

The relationship between OC and the different application rates of WTR at Ukulinga and Brookdale is shown in Figures 10.1a and b, respectively. The September 2001 sampling at Ukulinga displayed higher OC content (between 4 and 5 g kg^{-1}) on WTR-amended treatments in comparison to the control. At this sampling time the OC content of the WTR-amended treatments was statistically different from the controls,

but not statistically different from each other. The Ukulinga May 2002 samples showed significant but only small differences in OC between the different treatments. At Brookdale Farm, although significant differences in OC were observed across the different treatments in September 2001, both sampling times revealed small differences in OC (<3 g kg^{-1}) across the different treatments and between sampling times.

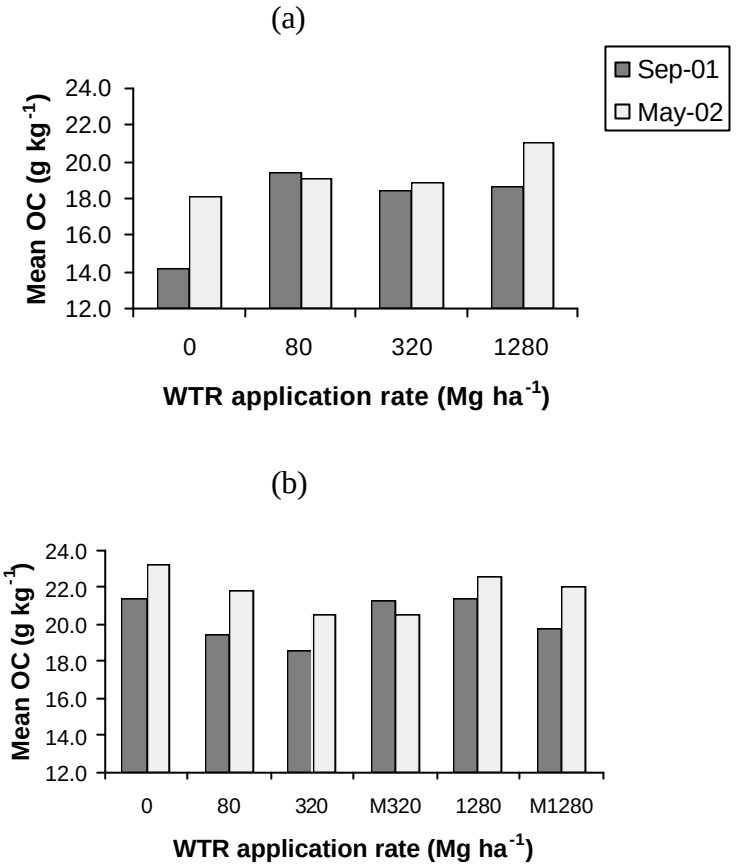


Figure 10.1 Mean organic carbon (OC) at (a) Ukulinga Farm and (b) Brookdale Farm at the different application rates of water treatment residue sampled in September 2001 and May 2002.

At Ukulinga the (status x depth) interaction (Figure 10.2) was significant in September 2001 and May 2002 (Appendix 10.1). The OC content of experimental plots under fallow treatment was marginally but consistently higher than the grassed treatments throughout the soil profile at both sampling times. The (status x depth) interaction at Brookdale Farm was non-significant at both sampling times (Appendix 10.1).

At Brookdale the (WTR x depth) interaction was significant at both sampling times, while at Ukulinga the interaction was significant in September 2001 only (Appendix 10.1). However, at both trials the significance of this interaction is more likely due to the significance of the depth effect since the trend in OC across all WTR application rates was very similar. Additionally, while Ukulinga samples showed significant (status x WTR) and (status x WTR x depth) interactions for the September 2001 sampling, these interactions were non-significant at Brookdale (Appendix 10.1).

However, it is probable that the significance of these interactions resulted again mainly from the WTR and depth effects.

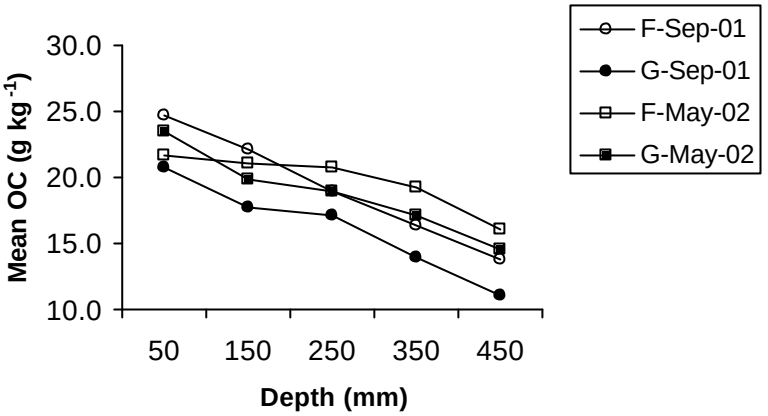


Figure 10.2 The trend in mean organic carbon (OC) at Ukulinga Farm under fallow (F) and grassed (G) conditions sampled in September 2001 and May 2002.

Gregorich *et al.* (1994) considered that the amount and rate of change in total OC is dependent more on the initial level of carbon than on the treatment or management practice imposed on the soil. Further, when looking at any statistical evaluation, one needs to be mindful that statistical significance does not necessarily result in changes to the studied ecosystem and its functioning. With the exception of the September 2001 sampling at Brookdale Farm, the addition of the WTR resulted in significant changes in OC. However, these changes are more likely a result of the heterogeneity of the soil rather than WTR addition. The minimal effect of WTR on soil OC content can be attributed to the very similar OC contents of the Midmar WTR (28 g kg^{-1}) and the Westleigh soil at Ukulinga Farm, which ranged between 20 and 25 g kg^{-1} in the top 200 mm and the Hutton at Brookdale Farm, where the OC content of the control soils averaged 32 g kg^{-1} in the top 200 mm.

Campbell *et al.* (1991) suggested that soils with an initially high level of organic matter may require prolonged and intense perturbation to show significant degradation compared to soils with initially lower organic matter contents. The implication is a change in soil quality, more specifically soil OC, would be detected earlier on the Westleigh soil at Ukulinga Farm than on the more strongly structured Hutton soil at Brookdale Farm. Although the field trials at Ukulinga and Brookdale had been running for almost 3 and 5 yr, respectively, neither indicated marked changes in soil OC (Appendices 10.2 and 10.3).

10.3.2 pH

At Brookdale the different application rates of WTR did not significantly impact on soil pH at either sampling time and at Ukulinga the change in pH was significant only in May 2002 (Appendix 10.4). Analysis of the Ukulinga May 2002 samples revealed that the pH of the WTR-amended soils was statistically different from the controls (Appendix 10.5). Although the change in pH at the different application rates of WTR is statistically significant, these changes did not exceed 1 pH unit.

At Ukulinga and Brookdale Farms, the change in pH with depth was significant at both sampling times (Appendix 10.4). At Ukulinga Farm, the range and trend of pH with depth in September 2001 and May 2002 were very similar (Figure 10.3a). However, at Brookdale Farm the near-surface soil samples displayed higher pH in September 2001 than in May 2002 (Figure 10.3b). At Brookdale the mean pH throughout the soil profile ranged between 5 and 6 at both September 2001 and May 2002 (Appendix 10.6). The mean pH at Ukulinga was higher than at Brookdale, ranging between 6 and 7 at both sampling times.

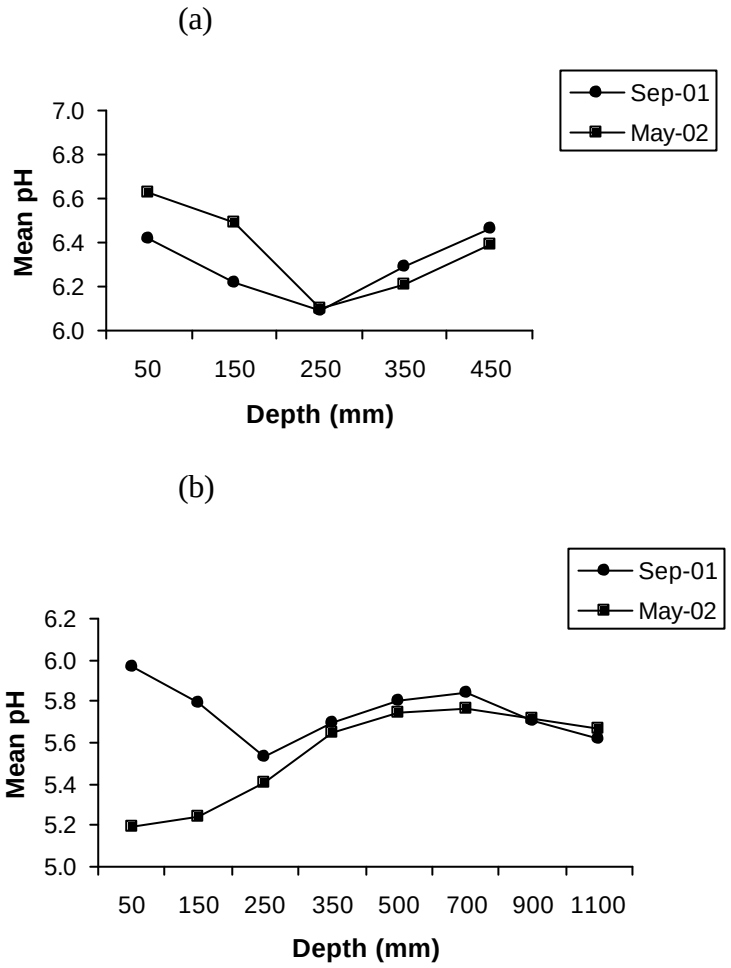


Figure 10.3 The trend in mean pH in the soil profile at (a) Ukulinga Farm and (b) Brookdale Farm sampled in September 2001 and May 2002.

At both trials the (WTR x depth) interaction was significant at both sampling times (Appendix 10.4) and WTR addition resulted in an increase in pH in the top 200 mm of the soil into which the WTR was incorporated. Below this depth the pH of the WTR-amended treatments was similar to that of the controls.

At Ukulinga there was an increase in pH with increasing application rates of WTR that was more pronounced at the earlier sampling date (Figure 10.4). The same trend was observed on both the mulch and incorporated treatments at Brookdale Farm. While the September 2001 samples displayed pH increases of up to approximately 2 units on the 1280 Mg ha^{-1} treatment (Figure 10.5), the May 2002 samples showed an

increase in pH on the mulch treatments only (Figure 10.6). However, these increases in pH were smaller in May 2002 than in September 2001.

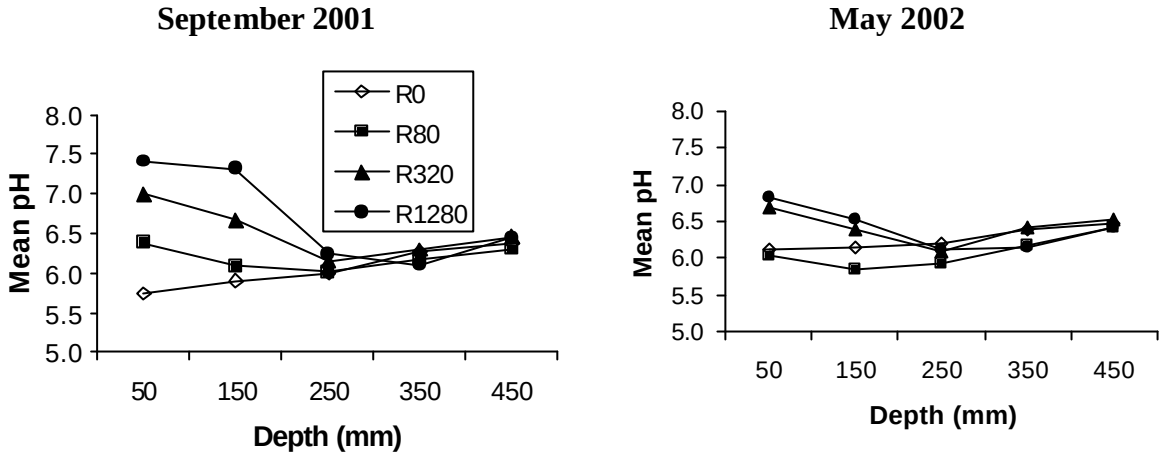


Figure 10.4 The trend in mean pH in the soil profile at the different application rates (Mg ha^{-1}) of water treatment residue (R) at Ukulinga Farm sampled in September 2001 and May 2002.

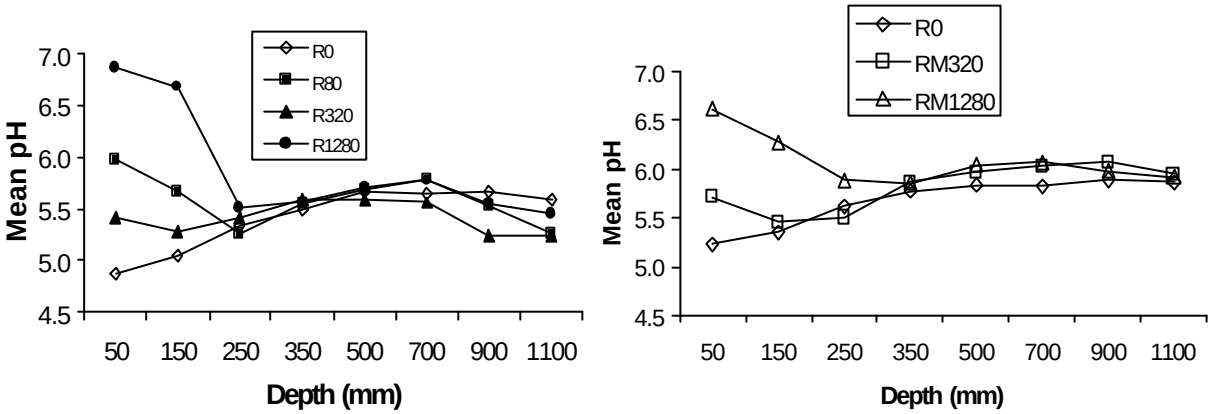


Figure 10.5 The trend in mean pH in the soil profile at the different application rates (Mg ha^{-1}) of water treatment residue (R) at Brookdale Farm sampled in September 2001 (M = mulch).

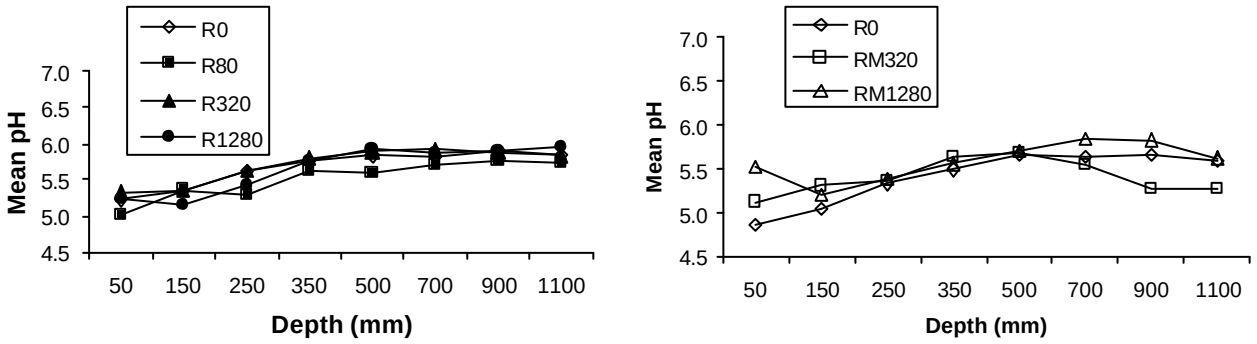
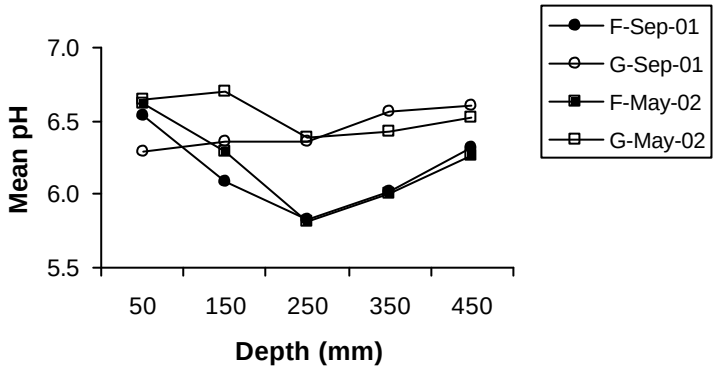


Figure 10.6 The trend in mean pH in the soil profile at the different application rates (Mg ha^{-1}) of water treatment residue (R) at Brookdale Farm sampled in May 2002 (M = mulch).

At both sampling times at Ukulinga Farm the (status x depth) interaction (Figure 10.7a) was significant (Appendix 10.4) with the pH of the grassed treatments higher than the fallow treatments. The pH of the grassed plots remained fairly constant throughout the soil profile but under fallow there was a decrease in pH from the surface to a depth of 200-300 mm. With greater depth the pH increased to approximately the values of the surface soil. At Brookdale Farm the (status x depth) interaction (Figure 10.7b) was significant in September 2001 and non-significant in May 2002 (Appendix 10.4). As with the Ukulinga data, the grassed treatments in May displayed higher pH than the fallow treatments, and displayed more constant pH throughout the soil profile. However, there was no apparent pH trend in September 2001 and observed differences in pH were small.

At Ukulinga the (status x WTR x depth) interaction (Figure 10.8) was significant in September 2001 and non-significant in May 2002, and displayed a more pronounced increase in pH in the surface soil under fallow conditions. At Brookdale Farm the (status x WTR x depth) interaction was non-significant at both sampling times (Appendix 10.4).

(a)



(b)

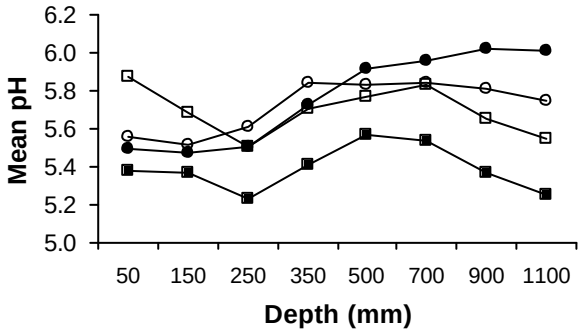


Figure 10.7 The trend in mean pH at (a) Ukulinga Farm and (b) Brookdale Farm under fallow (F) and grassed (G) conditions sampled in September 2001 and May 2002.

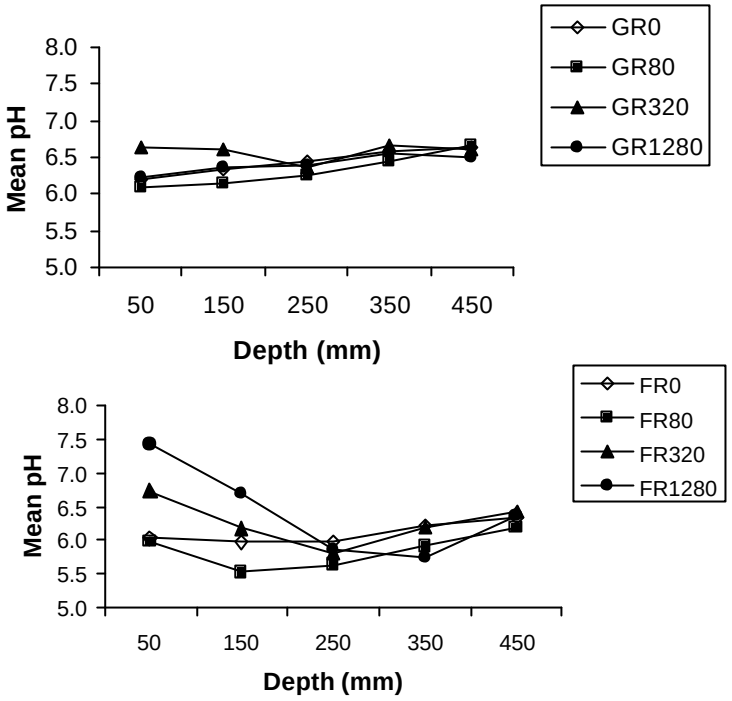


Figure 10.8 The trend in mean pH under fallow (F) and grassed (G) conditions at Ukulinga Farm at the different application rates (Mg ha^{-1}) of water treatment residue (R) sampled in September 2001.

The application of WTR to acidic soils has been shown to increase soil pH (Ahmed *et al.*, 1998) due to the lime used in the water treatment process. Poor plant growth in acidic soils is generally associated with inhibition of root growth due to high concentrations of Al (Bohn *et al.*, 1985). However, if soil pH is maintained between 6 and 6.5, Al toxicity does not pose a problem (Elliott and Dempsey, 1991). Thus, the pH-neutralizing potential of the Midmar WTR will reduce the possibility of Al toxicity. In view of such acidity problems in many South African soils, the potential of WTR to act as a soil ameliorant (Rengasamy *et al.*, 1980; Bugbee and Frink, 1985) could be beneficial. While the pH of the Midmar WTR was 7.70 (Table 4.2), a slightly acidic pH was noted at both field trials, with pH ranging between 5 and 6. At both field trials, an increase in pH was noted with increasing application rates of WTR, with a maximum increase of 2 pH units noted at the highest application rate of WTR (1280 Mg ha^{-1}). However, the field experiments had been running for 3 and 5 yr at Ukulinga and Brookdale, respectively, and the WTR resulted in greater pH increases at the start of the field experiments (results not shown), and the pH has since decreased.

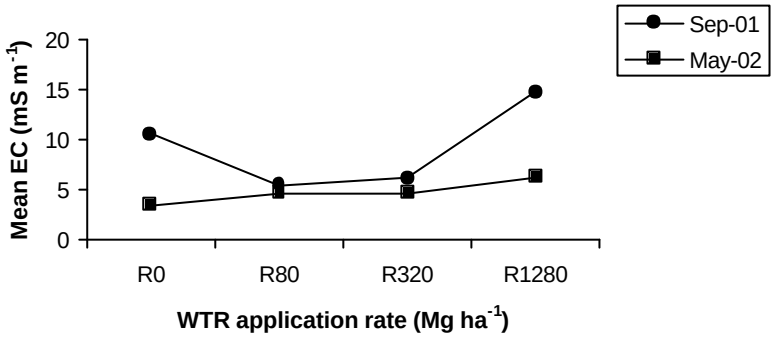
One of the most pH-sensitive reactions is biological nitrification, which is related to soil pH and is often used as an index of soil fertility. Since the optimum pH for nitrification may vary from 6.6 to 8.0, the increase in pH resulting from WTR additions on the Hutton and Westleigh soils is desirable for nitrification. In agricultural soils nitrification rates decrease below pH 6, and become negligible below pH 4.5, while high pH values inhibit the transformation of nitrite to nitrate. The measured pH increase resulting from WTR addition to both field experiments is more likely to encourage microbial activity than act as a deterrent.

10.3.3 Electrical conductivity

At both field trials, although some statistically significant relationships were found, the actual differences were generally small and the EC was always very low. At both sites the change in EC with depth was significant in September 2001 and May 2002 (Appendix 10.7). Both trials displayed higher EC in September 2001 than in May 2002. At Ukulinga the overall mean EC across all treatments ranged between 8.0 and 10.5 mS m^{-1} in September 2001 and between 3.5 and 8.0 mS m^{-1} in May 2002 (Appendix 10.8). At Brookdale it ranged between 6.5 and 10.5 mS m^{-1} in September 2001 and between 4.5 and 8.5 mS m^{-1} in May 2002 (Appendix 10.9).

At Ukulinga the change in EC resulting from the application of WTR was only significant in September 2001; at Brookdale it was significant at both sampling times (Appendix 10.7). At Ukulinga, the EC of the 80 and 320 Mg ha^{-1} treatments sampled in September 2001 and May 2002 was very similar. However, the September 2001 control and 1280 Mg ha^{-1} treatments displayed higher EC than in May 2002 (Figure 10.9a). At Brookdale the EC of September 2001 and May 2002 samples was very similar, with the main differences noted on the mulch treatments (Figure 10.9b).

(a)



(b)

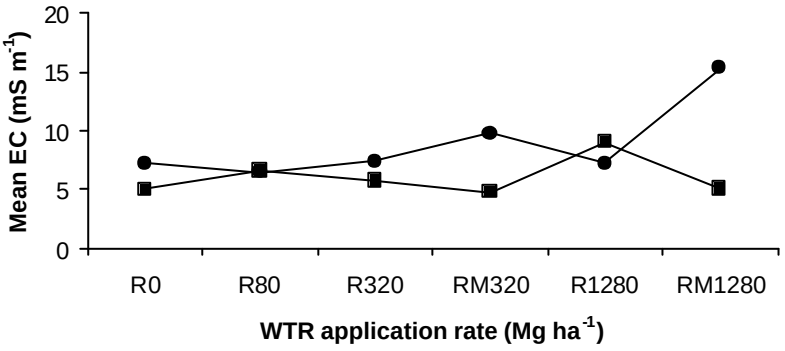


Figure 10.9 The trend in mean electrical conductivity (EC) at (a) Ukulinga Farm and (b) Brookdale Farm at the different application rates of water treatment residue (R) sampled in September 2001 and May 2002 (M = mulch).

At Ukulinga, the (WTR x depth) interaction was significant in September 2001 and non-significant in May 2002; at Brookdale Farm this interaction was significant at both sampling times (Appendix 10.7). The (status x depth) interaction at Ukulinga

(Figure 10.10a) was only significant in May 2002 (Appendix 10.7). At Brookdale Farm this interaction (Figure 10.10b) was only significant in September 2001. Both sites show higher EC under fallow treatments than under the grassed treatments. However, even when the (status x depth) interaction was significant, differences in mean EC between the fallow and grassed treatments were marginal.

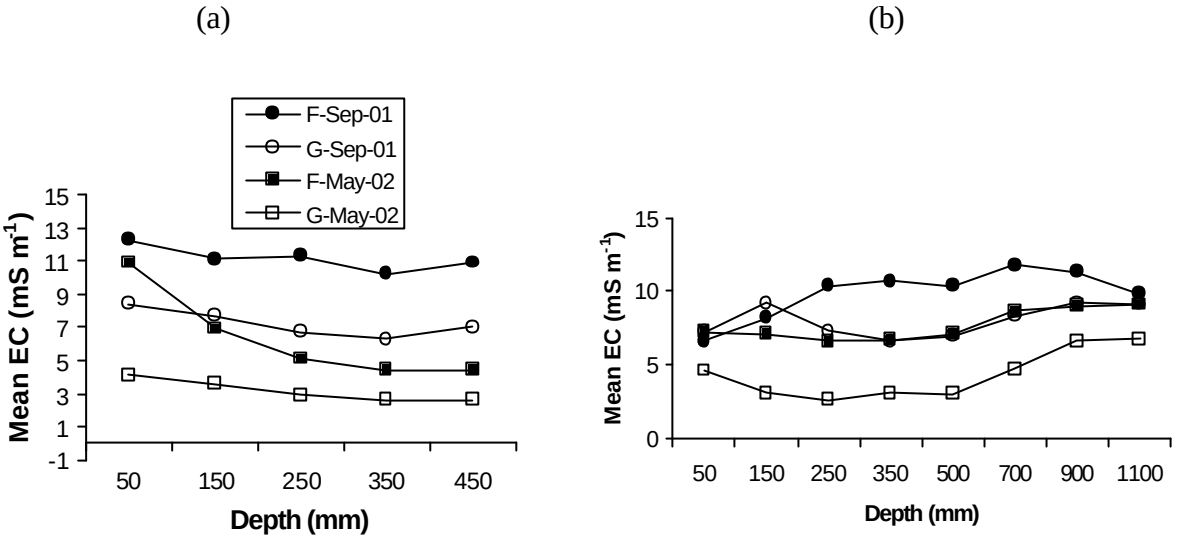


Figure 10.10 The trend in mean electrical conductivity (EC) at (a) Ukulinga Farm and (b) Brookdale Farm under fallow (F) and grassed (G) conditions sampled in September 2001 and May 2002.

At both Ukulinga (Figure 10.11) and Brookdale (Figure 10.12), the (status x WTR x depth) interaction was significant only in September 2001 (Appendix 10.7).

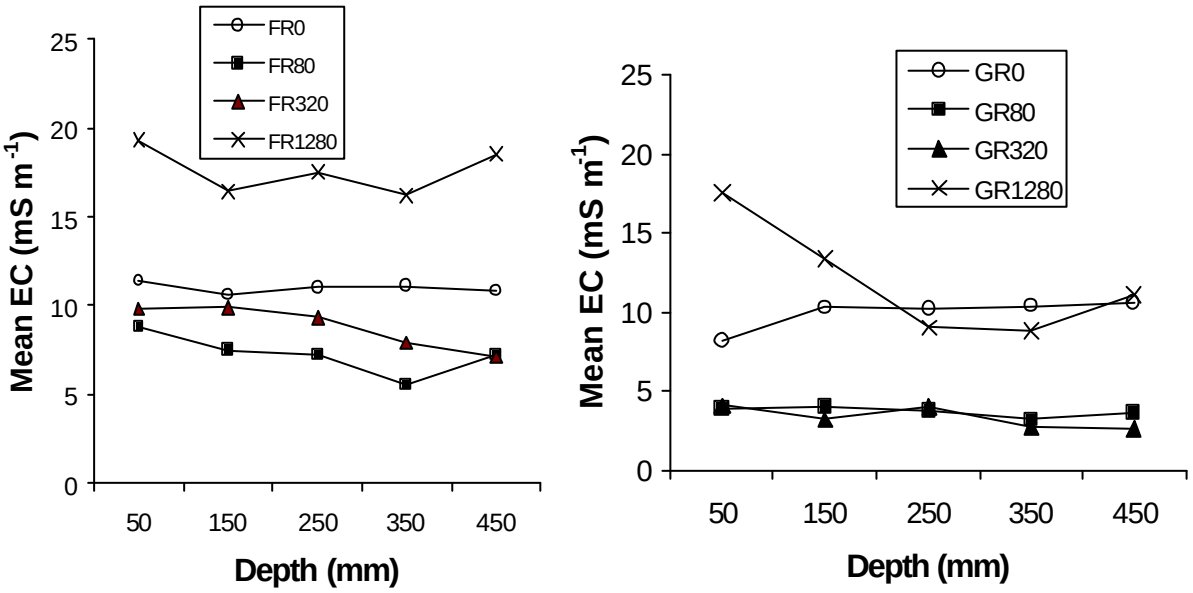


Figure 10.11 The trend in mean electrical conductivity (EC) under fallow (F) and grassed (G) conditions at Ukulinga Farm at the different application rates (Mg ha^{-1}) of water treatment residue (R) sampled in September 2001 (M = mulch).

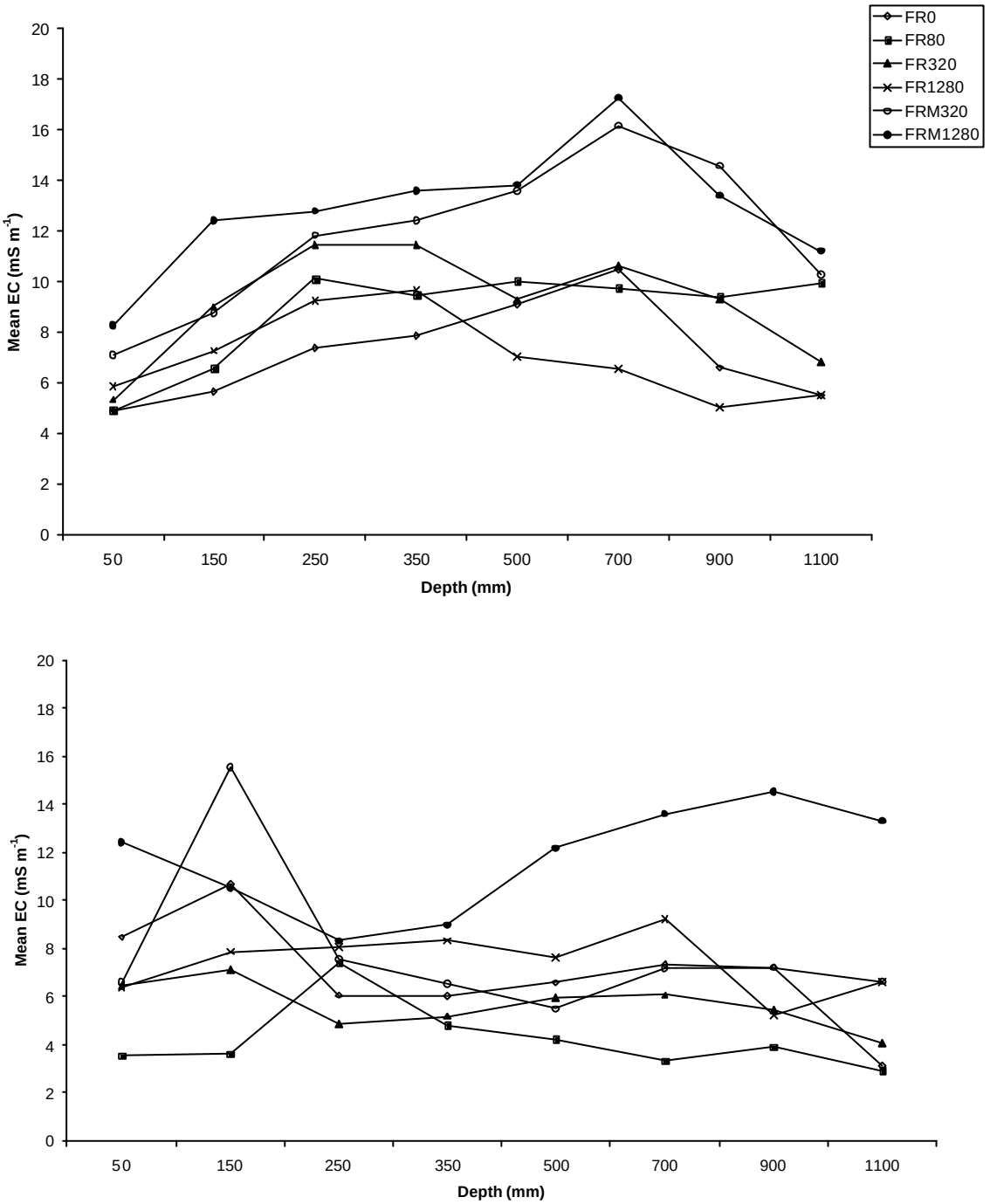


Figure 10.12 The trend in mean electrical conductivity (EC) under fallow (F) and grassed (G) conditions at Brookdale Farm at the different application rates (Mg ha^{-1}) of water treatment residue (R) sampled in September 2001 (M = mulch).

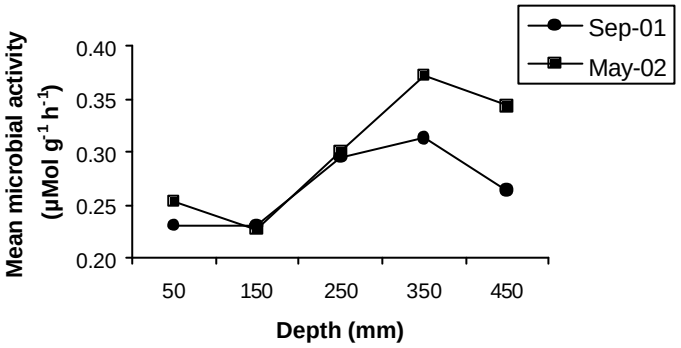
Due to the presence of soluble salts in the Midmar WTR (EC = 59.70 mS m^{-1}; Table 4.2), one would expect that the EC of WTR-amended treatments might be higher than the controls. However, at both field trials this trend is not apparent. This is possibly due to the period of time that has elapsed since the addition of the WTR to the trials. The salts may have leached, and a fraction may have become bound to exchange sites on the soil colloids, and are therefore no longer water-soluble.

The Ukulinga and Brookdale data indicated a fairly constant EC throughout the soil profile across all treatments. Although there is no field-based study to which the current EC data of WTR-amended soils can be compared, the most important finding is that, across all treatments, EC is below 400 mS m^{-1}. Although this value refers to a saturated paste determination it is clear that the levels recorded in the present work in the 1:2.5 soil:solution matrix are substantially lower and would never approach that value. This is significant since an EC higher than this is associated with saline soil and therefore is detrimental to crop growth (Dayton and Basta, 2001).

10.3.4 Microbial activity

At Ukulinga the change in microbial activity with depth was significant in May 2002, only. However, at Brookdale the change in microbial activity with depth was significant in both September 2001 and May 2002 (Appendix 10.10). In September 2001 and May 2002 microbial activity at Ukulinga ranged between 0.2 and 0.4 µMol g^{-1} h^{-1} (Figure 10.13a), while at Brookdale microbial activity ranged from 0 to 1.5 µMol g^{-1} h^{-1} (Figure 10.13b). In September 2001 and May 2002 microbial activity increased with increasing soil depth at both Ukulinga and Brookdale, reaching peak activity at 300-400 mm and 300-600 mm depth, respectively. The mean microbial activity values recorded at Ukulinga and Brookdale are given in Appendices 10.11 and 10.12, respectively.

(a)



(b)

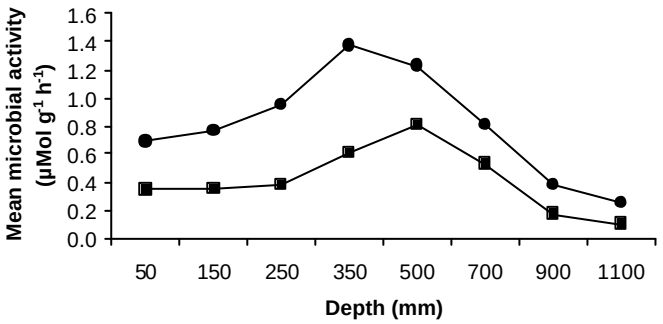


Figure 10.13 The trend in mean microbial activity in the soil profile at (a) Ukulinga Farm and (b) Brookdale Farm sampled in September 2001 and May 2002.

The change in microbial activity with the different application rates of WTR was non-significant at Ukulinga at both sampling times but was significant at Brookdale in September 2001. Despite this statistical significance there were only marginal differences in microbial activity between treatments. At Brookdale microbial activity was higher in September 2001 than in May 2002.

At Ukulinga the (status x depth) interaction (Figure 10.14a) was significant in May 2002, while at Brookdale this interaction (Figure 10.14b) was significant at both sampling times (Appendix 10.10). At Ukulinga the fallow plots displayed marginally higher activity than the grassed treatments, with a peak in activity at a depth of 300-400 mm. At Ukulinga the grassed plots displayed fairly constant microbial activity throughout the soil profile. The grassed treatments at Brookdale had marginally higher mean microbial activity in the 0-600 mm soil depth.

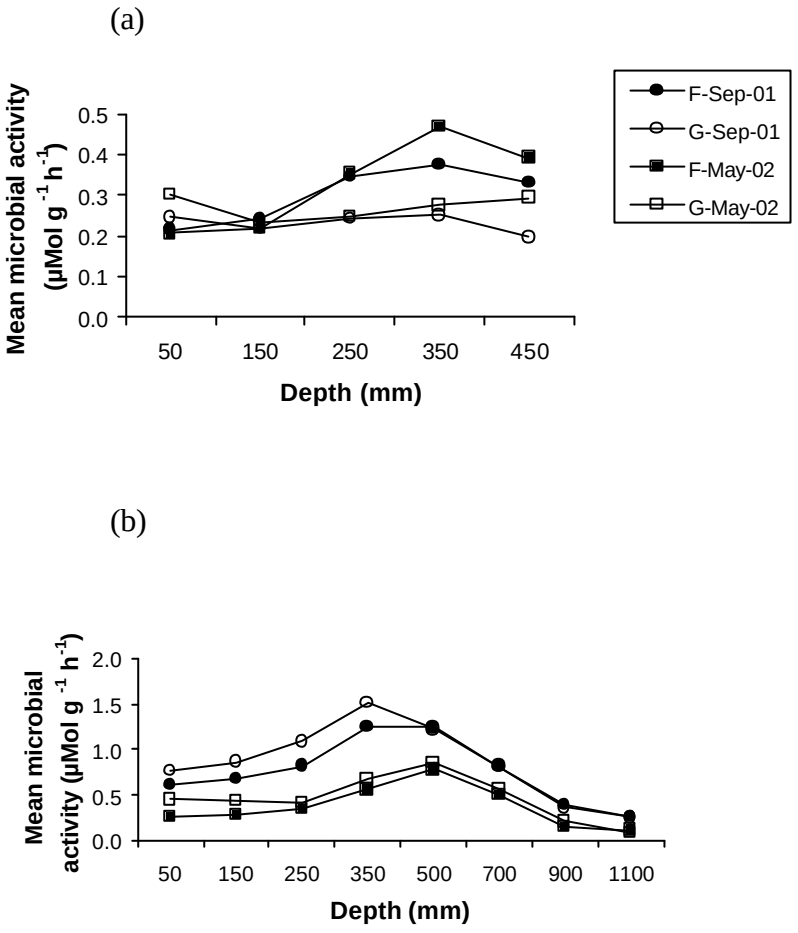


Figure 10.14 The trend in mean microbial activity at (a) Ukulinga Farm and (b) Brookdale Farm under fallow (F) and grassed (G) conditions sampled in September 2001 and May 2002.

At Ukulinga the (WTR x depth) interaction (Figure 10.15) was non-significant in September 2001 and May 2002 while at Brookdale this interaction (Figure 10.16) was significant at both sampling times (Appendix 10.10). At Brookdale all treatments showed an increase in microbial activity with increasing soil depth, reaching peak activity in the 300-600 mm soil samples. This peak activity declined from between 1 and 2 µMol g^{-1} h^{-1} in September 2001 to between 0.5 and 1.4 µMol g^{-1} h^{-1} in May 2002.

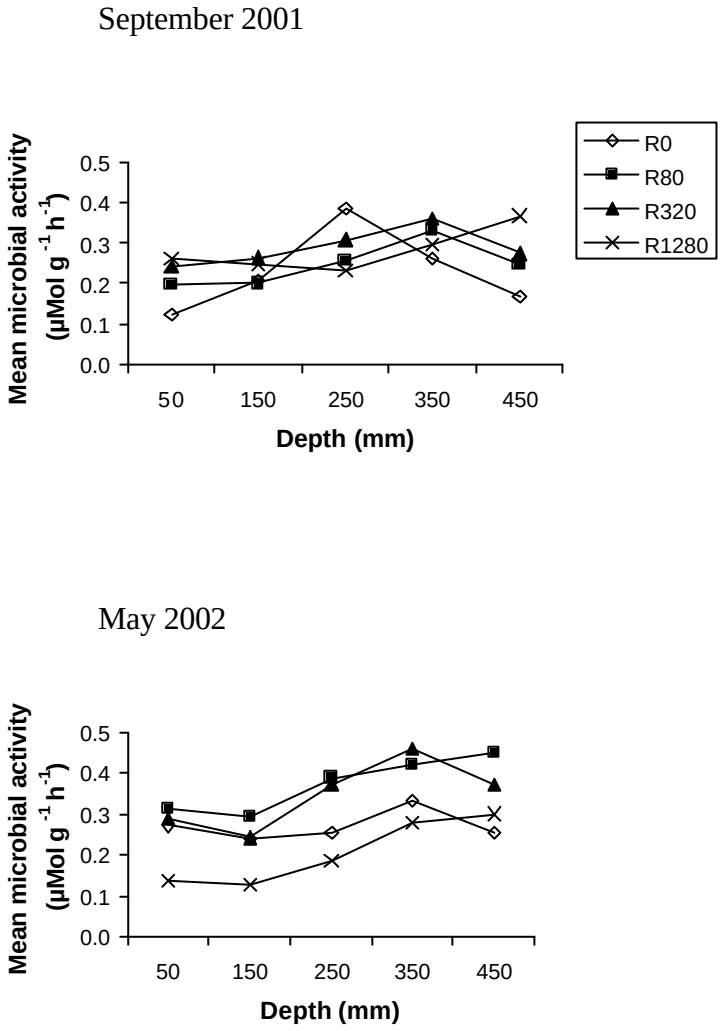


Figure 10.15 The trend in mean microbial activity in the soil profile at the different application rates (Mg ha^{-1}) of water treatment residue (R) at Ukulinga Farm sampled in September 2001 and May 2002.

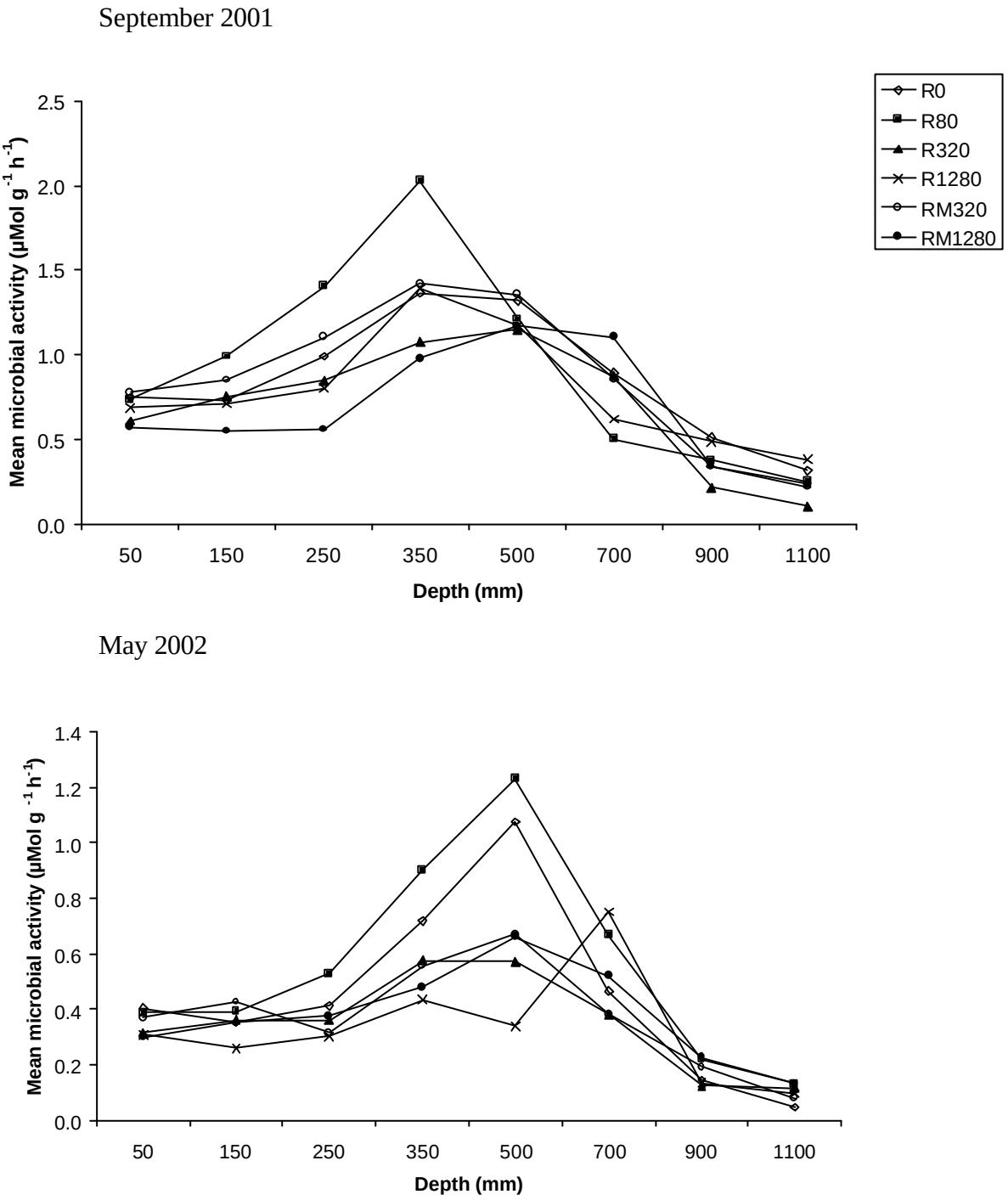
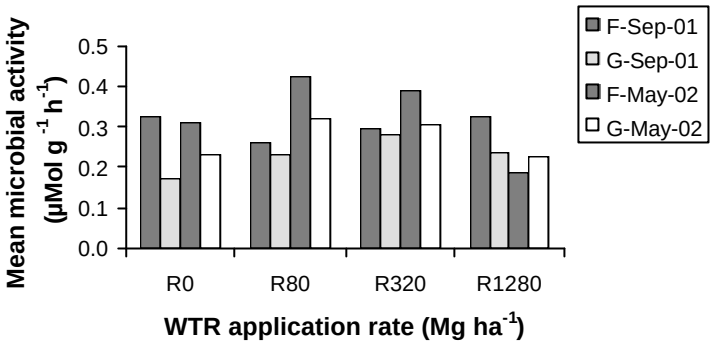


Figure 10.16 The trend in mean microbial activity in the soil profile at the different application rates (Mg ha^{-1}) of water treatment residue (R) at Brookdale Farm sampled in September 2001 and May 2002 (M = mulch).

At Ukulinga the (status x WTR) interaction was non-significant while at Brookdale Farm it was significant at both sampling times (Appendix 10.10). However, plots of these relationships indicated only small differences in microbial activity across all application rates of WTR under grassed and fallow conditions at Ukulinga (Figure 10.17a) and Brookdale (Figure 10.17b).

(a)



(b)

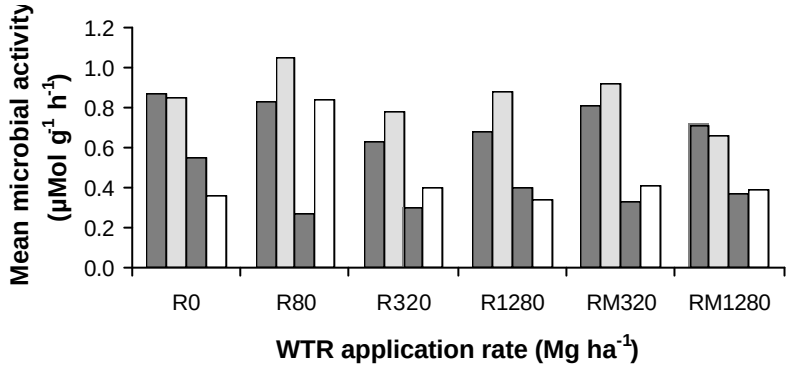


Figure 10.17 Mean microbial activity under fallow (F) and grassed (G) treatments at the different application rates of water treatment residue (R) at (a) Ukulinga Farm and (b) Brookdale Farm sampled in September 2001 and May 2002 (M = mulch).

There is only sparse literature regarding the microbial status of WTR. However, Elliott *et al*. (1990a) conducted a study into the land application of 20 WTRs in the United States. As part of this research they stated that since WTR was in contact with disinfectants, the possibility of contamination with pathogens was unlikely and none of the WTRs tested positive for the presence of coliform organisms. Similarly, the Midmar WTR used in the present study tested negative for the presence of *Escherichia coli* and *Salmonella* species (Section 10.2.1). To date there has been no research conducted into the effect of WTR on microbial activity and diversity in field and laboratory studies.

Although microbial activity is a sensitive indicator of changes or disturbances resulting from management practices (Schnurer and Rosswall, 1982), there is little information regarding the microbial status of South African soils (Nsabimana, 2002). Microbial activity in the Hutton soil at Brookdale Farm was higher than in the Westleigh soil at Ukulinga Farm probably due to the higher OC content of the former.

Also, it is likely that the apedal Hutton soil provided better soil aeration and moisture conditions for microbial growth.

The most apparent trend at both field trials was the relationship between microbial activity and depth. Soil enzyme activities have been found to decrease with soil depth (Ladd, 1985). Also, the numbers of all microbial populations usually decrease with increasing soil depth (Turco *et al.,* 1994). However, the bulk of the data pertaining to microbial activity is based on surface soil measurements (Kaiser *et al.,* 1992), and therefore cannot be directly compared to current data. Although the microbial activity of the topsoil is directly correlated with organic matter (C and N) contents (Ladd, 1985), there are few data on the relationship between microbial activity and soil organic carbon at depths of between 300 and 900 mm (Lavahun *et al.,* 1996).

At both trials, although the amount of OC decreased with increasing soil depth (Section 10.3.1), microbial activity increased with increasing soil depth to 300-400 mm, and 300-600 mm at Ukulinga and Brookdale, respectively, before declining with greater depth. This increase in activity with increasing soil depth may be attributed to a number of factors although it is considered that soil moisture was particularly important (Harris, 1981; Burns, 1989), since visual observation of the topsoil revealed very dry aggregates at both sampling times.

With respect to the chemical parameters measured at both trials, the EC from 0 mm to the sampling depth corresponding with peak microbial activity was constant, indicating that the effect of EC on activity was negligible. Although application of WTR at both trials resulted in an increase in pH in the top 200 mm, it is unlikely that the pH change is responsible for the lower microbial activity in the topsoil. With the exception of the highest WTR treatment, the increase in pH was not in excess of 1 pH unit, and therefore not likely to result in drastic changes to the microbial populations present.

Microbial activity helps to aggregate the soil and this reduces erosion, allows for good water infiltration, and maintains adequate aeration of the soil. However, an increase in microbial activity does not imply an improvement in soil quality (Kennedy and Papendick, 1995), with more emphasis being placed on the stability of microbial populations. Since at both trials the range of microbial activity recorded at both sampling times was similar, the implication is that stable microbial populations are present thus indicating good soil quality.

10.4 Conclusions

The effect of the Midmar WTR on the measured soil properties at the two field trial sites can perhaps be best summarized as neutral, after 3 and 5 yr following WTR application at Ukulinga and Brookdale Farms, respectively. Changes to OC and EC in both soils are minimal even on the very high application treatments. At both sites the upper 200 mm of soil (the depth of incorporation of the WTR) shows a rise in pH so that the liming effect of the WTR is still measurable. This increase in pH would be beneficial in reducing the natural acidity of both the Westleigh and Hutton soils and at the same time may encourage microbial activity. However, despite revealing a number of statistically significant trends with microbial activity, the differences between treatments were small. The Hutton soil at Brookdale Farm showed greater

microbial activity than the Westleigh soil at Ukulinga perhaps because of the higher OC content and better aeration in the former.

The most notable trend at both field trials was the increase in microbial activity to a certain depth (300-400 mm at Ukulinga; 300-600 mm at Brookdale). This may indicate that the Midmar WTR is responsible for this reduced activity in the upper part of the soil. However, a more likely explanation is that the upper part of the soil profile was too dry to encourage microbial growth and thus a peak in activity was found some distance below the surface. The range of microbial activity found at both sites was similar across all treatments and this strongly suggests that the microbial population in both soils is stable. Thus the WTR has apparently had no adverse effects since such stability is an indicator of good soil quality. Further evidence of this stability of the natural microbial population in the Hutton soil is discussed in Chapter 12.

CHAPTER 11

SHORT-TERM RESPIRATORY RESPONSE AND CHANGES TO pH AND ELECTRICAL CONDUCTIVITY OF THE HUTTON AND WESTLEIGH SOILS AMENDED WITH WATER TREATMENT RESIDUES

11.1 Introduction

The measurement of soil respiration has been used as an index of microbial activity due to its sensitivity and ease of use (Beare *et al.,* 1990; Gray, 1990; Nay *et al.,* 1994). To determine microbial respiration the measurement of carbon dioxide evolution has a wider application than oxygen uptake since carbon dioxide is evolved by both aerobic and anaerobic processes. The measurement of microbial respiration without the addition of organic substrates is termed basal respiration and this provides a measure of actual soil heterotrophic activity.

Respiration rates have frequently been used to determine the biological activity in soil in relation to seasonal change and changes in physical and chemical properties of soil. Generally the measurements are used to gain insight into how mineral nutrients and organic matter can be more efficiently managed (Nannipieri, 1994).

Soil respiration is also a well-established parameter to monitor organic matter decomposition, but is highly variable depending on substrate availability, moisture, and temperature. For valid comparisons to be made between soils, respiration must be measured under controlled laboratory conditions. When conditions of moisture and temperature are not limiting, the rate of carbon dioxide efflux can provide an indication of whether the soil is conducive to decomposition processes (Sparling, 1997).

The amount of respiration activity may be attributed to differences in soil moisture, soil temperature, soil texture, and the amount and quality of carbon returned to the system. Further, for respiration studies soil is often sieved, with the disadvantage that soil structure is destroyed. However, field measurements are difficult due to seasonal changes that affect both the soil and associated respiration.

The rate of hydrolysis of fluorescein diacetate (used for the field experiment samples; Chapter 10) and the measurement in the laboratory of respiration activity have been extensively used to quantify microbial activity in soil, and are closely correlated (Schnurer and Rosswall, 1982). However, apart from testing WTRs for the presence or absence of pathogenic microorganisms (Elliott *et al.,* 1990a), little attention has been paid to the effects of WTR on soil microbial properties.

To test the short-term microbial response of soils to a range of WTRs, two laboratory experiments were set up to measure microbial respiration. The experiments used the two field trial soils amended with WTR from five water treatment works in South Africa. To complement the respiration data and to provide a more detailed picture of soil quality changes, soil pH, and electrical conductivity (EC) were also measured. The aims of the respiration experiments were as follows:

- to assess the short-term changes in soil respiration, which is also an indication of microbial activity, pH and EC as a result of WTR addition;
- to draw comparisons between the different WTRs and their effects on soil respiration, pH and EC; and
- to compare, where possible, respiration data with microbial activity data from the field experiments (Chapter 10).

11.2 Materials and methods

11.2.1 Soil sampling and preparation

Bulk samples (from 0 to 200 mm) of the Westleigh and Hutton soils were collected from fallow locations within 10 m of the field experimental sites. On the day of sampling, soils were sieved (<15 mm) to remove stones and debris and re-moistened to 20% (m/m) soil moisture. Soils were weighed into the respective treatment pots of 2 L volume, sealed (with sufficient headspace to prevent anaerobic conditions from developing), and incubated at 25°C for 5 days to allow the soil to equilibrate. Following the equilibration period, WTR was added to the soils to achieve four loading rates (Table 11.1).

11.2.2 Water treatment residues and preparation

Dried WTR from Umgeni Water (Midmar Water Treatment Works), Faure Water Treatment Plant (Cape Town), Rand Water (Vereeniging), Amatola Water (East London), and Midvaal Water Company (Stilfontein) were milled and sieved to <2 mm. Information pertaining to the processes used at each of the treatment facilities and the additives used are given in Chapter 4.

Table 11.1 Preparation of treatments for the respiration experiments

WTR loading rates (% m/m)	Field equivalent rates (Mg ha^{-1})	Soil (g)	WTR (g)
0	0	1000	0
5	100	950	50
15	300	850	150
25	500	750	250

11.2.3 Laboratory experimental design

The experiment was conducted in two phases as the WTRs became available.

11.2.3.1 Experiment 1

Rand, Midmar, and Faure 1 WTR at rates of 5, 15, and 25% (m/m) were added to the Hutton and Westleigh soils after the 5-day equilibration period, mixed well, re-moistened (20% (m/m) moisture), sealed, and returned to an incubation temperature of 25°C. Six control pots consisting of unamended Hutton and Westleigh soil were prepared, while other treatments were prepared in duplicate.

11.2.3.2 Experiment 2

Due to insufficient WTR from Amatola Water and Midvaal Water, only rates of 5 and 15% were included in the experiment. Although there was ample Faure 2 WTR to allow for the 25% WTR treatment, this was omitted to allow for statistical analysis of the experiment. All treatment pots were prepared in duplicate as detailed in Experiment 1 (Section 11.2.3.1).

Subsequently, in both experiments, each treatment pot was sampled on Day 2, 5, 10 and 14, following the addition of WTR to the soil. The samples (30 g) removed for respiration analysis were oven-dried, composited, and then milled (<2 mm) for measurement of pH and EC (Section 10.2.3), following the measurement of respiration.

11.2.4 Microbial respiration

Respiration was determined by placing 30 g of soil/WTR mixture in a 50 mL beaker together with a vial containing 10 mL of 0.05M NaOH in a 1 L air-tight jar, and incubating the sealed jar in the dark at 25°C for 24 h (Anderson, 1982). The CO_2-C evolved was determined by back-titration with HCl. Modifications to the method included the use of 0.05M HCl as opposed to a 0.1M solution and the incubation of samples for 24 h instead of 10 days.

11.2.5 Statistical analysis

Statistical analysis was carried out using Genstat (Release 6.1, Lawes Agricultural Trust, Rothamsted Experiment Station). Analysis of variance (ANOVA) was carried out and separation of means was based on the principle of least significant difference (LSD) at the 5% level of significance. For both experiments ANOVA was carried out by the creation of three controls. Control 1 grouped all Hutton (unamended) treatments, Control 2 grouped all Westleigh (unamended) treatments, and Control 3 grouped all WTR-amended treatments.

11.3 Results and discussion

The pH, EC, organic carbon and microbial respiration values of the WTRs are given in Table 11.2.

11.3.1 Microbial respiration

Respiration of the unamended Hutton and Westleigh soils was similar throughout the 2-week sampling period in both experiments (Figures 11.1 and 11.2).

In Experiment 1 the ANOVA indicated significant differences in respiration between the controls, the different WTRs, WTR application rate, soil type, and sampling interval (Appendix 11.1). Respiration was influenced by the type of WTR and followed the sequence: Faure 1 < Midmar < Rand. The effect of Faure 1 WTR on the respiration activity was unclear and only small differences were noted in both the Hutton and Westleigh soils. The Midmar and Rand WTRs resulted in pronounced increases in respiration compared to the controls throughout the 2-week sampling

period. Respiration of soil amended with Rand and Midmar WTRs increased with increasing WTR application rate and these amendments resulted in higher respiration in the Hutton soil compared to the Westleigh soil.

Table 11.2 pH, electrical conductivity, organic carbon and microbial respiration values of the water treatment residues

Water treatment residue	pH (water)	Electrical conductivity ($mS\ m^{-1}$)	Organic carbon ($g\ kg^{-1}$)	Microbial respiration[a] ($\mu g\ CO_2\text{-}C\ g^{-1}\ day^{-1}$)
Midmar	7.7	59.70	28	54
Rand	8.5	25.80	8	212
Faure 1	6.6	8.27	74	160
Faure 2	7.4	41.90	103	251
Amatola	8.1	17.10	19	68
Midvaal	7.8	24.70	16	198

[a] Measured on water treatment residues with 20% (m/m) moisture following 2 days of incubation at 25°C.

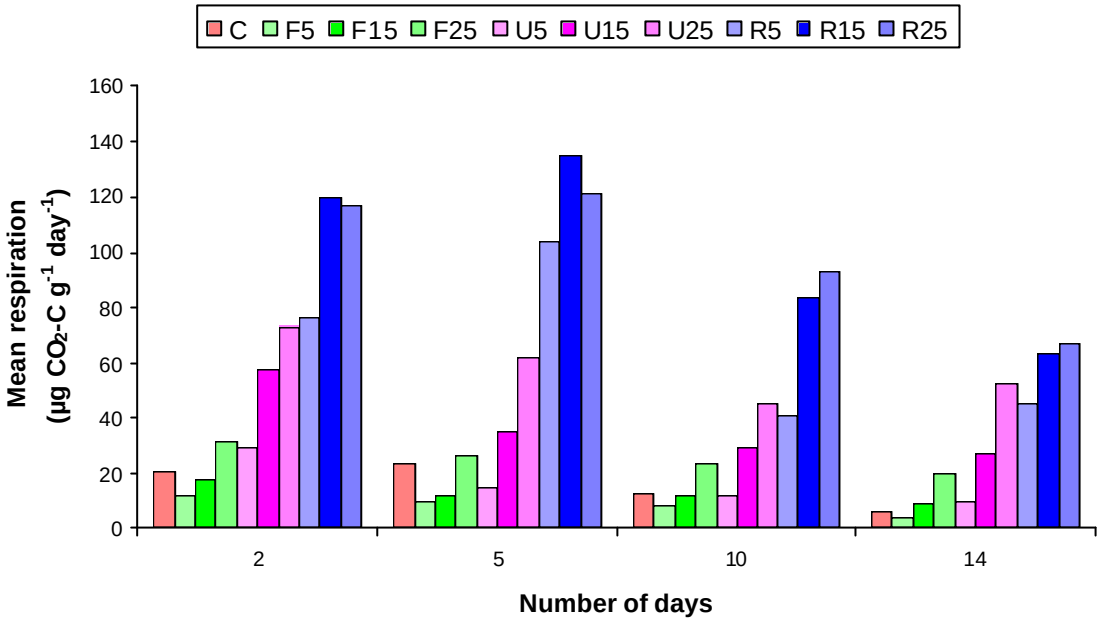
In Experiment 2 the ANOVA indicated significant differences in respiration between the controls, the different WTRs, WTR application rate, and sampling interval (Appendix 11.2). Respiration was again influenced by the type of WTR and followed the sequence: Amatola < Faure 2 < Midvaal. The Amatola WTR had no effect on the respiration activity of the Hutton soil, while it produced small increases in respiration in the Westleigh soil. Throughout the 2-week sampling period the Faure 2 and Midvaal WTRs resulted in pronounced increases in respiration compared to the controls with the highest respiration achieved at the 15% WTR treatment.

In both experiments the basal respiration decreased with time, e.g. in Experiment 1 the Hutton control declined from 21.2 µg CO_2-C g^{-1} day^{-1} at Day 2, to 5.5 µg CO_2-C g^{-1} day^{-1} by Day 14. In comparison, the Westleigh control basal respiration peaked at Day 5 (30.6 µg CO_2-C g^{-1} day^{-1}) and declined to 8.2 µg CO_2-C g^{-1} day^{-1} by Day 14.

With the exception of the Faure 1 and Amatola WTRs, the tested WTRs produced initial increases in respiration, which declined with time. Since the WTRs are predominantly inorganic in nature, the stimulated respiration effect was short-lived, as shown by marked decreases in respiration by Day 14. Further, findings from the field experiments (Section 10.3.4) indicated non-significant differences in microbial activity across all treatments 3 to 5 yr after the addition of WTR.

All unamended WTRs displayed higher respiration activity than both test soils which indicates the ability of the WTRs to support microbial activity, if only for a short period of time. The respiration activity was likely supported by the presence of easily available carbon sources including non-living microorganisms.

(a)



(b)

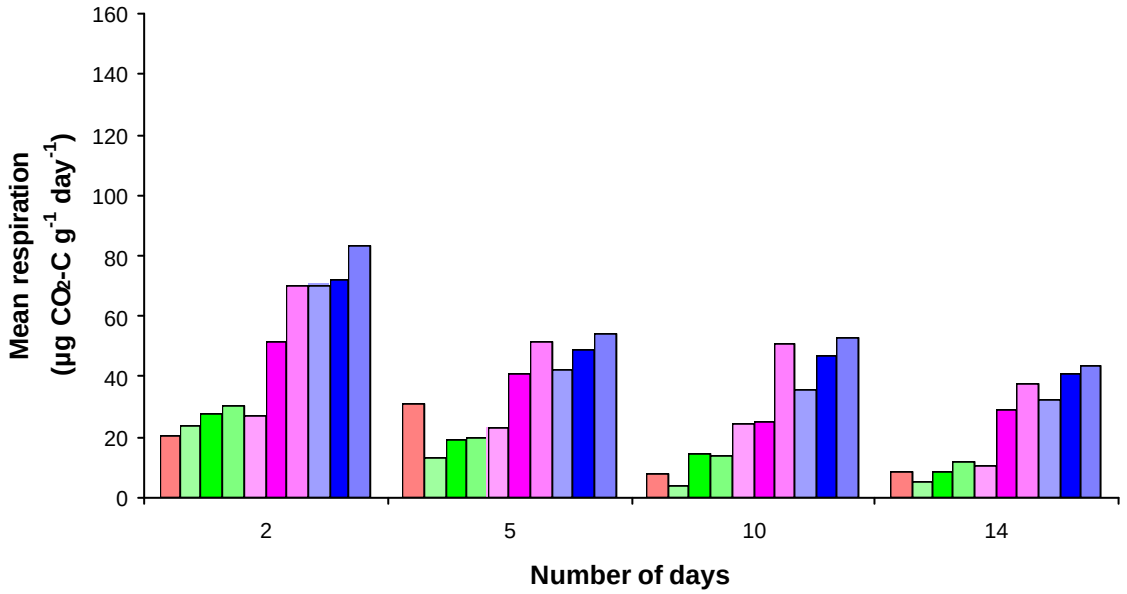
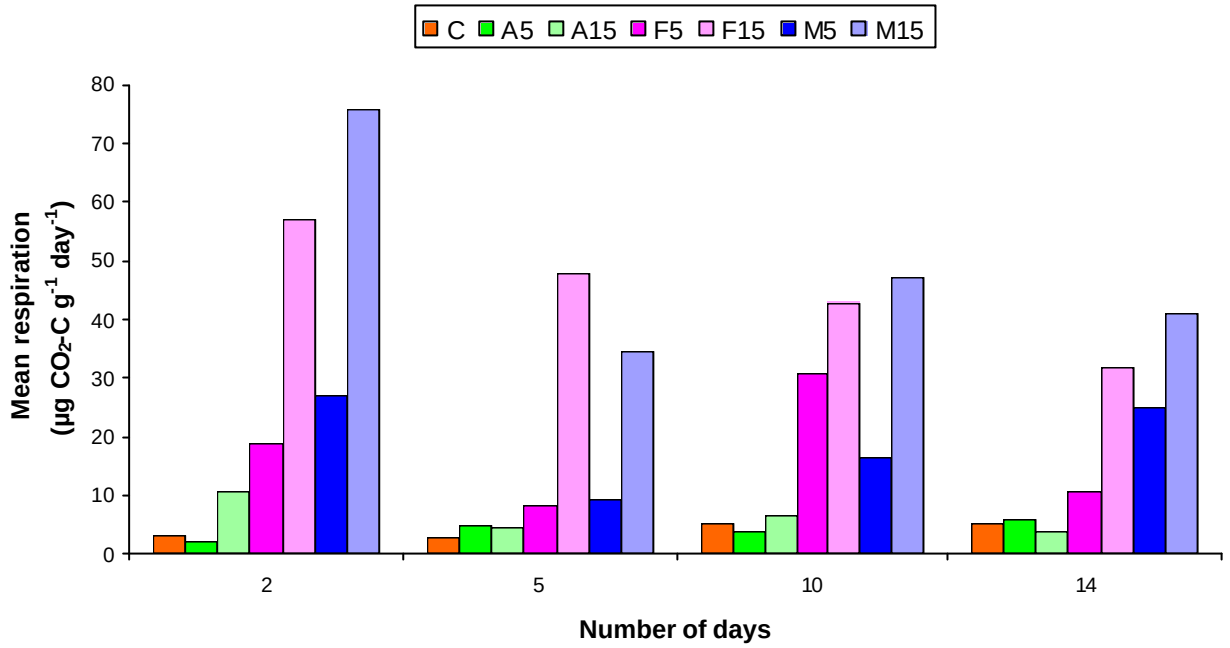


Figure 11.1 The effect of Faure 1 (F), Midmar (U) and Rand (R) water treatment residues at rates of 0 (C), 5, 15 and 25% (m/m) on the mean respiration (n=2) of (a) Hutton and (b) Westleigh soil. (C = control).

(a)



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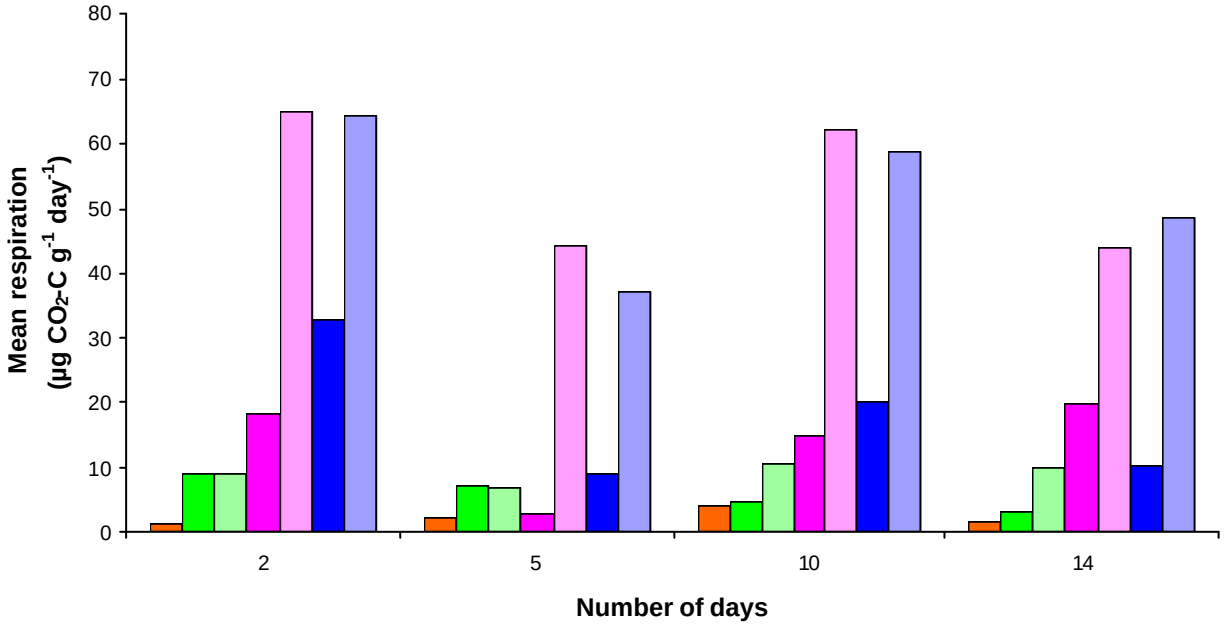


Figure 11.2 The effect of Amatola (A), Faure 2 (F) and Midvaal (M) water treatment residues at rates of 0 (C), 5 and 15% (m/m) on the mean respiration (n=2) of (a) Hutton and (b) Westleigh soil. (C = control).

Although statistical comparison between the two respiration experiments was not possible, the trends in respiration can be compared. In Experiment 1, the Faure 1 WTR (which had an OC content of 74 g kg^{-1}) exhibited the lowest respiration rates on both the Hutton and Westleigh soils (Figure 11.1). A possible explanation for the absence of increased respiration on soils amended with Faure 1 and Amatola WTRs was that the OC present was unavailable. This is supported by findings of Elliott *et al.* (1990a) that suggested that the OC associated with WTRs is often stable and resistant to breakdown. Conversely, the addition of Rand WTR (8 g kg^{-1} OC) resulted in the highest increases in respiration on both soils. Thus, the OC content of a WTR does not necessarily correlate to the amount or extent of respiration recorded. Since the Rand WTR has a high lime content, it is likely that the high respiration rates recorded on the Rand treatments resulted from the breakdown of the lime that released carbon dioxide. The Faure 1 WTR also contains a high amount of soluble Mn (Chapters 4 and 9) and this may have affected microbial respiration.

In Experiment 2 the Faure 2 WTR significantly increased the respiration of both the Hutton and Westleigh soils. Visual observations of the two Faure WTR samples revealed differences between them. The Faure 1 WTR aggregates were resistant to milling, whereas the Faure 2 WTR broke down easily into a fine powder. The powdery texture of the Faure 2 WTR and its higher OC content (103 g kg^{-1}), in comparison to the Faure 1 WTR, is probably due to the presence of more activated charcoal. Higher dosing with activated charcoal was necessary to combat taste and odour problems resulting from the presence of blue-green algae, which posed a problem for the treatment plant at the time of sampling. Further, blue-green algae probably present in the WTR would present an available source of OC, thus stimulating respiration activity of soils amended with the Faure 2 WTR.

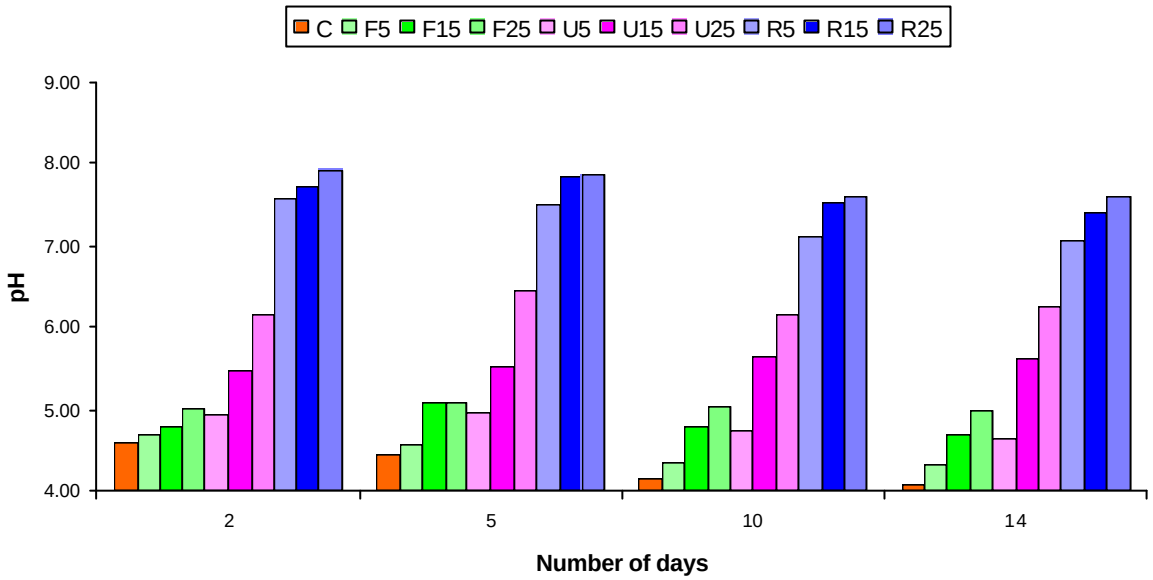
Where WTR addition resulted in significant increases in respiration (Midmar, Rand, Midvaal and Faure 2), it was also found that respiration rates increased with increasing application rate of WTR. Although the magnitude of the respiration increase varied with the type of WTR, a general trend shown was that the respiration rate of WTR-amended treatments decreased with time. This trend is likely to persist until such time that the available carbon is completely utilized, following which respiration of WTR-amended treatments would return to conditions of the controls (unless the physical and chemical conditions are dramatically altered).

The data from the field experiments revealed higher activity on the Hutton soil, compared with the Westleigh soil, and the current data show the same trend. However, both Experiments 1 and 2 revealed only small differences in basal respiration between the two soil types (Figures 11.1 and 11.2). It is possible that the apedal Hutton soil allows it to support a greater active microbial biomass, due to its better drainage and aeration. While sieving of soils for laboratory experiments has been shown to disrupt soil structure (Anderson, 1982), it is likely that sieving of the Westleigh soil improved aeration. The improved aeration status, in combination with favourable incubation conditions of moisture and temperature, thus improved the ability of the Westleigh soil to support microbial activity. Therefore, the difference in basal respiration activity between the Hutton and Westleigh soils was small, in comparison to the field activity measurements.

11.3.2 pH (composite samples)

There were small differences between the pH measured for the soil control treatments across the two experiments. In Experiment 1 the pH of the Hutton ranged between 4.0 and 4.5 (Figure 11.3a); the mean pH of the Westleigh between 5.0 and 5.5 (Figure 11.3b). In Experiment 2 the pH of the Hutton was between 4.3 and 4.8 (Figure 11.4a), and that of the Westleigh between 5.3 and 5.8 (Figure 11.4b).

(a)



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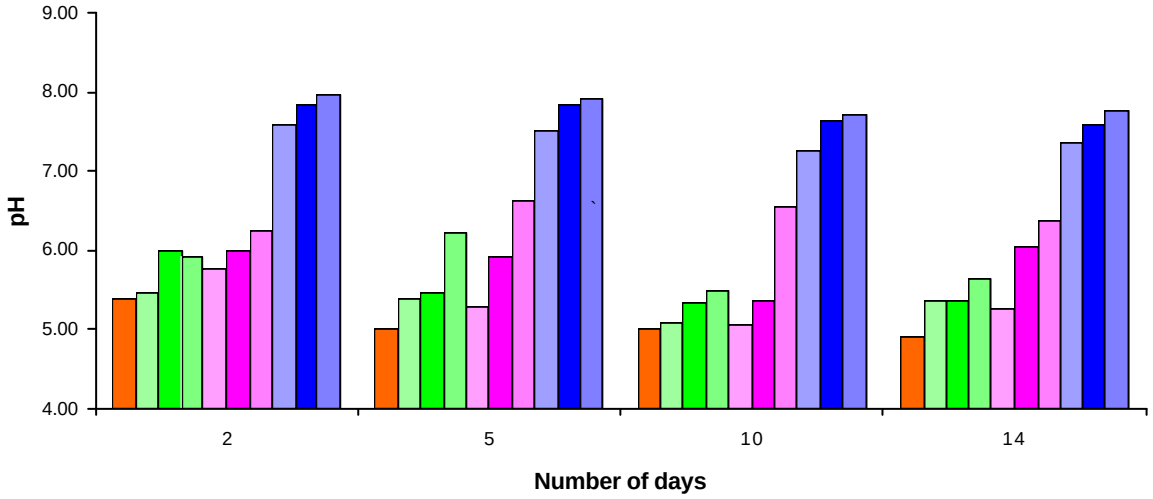
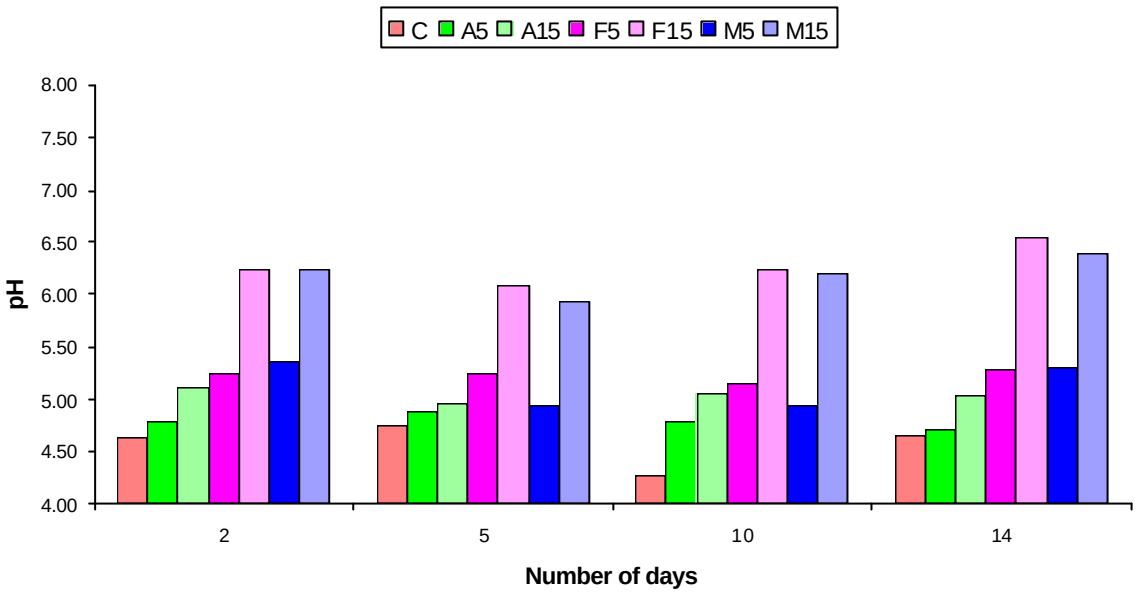


Figure 11.3 The effect of Faure 1 (F), Midmar (U) and Rand (R) water treatment residues at rates of 0 (C), 5, 15 and 25% (m/m) on pH of (a) Hutton and (b) Westleigh soil. (C = control).

(a)



(b)

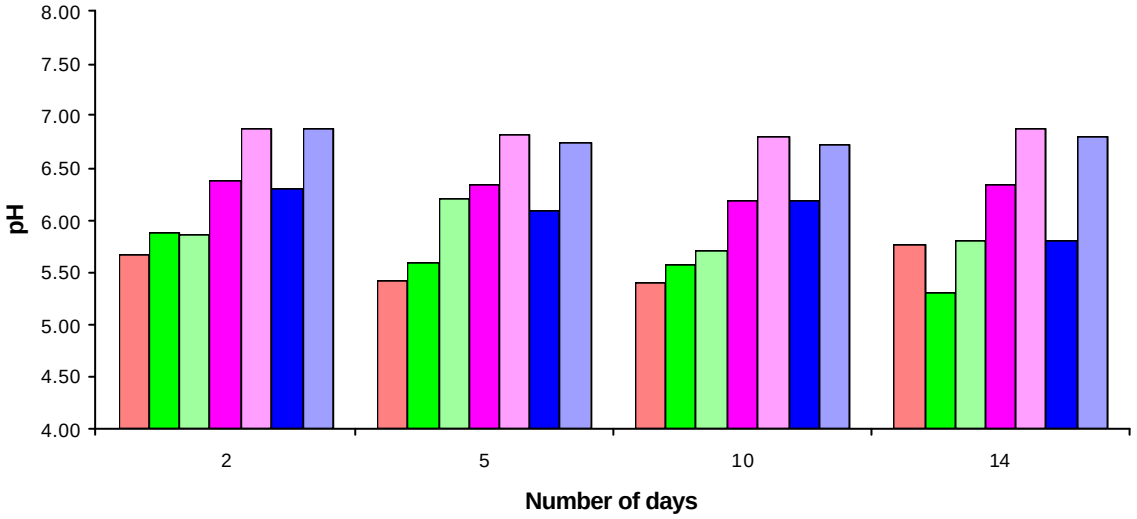


Figure 11.4 The effect of Amatola (A), Faure 2 (F) and Midvaal (M) water treatment residue at rates of 0 (C), 5 and 15% (m/m) on pH of (a) Hutton and (b) Westleigh soil. (C = control).

In both experiments the addition of WTR produced increases in pH, which were influenced by the type of WTR and application rate. In Experiment 1 the Rand WTR produced the greatest change in pH whereas the Faure 1 WTR had the least influence on pH. Similar pH changes were noted for both soil types throughout the sampling period. In Experiment 2, on both soil types, the Amatola WTR resulted in small increases in soil pH. The Faure 2 and Midvaal WTR treatments produced pH increases of between 1 and 2 pH units.

All the WTRs had a higher pH than both of the field trial soils. Addition of WTR therefore resulted in increases in pH that were stable for the duration of both experiments (Figures 11.3 and 11.4). Ahmed *et al.* (1997) suggested that the magnitude of the pH increase depends on several factors such as the original soil pH, the pH of the WTR, and the application rate of the residue. The present results support these findings with greater pH increases noted at the higher WTR application rates. Further, the Faure 1 WTR that had the lowest pH (6.6) produced the smallest increase in pH, while the Rand WTR (pH 8.5) produced the largest increases in pH of up to 3 pH units at the 25% (m/m) treatment.

While the field experiments were indicative of the acid-neutralizing effect of the Midmar WTR, both respiration experiments confirmed that the other WTRs tested produced similar pH increases. Since both experimental soils were acidic in nature, the WTR-induced increases in pH were not detrimental to soil health. Additionally, the effect of increasing pH on respiration activity is likely to support microbial growth, since most soil bacteria grow best at neutral pH (Brock and Madigan, 1991). Bacteria are also tolerant of a wide range of pH and growth occurs within the pH range from 4 to 9 (Paul and Clark, 1996).

11.3.3 Electrical conductivity (composite samples)

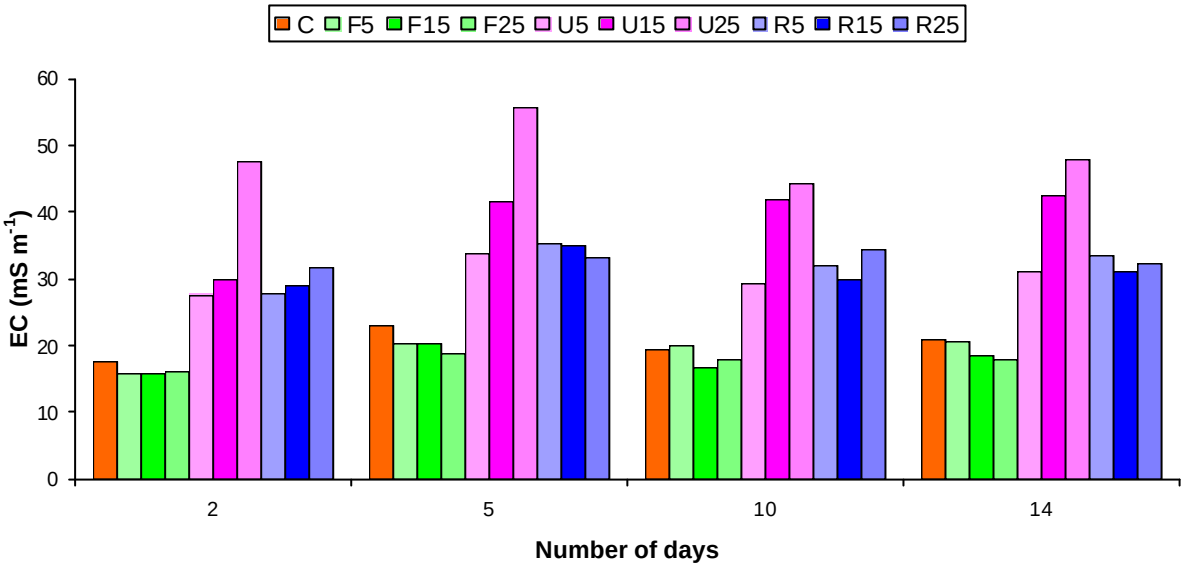
As for pH there were small differences in EC between the two experiments. In Experiment 1 the EC of the Hutton (Figure 11.5a) and Westleigh (Figure 11.5b) controls ranged between 18.0 and 23.0 mS m^{-1}, and from 10.0 to 14.0 mS m^{-1}, respectively. In Experiment 2 the comparable ranges were from 15.0 to 20.0 mS m^{-1} (Figure 11.6a), and from 15.0 to 25.0 mS m^{-1} (Figure 11.6b), respectively.

The addition of Faure 1 WTR did not appear to influence the EC of either soil. However, the Rand and Midmar WTR-amended treatments resulted in marked increases in EC. For both soil types the 25% (m/m) Midmar WTR amendment produced the most pronounced increase in EC.

All WTRs in Experiment 2 had only small effects on the EC of the Westleigh soil, whereas WTR addition to the Hutton soil resulted in an increase in EC on Days 2 and 5. Higher EC values were generally measured on the 15% (m/m) treatments as opposed to the 5% (m/m) treatments, although this increase was not consistently observed throughout the sampling period.

The effect of EC on microbial activity is difficult to assess. However, as with pH and respiration which generally increased with increasing WTR application rate, the same trend was noted for EC. Therefore, a likely assumption is that changes to soil EC did not have any detrimental effects on microbial activity.

(a)



(b)

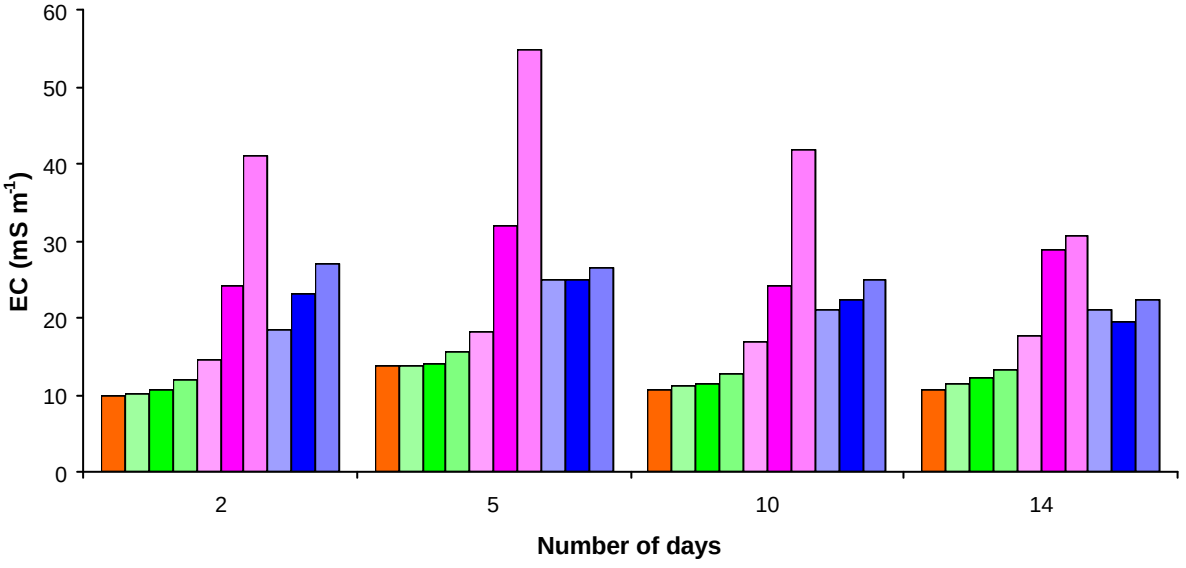
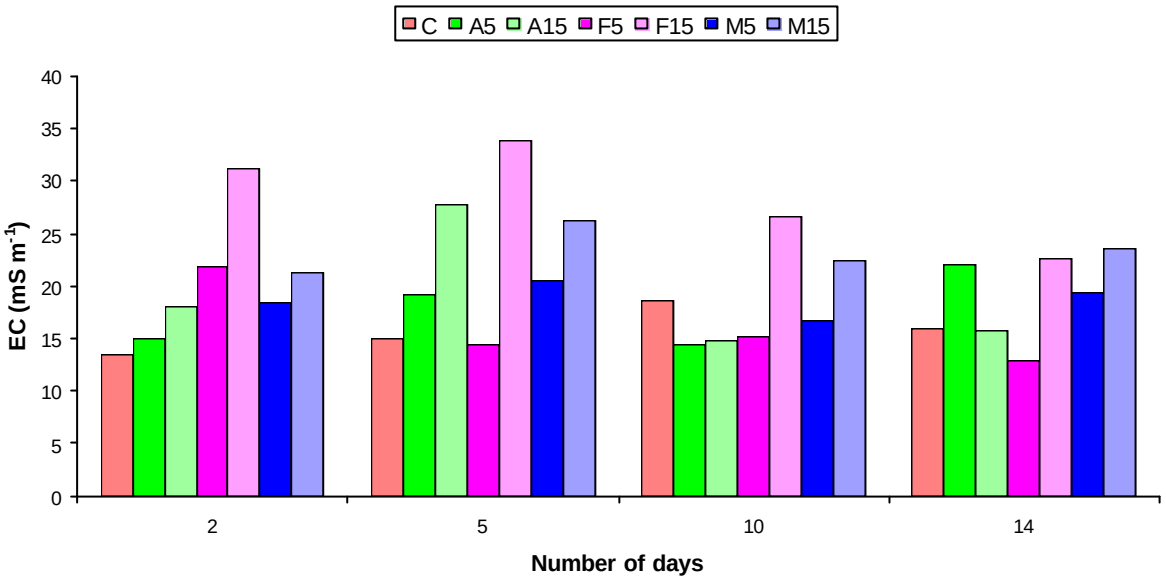


Figure 11.5 The effect of Faure 1 (F), Midmar (U) and Rand (R) water treatment residues at rates of 0 (C), 5, 15 and 25% (m/m) on electrical conductivity (EC) of (a) Hutton and (b) Westleigh soil. (C = control).

(a)



(b)

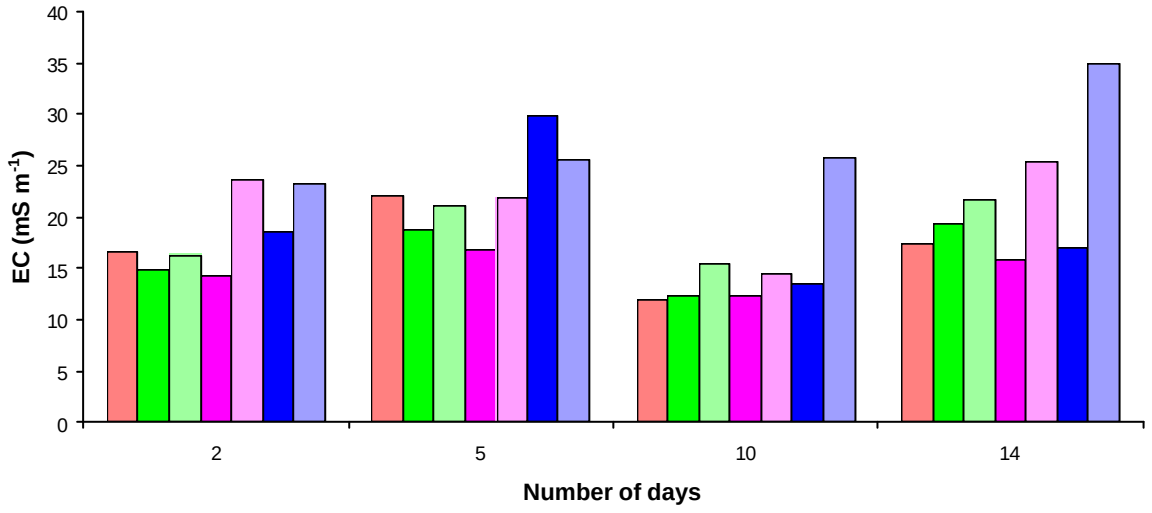


Figure 11.6 The effect of Amatola (A), Faure 2 (F) and Midvaal (M) water treatment residue at rates of 0 (C), 5 and 15% (m/m) on electrical conductivity (EC) of (a) Hutton and (b) Westleigh soil. (C = control).

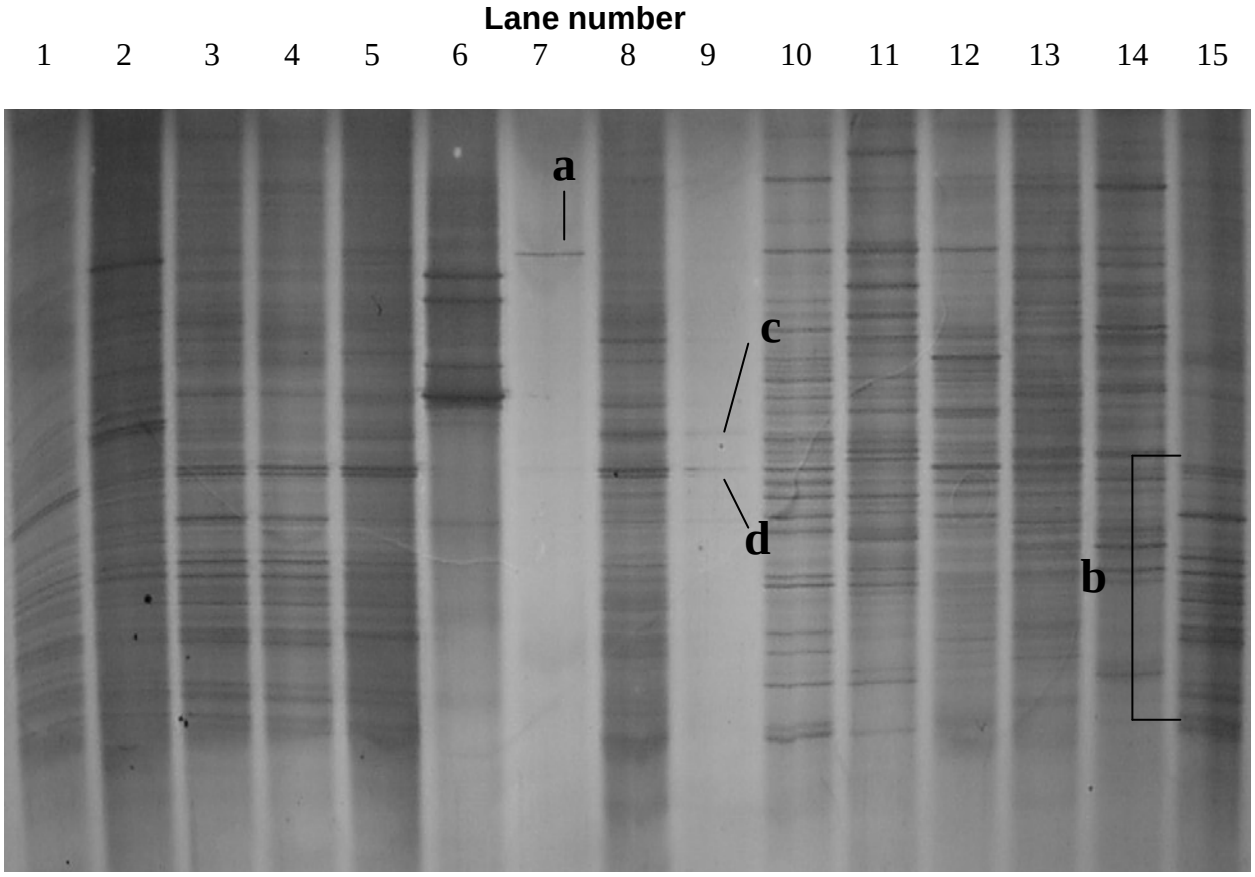
11.4 Conclusions

Basal respiration of the two soils from the field experiments when amended with different WTRs was greatly influenced by the type of WTR and its application rate. Generally respiration increased with rate of application. The Midmar, Rand, Midvaal and Faure 2 WTRs had the greatest effect on respiration, with the Amatola WTR only

having a slight influence on the respiration of the Hutton soil. Increases in respiration became less marked with time and signifies that such increases will be of short-term duration only. This supports the results from the field experiments (Chapter 10).

The presence of lime in all the WTRs caused the pH of the soil/WTR mixtures to increase and was directly related to the application rate. However, such a pH increase is most likely to be beneficial to microbial growth if land disposal of the WTRs was to be carried out on acidic soils.

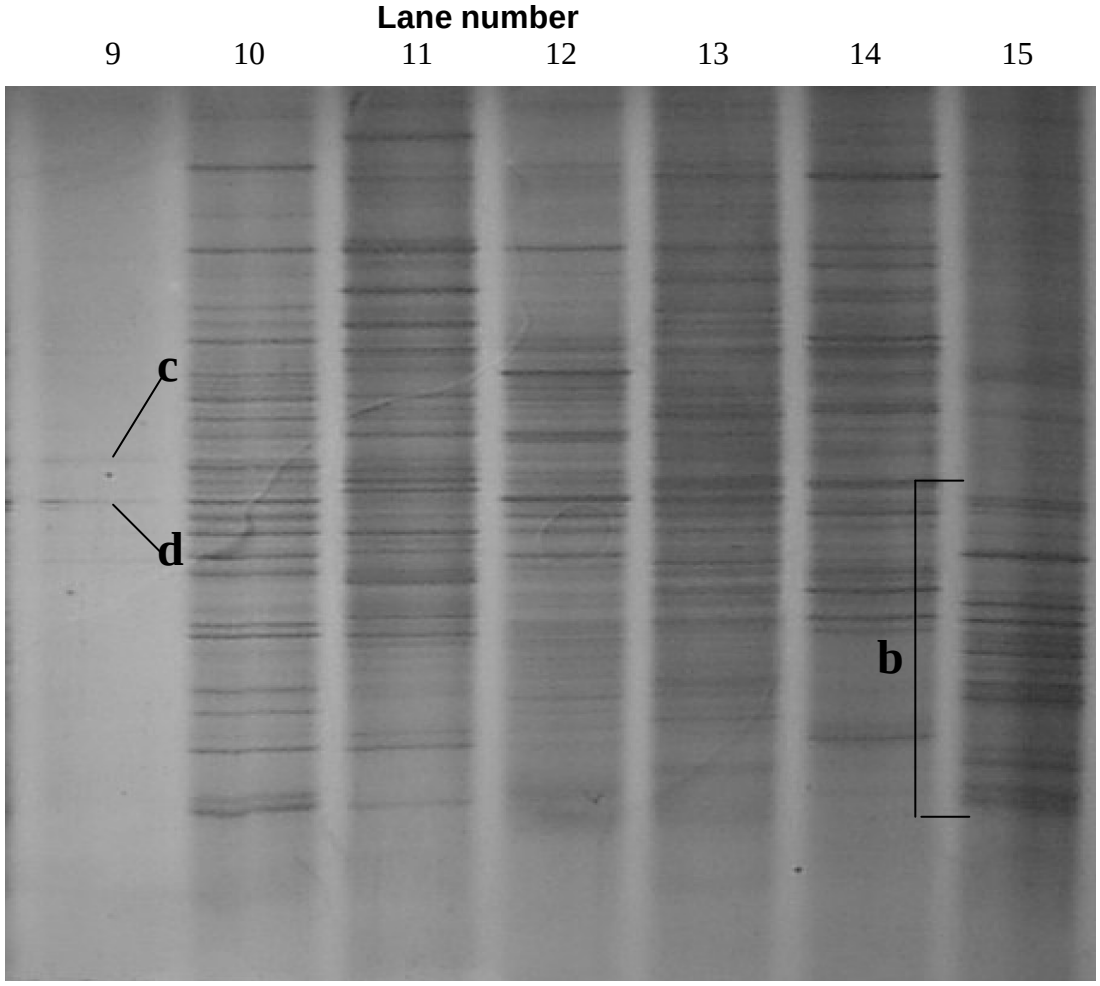
The effect of EC on basal respiration was unclear although EC tended to increase with increasing rate of WTR addition. That respiration followed the same trend suggests that the increases in EC measured were not detrimental to microbial activity.



Key:

1. Hutton/Midmar mixture
2. Hutton/Faure 2 mixture
3. Hutton/Faure 1 mixture
4. Hutton/Amatola mixture
5. Hutton/Midvaal mixture
6. Positive control (*Bacillus* B81)
7. Negative control
8. Hutton/Rand mixture
9. Rand WTR
10. Midvaal WTR
11. Midmar WTR
12. Amatola WTR
13. Faure 1 WTR
14. Faure 2 WTR
15. Hutton soil control

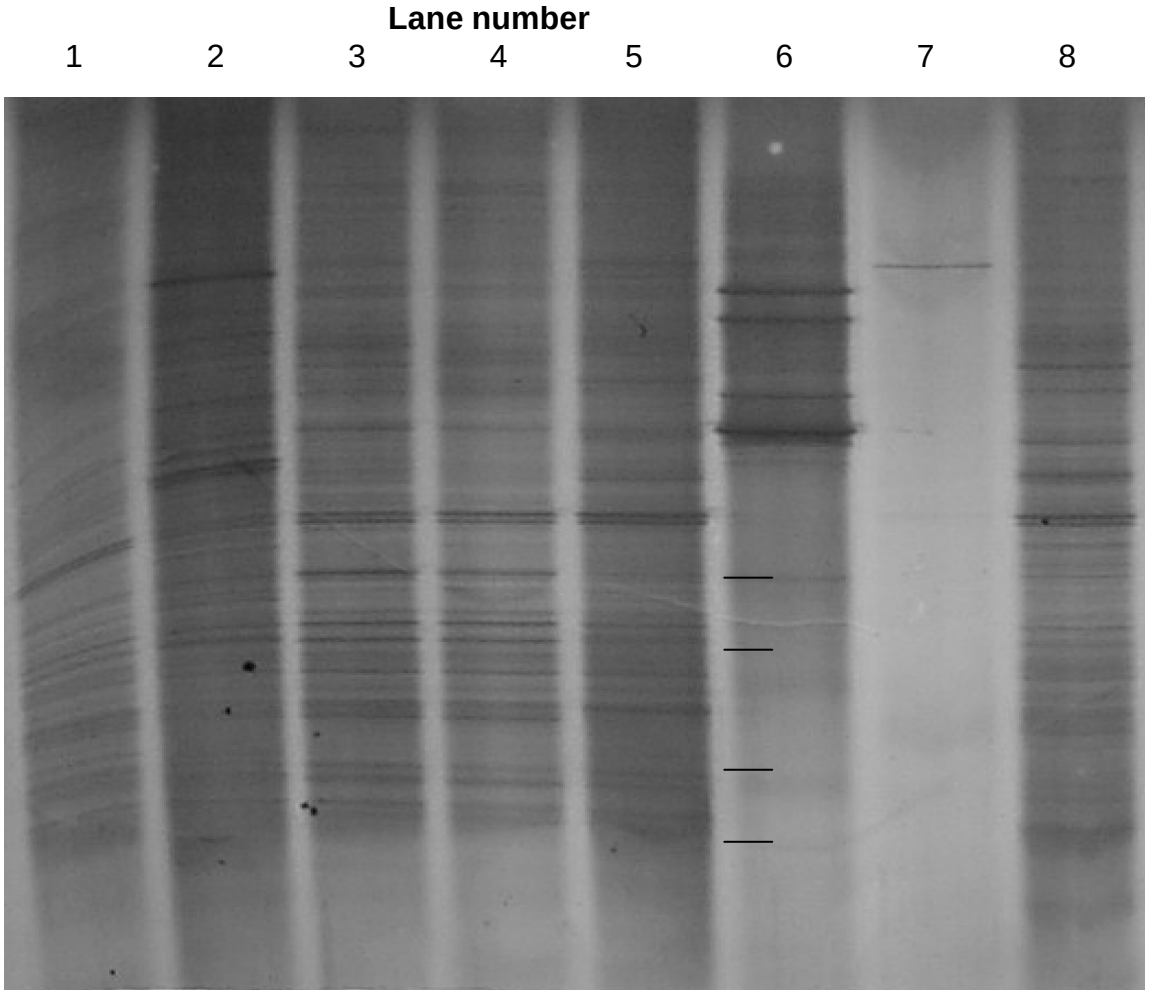
Figure 12.1 Silver-stained denaturing gradient gel showing the DNA banding patterns of the tested water treatment residues (WTRs), soil/WTR treatments and relevant controls. Lines indicated by a, b, c and d are referred to in the text.



Key:

9: Rand WTR
10: Midvaal WTR
11: Midmar WTR
12: Amatola WTR
13: Faure 1 WTR
14: Faure 2 WTR
15: Hutton soil control

Figure 12.2 Silver-stained denaturing gradient gel showing the DNA banding patterns of the tested water treatment residues (WTRs) in comparison to the Hutton soil control. Lines indicated by b, c and d are referred to in the text.



Key:

1: Hutton/Midmar mixture
2: Hutton/Faure 2 mixture
3: Hutton/Faure 1 mixture
4: Hutton/Amatola mixture
5: Hutton/Midvaal mixture
6: Bacillus B81
7: Negative control
8: Hutton/Rand mixture

Figure 12.3 Silver-stained denaturing gradient gel showing the DNA banding patterns of the soil/water treatment residue treatments. Arrows indicate specific points of comparison between the treatments.

CHAPTER 13

THE EFFECT OF A WATER TREATMENT RESIDUE ON THE GROWTH OF PERENNIAL RYEGRASS IN A GLASSHOUSE POT EXPERIMENT

13.1 Introduction

From the literature review (Chapter 3) it is apparent that the effects of water treatment residue (WTR) on plant growth in pot experiments depend on a number of factors, amongst which are WTR type/properties (Heil and Barbarick, 1989; Skene *et al.*, 1995), soil type (Rengasamy *et al.*, 1980; Heil and Barbarick, 1989), plant species (Ippolito *et al.*, 1999) and WTR rates (Rengasamy *et al.*, 1980; Elliott and Singer, 1988; Heil and Barbarick, 1989).

Using three WTR types, Heil and Barbarick (1989) found the best response with the ferric-based material for sorghum-sudan grass grown under greenhouse studies in an iron deficient soil. On the other hand, Skene *et al.* (1995) found a polymer WTR to be a better growth medium for beans than an alum WTR because of better K and N supply. It is in soils with low fertility that the material is likely to provide a nutritional benefit (Cox *et al.*, 1997) and where there is a benefit from its liming effect (Elliott and Singer, 1988; Heil and Barbarick, 1989). When the WTR rate of application is considered, rather conservative amounts to a maximum of 2.5% (m/m) have generally been suggested or indicated by results obtained (Heil and Barbarick, 1989; Geertsema *et al.*, 1994; Lucas *et al.*, 1994), a figure equivalent to approximately 44 Mg ha^{-1}. Some workers have exceeded this rate and still achieved results better than the control. Elliott and Singer (1988) observed a significant response to tomatoes grown in greenhouse studies with a WTR rate of 10% (m/m), although the highest yield was obtained at a rate of 6% (m/m). Ahmed *et al.* (1997), using a rate of 1 600 Mg ha^{-1}, reported positive results with lawngrass in both field and greenhouse experiments. Other workers grew plants directly on the residue (Skene *et al.*, 1995; Basta *et al.*, 2000) and measured an increase in yield. It would seem that the rate factor is not conclusive and would have to be established for particular plant species and soil conditions.

The results of these investigations are an indication of the agronomic usefulness of WTR, in spite of some negative reports of plant response that were mostly attributed to relatively large quantities of this material reducing P availability and thus reducing yields. Even in these instances, it was found that application of P with the WTR eliminated the problem (Bugbee and Frink, 1985; Lucas *et al.*, 1994).

Also polymer WTRs, which the material of concern in this work represents, have not been widely investigated, probably because they are deemed even more innocuous than the alum-based products that have been the subject of most studies. There was thus a need for the polymer WTR produced by Umgeni Water at its Midmar plant in Howick to be tested for its effects on plant growth.

The objectives of this preliminary investigation were as follows:-

- to determine the effects of application of the Midmar WTR on the growth of an indicator plant (perennial ryegrass, *Lolium perenne*) on different soils; and

- to establish changes in soil chemical properties following the application of the WTR.

13.2 Materials and methods

13.2.1 Soils

Five topsoils (Soil Classification Working Group, 1991) sampled from the 0-200 mm depth were used, namely two Hutton soils (Hu-M from a site adjacent to the water treatment works at Midmar; Hu-T from Mangosuthu Technikon about 20 km south of Durban), an Inanda (Ia-C from an experimental site at Cedara, near Pietermaritzburg), a Namib (Nb-F from a disused Mission Farm, near Durban), and a Shortlands form (Sd from Adam's Mission, south of Durban).

In addition to these five soils, a further six soils were sampled for use in the investigations reported in Chapters 15, 16 and 17. For completeness they are listed here and their basic chemical properties are reported together with those of the above five soils (Table 13.1). The other six soils were an Avalon (Av from Geluksburg at a KwaZulu-Natal Department of Agriculture experimental site), a Hutton (Hu-F from the Brookdale Farm field trial site; Chapter 5), an Inanda (Ia-W from World's View, Hilton, near Pietermaritzburg), a Namib (Nb-A from Adam's Mission, south of Durban), a Valsrivier (Va from Muden, near Greytown; Chapter 6), and a Westleigh (We from the Ukulinga Farm field trial site; Chapter 5). In terms of Soil Survey Staff (1998) and Isbell (1996), respectively, these soils are classified as follows: Hu-M (Typic Haplustult; Kandosol); Hu-T (Typic Ustrochrept; Tenosol); Ia-C (Humic, Rhodic, Hapludox; Kandosol); Ia-W (Humic, Rhodic, Kandiudox; Kandosol); Nb-A and Nb-F (Typic Psammaquent; Rudosol); Sd (Typic Haplustalf; Ferrosol); Av (Typic Plinthustult; Hydrosol/Kandosol).

13.2.2 Analysis of the water treatment residue and soils

All samples (Midmar WTR and soils) were air-dried and milled to pass a 2 mm sieve. Cation exchange capacity (CEC), pH, organic carbon (OC) and particle size distribution were determined by methods described in Section 4.2.2. To investigate extractants that would be suitable in the presence of unreacted lime in the WTR, as well as convenient for a single extraction, the WTR was extracted with 1M KCl (5 g soil:50 mL solution shaken for 10 min), and 0.1M $SrCl_2$ (5 g soil:25 mL solution shaken for 30 min). Four sequential extractions were carried out with $SrCl_2$ and were analysed both separately and after being combined and made up to 100 mL. Other extractants were 0.5M $BaCl_2$ buffered at pH 8.1 with triethanolamine (Thomas, 1982) and 0.1M unbuffered $BaCl_2$ (2 g sample extracted with 20 mL solution for 1 h; Gillman, 1979) at solid:solution ratios of 1:10.

Free carbonates in the WTR were determined by back-titration with NaOH after excess addition of HCl. Nitrogen was analysed by the Kjeldahl procedure. Total element concentrations were analysed by X-ray fluorescence spectrometry (XRF, Geology Section, University of KwaZulu-Natal, Durban).

Soluble cations and anions from the WTR were determined in 1:2 and 1:5 soil:distilled water extracts after shaking for 1 h (Rhoades, 1996). Extracts were filtered through Whatman No. 42 paper.

In all samples, Ca and Mg were determined by atomic absorption spectrophotometry and Na and K by flame emission (AAS, Varian SpectraAA-200), NH_4 by the method of Keeney and Nelson (1982), P colorimetrically (The Non-Affiliated Soil Analysis Work Committee, 1990) on a Varian Cary 1E UV-Visible spectrophotometer (UV-Vis) and bicarbonate, carbonate and chloride by titration (United States Salinity Laboratory Staff, 1954).

13.2.3 Pot experiment

Since this was a preliminary investigation, the WTR was applied at moderately low rates of 0, 40, 80 and 120 Mg ha^{-1} to triplicate 1 kg soil samples. In the Ia-C and Nb-F soils the WTR was also applied with two lime levels. The highest level (lime rate 2) was the amount of calcitic lime calculated to reduce the acid saturation percent of the respective soil to 5%, and the lower one (lime rate 1) was half of that. Assuming field incorporation to a depth of 200 mm, these rates were equivalent to 9 and 4.5 Mg ha^{-1} in the Ia-C soil, and 5 and 2.5 Mg ha^{-1} for the Nb-F soil, respectively. All treatments received a basal dressing of N (150 mg kg^{-1} as ammonium dihydrogen phosphate which was also the P source, and ammonium nitrate to provide the balance), P (75 mg kg^{-1}), K (50 mg kg^{-1} as potassium chloride), and Mg (37.5 mg kg^{-1}) and S (50 mg kg^{-1}) provided as hydrated magnesium sulphate.

Perennial ryegrass (*Lolium perenne*) was chosen as the test crop so that an exhaustive extraction of nutrients could be achieved. Thus even if the effects of the WTR were masked by initially high fertility, their role might become apparent once inadequacy of nutrients was experienced. Nutrient depletion was ensured by cutting plants after tillering and allowing them to regrow. Eight cuts in total, the last of which was the final harvesting, were made over a period of almost 12 months. The dates of the cuts were 10/12/1997, 07/01/1998, 29/01/1998, 20/03/1998, 30/04/1998, 17/07/1998, 01/09/1998 and 22/10/1998. Plant samples were kept for analysis. Soils were maintained close to field capacity by weighing and watering every day. At the termination of the experiment, soil samples were kept for chemical analyses.

13.2.3.1 Analysis of soils

Air-dried and milled (<2 mm) soil samples were analysed (Section 13.2.2) for pH and extractable acidity, and Ca, Mg and Na in 1M KCl extracts. Phosphorus was analysed colorimetrically (Murphy and Riley, 1962) with a UV-Vis spectrophotometer.

13.2.3.2 Analysis of plant tissue

A 1 g sample of milled plant material was ashed at 450^{o}C for 16 h. After cooling, a few drops of distilled water followed by 2 mL of concentrated HCl were added to the sample. Samples were evaporated to dryness on a sand bath, after which the sample was redissolved in 25 mL of 1M HCl before filtering through Whatman No. 41 paper. The digests were analysed for Ca, K, Mg, Na, Cu, Mn, Fe and Zn by AAS, P

colorimetrically with a UV-Vis spectrophotometer (Murphy and Riley, 1962) and N by the Kjeldahl procedure.

13.3 Results and discussion

13.3.1 General

The Midmar WTR contained 3.8% free carbonates and 0.01% N. The pH of the WTR measured in both water and KCl is basic (Table 13.1). This, together with the free carbonates, suggests that the WTR has the potential to act as a liming material. The amount of extractable basic cations and the relatively high CEC further support the benefits the WTR could have if used on infertile soils.

The clay texture of the WTR suggests a relatively high surface area for adsorption of chemical species, which would have a bearing on both nutrient and toxic substances where the reduction in mobility would reduce availability to plants and also delay migration to groundwater. Although the oxidisable OC is reasonably high and might suggest some benefits fom mineralisation, the low concentration of N (Table 4.4) indicates otherwise. The soils represent a wide range in pH, OC and texture (Table 13.1).

Table 13.1 Some chemical properties of the Midmar water treatment residue (WTR) and the soils used

Sample	pH		Acidity	Exchangeable		CEC	Acid satn.	Org. C	Sand	Silt	Clay
	KCl	H_2O		Ca	Mg						
			----------($cmol_c\ kg^{-1}$)----------				(%)	($g\ kg^{-1}$)	---------(%)--------		
WTR	7.78	8.00	0.20	31.0	9.1	26.6	0	28.0	6[a]	10[a]	84[a]
Hu-M	4.60	5.89	0.01	10.5	4.9	16.5	0	34.3	31	28	41
Hu-T	4.79	5.63	0.04	6.0	2.5	7.8	0	15.5	67	12	21
Ia-C	4.25	5.34	1.51	2.5	1.7	7.9	26	47.4	10	26	64
Nb-F	3.77	4.81	0.46	0.5	0.2	3.9	40	5.9	86	8	6
Sd	4.75	5.95	0.01	12.4	2.2	16.1	0	18.5	12	31	57
Av	3.77	4.03	3.45	0.3	0.1	1.4	90	13.5	36	37	27
Hu-F	4.22	5.21	0.86	5.1	4.6	8.6	8	33.5	13	48	39
Ia-W	3.77	4.19	3.33	0.3	0.2	1.9	87	59.2	43	10	47
Nb-A	4.28	5.35	0.04	0.7	0.6	1.3	3	4.8	80	10	10
Va	5.91	6.81	0.06	6.7	6.6	10.5	0	12.7	56	18	26
We	4.90	5.91	0.06	6.0	4.3	9.8	1	21.7	18	50	32

[a] wet water treatment residue data

13.3.2 Extractants

The electrical conductivity of the water extract (1:2) indicates a significant amount of soluble salts, with the dominant cations being calcium and magnesium, and the anions chloride and bicarbonate (Table 13.2).

Table 13.2 Water extracts of the Midmar water treatment residue

Ratio	EC	pH	Ca	K	Mg	Na	NH_4	Sum	HCO_3	Cl	NO_3	SO_4	Sum
	($mS\ m^{-1}$)		----------($mmol_c\ kg^{-1}$)----------										
1 : 2	169	7.26	5.1	0.8	3.1	1.0	0.6	10.6	5.4	12.7	0.3	0.6	19.0
1 : 5	70	7.41	2.9	0.4	1.7	0.8	0.4	6.2	2.8	5.4	0.1	0.4	8.7

It would be expected that migrating solutes in WTR-treated soils would be dominated by these ions although none is environmentally harmful, either directly or indirectly. Another notable fact about the data is the lack of balance between the anion and cation sum in the 1:2 ratio samples.

The different extractants used (Table 13.3) show that the highest amount of cations extracted was 49.4 $cmol_c\ kg^{-1}$ by the sequential extraction with 0.1M $SrCl_2$, which is approximately twice the CEC of 23.8 $cmol_c\ kg^{-1}$ (Table 13.1). This difference is possibly explained by extraction of free carbonates and a significant amount of soluble cations by the sequential extraction, as well as incomplete extraction of Sr by ammonium acetate in the determination of the CEC. The highest amount of cations was extracted by the $BaCl_2$ solutions and the least by the first $SrCl_2$ extraction. However, the difference in the effectiveness of the extractants (single extractions) is not that marked. It would thus seem that a single extraction recovers virtually only the soluble and (some) exchangeable cations whilst leaving the carbonates intact. This is based on the fact that they compare to the amount of cations extracted by buffered $BaCl_2$ that does not dissolve carbonates. Barium chloride would thus seem the most convenient extractant. It is more efficient than $SrCl_2$, easier to prepare than the buffered $BaCl_2$ and can be used to measure extractable K, unlike KCl.

Table 13.3 Salt extracts of the Midmar water treatment residue

Extractant	Ca	K	Mg	Na	NH_4	Sum
	----------	----------	($cmol_c\ kg^{-1}$)	----------	----------	----------
1M KCl	20.6	nd	8.3	1.7	0.7	31.3
0.1M $BaCl_2$	23.7	0.7	9.2	1.3	0.5	35.4
0.5M $BaCl_2$-TEA	22.7	0.8	9.0	1.8	0.2	34.5
0.1M $SrCl_2$	35.7	0.7	8.0	0.9	0.3	45.6
0.1M $SrCl_2$ [1][a]	21.7	0.4	5.4	0.5	0.4	28.4
[2][a]	8.6	0.2	1.5	0.3	0.1	10.7
[3][a]	4.4	0.1	0.6	0.4	0.1	5.6
[4][a]	3.9	0.1	0.3	0.3	0.1	4.7

[a] successive extractions. nd not determined.

The dominance of chloride (Table 13.2) is reflected in the XRF analyses of the WTR sampled in August 2000 (Appendix 4.4). It is thus not surprising that this element would dominate the soil solution, especially as it is an indifferent ion. Overall, the total concentrations of the potentially problematic elements are relatively low and thus from the point of view of heavy metal toxicity and pollution, it would seem that the Midmar WTR is unlikely to be problematic. This is more so considering its basic pH and carbonate content that will assist in reducing the mobility of such heavy metals.

13.3.3 Dry matter yield

The pattern of dry matter (DM) yield between the different cuts (results not shown) was essentially the same in all five soils with, in general, yield reaching maxima at Cuts 2 and 6. This observation was true even in the soils where Cut 1 yields were relatively high, namely Hu- T, Nb-F where lime was applied, and the Sd.

Two factors could be affecting this pattern of response within the same soil, namely nutrient concentrations, and the time between cuts. At the second cut the amount of available nutrients was still relatively high, so although the ryegrass had grown for only 22 days after the first cut, the DM yield was the highest. At Cut 6, where the second highest yield was obtained, the harvest was done 78 days after the Cut 5 which was the longest period between cuts. This lengthy period obviously allowed the plants to accumulate the high mass.

A similar pattern in the yield response to WTR discussed above was also observed with lime in the strongly acid Ia-C and Nb-F soils. The yield maxima at Cuts 2 and 6 were again prominent at all lime and WTR rates, except in the Nb-F soil where either no lime or WTR was applied. There is overall a similarity to the yield pattern of perennial ryegrass in response to WTR and agricultural lime. The results for the Nb-F soil in particular, with the creation of a yield maximum with the addition of either lime or WTR, implies that there is some common factor. Both introduce Ca to the soil, and because of the presence of free carbonates in the WTR it could be expected to have a liming effect as well. It is possible that the positive response of perennial ryegrass to either lime or WTR in the Nb-F soil was partly due to this introduction of Ca. The Ia-C soil, with a higher Ca content, showed more prominent yield maxima, and addition of lime did not noticeably improve yield at those cuts.

For the Hu-M, Hu-T, Ia-C, Nb-F and Sd soils the yield increases from the control treatments at the highest rate of WTR application were 19, 22, 35, 63 and 18%, respectively (Figure 13.1). All these increases were significant ($p<0.05$). The better yield response in the Ia-C and Nb-F soils suggested either that the liming effect of the WTR was in operation, and/or that Ca nutrition made an improvement in growth. Elliott and Singer (1988) and Heil and Barbarick (1989) also suggested that a pH increase as a result of WTR application could improve yields.

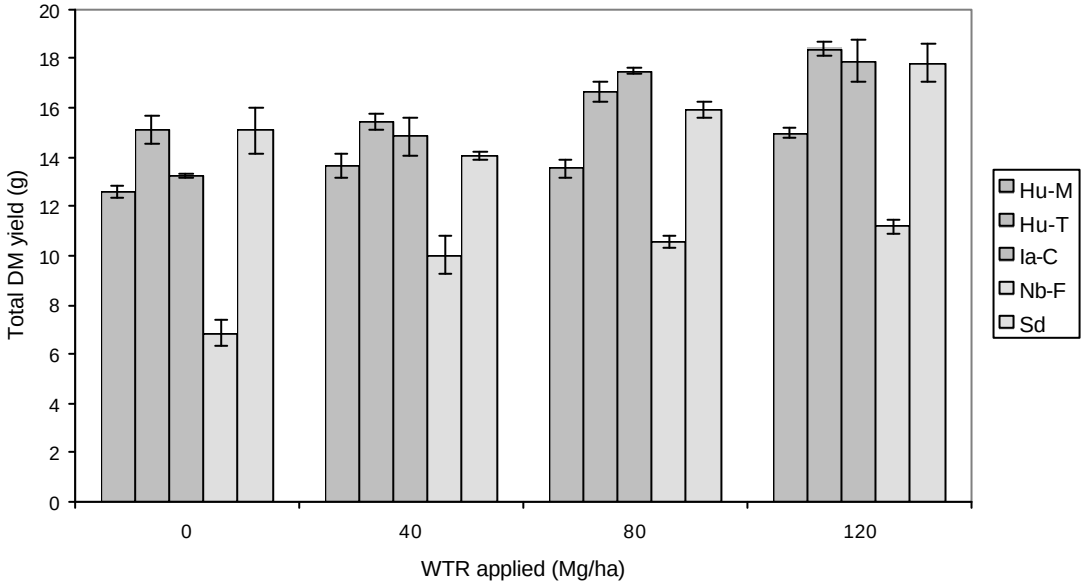


Figure 13.1 Total yield of ryegrass on five soil types amended with four rates of Midmar water treatment residue.

Not easy to explain is the significant increase in the other three soils which had pH values between 5.5 and 7.0 and moderately high extractable Ca. It is unlikely to be improved physical properties (Rengasamy *et al.*, 1980; Skene *et al.*, 1995) as these three soils have inherently good physical properties. It appears therefore that a combination of factors are involved in the impact of WTR on plant yield.

In Figures 13.2 and 13.3 the total DM yield of the strongly acid soils in response to applied WTR is considered at different lime levels. Even in the presence of lime the increases in yields are significant ($p<0.05$) in both soils. In this case the two materials appear to complement each other.

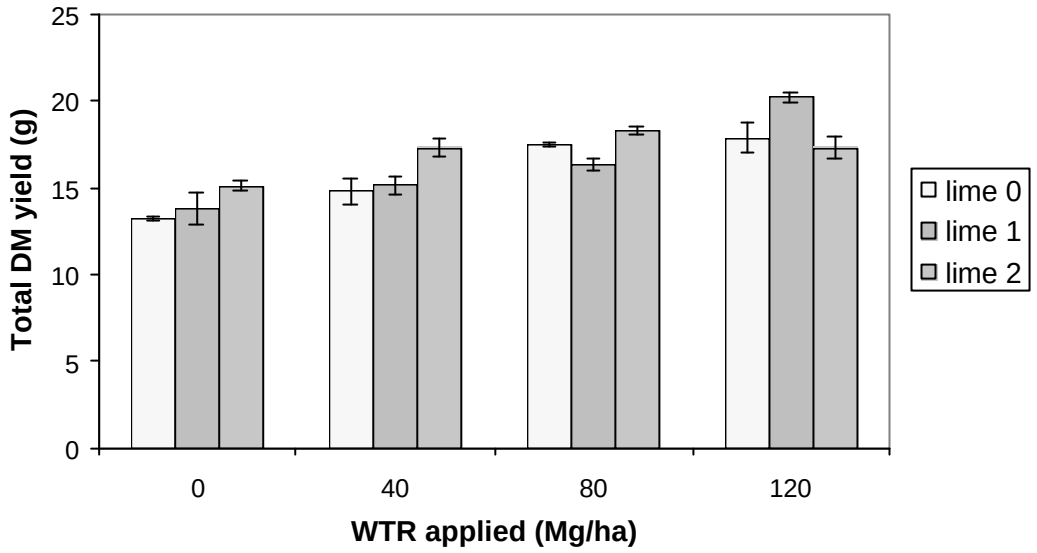


Figure 13.2 Total dry matter yield (±SE) on the Ia-C soil amended with three lime rates and four rates of Midmar water treatment residue.

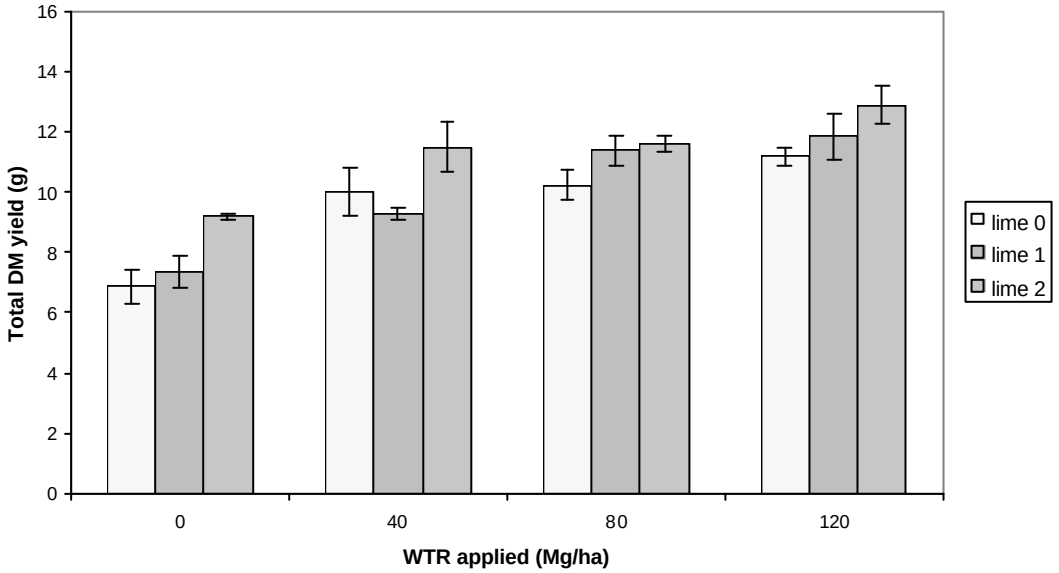


Figure 13.3 Total dry matter yield (±SE) on the Nb-F soil amended with three lime rates and four rates of Midmar water treatment residue.

Lime at similar rates of WTR, gave increases not as high as those of WTR (at similar lime levels). In the Ia-C soil the highest increase due to WTR application was 6.43 g whereas that due to lime was 2.32 g; the corresponding figures for the Nb-F soil were 4.49 and 2.50 g. These observations indicate that the suggested liming effect is not the only cause of the increase in DM yield.

13.3.4 pH and extractable elements in the soils

Measured pH values show an increase in both KCl and water, confirming that the residue has a liming effect (Table 13.4).

Table 13.4 Chemical analyses of the five soils at the end of the pot experiment

Soil	Lime	WTR	pH	pH	Acidity	Ca	Mg	Acid satn.	P
	----(Mg ha^{-1})----		(KCl)	(H_2O)	----($mmol_c$ kg^{-1})----			(%)	(mg kg^{-1})
Hu-M	0	0	4.48	5.52	0.19	54	48	2	7
		40	4.85	5.72	0.04	63	48	0	5
		80	5.23	6.00	0.04	74	48	0	5
		120	5.73	6.19	0.06	90	48	0	5
Hu-T	0	0	4.73	5.30	0.12	27	20	4	13
		40	5.51	5.82	0.04	40	21	3	7
		80	6.05	6.28	0.00	50	22	0	8
		120	6.20	6.60	0.04	55	19	0	8
Ia-C	0	0	4.25	5.45	1.26	19	14	27	5
		40	4.60	5.68	0.29	38	14	5	6
		80	4.99	5.78	0.10	52	17	2	6
		120	5.37	5.94	0.06	64	19	1	5
	4.5	0	4.78	5.67	0.18	49	13	3	6
		40	5.20	5.78	0.07	64	16	1	5
		80	5.70	5.85	0.06	64	15	0	4
		120	5.87	6.06	0.07	96	14	1	5
	9.0	0	5.42	6.05	0.04	79	12	0	6
		40	5.78	6.33	0.09	92	13	1	6
		80	6.03	6.53	0.07	99	13	1	6
		120	6.37	6.63	0.06	110	13	0	6
Nb-F	0	0	3.91	4.72	0.62	6	3	37	96
		40	4.78	5.36	0.08	24	4	2	59
		80	5.71	5.90	0.04	29	5	1	36
		120	6.46	6.51	0.03	36	5	1	36
	2.5	0	4.55	5.32	0.12	19	3	5	80
		40	5.62	6.31	0.06	25	3	2	39
		80	6.44	6.46	0.02	33	4	2	36
		120	6.77	6.84	0.02	39	5	0	32
	5.0	0	5.46	6.12	0.05	28	4	1	53
		40	6.08	6.45	0.01	38	4	0	53
		80	6.81	6.77	0.01	39	4	1	36
		120	6.84	6.96	0.01	39	4	0	46
Sd	0	0	4.60	5.72	0.10	69	86	1	5
		40	4.88	5.96	0.07	79	84	0	4
		80	5.32	6.27	0.02	103	88	0	4
		120	5.75	6.58	0.05	122	81	0	5

This is further confirmed by the reduction in extractable acidity and percent acid saturation, notably in the Ia-C and Nb-F soils where the acid saturation decreased from 27 to 1%, and from 37 to 1%, respectively.

Extractable Ca increased as expected, whilst Mg was virtually unaffected. Extractable P decreased noticeably in the Nb-F soil and to some extent in the Hu-T soil. These decreases were apparently not enough to cause a corresponding decrease in plant tissue P or reduction in yields, thus a decrease in the extractable levels of this nutrient does not necessarily lead to deficiencies or reduced levels in plants.

13.3.5 Nutrient levels in plant tissue

These data are presented in Appendix 13.1.

As expected in almost all soils and all cuts analysed, tissue Ca increased with amount of WTR applied. This might indicate that this nutrient could contribute to an increase in yield as suggested for the Nb-F soil above. The higher yielding Cuts 2 and 6 have lower concentrations of Ca (and Mg) compared to the lower yielding Cuts 4 and 8, probably due to a dilution effect where a higher yield gave lower concentrations at similar cation levels.

Tissue N and P do not show any trend. No contribution to N levels was expected from the WTR since it contains very little N. The indifferent response of P is, however, unexpected. Not only does the material contain P, it also was expected to sorb P (Sections 3.3 and 4.3.6) and so reduce its availability. Levels of Mn tended to decrease as the rate of WTR applied increased except in the Nb-F soil where it tended to increase. Zinc and Fe did not show any definite pattern of response.

13.4 Conclusions

From both agricultural and environmental points of view, the results obtained from the pot experiment are encouraging as perennial ryegrass can be used as feed for animals and for rehabilitation. In all five soils there was a significant positive response of DM yield of perennial ryegrass to the application of WTR. Thus whether the soils needed lime or not the material was of benefit to the plant concerned. It appears that the material is not soil specific as the soils used had different pH values, clay percentages and fertility status.

What is more difficult to identify is the actual cause(s) of the observed response**.** None of the nutrient levels in the plant was consistent with the DM yields. The common factors in all soils after application of the residue were an increase in pH and Ca. However, neither of these could satisfactorily explain the established response. Similarly an improvement in physical properties was not a conclusive explanation as the Nb-F soil was the only soil with initially poor physical properties.

CHAPTER 14

THE EFFECT OF A WATER TREATMENT RESIDUE ON THE SOILS, GROUNDWATER AND GROWTH OF PERENNIAL RYEGRASS AND TALL FESCUE IN THE FIELD EXPERIMENTS AT BROOKDALE AND UKULINGA FARMS

14.1 Introduction

The literature review (Chapter 3) revealed that observed negative effects of applied WTR on plant growth have been in greenhouse experiments while no such effects have been reported for field trials. In the field experiments of Geertsema *et al.* (1994) and Ahmed *et al.* (1997) where loading rates up to about 55 and 1 600 Mg ha^{-1} were used, there were no negative effects on the growth of pine trees and lawn grass, respectively.

Four possible effects of land treated-WTR need to be considered i.e., agricultural influence (uptake of elements and plant growth), soil properties, composition of drainage water, and impact on the activity of undesirable and/or excessive chemical species in the soil.

The agricultural issue refers to phytotoxicity to plants growing on the treated soil, or zootoxicity to animals feeding on treated lands. Buttigieg *et al*. (1989) pointed out three possible ways by which potentially toxic elements might pose problems to grazing ruminants i.e., adhering to leaf surfaces during application, ingestion of the material or contaminated soil from the ground, and feeding on herbage that has absorbed the species. Characterisation of the Midmar WTR (Chapter 4) established that it had a certain amount of heavy metals, some of which in large quantities are potential toxins.

The results of the pot experiment (Chapter 13) suggested benefits of application of WTR to growth of perennial ryegrass, although the mechanisms behind this positive response were unclear. Minyi (1989), Hopkins *et al*. (1994) and McKenzie and Jacobs (2002) have shown the importance of nutrient adequacy and/or balance in grass herbage. For temperate grasses, which provide forage to livestock and are also responsible for protection and conservation of soil (Van der Meer and Wedin, 1989), this would be an issue to consider. It is therefore necessary to establish whether land disposal of WTR has an impact on the plant-nutrient relationships.

The objectives of this investigation were as follows:

- to determine the effects of applied WTR on performance of a test plant under field conditions;
- to establish uptake of elements by the grass species; and
- to establish whether the WTR applied to the field had influenced (i) the depth distribution of pH; (ii) the migration of major solutes (excluding P); and (iii) the soil solution composition.

14.2 Materials and methods

14.2.1 Field sites and grass analysis

The field experiment sites and all details regarding their set-up and maintenance are described in Chapter 5. The dates of the grass harvests and the methodology are given in Section 5.7.1. Yield data were collected as described in Sections 5.7.1.1 and 5.7.1.2 for the Brookdale and Ukulinga sites, respectively. The chemical analysis of the grass is described in Section 5.7.2.

14.2.2 Statistical analyses and comparison of results

All samples were analysed in duplicate and statistically analysed using one-way analysis of variance (at $p<0.05$). The element levels were compared with research results acquired from the KwaZulu-Natal Department of Agriculture, Cedara (Dr. N. Miles, pers. comm., 2001). The comparisons are not directly appropriate since the research results are based on a date corresponding to 2/3 of canopy for perennial ryegrass 6 to 8 weeks after sowing or 4 weeks regrowth; the corresponding conditions for tall fescue are 5 to 7 weeks regrowth of the green leaf material in the top half of the canopy. They, however, serve as an indication of 'ideal' conditions.

14.2.3 Soil analysis

Selected soil samples (mainly from the 0 and 1280 Mg ha^{-1} plots, both incorporated and mulched) collected from the two experimental sites at dates and depths indicated in Section 14.4 were analysed for pH in 1:2.5 soil:water and KCl solutions. Extractable Ca and Mg (5 g soil:50 mL 1M KCl, shaken for 10 min) were analysed using atomic absorption spectrophotometry (AAS). The 1280 Mg ha^{-1} mulch treatment plots were sampled from the surface of the actual soil i.e., from below the mulch.

To determine the soluble species, the soil solution was separated from a saturated paste by vacuum following overnight equilibration (United States Salinity Laboratory Staff, 1954). Electrical conductivity (EC) of the saturation extract was determined at 25^{o}C using a Radiometer CDM83 electrical conductivity meter, and Ca and Mg were analysed as indicated above. Bicarbonate and chloride were determined by titration (United States Salinity Laboratory Staff, 1954), and nitrate colorimetrically using a TRAACS 2000 continuous flow auto analyser.

14.2.4 Water analysis

Samples obtained from the soil water collectors at Ukulinga Farm were analysed for EC (as above), Ca and Mg by AAS, and Na and K by flame emission (Varian SpectraAA-200), nitrate (as above), phosphate (colorimetrically; Section 4.2.2) and Cd, Co, Cr, Cu, Fe, Mn, Zn and Ni by AAS.

Water samples were collected from the dam and borehole at Brookdale Farm by Umgeni Water and analysed in their laboratories.

14.3 Results and discussion

14.3.1 Observed growth of the grass at both field experiments

Neither the level nor the mode of application of the WTR was discerned to cause any negative impact on the growth of the ryegrass (or the tall fescue planted subsequently) with respect to either the density, height or appearance of the grass plants; if anything, the grass appeared to grow better where the WTR was applied. This was especially true for the highest application rate of 1280 Mg ha^{-1}, both incorporated and mulched, and in particular the latter treatments. Such visual improvement was consistently observed throughout in both the perennial ryegrass and the tall fescue at both sites.

14.3.2 Dry matter yield of tall fescue from the Ukulinga experiment

The ANOVA for all the DM yields measured is presented in summary form in Table 14.1. This shows that there were no statistical differences between the harvests except in July 2000 when the yields at the 320 and 1280 Mg ha^{-1} rates were significantly higher than the other treatments, and in August 2002 when all three rates of WTR gave significantly higher yields than the control. Neither the WTR nor the other treatments suppressed the growth of the crop and in general there were slight increases in yield with application of the WTR.

Where half of the plots were fertilised (April 2001 harvest), the yield was significantly higher than where no fertilisation had occurred. To ascribe the yield response to increased K content in the plant would only explain the response at 0 and 80 Mg ha^{-1} application rates of WTR. It is more probable that the introduction of all three primary macronutrients improved the performance of the grass. Elliott and Singer (1988) recommended that introduction of WTR's to croplands should be accompanied by application of N, P and K. A review by Elliott and Dempsey (1991) also established that WTR's had little impact on soil fertility as a result of their low N contents, no increases in mineralisation rates following their application, and their reduction of plant available P. After testing the material as a potential plant growth medium, Skene *et al.* (1995) concluded that fertiliser application with WTR's is necessary for optimum plant growth. Results of Rengasamy *et al.* (1980) in pot experiments were mixed, with increase in growth recorded with and without fertiliser application. Application of WTR for agronomic purposes should not make one lose sight of the importance of nutrient balance and adequacy in the soil.

14.3.3 Elements in grass harvests from the Brookdale experiment

The results of the ANOVA are given in Table 14.2 for both the initial perennial ryegrass and for the Dovey tall fescue that replaced it.

14.3.3.1 Perennial ryegrass

In the October 1999 harvest, no definitive trend appeared as to the effects on various elements of either the WTR or the lime. Calcium was the only element that seemed to respond to the treatments, and that to the WTR. Calcium tissue levels increased by 0.08 and 0.13% on the 640 and 1280 Mg ha^{-1} mulch treatments relative to the control, but it was only at the higher application rate that the gain was statistically significant.

A similar trend is observed in the December 1999 harvest. Amounts of K also increase, together with Ca, especially at application rates above 160 Mg ha^{-1} although none of the increases is significant. In this harvest the increase in tissue Ca occurs at application rates of WTR over 320 Mg ha^{-1}, irrespective of its mode of application, but it is again on the 1280 Mg ha^{-1} mulch treatment that the result is significant. Both lime treatments show a non-significant increase for both these elements. It could be expected that tissue Ca would increase with WTR application considering its high concentration in the material. The results for K are somewhat unexpected as the WTR contains a low K concentration, and the increasing Ca levels with increasing application rates of either the residue or lime might be expected to interfere with the uptake of K.

Table 14.1 Mean (n=2) dry yield (Mg ha^{-1}) of tall fescue harvests at Ukulinga Farm for different sampling dates

Date		WTR application rate (Mg ha^{-1})				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
		0	80	320	1280						
July 2000	Mean	1.23c*	1.65bc	2.58a	2.85a	1.89b	1.33bc	1.33bc	0.65	10.95	0.003
	SE	0.18	0.39	0.34	0.42	0.12	0.10	0.18			
September 2000	Mean	3.30	2.82	3.23	3.16	3.09	3.17	3.18	NS	0.26	0.940
	SE	0.05	0.37	0.34	0.29	0.74	0.62	0.02			
February 2001	Mean	2.49	2.17	3.64	3.26	3.09	2.98	2.37	NS	2.49	0.129
	SE	0.23	0.26	1.15	0.06	0.20	0.08	0.31			
April 2001 (Fert[a])	Mean	2.25	2.60	2.43	3.10	1.92	2.36	2.36	NS	1.18	0.412
	SE	0.33	0.47	0.86	0.03	0.03	0.69	0.06			
April 2001 (Unfert[a])	Mean	1.24	1.07	1.36	1.41	1.25	1.19	1.01	NS	0.80	0.602
	SE	0.06	0.03	0.21	0.34	0.37	0.08	0.25			
August 2001	Mean	1.54	1.33	1.79	1.40	1.80	1.11	1.19	NS	0.86	0.563
	SE	0.37	0.42	0.43	0.37	0.59	0.12	0.45			
November 2001	Mean	3.11	2.19	2.91	3.27	2.54	2.80	1.68	NS	1.08	0.455
	SE	0.76	0.42	0.21	1.22	0.03	1.31	0.17			
February 2002	Mean	2.46	2.76	3.65	3.75	3.05	3.14	2.26	NS	2.20	0.162
	SE	0.43	0.12	0.59	0.87	0.75	0.35	0.02			
August 2002	Mean	0.86c	1.49ab	1.45ab	1.92a	1.09bc	0.77c	1.26bc	0.50	7.24	0.010
	SE	0.18	0.19	0.07	0.14	0.15	0.41	0.14			
November 2002	Mean	1.70	1.73	2.24	2.42	2.04	2.05	1.78	NS	1.13	0.432
	SE	0.50	0.59	0.21	0.36	0.36	0.02	0.18			
February 2003	Mean	1.66	1.79	2.02	1.71	2.16	1.46	1.31	NS	1.94	0.204
	SE	0.27	0.06	0.02	0.27	0.67	0.00	0.23			

* Letters that are different indicate significant differences between means.
NS non-significant F-statistic.
[a] Fert and Unfert refer to the upper half of each plot remaining unfertilised while the lower half received fertiliser (Section 5.6).

Calcium and Mg levels are within their respective 0.26-1.0% and 0.2-0.5% ranges of adequacy for ryegrass. The concentrations of K were more in the 2.5-6.0% range of adequacy than the 2.0-3.0% range of critical levels. However, N and P are below the adequacy ranges of 3.6-6.0% and 0.25-0.36%, respectively. For N the levels are in fact clearly below the critical 3.5% values whilst for P they are close to the critical concentration of 0.24%. The overall results, where those of the control were no exception to these observations, suggested that it was the low concentrations of these elements in the soil rather than the effect of the treatments that caused the inadequate tissue levels.

Table 14.2 Summary ANOVA statistics for elemental uptake by the perennial ryegrass and tall fescue grown at Brookdale Farm on different treatments of water treatment residue, lime, gypsum and polyacrylamide

Date	Statistic	Element									
		Ca	**Mg**	**K**	**P**	**N**	**Na**	**Zn**	**Cu**	**Mn**	**Fe**
Oct 1999a	$LSD_{5\%}$	NS	NS	NS	NS	0.69	0.23	NS	NS	NS	
	VR	1.80	1.43	2.24	1.87	2.36	2.49	1.14	2.00	1.45	nd
	F-pr	0.127	0.243	0.060	0.12	0.050	0.04	0.4	0.091	0.234	
Dec 1999a	$LSD_{5\%}$	0.123	NS	NS	NS	0.74	NS	NS	3.79	NS	
	VR	3.81	1.25	1.34	1.15	3.82	1.35	1.26	2.86	2.19	nd
	F-pr	0.006	0.331	0.285	0.394	0.006	0.279	0.327	0.022	0.066	
Nov 2001b	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	93.05	NS
	VR	0.57	1.05	1.01	0.62	nd	0.65	1	1.64	2.67	1.58
	F-pr	0.862	0.458	0.493	0.822		0.793	0.5	0.17	0.03	0.187
Feb 2002b	$LSD_{5\%}$	0.05	NS	NS	NS		NS	4.74	NS	NS	NS
	VR	2.91	1.66	1.75	0.53	nd	1.21	3.20	0.354	1.00	0.92
	F-pr	0.021	0.162	0.139	0.887		0.357	0.013	1.21	0.496	0.561
Nov 2002b	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	0.75	1.36	0.76	1.33	nd	1.12	0.60	0.90	1.01	0.92
	F-pr	0.710	0.272	0.696	0.288		0.408	0.836	0.579	0.487	0.559
Feb 2003b	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	0.99	1.21	1.49	1.19	nd	0.98	0.53	0.44	0.99	0.87
	F-pr	0.504	0.354	0.218	0.365		0.510	0.887	0.939	0.508	0.606

a perennial ryegrass. b Dovey tall fescue.
NS non-significant F-statistic. nd not determined.

No trend of response to treatments was observed with respect to minor elements, except possibly for Mn where there was a suggestion of some significant decreases in Mn tissue concentrations with application of WTR or lime. The higher lime level gave a significantly lower Mn concentration in the October harvest and a non-significantly lower one in the December harvest. Levels of Cu, Mn and Zn were generally within their adequacy ranges of 6-12, 50-300 and 15-20 mg kg^{-1}, respectively. Copper concentrations were sometimes close to or just below the lower limit, whilst those of Mn were somewhat elevated in the February 2002 and October 2002 harvests. Zinc levels were also notably higher in the October 2001 harvest. There was, however, no clear indication that these levels were caused by the application of the WTR since control treatments were similarly affected. Also even these relatively high Mn and Zn concentrations were well below the 1000 and 300-500 mg kg^{-1} DM limits, respectively, suggested by Webber *et al.* (1984; cited by Buttigieg *et al.*, 1989) as the maximum tolerable dietary concentrations for long-term feeding of perennial ryegrass to ruminants.

14.3.3.2 Dovey tall fescue

Neither the major nor minor elements exhibited any trends with respect to increases in the WTR or the lime applied. The adequate levels for this grass are Ca (0.22-0.31%), K (2.2-3.5%), Mg (0.20-0.36%), and P (0.25-0.35%); the adequate levels for minor elements are not known. Except for K and P in the October 2002 harvest, the elements were within these ranges. Even for these exceptions, it was clear that the deficiencies were more a function of the soil conditions at the time than the material applied, as the controls also exhibited similarly low concentrations.

Of the micronutrients, it was only the levels of Mn that tended to decrease with application of either the WTR or the lime although the differences were statistically non-significant.

14.3.4 Elements in tall fescue from the Ukulinga experiment

The summary ANOVA results are given in Table 14.3 and there was no definitive pattern to the uptake of elements in response to the treatments. Also, although there were some general increases in some elements, they were not significant. As for the ryegrass at Brookdale, it would seem that tall fescue was generally insensitive to the application of either the WTR or the lime as indicated by uptake of elements. Nitrogen (where analysed) was the only element that tended to show increases in response to the WTR. These increases were, however, not statistically significant.

From the data, it is clear that the concentrations of the major elements in the grass tissue were largely in the suggested ranges for adequate levels; and more importantly, the WTR did not cause the element levels to be outside these ranges.

Of the minor elements, it was again Mn that showed signs of decreasing with application of either the WTR or the lime. Whilst not statistically significant, these decreases were nonetheless consistent.

14.3.5 Some heavy metals in grass grown at the two sites

Analytical data for Cd, Co, Cr, Ni and Pb showed that concentrations of Cd were below the detection limit of the method used and so the results for this element are not reported. For the other elements the results for the Brookdale trial are given in Table 14.4 and for Ukulinga in Table 14.5.

In the Brookdale 1999 harvest, Cr and Ni tissue contents significantly decreased with WTR applied at the highest rate, both incorporated and mulched. The concentrations of Co and Pb were essentially unchanged by the application of WTR. In the mulch treatment of the 2001 harvest, the levels of Co and Cr were significantly higher than those of the control whereas those of Ni and Pb were non-significantly higher.

At Ukulinga the Co tissue levels at the 1280 Mg ha^{-1} WTR application rate were significantly higher than those of the control. Levels of Cr were unaffected by the rate of WTR in the 2000 harvest and increased (but not significantly) in the 2001 harvest. Nickel and Pb differences were non-significant except for Ni at 1280 Mg ha^{-1} in the 2001 harvest. Amounts of Cr and Ni appear to increase in the later harvests.

Table 14.3 Summary ANOVA statistics for elemental uptake by the tall fescue grown at Ukulinga Farm on different treatments of water treatment residue, lime, gypsum and polyacrylamide

Date	Statistic	Element									
		Ca	**Mg**	**K**	**P**	**N**	**Na**	**Zn**	**Cu**	**Mn**	**Fe**
July 2000	$LSD_{5\%}$	NS	NS	0.43	NS	0.84	NS	NS	NS	19.77	
	VR	0.45	1.09	5.26	2.54	6.22	1.58	2.22	2.00	5.99	nd
	F-pr	0.828	0.45	0.023	0.124	0.015	0.28	0.160	0.193	0.016	
September 2000	$LSD_{5\%}$	NS	0.04	NS	0.52	NS	NS	NS	NS	44.58	
	VR	2.73	10.30	0.46	4.73	1.76	1.31	0.84	0.67	4.78	nd
	F-pr	0.108	0.004	0.820	0.031	0.237	0.362	0.576	0.681	0.030	
February 2001	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	87.71	
	VR	1.21	0.26	2.07	1.44	nd	3.59	0.69	0.83	5.47	nd
	F-pr	0.400	0.939	0.181	0.32		0.059	0.67	0.58	0.040	
April 2001 (Fert[a])	$LSD_{5\%}$	0.06	NS	NS	NS		NS	NS	NS	36.32	
	VR	6.34	3.28	0.51	7.06	nd	0.29	1.67	0.48	4.83	nd
	F-pr	0.014	0.073	0.787	0.011		0.926	0.258	0.808	0.029	
April 2001 (Unfert[a])	$LSD_{5\%}$	NS	NS	NS	NS		NS	4.24	NS	97	
	VR	0.84	2.06	3.25	1.49	nd	3.73	5.28	1.17	4.62	nd
	F-pr	0.578	0.184	0.074	0.306		0.054	0.023	0.417	0.032	
August 2001	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	0.71	0.55	0.25	0.71	nd	2.32	0.62	0.86	0.63	0.8
	F-pr	0.655	0.76	0.943	0.656		0.147	0.712	0.567	0.705	0.598
November 2001	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	2.52	1.81	3.13	0.85	nd	0.66	1.21	1.14	3.61	1.15
	F-pr	0.126	0.228	0.081	0.57		0.683	0.400	0.427	0.059	0.422
February 2002	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	0.97	1.11	1.27	2.21	nd	1.95	2.16	0.89	2.32	0.56
	F-pr	0.505	0.441	0.378	0.161		0.201	0.169	0.549	0.148	0.752
April 2002	$LSD_{5\%}$	NS	NS	NS	NS		0.36	NS	NS	NS	NS
	VR	2.41	2.27	3.00	0.45	nd	4.29	0.36	0.51	1.47	0.50
	F-pr	0.138	0.154	0.089	0.825		0.039	0.881	0.782	0.312	0.790
August 2002	$LSD_{5\%}$	NS	NS	NS	NS		0.41	NS	NS	NS	NS
	VR	0.78	1.87	1.91	1.85	nd	7.08	0.69	1.75	1.43	1.26
	F-pr	0.609	0.216	0.208	0.220		0.010	0.669	0.240	0.322	0.381
November 2002	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	45.92
	VR	1.87	0.46	1.39	0.45	nd	0.69	0.62	0.48	2.88	5.81
	F-pr	0.216	0.821	0.334	0.823		0.668	0.709	0.805	0.096	0.018
February 2003	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	0.95	0.34	1.25	0.81	nd	0.23	0.52	0.17	2.48	1.68
	F-pr	0.514	0.893	0.383	0.591		0.953	0.78	0.977	0.13	0.255
May 2003	$LSD_{5\%}$	NS	NS	NS	NS		NS	NS	NS	NS	NS
	VR	0.78	3.51	1.81	1.57	nd	1.52	0.53	1.62	1.65	0.53
	F-pr	0.61	0.063	0.228	0.283		0.298	0.769	0.27	0.262	0.773

NS non-significant F-statistic

[a] Fert and Unfert refer to the upper half of each plot remaining unfertilised while the lower half received fertiliser (Section 5.6).

nd not determined.

Table 14.4 Some heavy metal composition of ryegrass (October 1999) and tall fescue (October 2001) grown at Brookdale Farm

Harvest date	WTR (Mg ha^{-1})	Co	Cr	Ni	Pb
		(mg kg^{-1})			
October 1999	0	7.5	8.9	7	3.8
	320	7.2	7.6	5.3	3.9
	1280	7.9	6	3.5	3.8
	1280[a]	6.9	3	1.5	3.9
	$LSD_{5\%}$	3.17	1.82	1.19	0.89
October 2001	0	6.9	3.6	2.3	3.6
	320	8.2	3.3	2.1	3.5
	1280	7.8	3.1	1.7	3.8
	1280[a]	12.1	5.8	3.4	4.5
	$LSD_{5\%}$	3.21	1.58	1.34	0.91

[a] Mulch treatment

Table 14.5 Some heavy metal composition of tall fescue grown at Ukulinga Farm at two harvest dates

Harvest date	WTR (Mg ha^{-1})	Co	Cr	Ni	Pb
		(mg kg^{-1})			
July 2000	0	5.4	3.3	5.2	6.2
	320	4.9	2.4	5.4	5.9
	1280	8.8	3.1	3.6	7.3
	$LSD_{5\%}$	2.78	2.29	4.46	3.66
October 2001	0	5.1	8.1	7.4	4.6
	320	7.1	6.7	5.9	4.3
	1280	13.1	11.2	9	5.8
	$LSD_{5\%}$	7.13	4.09	1.48	3.24

No reason has been found to explain the differences in Cr and Ni concentrations for the comparative harvests. It should be noted, however, that for the Brookdale results two different grasses were involved; in the Ukulinga data the 2000 harvest was in winter compared to spring of 2001. Also difficult to explain was the uptake of Co as it is seemingly contrary to those of the other metals; the Co tissue concentrations tended to consistently increase with an increase in WTR application rate. A decrease in Ni uptake on application of WTR has been reported (Elliott and Singer, 1988) and ascribed to immobilization by the alkaline conditions created by the WTR. On the whole, it can be stated that the field application of WTR up to rates of 1280 Mg ha^{-1} on the Hutton and Westleigh soils planted with perennial ryegrass and tall fescue did not radically alter the tissue concentrations of pollutant metals.

Tolerable dietary concentrations for long-term feeding to ruminants are Cr (III): 3000, Ni: 50 and Pb: 30 mg kg^{-1} DM (Webber *et al*., 1984; cited by Buttigieg *et al*., 1989). Since the metal concentrations measured at both field experiments are well below these concentrations, and the DM yields showed no signs of decline, it can be reasonably concluded that the concentrations were neither zootoxic nor phytotoxic.

14.4 Analysis of saturation extracts

14.4.1 Brookdale Farm

To determine whether there was a change in solute concentration (in particular base cations) with depth in the soil profile, samples (for saturated paste analysis) were collected at 100 mm intervals from the control treatment and the mulched WTR treatments (below the actual soil surface) to a depth of 800 mm during April 2000. The results of this analysis are given in Table 14.6.

Table 14.6 Saturated paste extract data from selected fallow treatments at different depths, sampled in April 2000 at Brookdale Farm

Treatment (Mg ha^{-1})	Depth (mm)	EC (mS m^{-1})	Ca	Mg	Na	K
			----------(mmol$_c$ L^{-1})----------			
0	0 - 100	28.60	0.68	0.81	0.42	0.12
	100 - 200	37.50	0.79	1.18	0.45	0.16
	200 - 300	30.50	0.66	1.26	0.44	0.00
	300 - 400	29.40	0.48	1.12	0.40	0.07
	400 - 500	28.90	0.54	1.35	0.48	0.00
	500 - 600	44.40	0.71	1.87	0.57	0.07
	600 - 700	47.60	0.97	2.35	0.58	0.06
	700 - 800	36.80	0.16	0.99	0.60	0.12
Mulched 320	0 - 100	41.90	2.36	1.44	0.48	0.05
	100 - 200	48.60	1.28	1.46	0.47	0.04
	200 - 300	34.30	1.17	1.22	0.50	0.00
	300 - 400	29.40	0.49	1.01	0.44	0.03
	400 - 500	22.70	0.47	0.95	0.43	0.00
	500 - 600	31.20	0.39	1.08	0.48	0.01
	600 - 700	35.90	0.72	1.54	0.54	0.00
	700 - 800	44.30	0.73	1.96	0.59	0.02
Mulched 640	0 - 100	45.60	1.42	1.34	0.38	0.01
	100 - 200	46.60	0.99	1.42	0.49	0.03
	200 - 300	44.00	2.83	1.64	0.52	0.00
	300 - 400	43.90	0.79	1.26	0.47	0.01
	400 - 500	38.20	1.05	1.62	0.57	0.04
	500 - 600	41.70	0.48	1.42	0.69	0.07
	600 - 700	50.90	1.10	2.32	0.55	0.00
	700 - 800	67.00	0.00	0.06	0.66	0.11
Mulched 1280	0 - 100	87.90	4.86	3.03	0.74	0.00
	100 - 200	97.50	3.36	2.99	0.67	0.02
	200 - 300	109.60	4.81	5.48	1.04	0.00
	300 - 400	214.00	5.40	8.85	1.11	0.07
	400 - 500	198.00	3.55	9.72	1.02	0.00
	500 - 600	247.00	3.61	11.47	0.85	0.02
	600 - 700	193.00	5.09	10.13	0.96	0.00
	700 - 800	130.00	3.04	7.37	0.86	0.01

The effect of the 320 and 640 Mg ha^{-1} mulch treatments had a marginal influence on the EC of the soil solution, although at equivalent soil depths the EC for these

treatments was greater than that for the control treatment. The control treatment on the other hand, shows a near constant EC in the 0 to 500 mm depth but this increases slightly with increasing depth. The 1280 Mg ha^{-1} mulch treatment shows substantially higher EC values than the other treatments. Between 0 and 300 mm, the EC for this treatment increases gradually but below 300 mm the EC increases sharply to a maximum of 247 mS m^{-1} at between 500 and 600 mm, before decreasing below 700 mm.

As was expected the higher application rate of WTR increased the Ca concentration more substantially than the lower amounts of WTR. Compared to the rest of the treatments the 1280 Mg ha^{-1} treatment also shows substantially higher Mg concentrations. The 320 and 640 Mg ha^{-1} treatments were very little different from the control. Although there was some leaching of K from the WTR to greater soil depths in the 1280 Mg ha^{-1} treatment, in general the levels of K in the saturation extract for the other treatments were low. The levels of Na for all treatments were generally low and with the exception of the 1280 Mg ha^{-1} treatment were generally < 0.7 $mmol_c$ L^{-1}.

From these initial data, it was decided to continue monitoring the movement of selected cations and anions from the control and 1280 Mg ha^{-1} mulch treatments, as well as including the incorporated 320 and 1280 Mg ha^{-1} WTR treatments. As this was a monitoring exercise, the depth interval was increased to every 200 mm down to 1000 mm, with only the 0-200, 400-600 and 800-1000 mm samples being analysed. The Ukulinga Farm experiment was included in this study, with the 0, 320 and 1280 Mg ha^{-1} WTR treatments being sampled every 100 mm to 500 mm depth, with only the 0-100, 200-300 and 400-500 mm depths being analysed. Initially (February 2001) only the fallow plots were sampled, but subsequently (September 2001, October 2002 and June 2003) the grassed plots were included. Electrical conductivity was also measured on the paste extract, and the pH of a 1:2.5 soil:water solution for the respective treatments and depths.

Tables 14.7 and 14.8 give the results of the saturated paste extracts for the different sampling dates at Brookdale Farm. The EC was low for all treatments, although the soil below the mulch treatment did tend to have higher EC than the equivalent depths of the other treatments for the February and September 2001 sampling dates. The subsequent samplings showed that the mulch treatment had similar ECs to the other treatments, suggesting that salts had moved out of the profile. The EC of the grassed plots were also generally lower than the EC of the fallow plots for an equivalent depth and treatment (in agreement with the data given in Section 10.3.3). There appeared to be a decrease of EC in all the treatments over time, with the June 2003 sampling generally having the lowest EC values for most treatments and depths. The EC of the grassed plots were particularly low at this sampling date.

The pH of most of the treatments at all sampling dates showed small changes with depth. In February 2001 the pH of the fallow plots tended to increase with depth for all treatments. A similar trend was seen for September 2001, which also included the grassed treatments. Frequently the highest pH was at the 400-600 mm depth. This pattern continued for the October 2002 and June 2003 sampling dates.

Table 14.7 Depth distribution of electrical conductivity (EC), nitrate (NO_3), Ca, Mg, K and Na as measured in saturated paste extracts, and pH for selected treatments sampled from Brookdale Farm during February and September 2001 from both fallow (F) and grassed (G) plots

Date	Treatment (Mg ha^{-1})	Depth (mm)	EC (mS m^{-1})		pH (1:2.5 H_2O)		---NO_3---		----Ca----		----K----		----Mg---		---Na---	
							----------(mmol$_c$ L^{-1})----------									
			F	G	F	G	F	G	F	G	F	G	F	G	F	G
	0	0-200	57.15	nd	5.37	nd	3.61	nd	1.90	nd	0.16	nd	1.58	nd	0.42	nd
		400-600	39.50	nd	5.70	nd	2.44	nd	1.02	nd	0.03	nd	1.49	nd	0.32	nd
		800-1000	31.10	nd	5.45	nd	1.58	nd	0.54	nd	0.10	nd	1.16	nd	0.39	nd
	320	not determined on this occasion, only for subsequent sampling.														
Feb 2001	1280	0-200	49.25	nd	5.65	nd	2.54	nd	1.96	nd	0.13	nd	1.40	nd	0.31	nd
		400-600	43.95	nd	5.75	nd	2.15	nd	1.26	nd	0.02	nd	1.43	nd	0.32	nd
		800-1000	32.95	nd	6.54	nd	1.37	nd	0.72	nd	0.02	nd	1.30	nd	0.30	nd
	1280 mulched	0-200	92.30	nd	5.37	nd	5.76	nd	3.71	nd	0.13	nd	2.41	nd	0.37	nd
		400-600	88.75	nd	5.69	nd	5.95	nd	2.35	nd	0.02	nd	3.44	nd	0.39	nd
		800-1000	123.10	nd	5.56	nd	nd	nd	2.55	nd	0.02	nd	5.44	nd	0.50	nd
	0	0-200	39.70	27.00	5.05	5.25	2.88	1.70	1.41	0.81	0.04	0.03	1.08	1.03	0.62	0.64
		400-600	58.35	26.15	5.55	5.89	5.61	0.61	1.44	0.69	0.02	0.02	2.43	1.13	0.66	0.77
		800-1000	39.50	27.15	5.33	6.11	3.11	0.33	0.65	0.65	0.02	0.01	1.37	1.37	0.82	0.57
	320	0-200	58.15	38.25	5.01	5.49	5.05	2.55	2.48	1.08	0.05	0.16	1.71	1.27	1.43	1.52
		400-600	57.25	24.95	5.38	5.84	5.85	0.57	1.92	0.71	0.01	0.01	2.56	1.26	1.05	1.03
Sept 2001		800-1000	40.95	39.10	5.48	5.74	3.26	0.67	1.49	0.57	0.00	0.02	2.05	1.24	1.38	1.77
	1280	0-200	48.70	32.00	5.18	5.44	4.48	2.22	2.56	1.02	0.06	0.10	1.28	0.97	1.53	0.69
		400-600	55.45	28.80	5.51	5.55	5.38	1.34	2.31	1.84	0.04	0.02	2.37	1.23	1.80	0.55
		800-1000	36.45	17.90	5.46	5.17	2.88	0.47	1.58	1.41	0.01	0.02	1.59	0.71	1.72	0.49
	1280 mulched	0-200	68.50	38.50	4.98	4.72	7.17	4.39	2.87	1.58	0.03	0.04	2.36	1.27	1.81	0.74
		400-600	68.60	59.85	5.55	5.27	6.93	5.52	1.77	2.01	0.01	0.03	3.22	2.88	1.76	0.57
		800-1000	85.30	99.60	5.61	4.81	7.41	4.95	2.88	2.50	0.00	0.01	4.39	6.41	1.90	0.68

nd not determined.

Nitrate concentrations were consistently higher on the fallow plots for all treatments, depths and dates. The mulch treatments also tended to have higher nitrate concentrations than the other treatments for the February and September 2001 sampling periods. By October 2002 the mulch treatments had similar levels to that of the 1280 Mg ha^{-1} incorporated treatment, followed by a sharp decrease in June 2003. The grassed plots showed a consistent decrease in nitrate concentration with depth, regardless of treatment or sampling date. The lower concentrations found on the grassed plots compared to the fallow treatments are probably due to uptake of N by the plants. Low concentrations of Cl were also measured for all treatments and depths (results not shown), but the pattern in the distribution was not very clear

Calcium concentrations tended to decline with depth in all treatments, although the mulch treatments tended to have higher concentrations than the other treatments. As was the case for nitrate, the grassed plots tended to have lower Ca concentrations than the equivalent depth and treatment of the fallow plots. Overall the lowest

concentrations were reported for October 2002, but with a slight increase in June 2003. Magnesium concentrations followed a similar pattern to that of Ca. Potassium and Na concentrations tended to be quite low, with no clear pattern in distribution down the profile for any treatment or date.

Table 14.8 Depth distribution of electrical conductivity (EC), nitrate (NO_3), Ca, Mg, K and Na as measured in saturated paste extracts, and pH for selected treatments sampled from Brookdale Farm during October 2002 and June 2003 from both fallow (F) and grassed (G) plots

Date	Treatment (Mg ha^{-1})	Depth (mm)	EC (mS m^{-1})		pH (1:2.5 H_2O)		----NO_3---- (mmol$_c$ L^{-1})		----Ca---- (mmol$_c$ L^{-1})		----K---- (mmol$_c$ L^{-1})		----Mg---- (mmol$_c$ L^{-1})		----Na---- (mmol$_c$ L^{-1})	
			F	G	F	G	F	G	F	G	F	G	F	G	F	G
Oct 2002	0	0-200	45.05	12.30	5.06	5.80	4.74	2.59	0.79	0.14	0.04	0.10	0.13	0.07	0.18	0.22
		400-600	50.65	11.00	5.37	5.56	5.18	0.36	0.61	0.11	0.01	0.01	0.26	0.10	0.18	0.29
		800-1000	29.40	10.40	5.33	5.66	3.57	0.72	0.31	0.20	0.03	0.01	0.21	0.13	0.30	0.26
	320	0-200	43.20	14.85	5.40	5.39	2.55	2.45	1.09	0.16	0.01	0.05	0.25	0.07	0.32	0.37
		400-600	50.00	11.00	5.76	5.63	5.30	0.31	0.82	0.10	0.02	0.01	0.30	0.09	0.19	0.18
		800-1000	33.85	17.30	5.70	5.98	4.40	0.21	0.33	0.16	0.01	0.01	0.19	0.17	0.14	0.25
	1280	0-200	31.10	19.70	4.46	5.56	3.60	2.69	0.70	0.41	0.01	0.02	0.05	0.09	0.18	0.22
		400-600	41.70	12.15	5.05	5.40	3.48	0.00	0.70	0.21	0.01	0.01	0.15	0.11	0.14	0.24
		800-1000	47.75	24.35	5.04	5.21	4.65	0.59	0.57	0.28	0.00	0.04	0.24	0.28	0.20	0.19
	1280 mulched	0-200	42.20	13.70	5.48	5.71	4.30	0.00	1.15	0.15	0.02	0.01	0.39	0.10	0.27	0.15
		400-600	35.80	19.25	5.89	5.58	4.30	0.00	0.62	0.32	0.02	0.01	0.24	0.16	0.18	0.27
		800-1000	53.00	34.65	5.80	5.60	4.90	0.00	0.63	0.51	0.01	0.01	0.51	0.42	0.20	0.24
June 2003	0	0-200	28.80	16.75	5.14	4.87	4.91	1.71	1.83	0.66	0.06	0.10	0.74	0.36	0.12	0.14
		400-600	32.90	9.90	5.37	5.41	5.29	1.24	1.49	0.29	0.05	0.01	1.16	0.32	0.11	0.13
		800-1000	20.50	9.60	5.10	6.17	3.12	0.50	0.65	0.26	0.08	0.01	0.71	0.37	0.12	0.10
	320	0-200	41.90	14.40	5.23	5.47	5.38	2.10	2.46	0.45	0.06	0.12	0.90	0.30	0.12	0.08
		400-600	38.30	9.40	5.49	5.93	6.39	1.50	2.16	0.27	0.03	0.01	1.32	0.35	0.12	0.08
		800-1000	41.00	7.90	5.59	6.02	5.46	0.26	1.60	0.11	0.03	0.01	1.30	0.29	0.09	0.09
	1280	0-200	31.75	10.20	5.74	5.64	4.52	2.07	1.97	0.33	0.08	0.09	0.68	0.14	0.11	0.14
		400-600	30.85	12.35	5.78	5.80	4.15	1.02	1.56	0.26	0.02	0.02	0.84	0.27	0.09	0.11
		800-1000	29.35	8.20	6.14	5.64	4.22	0.52	1.13	0.16	0.01	0.02	1.12	0.20	0.14	0.11
	1280 mulched	0-200	41.90	18.35	5.15	5.64	1.56	3.49	2.84	0.96	0.07	0.01	0.92	0.32	0.13	0.17
		400-600	26.65	22.95	5.65	5.58	1.52	1.33	1.41	1.03	0.03	0.02	0.89	0.57	0.15	0.11
		800-1000	30.30	37.60	5.73	5.30	1.69	2.34	1.25	1.29	0.02	0.02	1.17	1.30	0.10	0.05

14.4.2 Ukulinga Farm

Generally the EC of all the treatments were low, and would not present any soil salinity problems (Table 14.9). In February 2001 there was an increase in EC in the 1280 Mg ha^{-1} treatment compared to the control, although for both treatments the change with depth was not marked. The September 2001 sampling showed an increase in EC with depth for the control treatment, while the reverse trend was evident for the WTR treatments. It is possible, however, that the high EC of the 400-500 mm depth for the control is an anomalous reading (similarly the 0-100 mm depth for the grassed control plot in October 2002). The EC of the grassed plots tended to be a little lower than that of the fallow plots for equivalent treatments. Subsequent

samplings tended to show similar patterns as previously, although the EC was marginally lower than before. This may reflect the loss of salts down the profile, or in the case of the grassed plots, uptake by the plants.

Table 14.9 Depth distribution of electrical conductivity (EC), nitrate (NO_3), Ca, Mg, K and Na as measured in saturated paste extracts, and pH for selected treatments sampled from Ukulinga Farm for different sampling dates from both fallow (F) and grassed (G) plots

Date	Treatment (Mg ha^{-1})	Depth (mm)	EC (mS m^{-1})		pH (1:2.5 H_2O)		----NO_3--- (mmol$_c$ L^{-1})		----Ca---- (mmol$_c$ L^{-1})		-----K----- (mmol$_c$ L^{-1})		----Mg---- (mmol$_c$ L^{-1})		----Na---- (mmol$_c$ L^{-1})	
			F	G	F	G	F	G	F	G	F	G	F	G	F	G
Feb 2001	0	0-100	40.35	nd	6.05	nd	2.14	nd	0.90	nd	0.12	nd	0.82	nd	0.74	nd
		200-300	45.55	nd	5.93	nd	2.34	nd	1.08	nd	0.04	nd	0.95	nd	0.89	nd
		400-500	39.60	nd	6.11	nd	0.98	nd	0.64	nd	0.06	nd	0.64	nd	0.85	nd
	320	This was not determined on this occasion, only for subsequent sampling.														
	1280	0-100	87.10	nd	6.97	nd	4.98	nd	4.99	nd	0.14	nd	1.94	nd	0.61	nd
		200-300	97.95	nd	6.19	nd	5.37	nd	4.94	nd	0.05	nd	2.88	nd	0.52	nd
		400-500	90.10	nd	6.33	nd	nd	nd	3.47	nd	0.09	nd	2.20	nd	0.86	nd
Sept 2001	0	0-100	59.24	37.00	5.64	6.10	3.92	2.55	1.31	1.39	0.01	0.02	1.14	1.07	2.08	3.16
		200-300	45.05	44.65	5.74	6.20	3.49	2.78	1.53	1.64	0.00	0.02	1.35	1.11	1.57	3.63
		400-500	91.20	35.55	7.39	6.43	6.23	1.84	6.41	1.30	0.13	0.03	1.72	0.89	0.00	3.00
	320	0-100	78.35	43.40	6.70	7.37	5.57	1.18	3.52	2.08	0.03	0.07	2.02	1.23	1.17	2.70
		200-300	65.60	37.85	5.95	6.49	4.48	0.52	2.17	1.38	0.00	0.04	1.71	0.98	1.07	3.07
		400-500	48.40	29.85	6.21	6.62	3.16	0.66	1.13	0.92	0.00	0.02	0.91	0.41	1.10	2.82
	1280	0-100	85.50	62.10	7.41	7.86	6.13	3.40	5.74	3.22	0.10	0.05	1.49	1.46	0.50	3.05
		200-300	95.60	62.40	5.59	6.34	7.74	3.00	2.82	2.15	0.00	0.03	2.96	2.02	1.23	3.83
		400-500	70.75	58.00	6.13	6.78	5.76	1.81	2.82	2.66	0.00	0.02	1.33	1.31	2.49	3.89
Oct 2002	0	0-100	66.40	166.90	6.64	7.86	4.70	2.10	0.61	0.21	0.04	0.17	0.53	0.13	0.54	0.96
		200-300	34.65	50.80	5.79	5.86	4.13	0.54	0.66	1.68	0.02	0.15	0.34	0.75	1.19	0.42
		400-500	36.10	22.85	6.32	6.40	1.05	0.35	0.25	0.17	0.02	0.16	0.15	0.20	0.47	0.74
	320	0-100	43.55	31.00	5.68	7.72	4.89	0.23	1.49	0.29	0.04	0.10	0.12	0.17	0.30	1.36
		200-300	44.50	24.35	5.87	6.52	6.79	0.15	1.16	1.08	0.02	0.09	0.31	0.26	0.39	0.54
		400-500	26.15	23.15	6.53	6.78	3.60	0.14	0.50	0.15	0.02	0.10	0.17	0.12	0.57	0.42
	1280	0-100	53.45	112.75	6.94	7.87	4.52	7.22	1.00	4.87	0.08	0.09	0.01	0.61	0.27	0.43
		200-300	58.60	32.10	6.16	5.98	2.75	3.19	2.09	0.41	0.03	0.08	0.40	0.26	0.54	0.28
		400-500	43.65	27.25	6.57	6.45	3.91	0.56	0.76	2.83	0.02	0.16	0.24	1.40	0.66	0.21
June 2003	0	0-100	48.75	47.25	5.18	5.42	4.62	3.95	1.80	1.99	0.05	0.07	0.72	0.93	0.23	0.21
		200-300	31.10	52.15	5.56	5.78	2.38	4.19	0.84	2.16	0.02	0.02	0.46	1.09	0.20	0.26
		400-500	31.70	47.85	5.69	5.83	2.15	3.33	0.80	1.54	0.02	0.03	0.46	0.83	0.23	0.29
	320	0-100	49.45	31.55	6.17	6.33	7.36	1.81	3.63	1.32	0.04	0.04	1.10	0.51	0.25	0.22
		200-300	36.85	30.55	5.69	5.81	3.05	2.34	1.24	1.08	0.03	0.01	0.58	0.55	0.22	0.24
		400-500	31.60	31.30	5.74	5.85	2.63	2.42	0.82	0.93	0.01	0.01	0.46	0.52	0.23	0.29
	1280	0-100	45.00	33.70	6.56	6.36	4.27	3.33	2.87	1.69	0.06	0.04	0.65	0.55	0.13	0.09
		200-300	44.50	32.85	5.46	5.84	4.92	3.64	2.34	1.26	0.02	0.01	0.91	0.70	0.14	0.16
		400-500	33.85	33.00	5.61	5.92	3.12	3.14	1.43	1.05	0.02	0.03	0.74	0.63	0.19	0.14

The change in pH down the profile for the different sampling dates was not consistent within a single treatment. There was, however, an apparent increase in pH as WTR application rate increased for any particular date, although this was more notable in the upper soil layers (where the WTR was applied). The grassed plots also tended to have slightly higher pH than the fallow plots for equivalent treatment and depth. These trends in EC and pH are again supported by the data given in Sections 10.3.2 and 10.3.3, respectively.

Nitrate concentrations were typically higher in the fallow plots, regardless of treatment. This is possibly due to N uptake by the grass, even though additional N was added to these treatments. In the absence of N uptake by plants on the fallow plots, any N mineralisation that occurred could have led to the observed increase. Apart from some anomalous values, nitrate concentrations tended to decrease with depth on both fallow and grassed plots. The addition of WTR did not seem to have a very marked influence on nitrate concentrations, but it did appear that there were marginal increases with increasing WTR application rates, especially at depth. It may be that the improved aeration (Section 6.4) due to WTR additions slightly increased N mineralisation.

Generally the upper soil layers had higher soluble Ca concentrations, with a decrease down the profile. The grassed plots also tended to have slightly lower concentrations than the fallow plots, again possibly linked to plant uptake. While the change with time was not clear, the addition of WTR did increase Ca concentrations, generally at all depths. Potassium did not show any clear trend at Ukulinga, the concentrations being slightly higher for all treatments for the February 2001 sampling. The fallow and grassed plots did not show discernible differences either, even though fertiliser K was added to the grassed plots. Magnesium showed a similar pattern to that of Ca, although there appeared to be a decrease in Mg concentration with time. Sodium concentrations were generally low.

Chloride and bicarbonate concentrations were also measured (data not shown). Bicarbonate concentrations were negligible, and while some elevated Cl concentrations were noted, in particular for the high WTR treatments, the distribution was not consistent, with some high levels also being noted in the control treatments. Unlike the laboratory studies (Section 15.3.2), the addition of WTR did not have a clear impact on Cl concentrations, possibly due to losses prior to commencement of these investigations.

14.5 Soil water collectors

It is clear that in the samples collected during 2000 there was an increase in EC as WTR application rate increases (Table 14.10) for all sampling dates. There was also a notable increase in Ca and K concentrations at the 1280 Mg ha^{-1} WTR application rate, while the 320 Mg ha^{-1} treatment and the control were similar. Sodium concentrations were generally low, although there was an increase for all treatments at the last sampling period. Magnesium showed the highest concentrations at the 320 Mg ha^{-1} WTR application rate, with the 1280 Mg ha^{-1} treatment being marginally lower than the control treatment at all sampling dates.

Table 14.10 Characteristics of soil solution collected from selected fallow plots at Ukulinga Farm at selected sampling dates during the year 2000 using soil water collectors. The soil water collectors were positioned in the upper half of the plots

Date	Treatment (Mg ha^{-1})	EC (mS m^{-1})	-----Ca----	-----K-----	-----Mg-----	------Na----
			----------(mmol$_c$ L^{-1})----------			
18/05/00	0	54.50	1.42	1.60	2.76	bd
	320	79.50	1.79	1.95	3.61	bd
	1280	118.00	4.94	3.77	2.66	bd
26/05/00	0	49.60	1.43	1.48	3.11	0.01
	320	ns	ns	ns	ns	ns
	1280	108.70	4.70	3.29	2.75	0.01
02/10/00	0	49.40	1.19	1.36	1.93	0.17
	320	63.20	1.29	1.59	2.99	0.16
	1280	106.30	4.29	3.47	1.85	0.17

ns no sample was obtained from the soil water collector.

The chemical analyses of the solutions collected during 2001 and 2002 are given in Table 14.11 (basic chemical characteristics) and Table 14.12 (metal concentrations). As the soil water collector requires a relatively moist soil profile to function properly, reasonably good rainfall was required to collect adequate sample, hence frequently some treatments did not produce results.

The EC showed a similar pattern to that seen for the earlier sampling dates. Where sample was obtained the collectors placed outside a plot showed a similar value to that found inside that plot. As for the saturated paste data (Section 14.4), the EC of the grassed plots tended to be lower than the equivalent fallow plot. There was also less difference between ECs of the treatments for the grassed plots.

Nitrate concentrations showed a similar pattern to that seen for saturated paste data (Section 14.4). Generally the concentrations of the fallow plots were higher than the equivalent grassed plots (due to uptake of N by the grass), while there was an apparent increase in concentration with increasing WTR application (although this could not be determined with confidence due to lack of sample from many treatments). Where adequate sample was collected, it would appear that nitrate concentrations were marginally lower outside the plots than inside for the fallow treatments. The grassed plots showed a reverse trend, the outside having higher nitrate concentrations, possibly due to the lack of vegetation. Phosphate concentrations were all below detection, even in the control plots and the fertilised grassed plots.

Calcium and Mg concentrations followed a similar trend to that seen for nitrate. In the fallow plots there was an increase in the concentrations of both elements with increasing WTR application rate, with the values outside the plots being marginally lower. In the grassed plots this pattern was the same, except that outside the plots the concentrations were generally similar to the concentrations found inside the plots. Overall the grassed plots had lower concentrations than the fallow plots. Potassium concentrations were generally very low, while Na showed some elevated levels. This

may reflect the increase for the last sampling date noticed for the earlier sampling periods shown in Table 14.10. The pattern of distribution was similar to that of Ca. The concentrations were notably higher than recorded for the saturated paste extracts, the cause of this not being determined, although with no apparent ill-effects on grass growth or the physical properties of the soil.

Table 14.11 Characteristics of soil solution collected from 6 November 2001 to 10 February 2002, for selected fallow (F) and grassed (G) plots at Ukulinga Farm. "Upper" refers to the collector positioned in the upper half of a plot; "Out" refers to the collector positioned about 0.4 m outside the lower end of a plot

Date	Treatment (Mg ha^{-1})	Position	EC (mS m^{-1})		NO_3		Ca		K		Mg		Na	
					(mmol$_c$ L^{-1})									
			F	G	F	G	F	G	F	G	F	G	F	G
6/11/01	0	Upper	73.00	ns	0.38	ns	1.19	ns	0.04	ns	0.55	ns	0.10	ns
	320	Upper	71.80	ns	0.21	ns	0.38	ns	0.04	ns	0.48	ns	0.18	ns
	1280	Out	ns	79.50	ns	1.70	ns	3.26	ns	0.03	ns	2.74	ns	1.14
28/11/01	0	Upper	73.80	35.20	5.66	0.62	2.43	0.98	bd	0.01	2.97	1.09	1.49	1.69
	320	Upper	65.20	38.60	3.96	bd	1.46	1.04	0.01	0.02	1.89	1.09	4.35	1.62
	1280	Upper	124.60	53.40	9.06	0.02	5.46	2.54	0.08	0.02	4.59	1.91	4.40	1.21
	1280	Out	122.10	60.70	7.36	1.08	4.73	2.03	0.09	bd	4.34	2.34	4.35	1.19
18/12/01	0	Upper	55.00	44.10	3.77	1.04	1.67	0.82	bd	bd	1.57	0.94	1.18	2.04
	320	Upper	52.70	ns	2.36	ns	1.24	ns	bd	ns	0.99	ns	2.23	ns
	1280	Upper	ns	62.50	ns	bd	ns	2.87	ns	0.02	ns	1.68	ns	1.59
	1280	Out	97.00	51.50	4.72	0.28	2.85	1.83	0.01	0.06	2.41	1.35	2.28	0.92
05/02/02	0	Upper	ns	37.80	ns	0.02	ns	0.58	ns	bd	ns	0.89	ns	1.85
	1280	Upper	ns	49.10	ns	0.04	ns	2.19	ns	0.02	ns	1.06	ns	1.62
	1280	Out	ns	44.00	ns	0.23	ns	1.39	ns	bd	ns	1.03	ns	1.40
10/02/02	0	Upper	40.90	43.50	2.26	bd	1.28	0.57	0.01	bd	1.02	0.97	0.97	1.91
	320	Upper	ns	53.40	ns	bd	ns	1.04	ns	0.01	ns	0.98	ns	2.41
	1280	Upper	ns	53.10	ns	0.11	ns	2.19	ns	0.03	ns	1.15	ns	1.43
	1280	Out	ns	44.50	ns	bd	ns	1.30	ns	0.01	ns	1.07	ns	1.40

ns no sample was obtained from the soil water collector.
bd below detection.

Metal concentrations were all very low (Table 14.12), with Ni being below detection or negligible (results not shown). There did not appear to be any definite trend in metal distribution across treatments, time or position. Generally the concentrations for any one metal were similar regardless of the treatment, although the concentrations of Zn and Fe were marginally lower in the grassed plots than in the fallow plots. Overall the metal concentrations were very low and would not present any problems for toxicity to groundwater or plants.

Table 14.12 Metal concentrations of the soil solution collected from 6 November 2001 to 10 February 2002 for selected fallow (F) and grassed (G) plots at Ukulinga Farm. "Upper" refers to the collector positioned in the upper half of a plot; "Out" refers to the collector positioned about 0.4 m outside the lower end of a plot

Date	Treatment (Mg ha^{-1})	Position	----Cd----		----Co----		----Cr----		---Cu----		----Fe-----		----Mn----		-----Zn----	
			----------(µg L^{-1})----------													
			F	G	F	G	F	G	F	G	F	G	F	G	F	G
6/11/01	0	Upper	9	ns	8	ns	5	ns	49	ns	19	ns	10	ns	102	ns
	320	Upper	7	ns	0	ns	5	ns	23	ns	14	ns	5	ns	28	ns
	1280	Out	ns	24	ns	bd	ns	8	ns	88	ns	20	ns	24	ns	54
28/11/01	0	Upper	16	22	5	4	9	29	25	23	2	18	33	13	96	4
	320	Upper	54	15	6	bd	11	5	17	87	16	19	12	26	29	17
	1280	Upper	ns	25	ns	9	ns	30	ns	71	ns	42	ns	21	ns	3
	1280	Out	24	19	5	bd	21	16	23	7	22	20	25	27	18	12
18/12/01	0	Upper	24	25	6	3	54	34	32	30	14	34	51	32	35	7
	320	Upper	25	ns	6	ns	32	ns	16	ns	26	ns	21	ns	12	ns
	1280	Upper	ns	26	ns	3	ns	52	ns	55	ns	37	ns	20	ns	4
	1280	Out	24	25	4	19	40	48	18	31	47	13	73	20	317	4
05/02/02	0	Upper	ns	23	ns	6	ns	59	ns	112	ns	43	ns	49	ns	26
	1280	Upper	ns	28	ns	22	ns	60	ns	60	ns	35	ns	93	ns	9
	1280	Out	ns	25	ns	11	ns	64	ns	15	ns	47	ns	42	ns	4
10/02/02	0	Upper	26	26	17	7	73	58	20	72	28	41	177	775	39	12
	320	Upper	ns	26	ns	17	ns	81	ns	54	ns	87	ns	14	ns	10
	1280	Upper	ns	25	ns	13	ns	81	ns	42	ns	46	ns	69	ns	3
	1280	Out	ns	28	ns	4	ns	74	ns	10	ns	49	ns	57	ns	7

ns no sample collected.
bd below detection.

14.6 Groundwater analysis at Brookdale Farm

The results for the dam are given in Appendix 14.1 and those for the borehole in Appendix 14.2. From these data it is clear that there is no evidence of contamination of groundwater as a result of the disposal of the WTR at Brookdale Farm. This supports the results discussed above from both the saturated paste extracts of the soils on the Brookdale field experiment and the evidence from the soil water collectors at Ukulinga Farm.

14.7 Conclusions

From an agricultural point of view, land disposal of the Midmar WTR might be deemed unproductive since it did not bring about any improvements in the growth of the grasses at either field trial site. This aspect was, however, neither the only nor the main issue. It is clearly encouraging from a land disposal, and thus an economic,

viewpoint that no negative effects on either the perennial ryegrass or tall fescue were evident.

The main issue is safe disposal of the material onto land, and to that extent it can be said that the investigated option of land application is appealing. Whether the material is spread on the surface (mulch treatment) or incorporated with the soil did not affect the performance of the grass species. Indeed the successful growth of grass in the mulch treatment (where the majority of the roots remained concentrated) was indicative of the possible use of this WTR as a soil substitute.

Although some effects of especially the very high rate of addition of the WTR were found on the soluble elements as measured in the saturated paste extracts, the land treatment of the WTR did not seem to have any drastic influences on soil chemical properties under field conditions with respect to the migration of these elements, EC or pH. The results from the soil water collectors at Ukulinga that recorded very low leaching volumes and no contamination also support these findings. Further support for this conclusion is given by the data from the dam and the borehole at Brookdale Farm monitored by Umgeni Water.

It is clear that no leaching of any potentially toxic heavy elements occurs even under the extremely high rates of WTR applied in the field experiments. This therefore shows that the danger of groundwater pollution as a result of the land disposal of the Midmar WTR is minimal.

The WTR may therefore release its solutes at such a rate that they tend to merge and be diluted within the soil as a whole. As commented in Chapter 3 and again later in Chapter 17 with regards to P, water treatment residues have some characteristics of a slow release ‘fertiliser’, and the data given above reflect this behaviour.

CHAPTER 15

THE EFFECT OF A WATER TREATMENT RESIDUE ON SOME CHEMICAL CHANGES IN SOILS

15.1 Introduction

Two sets of chemical properties of the Midmar water treatment residue (WTR) stand out as those likely to have the greatest impact on soil chemical changes. These are the basic pH and free carbonates on one side, and the extractable ions and soluble solutes on the other. In Chapter 13 it was shown in a pot experiment how this WTR increased pH in all five soils used, and decreased the amount of extractable acidity in the Ia-C and Nb-F soils. These effects clearly indicate the liming potential of this material.

When the WTR is applied to soil, dissolution of some of its constituents should be one of the first processes to occur. One effect of this would be an increase in the electrical conductivity of the soil solution, followed by cation exchange reactions involving soluble and extractable cations. One of these exchange reactions is that involving Al and Ca that resulted in the liming effect seen in Chapter 13.

Most of the studies that have been carried out on WTRs (Chapter 3) have concerned alum materials. Also, except in a few investigations, the liming/pH influence of the WTRs has not been an issue. From an environmental point of view liming might be used to reclaim chemically degraded soils (Logan, 1990) and, as a corollary to that, could prevent chemical degradation of soils; a major agricultural benefit of lime is the amelioration of acid soils. Under controlled conditions, WTR has been found to have different influences on soil pH values with a decrease (Wang *et al.*, 1998), no marked change (Rengasamy *et al.*, 1980) and an increase (Elliott and Singer, 1988; Heil and Barbarick, 1989; Ahmed *et al.*, 1997) in this soil property having been reported. In the field, Geertsema *et al.* (1994) reported that the WTR (and lime) did not have any significant effects on pH after 30 months of application.

These differences in results that at first sight appear contradictory can be explained by considering the following. The alum WTRs used by Wang *et al.* (1998) had low pH values of 3.9 and 5.3. Rengasamy *et al.* (1990) used low rates of the alum WTR with the highest being 20 Mg ha^{-1}. This, coupled with the relatively low pH (6.5) of the material and thus probably insignificant quantities of free carbonates, meant that no appreciable pH changes could be expected. On the other hand Elliott and Singer (1988), Heil and Barbarick (1989) and Ahmed *et al.* (1997 used ferric (pH 9.3), ferric (pH 7.3) and alum (pH 7.45) WTRs, respectively. The corresponding effects were to raise the soil pH values from 5.3 to 8.0 at 8% dry mass application, from 4.7 to 7.0 at 20 g kg^{-1}, and from 5.7 to 7.5 at 800 Mg ha^{-1}, respectively. If a depth of incorporation of 0.15 m and a soil bulk density of 1 340 kg m^{-3} are assumed, the first two rates would be equivalent to 120 Mg ha^{-1} and 50 Mg ha^{-1}, respectively.

Although applied to ameliorate acid soils, lime has, however, also been demonstrated to sometimes have undesirable side effects, amongst which were to reduce extractable Mg (Grove *et al.*, 1981) and to decrease K potential (Wooldridge, 1990). Also of concern is how rapidly, and to what extent, the lime reacts with soils. Because of its slow rate of reaction the Fertilizer Advisory Service of the Department of Agriculture

in KwaZulu-Natal recommends the application of lime about a month before planting; this also assumes that the soil is adequately moist in that period.

Cation exchange reactions determine the relative affinity of the competing cations for the soil adsorption sites (Kumar *et al.*, 1997), and can affect chemical transport in soils (Leij and Dane, 1990). Both of these are of considerable relevance to the land disposal of WTR. The soluble products of the cation exchange reactions expected after dissolution of the WTR would indicate which species are likely to be redistributed or leached. Solubility and redistribution of solutes is critical in determining the agronomic acceptability and environmental influence of the land disposal of WTR.

Although the materials investigated in this report (Section 4.3.2) have low amounts of free carbonates (with the exception of the Rand WTR) and relatively low electrical conductivities, at the quantities that may be applied these might end up at excessive levels. Thus over-liming and salinisation might result which, from an agronomic point of view, would exclude such high application rates. However, as pointed out before, the study is of environmental concern as well, so that the quantities of WTR land treated would not only be limited by agronomic concerns but also by perceived effects on the environment.

The objectives of this section are as follows:

- to establish to what extent the Midmar WTR increases pH and reduces acidity in acid soils;
- to monitor the reaction of the WTR with respect to some chemical changes over time;
- to determine the effects of the WTR on soil water extracts; and
- to establish the effects of the WTR on extractable basic cations.

15.2 Materials and methods

15.2.1 Incubation experiment: set-up and monitoring

The 11 soils described previously (Section 13.2.1) were used with the strongly acid Av and Ia-W soils of particular interest to test the liming potential of the WTR.

Soil samples (2.5 kg) of the soils, excluding the Av and Ia-W, were incubated at ambient temperature and field capacity for 3 months after being treated with WTR rates of 0, 40, 80, 120, 320 and 1280 Mg ha^{-1}. In order to monitor the WTR reaction, sub-samples were taken during the incubation period, with the first being of the initial dry mixture (indicated as 'Day 1' in the results). Other samples were taken as indicated in the results. After air-drying, these samples were analysed for pH (duplicate 10 g samples suspended in 25 mL water for 1 h). Extractable cations were not measured, since the salt solutions used could confound results by extracting potentially reactive, but as yet not reacted, species (Section 13.3.2). pH was also measured in 1M KCl (1:2.5 soil:solution ratio for 1 h) as a monitoring exercise rather than to follow trends.

The experiment using the Av and Ia-W soils was set-up after the one with the other nine soils was terminated, and ran for 2 months. The same rates of WTR were applied but with the addition of 20, 60 and 100 Mg ha^{-1}, and dolomitic lime at rates equivalent to 7.5 and 15 Mg ha^{-1}. The higher lime level was calculated to reduce the acid saturation to 1%. The monitoring procedure was the same as for the nine soils.

All treatments were based on the density of the soil sample and an assumed field incorporation of 0.15 m.

15.2.2 Extractable ions and cation exchange capacity

At the termination of the incubation experiment, duplicate air-dry samples of selected treatments were extracted with 0.1M $BaCl_2$ (2 g sample extracted with 20 mL solution for 1 h) or 1M KCl (5 g sample with 50 mL solution). Water extracts were obtained by shaking soil with distilled water in a soil:water ratio of 1:2 (Sonnevelt and Van der Ende, 1971; cited by Rhoades, 1996). This ratio was selected as it is relatively close to a saturation extract but easier to obtain, and also because relative changes rather than absolute solute concentrations were needed (Rhoades, 1996). Samples were analysed for EC and pH (Chapter 4), acidity (titration with 0.01M NaOH), Ca and Mg (atomic absorption spectrophotometry) and K (flame emission), bicarbonate and chloride (United States Salinity Laboratory Staff, 1954), nitrate (by auto analyser; Chapter 4), phosphate (Murphy and Riley, 1962) and sulphate (by precipitation as barium sulphate).

The cation exchange capacity was determined in the Av and Ia-W soils for selected treatments by extracting the soil four times with strontium chloride followed by extraction with ammonium acetate (Hughes and Girdlestone, 1994).

15.3 Results and discussion

15.3.1 pH and extractable acidity changes with time

The results of monitoring the reaction of the WTR are given in Appendix 15.1 for the nine soils. There was an increase in pH in both water and KCl as the amount of WTR applied increased. The increase was generally observed in the first 14 days, after which the pH tended to remain fairly constant.

There were some soils and treatments that did not fully follow this general trend. These deviations were not, however, caused by the applied material since the control results were similarly affected. In some cases the pH decreased after reaching a maximum i.e., the Hu-M soil after 35 days; Hu-T (water pH) after 14 days; Ia-C (water pH) at all WTR rates after about 35 days; Nb-A (water pH) at all rates of WTR; Nb-F (water pH) at WTR rates <320 Mg ha^{-1}; Sd (water pH) at all levels of WTR; Sd (KCl pH) at WTR levels < 320 Mg ha^{-1}; and We (pH water) where the WTR was applied at rates < 320 Mg ha^{-1}. In the Va soil the pH did not show any clear response to the WTR over time although the pH measured in both water and KCl did increase with increase in the application rate of WTR.

The most common factor between these somewhat aberrant results is that the pH was measured in water. It is possible therefore that the poorly buffered water suspensions

were subject to a decrease in pH on absorbing atmospheric carbon dioxide. Also at the relatively low rates of application where the decrease in pH was mostly observed, the WTR probably did not supply enough soluble salts to resist the carbon dioxide influence.

In the Av and Ia-W soils (Appendix 15.2), the maximum pH was reached after 6 days for both the lime and WTR treatments. Comparing these results with those of the other nine soils, it appears that liming materials react faster where pH is initially lower, although a direct comparison is not possible as the experiments were conducted at different times and therefore at slightly different ambient temperatures.

Potassium chloride extractable acidity was also fairly constant in both soils after Day 6 for rates up to 100 Mg ha^{-1} in the Av soil and 120 Mg ha^{-1} in the Ia-W soil (Appendix 15.3). The lime treatment (L1 rate) behaved similarly. For WTR rates higher than those mentioned above for the respective soils, and for the L2 rate of lime, the reaction was completed in an even shorter time.

15.3.2 Extractable ions and cation exchange capacity

As expected, since the WTR contains a high amount of extractable Ca and an appreciable content of Mg (Section 4.3.4), the salt extractable forms of these cations in the nine soils increased with increasing application rate of WTR (Table 15.1a). Results for the Av and Ia-W soils are given in Table 15.1b. Potassium and Na (results not shown) were both unaffected and were in low concentrations throughout (<0.5 $cmol_c\ kg^{-1}$). As in the case of lime, the WTR increased extractable Ca and Mg whilst reducing acidity and Al. The decrease in acid saturation was due to both an increase in basic cations and a decrease in acidic cations.

Table 15.1a Calcium and magnesium extracted with barium chloride solution from nine soils treated with four rates of Midmar water treatment residue

Soil	WTR (Mg ha^{-1})	Ca --$cmol_c\ L^{-1}$--	Mg	Soil	WTR (Mg ha^{-1})	Ca ---$cmol_c\ L^{-1}$---	Mg	Soil	WTR (Mg ha^{-1})	Ca ---$cmol_c\ L^{-1}$---	Mg
Hu-F	0	5.04	1.94	Hu-M	0	4.97	3.29	Hu-T	0	2.36	1.48
	80	6.48	2.19		80	5.27	3.41		80	2.68	1.63
	320	7.03	2.41		320	5.46	4.09		320	5.65	1.79
	1280	8.77	2.77		1280	5.91	4.71		1280	10.60	3.41
Ia-C	0	1.99	0.91	Nb-A	0	0.81	0.58	Nb-F	0	1.65	0.56
	80	2.22	1.57		80	1.43	0.63		80	2.16	0.60
	320	6.46	1.65		320	2.55	0.72		320	4.55	0.77
	1280	11.76	3.33		1280	5.13	1.75		1280	8.46	3.24
Sd	0	4.78	4.76	Va	0	4.69	2.53	We	0	4.91	2.82
	80	6.74	5.04		80	5.35	2.80		80	7.11	3.02
	320	8.24	5.90		320	7.21	3.43		320	8.09	3.25
	1280	8.34	6.78		1280	8.80	3.54		1280	8.90	3.38

Table 15.1b pH (water and KCl), potassium chloride extractable cations and acid saturation in the Av and Ia-W soils treated with Midmar water treatment residue (R) and lime (L)

Soil	Treatment (Mg ha^{-1})	pH (H_2O)	pH (KCl)	Acidity	Al	Ca	Mg	Acid satn
				---------- $cmol_c$ kg^{-1} ----------				(%)
Av	R0	4.13	3.95	3.45	2.93	0.49	0.13	84.7
	R20	4.51	4.02	1.91	1.58	1.94	0.33	45.7
	R40	4.83	4.27	0.86	0.59	2.68	0.47	21.5
	R60	5.32	4.67	0.14	0.14	3.43	0.63	3.3
	R80	5.66	4.94	0.06	0.13	3.93	0.77	1.3
	R100	5.86	5.22	0.05	0.06	5.06	0.89	0.8
	R120	6.07	5.55	0.04	0.03	5.34	0.93	0.6
	R320	6.80	6.87	0.03	0.01	8.26	1.23	0.3
	R1280	7.36	7.48	0.00	0.00	10.34	2.89	0.0
	L7.5	6.26	5.43	0.02	0.00	2.40	2.50	0.4
	L15	7.07	6.77	0.01	0.00	3.46	3.31	0.2
Ia-W	R0	3.83	3.84	3.89	3.35	0.41	0.18	86.8
	R20	4.16	3.97	2.63	1.85	1.71	0.41	55.4
	R40	4.41	4.13	1.57	0.77	2.67	0.71	31.7
	R60	4.60	4.24	0.86	0.42	2.93	0.85	18.5
	R80	4.73	4.35	0.55	0.27	4.77	0.94	8.8
	R100	4.91	4.58	0.25	0.12	5.49	1.15	3.6
	R120	5.01	4.67	0.17	0.07	6.43	1.33	2.1
	R320	5.94	5.90	0.05	0.02	10.39	2.06	0.4
	R1280	6.91	7.16	0.00	0.00	13.13	3.00	0.0
	L7.5	5.33	4.33	0.84	0.49	2.27	2.27	16.0
	L15	5.90	5.39	0.05	0.01	3.41	3.41	0.7

In the Av soil an acid saturation of about 20% was achieved at about 40 Mg ha^{-1} of applied WTR and at pH values of 4.83 (H_2O) and 4.27 (KCl). The comparable values for the Ia-W soil were 60 Mg ha^{-1} of WTR and pH values of 4.60 (H_2O) and 4.24 (KCl). Thus the Ia-W soil, with appreciably higher organic matter content that contributes to buffering, needed a higher rate of WTR to reach similar pH values and acid saturation. The lower lime level in the Ia-W soil gave an acid saturation of 16% at a pH of 5.33 (H_2O) and 4.33 (KCl), the water value being notably higher than those of the comparative WTR application rates. If lime and the WTR are compared with respect to pH (H_2O), then in the Av soil the lower lime level gave the value of a WTR rate between 120 and 320 Mg ha^{-1} and between 100 and 120 Mg ha^{-1} for the pH (KCl). In the Ia-W soil the corresponding values were again between 120 and 320 Mg ha^{-1} for pH (H_2O) and about 80 Mg ha^{-1} for pH (KCl). So different results are obtained by using acid saturation or pH to compare the liming potential of the WTR with that of the lime in terms of equivalent application rates of WTR.

Results for water extractable ions (Tables 15.2a and b) showed a similar trend to that of salt extractable cations for Ca and Mg. For the lime treatment, the concentrations are very low, with Ca and Mg amounts being equivalent to those of between 0 and 80 Mg ha^{-1} of applied WTR. This was expected since in these variable charge soils the increase in pH will have created negative charges that attracted Ca and Mg to the

surfaces of soil colloids thus reducing their solubility. The data in Tables 15.2 a and b also show that there is an increase in chloride and nitrate with the addition of WTR.

Table 15.2a Water extractable ions from nine soils treated with four rates of Midmar water treatment residue

Soil	WTR (Mg ha^{-1})	Ca	Mg	Cl	NO_3	Soil	WTR (Mg ha^{-1})	Ca	Mg	Cl	NO_3
		--------cmol$_c$ L^{-1}-------						--------cmol$_c$ L^{-1}-------			
Hu-F	0	0.24	0.14	0.06	0.40	Hu-M	0	0.27	0.42	0.04	0.11
	80	1.27	0.17	0.08	0.44		80	0.30	0.47	0.04	0.97
	320	1.53	0.20	0.13	0.53		320	0.33	0.45	0.04	0.97
	1280	2.51	0.36	0.35	1.08		1280	0.39	0.42	0.07	0.97
Ia-C	0	0.27	0.27	0.07	0.91	Nb-A	0	0.02	0.03	0.08	0.09
	80	0.54	0.30	0.09	1.25		80	0.07	0.08	0.10	0.15
	320	0.71	0.40	0.15	1.37		320	0.22	0.12	0.12	0.35
	1280	1.38	0.43	0.48	1.71		1280	0.99	0.28	0.26	1.06
Sd	0	0.27	0.20	0.00	0.05	Va	0	0.05	0.05	0.08	0.08
	80	0.44	0.32	0.12	0.72		80	0.17	0.39	0.11	0.22
	320	0.68	0.37	0.22	0.73		320	0.31	0.58	0.15	0.47
	1280	0.85	0.45	0.23	0.76		1280	0.97	0.78	0.34	0.70

Soil	WTR (Mg ha^{-1})	Ca	Mg	Cl	NO_3
		----------cmol$_c$ L^{-1}----------			
Hu-T	0	0.15	0.16	0.04	0.35
	80	0.20	0.18	0.06	0.59
	320	0.33	0.22	0.15	0.62
	1280	1.16	0.47	0.48	1.03
Nb-F	0	0.04	0.03	0.06	0.09
	80	0.14	0.08	0.10	0.12
	320	0.27	0.12	0.14	0.28
	1280	1.00	0.28	0.31	0.63
We	0	0.02	0.02	0.09	0.01
	80	0.58	0.12	0.15	0.31
	320	1.33	0.19	0.20	0.48
	1280	1.50	0.37	0.30	0.66

The chloride results could be expected since the WTR contains significant quantities of this element (Section 13.3.2). Nitrate, however, was not expected to increase since both Kjeldahl and soluble forms were low (Table 4.4). If the nitrate originated from the soil, then it could have been through supply of moisture, or pH amelioration that increased the activity of mineralising microorganisms. If this were the case, then the Nb-A and Nb-F soils, with low contents of organic carbon, should have shown little response. Results in Table 15.2a however, show that the nitrate levels increased by between seven- and ten-fold at the highest rate of WTR in these soils. If an increase in pH were the cause, the higher nitrate levels would have been observed only in the Av and Ia-W soils which had low initial pH values; again this was not the case. Also against the role of pH was the fact that lime did not increase the concentration of nitrate compared to the control.

Table 15.2b Water extractable ions in the Av and Ia-W soils treated with Midmar water treatment residue (R) and lime (L)

Soil	Treatment (Mg ha^{-1})	Ca	Mg	Cl	NO_3
		----------(cmol$_c$ L^{-1})----------			
Av	R0	0.17	0.05	0.06	0.15
	R80	0.39	0.09	0.13	0.21
	R320	1.09	0.20	0.35	0.44
	R1280	1.54	0.45	0.64	0.67
	L7.5	0.18	0.32	0.07	0.17
	L15	0.25	0.44	0.11	0.19
Ia-W	R0	0.09	0.08	0.05	0.35
	R80	0.43	0.15	0.20	0.44
	R320	1.30	0.36	0.55	0.75
	R1280	2.49	0.61	0.74	1.16
	L7.5	0.14	0.40	0.03	0.04
	L15	0.16	0.50	0.06	0.05

To clarify whether the increase in nitrate with applied WTR was a function of time, non-incubated soil-WTR and soil-lime mixtures of five selected soils were compared with the incubated soils. These results (Table 15.3) show that incubation increased water extractable nitrate, and that untreated soils also released nitrate with time.

Table 15.3 Water extractable nitrate in selected non-incubated and incubated soils treated with Midmar water treatment residue (R) and lime (L)

Soil	Treatment (Mg ha^{-1})	Non-incubated	Incubated
		----nitrate (cmol$_c$ L^{-1})----	
Av	R0	0.11	0.19
	R80	0.11	0.24
	R320	0.09	0.45
	R1280	0.07	0.92
	L7.5	0.10	0.11
	L15	0.11	0.12
Ia-W	R0	0.07	0.32
	R80	0.07	0.40
	R320	0.06	0.79
	R1280	0.05	1.29
	L7.5	0.06	0.29
	L15	0.06	0.32
Hu-M	R0	0.03	0.24
	R80	0.03	0.43
	R320	0.03	0.67
	R1280	0.03	0.73
Sd	R0	0.00	0.03
	R80	0.00	0.60
	R320	0.00	0.67
	R1280	0.00	0.83
Nb-A	R0	0.00	0.03
	R80	0.00	0.14
	R320	0.00	0.32
	R1280	0.00	0.71

Some of the water extractable nitrate came from the soil, but the majority came from the WTR. The incubated Nb-A soil, for example, released only 0.03 $cmol_c\ L^{-1}$ of nitrate, but when mixed with the lowest rate of the WTR (80 Mg ha^{-1}) four times as much nitrate was released.

Bicarbonate, phosphate and sulphate could not be detected by the analytical methods used. Similarly amounts of K, Na and NH_4, were either very low or undetectable. Calcium, Mg, Cl and NO_3 were thus the dominant and significant ions in the water extracts; the others can be considered not to be influential at the very low concentrations measured. Cation exchange capacity in the Av and Ia-W soils increased with increase in amount of WTR or lime applied (Table 15.4) although it was only at the 1280 Mg ha^{-1} application rate that the increase was significant.

Table 15.4 Changes in the cation exchange capacity (CEC) of the Av and Ia-W soils after application of Midmar water treatment residue (R) and lime (L)

Treatment (Mg ha^{-1})	CEC ----($mmol_c\ kg^{-1}$)----	
	Av	**Ia-W**
R0	1.1	1.5
R80	1.1	1.4
R320	1.9	2.1
R1280	4.0	5.4
L7.5	1.4	1.7
L15	1.7	1.9

15.4 Conclusions

The Midmar WTR applied to a range of soils increased pH, extractable Ca and Mg, soluble salt content, chloride, nitrate and cation exchange capacity. From an agronomic point of view, these are favourable changes. From an environmental point of view there might be some concern with respect to increased solubility of chloride and nitrate. These two ions are highly mobile and might cause relatively high amounts of Ca and Mg, the other dominant ions, to be leached to the groundwater. However, the evidence from the field experiments is that such amounts are low. Perhaps of greater concern, however, would be if heavy metals were amongst such companion cations. Again the field experiment evidence is that such movement is negligible but the following chapter investigates this question from a laboratory perspective.

CHAPTER 16

WATER TREATMENT RESIDUE AND BEHAVIOUR OF SOME TRANSITION METALS

16.1 Introduction

The concentrations of heavy metals in soils are of importance for three main reasons i.e., deficiency of those which are essential nutrients, toxicity to animals or plants, and migration to water bodies or groundwater.

The fate of metals, both natural and anthropogenic, in soil is determined by the extent of their retention by soil constituents. Retention is in turn governed by *inter alia* the chemical and physical properties of the soil, which determine the form in which the metal exists e.g. soluble, exchangeable, etc. This controls the extent of mobility which decides whether the cation migrates or not and, if so at what rate and to what extent. Amongst chemical properties that affect sorption are pH (Ma and Liu, 1997; Filius *et al*., 1998), other cations (Bibak, 1997; Hanafi and Sjiaola, 1998) and electrolyte or soil solution concentration (Pardo and Guadalix, 1996; Escrig and Morell, 1998).

Although it is generally considered that most heavy metals are virtually immobile in soils (Karathanasis, 1999), there nevertheless are conditions under which this assumption does not hold true. Moalla and Pulford (1995) concluded that flooding could lead to lowering of redox potential that could mobilize and encourage redistribution of iron. Arnesen and Singh (1998) reported increases in plant available Cu and Zn following application of some organic materials. Organic anions derived from these materials presumably formed relatively soluble complexes with these cations. Sub-surface migration of Cu and Zn (Karathanasis, 1999) has been shown to be enhanced by colloids in a laboratory study in undisturbed columns. Application of urea was found to increase Cd concentrations in wheat grain grown in a pot experiment (Mitchell *et al*., 2000). The effects were attributed to increase in ionic strength and cation exchange between Cd and ammonium, a product of urea hydrolysis.

Disposal of water treatment residue (WTR) to land, by virtue of it containing some heavy metals, would constitute anthropogenic addition of these species. These metals in the WTR would add to those already in the soils from weathering of minerals. Anthropogenic additions may pose a greater threat to the environment because of animal and plant uptake at the surface, and also because metal forms from such sources are more bioavailable and soluble and thus are environmentally unstable (Naidu *et al*., 1997).

Elliott *et al*. (1990b) investigated the forms of metals in alum and ferric chloride WTRs but not in soils treated with these materials. Of concern in the current study was the response of soils to metals after treatment with WTR (rather than the transformation of WTR in soils). Objectives of this chapter are as follows:

- to determine the effect of the Midmar WTR on metal sorption by soils; and
- to establish the nature of the association of metals in soils following addition of the Midmar WTR.

16.2 Materials and methods

16.2.1 Soils

Some treated samples of soils from the pot experiment (Chapter 13) and incubation experiment (Chapter 15) were included in different aspects of the investigation. Field samples from the two trial sites at Brookdale and Ukulinga were also included for certain aspects. All samples were analysed in duplicate.

16.2.2 Sorption of metals as affected by water treatment residue and lime

To 1 g of soil was added 50 mL of 0.005M $CaCl_2$ solution containing 50 µg of Cd, Ni or Zn. After 6 h of end-over-end shaking, the suspensions were centrifuged, filtered and analysed by atomic absorption spectrophotometry (AAS) for the metals concerned. Cadmium was chosen to represent potential phytoxicity and zootoxicity, Ni because it is used as an indicator cation for safe disposal of biosolids, and Zn to represent a nutrient that is often deficient in South African soils.

16.2.3 Fractionation of metals in the water treatment residue and soils

Metal fractions were determined by the method of Johnson and Petras (1998). The method involved separating the fractions into water soluble plus exchangeable by 0.05M $CaCl_2$ extraction, inorganically bound forms extracted with acetic acid (2.5% v/v), organically bound forms extracted with 0.1M potassium pyrophosphate, that bound in amorphous oxides extracted with acid ammonium oxalate (pH 3.0), and the mineral lattice (residual) form as analysed in a sulphuric acid/hydrofluoric acid digest. The exchangeable and inorganically bound forms were extracted from 4 g sample equilibrated for 17 h with 40 mL solution; the organic and amorphous fractions from 1 g sample equilibrated for 17 h in 50 mL solution. The residual fraction was not included in the current study. Metals investigated in the WTR and soil samples were Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn. The procedure followed a batch methodology rather than a sequential one. The results are thus expressed as absolute concentrations of the metals calculated by subtracting the concentration obtained in the weaker extractant from that in the next harsher extractant. Negative differences were taken as zero.

16.2.4 Depth distribution of metals in field soils

The same metals (Section 16.2.3) were analysed from depth intervals of 0-200, 200-400 and 400-600 mm of the Brookdale Hu-M soil sampled in 1999 and 2000 (Section 5.8). From Ukulinga soil samples collected in 1999 and 2001 were used (Section 5.8), although in the former only the 0-200 mm depth samples were available. Samples were analysed from the control plots and 1280 Mg ha^{-1} WTR treatments (both mulched and incorporated at Brookdale). A 1 g sample of soil was extracted with 50 mL of 0.05M $CaCl_2$ on an end-over-end shaker for 6 h. After centrifugation and filtering the combined soluble and exchangeable forms were determined by AAS.

16.3 Results and discussion

16.3.1 Sorption of metals

For seven selected soils, the results for Cd, Ni and Zn are given in Table 16.1. The sorption of all three metals increased with increase in amount of WTR applied in most of the soils. This applied to the lime-treated samples of the Av and Ia-W soils and is evidence that an increase in pH was playing a role in this sorption of metals. Such a mechanism would reduce metal migration, whose potential to pollute groundwater might mediate against the practice of land disposal. On the other hand, sorption would be expected to reduce availability of Zn, and may even induce deficiency of this nutrient. However, neither the plants grown in the pot experiment (Chapter 13), nor those in the field experiments (Chapter 14) showed any evidence of trace element deficiencies. If co-disposal were to be considered in the future, these results suggest the option of using the WTR to prevent leaching of pollutants from metal-rich sewage sludges.

Table 16.1 Sorption of cadmium, nickel and zinc by seven soils treated with different rates of water treatment residue (WTR) and lime

Material	Rate	Av	Hu-F	Hu-T	Ia-W	Nb-F	Va	We
applied (Mg ha^{-1})		Cd (mg kg^{-1})						
WTR	0	4.0	28.2	14.1	14.1	18.9	38.6	32.6
	20	14.3	nd	nd	18.3	nd	nd	nd
	40	18.6	30.3	17.2	21.7	22.8	41.6	32.9
	60	20.6	nd	nd	23.1	nd	nd	nd
	80	24.8	31.9	19.8	26.1	26.8	42.4	34.4
	100	28.2	nd	nd	27.9	nd	nd	nd
	120	32.1	33.3	25.9	30.2	29.9	43.9	36.2
	320	44.1	40.1	37.2	41.8	39.3	46.0	41.7
	1280	45.9	41.1	44.1	44.9	46.8	47.4	42.9
Lime	7.5	27.4	nd	nd	24.1	nd	nd	nd
	15	42.4	nd	nd	35.2	nd	nd	nd

Material	Rate	Av	Hu-F	Hu-T	Ia-W	Nb-F	Va	We
applied (Mg ha^{-1})		Ni (mg kg^{-1})						
WTR	0	1.8	19.4	15.5	6.8	8.2	26.5	21.7
	20	2.4	nd	nd	10.7	nd	nd	nd
	40	5.1	25.7	19.9	12.1	8.9	32.1	23.7
	60	11.8	nd	nd	15.4	nd	nd	nd
	80	16.1	19.7	20.5	19.7	10.7	31.8	24.0
	100	21.1	nd	nd	21.5	nd	nd	nd
	120	24.6	22.4	19.2	25.2	15.1	33.8	25.0
	320	44.5	24.5	29.5	41.0	18.5	36.7	31.5
	1280	47.0	22.4	32.9	45.1	18.1	37.5	31.2
Lime	7.5	20.3	nd	nd	18.5	nd	nd	nd
	15	43.2	nd	nd	34.1	nd	nd	nd

Table 16.1 (cont.) Sorption of cadmium, nickel, and zinc by seven soils treated with different rates of water treatment residue (WTR) and lime

Material applied	Rate (Mg ha^{-1})	Av	Hu-F	Hu-T	Ia-W	Nb-F	Va	We
		----------Zn (mg kg^{-1})----------						
WTR	0	10.5	0.0	0.0	14.3	0.0	36.1	23.5
	20	14.3	nd	nd	18.8	nd	nd	nd
	40	19.3	4.7	0.0	21.1	0.0	40.7	24.4
	60	25.6	nd	nd	24.4	nd	nd	nd
	80	32.1	7.9	0.0	26.9	4.8	41.5	26.4
	100	37.3	nd	nd	28.8	nd	nd	nd
	120	42.6	9.1	0.0	32.6	13.9	41.9	29.5
	320	48.0	28.7	27.5	46.8	38.6	44.2	37.8
	1280	48.5	32.2	38.5	48.1	48.2	44.1	39.7
Lime	7.5	39.3	nd	nd	24.6	nd	nd	nd
	15	48.2	nd	nd	40.5	nd	nd	nd

nd not determined

16.3.2 Fractionation of metals

Metal fractions in the WTR (Table 16.2) were generally low, with the exchangeable plus soluble forms below detection limits. Therefore if no chemical reaction occurs between the soil and the WTR, the soluble and exchangeable forms of the metals ($CaCl_2$) in the WTR-treated soil would be expected to decrease. The organic forms (pyrophosphate) of Cd, Mn and Pb, and the amorphous fractions (oxalate) of Cr, Ni and Pb would similarly decrease. The metal with by far the highest concentrations is Mn in the inorganic (acetic acid) and amorphous fractions. Other metals that are in concentrations greater than 10 mg kg^{-1} are Cr, Cu, Ni and Zn in the organic fraction and Cu and Zn in the amorphous fraction.

Table 16.2 Metal fractions in the Midmar water treatment residue

Metal	$CaCl_2$	Acetic acid	Pyrophosphate	Oxalate
	----------(mg kg^{-1})----------			
Cd	bd	0.4	0	0.4
Co	bd	2.7	7.2	6.9
Cr	bd	3.1	21.9	0
Cu	bd	1.2	18.8	59.2
Mn	bd	1681.9	0	3642.1
Ni	bd	3.0	25.2	0
Pb	bd	0.3	0	0
Zn	bd	4.9	19.4	12.9

bd below detection

In the soil samples from the pot experiment, Mn and Zn were the only metals that could be detected in the exchangeable and soluble forms in all five soils used (Table 16.3). Also, these forms of these metals in the treated soils decreased as predicted with application of the WTR. Manganese was at a high concentration in the inorganic fractions and, as expected, increased with application of the WTR in all soils. In the organic fraction Mn was expected to either decrease or remain the same since no

organically-bound Mn was detected in the WTR. The results in Table 16.3 confirm this trend except for the Nb-F soil. This re-association of Mn with the organic fraction in this coarse-textured soil cannot be readily explained. It is notable, however, that the limed Ia-C soil at 120 Mg ha^{-1} (L1R120) gave a similar result when compared with the limed but not WTR-treated sample (L1R0). It would seem that a liming effect in the presence of the WTR redistributed the Mn to the organic fraction.

Table 16.3 Fractionation of metals in soils from the pot experiment (Chapter 13)

Metal	Treatment[a]	$CaCl_2$	Acet.[b]	Pyro.[c]	Oxal.[d]	Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------						----------(mg kg^{-1})----------			
		Hu-M						Hu-T			
Cd	L0R0	0	0	1.0	0	Cd	L0R0	0	0	1.9	0
	L0R120	0	0	0.6	0		L0R120	0	0	1.8	0
Co	L0R0	0	4.2	3.9	17.4	Co	L0R0	0	4.0	7.7	9.9
	L0R120	0	2.5	3.1	20.6		L0R120	0	3.6	5.2	11.6
Cr	L0R0	0	1.7	21.3	0	Cr	L0R0	0	1.4	20.6	0
	L0R120	0	1.8	21.4	0		L0R120	0	1.6	19.0	0
Cu	L0R0	0	0.4	18.3	2.3	Cu	L0R0	0	0.4	16.4	0
	L0R120	0	0.3	18.0	2.0		L0R120	0	0.4	16.1	0
Mn	L0R0	42.3	30.5	132.8	261.1	Mn	L0R0	58.1	81.8	273.1	282.9
	L0R120	6.4	97.3	87.6	905.1		L0R120	14.3	144.5	267.2	565.0
Ni	L0R0	0	0.2	26.5	0	Ni	L0R0	0	1.0	25.2	0
	L0R120	0	0.6	27.3	0		L0R120	0	0.7	26.1	0
Pb	L0R0	0	0.1	0	0.3	Pb	L0R0	0	0.1	0.8	0.2
	L0R120	0	0.1	0	0.2		L0R120	0	0.1	0.8	0.2
Zn	L0R0	0.9	1.9	24.7	0	Zn	L0R0	2.8	2.1	31.9	0
	L0R120	0.2	2.8	24.2	0		L0R120	0.3	3.0	27.2	0

Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------			
		Sd			
Cd	L0R0	0	0	0.5	0
	L0R120	0	0	2.4	0
Co	L0R0	0	3.1	2.1	37.9
	L0R120	0	2.4	0	40.8
Cr	L0R0	0	1.9	8.9	0.8
	L0R120	0	2.1	8.7	0
Cu	L0R0	0	0.5	26.9	9.8
	L0R120	0	0.5	23.7	12.0
Mn	L0R0	51.7	30.4	259.1	751.3
	L0R120	24.3	125.9	92.6	1261.6
Ni	L0R0	0	1.2	3.9	11.1
	L0R120	0	1.2	4.4	10.5
Pb	L0R0	0	0.1	0	0
	L0R120	0	0.1	0	0
Zn	L0R0	1.0	1.0	0	0
	L0R120	0.2	2.0	1.1	1.1

Table 16.3 (cont.) Fractionation of metals in soils from the pot experiment (Chapter 13)

Metal	Treatment[a]	$CaCl_2$	Acet.[b]	Pyro.[c]	Oxal.[d]	Metal	Treatment[a]	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------						----------(mg kg^{-1})----------			
		Ia-C						Nb-F			
Cd	L0R0	0	0	0.4	0	Cd	L0R0	0.1	0.3	0.3	1.1
	L0R120	0	0	0.5	0		L0R120	0.2	0.2	0.6	0.8
	L1R0	0	0	0.9	0		L1R0	0.3	0	1.0	0.4
	L1R120	0	0	0.8	0		L1R120	0.3	0	0.8	0
Co	L0R0	0	2.6	2.9	2.1	Co	L0R0	0	2.6	0	0.6
	L0R120	0	2.4	3.9	3.6		L0R120	0	2.7	0	0.6
	L1R0	0	1.9	1.7	5.0		L1R0	0	0.5	0.5	0
	L1R120	0	2.7	0.8	6.5		L1R120	0	0.6	0.9	0
Cr	L0R0	0	1.4	16.0	0	Cr	L0R0	0	2.9	2.4	6.8
	L0R120	0	1.4	15.6	0		L0R120	0	0.4	5.2	4.6
	L1R0	0	0.7	12.4	0		L1R0	0	0.1	7.4	1.6
	L1R120	0	1.1	12.3	0		L1R120	0	0	9.3	0
Cu	L0R0	0	0.4	19.4	0	Cu	L0R0	0	1.2	13.1	0
	L0R120	0	0.3	18.3	0		L0R120	0	0.6	13.7	0
	L1R0	0	0.3	17.9	0		L1R0	0	0.3	14.4	0
	L1R120	0	0.2	18.4	0		L1R120	0	0.3	13.6	0
Mn	L0R0	30.9	54.1	59.4	72.8	Mn	L0R0	2.8	65.6	0	8.1
	L0R120	6.5	137.4	56.0	609.9		L0R120	0.2	88.3	57.5	393.6
	L1R0	15.3	64.6	0	108.6		L1R0	2.2	1.4	8.1	0
	L1R120	0.0	156.9	17.2	592.3		L1R120	0	45.8	103.6	407.3
Ni	L0R0	0	0.6	24.2	0	Ni	L0R0	0	0.1	21.7	0
	L0R120	0	0.6	25.3	0		L0R120	0	0.4	22.3	0
	L1R0	0	0.4	23.4	0		L1R0	0	0.2	19.4	0
	L1R120	0	0.6	22.8	0		L1R120	0	0.4	22.2	0
Pb	L0R0	0	0.1	0	0.5	Pb	L0R0	0	0.2	0.1	0.1
	L0R120	0	0.1	0	0.5		L0R120	0	0.1	0.3	0
	L1R0	0	0.1	0	0.2		L1R0	0	0.1	0.3	0
	L1R120	0	0.1	0	0.1		L1R120	0	0.1	0	0.2
Zn	L0R0	1.3	1.1	22.5	0	Zn	L0R0	2.6	0.9	13.2	0
	L0R120	0.2	2.6	21.3	0		L0R120	0.2	2.6	12.1	0
	L1R0	0.1	1.9	19.7	0		L1R0	2.2	0.5	30.4	0
	L1R120	0.2	1.4	19.0	0		L1R120	0.1	2.2	30.1	0

a L is the lime application rate; R is the water treatment residue application rate in Mg ha^{-1}.
b Acetic acid; c Pyrophosphate; d Oxalate

There was virtually no change in the organic fractions of all other metals in all soils. In the amorphous fraction the concentration of Mn was again high and increased with application of the WTR in all soils. Cobalt was generally the only other metal to be in measurable quantities in the amorphous fraction (Table 16.3).

The trend in metal distribution found in the soil samples from the pot experiment generally continued in the incubated samples (Table 16.4). Amongst the soils common to both experiments there were some differences e.g. the soluble and exchangeable fraction of Mn increased in the Hu-M soil, and the organic fraction of

this metal decreased in the limed and WTR-treated Ia-C soil. In the four soils that were not used in the pot experiment there was also some data that were anomalous. In the non-limed, WTR-treated Hu-F soil the soluble and exchangeable fraction of Mn increased, the inorganic fraction decreased and the organic fraction increased compared to the control. In the Va soil, the WTR increased the soluble and exchangeable Mn, decreased the inorganic fraction and increased the organic fraction. In the We soil, the inorganic fraction of Mn decreased while the organic fraction increased.

Table 16.4 Fractionation of metals in soils from the incubation experiment (Chapter 15)

Metal	Treatment[a]	$CaCl_2$	Acet.[b]	Pyro.[c]	Oxal.[d]	Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		(mg kg^{-1})						(mg kg^{-1})			
		Hu-F						Ia-C			
Cd	L0R0	0.1	0.3	0.1	1.5	Cd	L0R0	0.1	0.2	1.8	0
	L0R1280	0.1	0.3	0	1.6		L0R1280	0.1	0.3	1.7	0
	L1R0	0.1	0.3	1.7	0.0		L1R0	0	0.3	1.9	0
	L1R1280	0.1	0.4	0.7	1.3		L1R1280	0	0.4	1.6	0.3
Co	L0R0	0	5.1	4.4	17.2	Co	L0R0	0	1.9	10.3	0
	L0R1280	0	2.7	5.6	9.8		L0R1280	0	0.7	9.4	0
	L1R0	0	4.9	1.8	18.1		L1R0	0	1.6	10.5	0
	L1R1280	0	1.9	6.4	0		L1R1280	0	0.9	8.5	0
Cr	L0R0	0	2.4	23.2	0	Cr	L0R0	0	0.6	18.9	0
	L0R1280	0	2.8	21.1	0		L0R1280	0	0.8	15.8	0
	L1R0	0	0.9	20.4	0		L1R0	0	0.8	19.2	0
	L1R1280	0	1.5	19.2	0		L1R1280	0	1.0	16.3	0
Cu	L0R0	0	0.5	19.7	5.8	Cu	L0R0	0	0.7	13.9	3.2
	L0R1280	0	0.6	19.5	8.3		L0R1280	0	0.7	10.3	12.6
	L1R0	0	0.5	18.5	0		L1R0	0	0.5	12.6	4.5
	L1R1280	0	0.8	14.2	12.4		L1R1280	0	0.6	13.7	11.0
Mn	L0R0	6.8	312.1	0	420.6	Mn	L0R0	66.4	2.9	72.6	66.1
	L0R1280	12.4	63.2	131.8	1723.1		L0R1280	13.0	363.2	0	1844.7
	L1R0	105.1	11.7	354.4	0		L1R0	32.1	7.9	55.7	68.0
	L1R1280	4.7	518.7	0	4386.3		L1R1280	18.6	389.2	0	1896.1
Ni	L0R0	0	0.4	17.3	0	Ni	L0R0	0	0.4	2.2	4.0
	L0R1280	0	1.3	15.3	0		L0R1280	0	1.0	0	7.9
	L1R0	0	0.5	21.0	0		L1R0	0	0.4	1.5	5.2
	L1R1280	0	1.2	18.0	0		L1R1280	0	1.2	0	8.5
Pb	L0R0	0	0.2	1.3	0	Pb	L0R0	0	0.1	1.3	0
	L0R1280	0	0.2	1.3	0		L0R1280	0	0.1	1.3	0
	L1R0	0	0.2	1.1	0		L1R0	0	0.1	1.4	0
	L1R1280	0	0.2	0.9	0		L1R1280	0	0.1	1.2	0
Zn	L0R0	0.2	4.1	12.3	4.5	Zn	L0R0	1.7	0.5	7.6	1.4
	L0R1280	0.2	41.2	31.6	97.0		L0R1280	0	34.7	39.3	90.6
	L1R0	1.7	4.0	24.6	0		L1R0	0.9	2.6	5.4	4.5
	L1R1280	0	3.6	19.9	1.3		L1R1280	0.2	34.8	35.6	87.5

Table 16.4 (cont.) Fractionation of metals in soils from the incubation experiment (Chapter 15)

Metal	Treatment[a]	$CaCl_2$	Acet.[b]	Pyro.[c]	Oxal.[d]	Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------						----------(mg kg^{-1})----------			
		Hu-M						Hu-T			
Cd	L0R0	0.1	0.3	1.4	0.5	Cd	L0R0	0.1	0.3	0.8	1.2
	L0R1280	0.1	0.3	1.6	0.4		L0R1280	0.2	0.3	0.6	1.5
Co	L0R0	0	3.8	4.2	14.4	Co	L0R0	0	4.2	3.7	16.0
	L0R1280	0	3.1	5.5	14.4		L0R1280	0	2.1	5.9	11.0
Cr	L0R0	0	0.8	20.9	0	Cr	L0R0	0	1.4	23.6	0
	L0R1280	0	0.9	21.9	0		L0R1280	0	2.0	19.9	0
Cu	L0R0	0	0.4	13.0	7.6	Cu	L0R0	0	0.4	12.1	0.3
	L0R1280	0	0.3	13.1	9.5		L0R1280	0	0.8	13.4	7.7
Mn	L0R0	6.8	68.2	188.5	188.1	Mn	L0R0	210.2	2.0	156.7	512.6
	L0R1280	12.4	104.6	160.8	390.4		L0R1280	13.9	424.8	0	2074.6
Ni	L0R0	0	0.3	21.3	0	Ni	L0R0	0	1.1	17.1	0
	L0R1280	0	0.4	22.2	0		L0R1280	0	1.7	15.5	0
Pb	L0R0	0	0.1	0.9	0	Pb	L0R0	0	0.1	0.1	0.1
	L0R1280	0	0.2	0	0.3		L0R1280	0	0.2	0	0.2
Zn	L0R0	0.1	2.9	10.0	0.1	Zn	L0R0	4.2	1.8	30.6	0
	L0R1280	0.2	5.8	15.6	9.7		L0R1280	0.3	49.1	31.5	93.9

Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.	Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------						----------(mg kg^{-1})----------			
		Nb-A						Nb-F			
Cd	L0R0	0.2	0.1	1.8	0	Cd	L0R0	0.2	0.2	0.6	0.7
	L0R1280	0.1	0.3	1.4	0.4		L0R1280	0.1	0.4	0.5	0.9
Co	L0R0	0	0.9	8.8	0	Co	L0R0	0	1.8	0.8	18.9
	L0R1280	0	1.2	12.1	0		L0R1280	0	2.2	1.3	13.8
Cr	L0R0	0	0.5	16.7	0	Cr	L0R0	0	1.7	20.8	0
	L0R1280	0	1.2	18.1	0		L0R1280	0	2.2	20.3	0
Cu	L0R0	0	0.2	9.0	0	Cu	L0R0	0	0.2	8.0	4.4
	L0R1280	0	0.9	11.3	4.5		L0R1280	0	0.8	11.4	9.7
Mn	L0R0	23.2	0	202.6	0	Mn	L0R0	8.5	358.4	0	669.4
	L0R1280	2.8	514.1	0	1674.7		L0R1280	6.2	16.7	112.7	1386.8
Ni	L0R0	0	0.3	2.3	0	Ni	L0R0	0	0.3	27.9	0
	L0R1280	0	1.6	20.4	0		L0R1280	0	1.2	27.4	0
Pb	L0R0	0	0.1	1.2	0	Pb	L0R0	0	0.1	0	0
	L0R1280	0	0.2	1.1	0		L0R1280	0	0.1	0	0.1
Zn	L0R0	0.4	0.4	22.6	0	Zn	L0R0	1.3	0.7	14.8	0
	L0R1280	0	57.9	12.7	101.6		L0R1280	0.1	47.5	37.0	77.7

Table 16.4 (cont.) Fractionation of metals in soils from the incubation experiment (Chapter 15)

Metal	Treatment[a]	$CaCl_2$	Acet.[b]	Pyro.[c]	Oxal.[d]	Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------						----------(mg kg^{-1})----------			
		Sd						Va			
Cd	L0R0	0	0.2	2.2	0	Cd	L0R0	0.1	0.3	0.8	1.0
	L0R1280	0	0.3	2.1	0		L0R1280	0.1	0.4	0.3	1.5
Co	L0R0	0	1.7	1.7	30.9	Co	L0R0	0	2.3	1.7	5.5
	L0R1280	0	0.6	3.9	15.7		L0R1280	0	2.3	0.5	8.0
Cr	L0R0	0	0.3	13.4	0	Cr	L0R0	0	2.1	20.2	0
	L0R1280	0	0.6	12.7	0		L0R1280	0	2.6	20.1	0
Cu	L0R0	0	0.5	24.7	6.9	Cu	L0R0	0	0.5	12.3	0
	L0R1280	0	0.9	21.5	10.9		L0R1280	0	0.7	13.3	6.8
Mn	L0R0	141.4	0	362.7	795.1	Mn	L0R0	6.4	351.2	0	311.7
	L0R1280	14.0	393.5	0	2279.8		L0R1280	97.1	0	274.4	1478.5
Ni	L0R0	0	1.5	4.3	4.6	Ni	L0R0	0	0.6	18.8	0
	L0R1280	0	2.0	3.3	6.4		L0R1280	0	1.4	16.5	0
Pb	L0R0	0	0.1	1.3	0	Pb	L0R0	0	0.1	0.2	0
	L0R120	0	0.1	0.3	0.1		L0R1280	0	0.2	0.3	0
Zn	L0R0	2.3	1.5	15.9	0	Zn	L0R0	0.2	2.9	12.3	1.2
	L0R1280	0	40.1	36.1	91.9		L0R1280	1.8	41.5	29.2	99.4

Metal	Treatment	$CaCl_2$	Acet.	Pyro.	Oxal.
		----------(mg kg^{-1})----------			
		We			
Cd	L0R0	0.1	0.3	0	0
	L0R1280	0.1	0.4	0.1	1.5
Co	L0R0	0	2.9	0	0
	L0R1280	0	2.7	4.5	9.9
Cr	L0R0	0	2.6	0	0
	L0R1280	0	3.1	20.8	0
Cu	L0R0	0	0.4	0	0
	L0R1280	0	1.0	16.7	6.2
Mn	L0R0	22.8	333.3	0	0
	L0R1280	10.7	126.1	163.7	2255.6
Ni	L0R0	0	0.9	0	0
	L0R1280	0	1.5	17.3	0
Pb	L0R0	0	0.1	0	0
	L0R1280	0	0.2	1.2	0
Zn	L0R0	0.3	1.5	0	0
	L0R1280	0.2	42.6	24.7	98.1

[a] L is the lime application level; R is the water treatment residue application rate in Mg ha^{-1}.
[b] Acetic acid; [c] Pyrophosphate; [d] Oxalate

The overall general trend, however, is for the concentrations of the metals in the various extractants from the WTR-treated soils to conform with their distribution in the WTR rather than in the soils themselves. Most importantly this implies a decrease in the highly active soluble and exchangeable fractions. In addition there will be an

increase or no change in the relatively inactive inorganic fraction, no change or a decrease in the organic fraction and no change or an increase in the inert amorphous fractions. Therefore, in total, addition of even very high amounts of WTR to a wide range of soils will not result in any increased solubility or mobility of the metals contained in the WTR. This finding is important since it shows that the dangers of these heavy metals either becoming available and thus toxic to plants or being sufficiently mobile to pollute groundwater are minimal.

16.3.3 Metals in field samples

Of the eight metals analysed, only three could be detected, namely Cd, Mn and Zn. In the soil from Brookdale Farm (Table 16.5) only Mn was affected by application of the WTR. There is an indication that Mn concentrations increased at depths of 200-400 and 400-600 mm.

Table 16.5 Depth distributions of cadmium, manganese and zinc (mg kg^{-1}) in the soil from the Brookdale Farm field experiment

Metal	Year	-------0 - 200 mm-----			------200 - 400 mm------			------400 - 600 mm-----		
		0	1280[a]	1280[b]	0	1280[a]	1280[b]	0	1280[a]	1280[b]
Cd	1999	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	2000	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	2001	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mn	1999	90.2	49.0	86.6	51.2	79.2	70.1	5.8	10.6	9.3
	2000	52.4	0.8	2.8	4.0	42.4	22.2	1.4	2.6	3.2
	2001	79.5	25.1	45.6	34.4	48.5	41.7	4.2	29.3	17.8
Zn	1999	0.9	0.3	1.1	0.4	0.5	0.6	0.3	0.3	0.4
	2000	1.0	0.4	0.8	0.4	0.7	0.6	0.4	0.5	0.5
	2001	1.3	0.5	1.1	0.6	0.9	0.5	0.5	0.5	0.5

[a] Mulch treatment (1280 Mg ha^{-1}); [b] incorporated treatment (1280 Mg ha^{-1})

This result was not observed in the We soil from Ukulinga Farm (Table 16.6), which contains a lower clay content and less amorphous material. Except for Mn in the Ukulinga soil, no other metal showed differing concentration and Pb is given as an example of the situation for the other metals, the levels of which were even lower.

Table 16.6 Depth distributions of lead, manganese, nickel and zinc (mg kg^{-1}) in the soil from the Ukulinga Farm field experiment

Metal	Year	----0 - 200 mm----		---200 - 400 mm---		--400 - 600 mm--	
		0	1280[a]	0	1280	0	1280
Pb	1999	0.6	0.6	nd	nd	nd	nd
	2001	0.6	0.6	0.6	0.6	0.6	0.6
Mn	1999	66.4	52.7	nd	nd	nd	nd
	2001	20.6	1.2	1.0	0.8	1.4	1.8
Ni	1999	0.2	0.2	nd	nd	nd	nd
	2001	0.2	0.2	0.2	0.4	0.2	0.2
Zn	1999	0.5	0.4	nd	nd	nd	nd
	2001	0.6	0.2	0.2	0.2	0.2	0.2

[a] incorporated treatment (1280 Mg ha^{-1})

16.4 Conclusions

Application of the WTR can reduce the amount of soluble metals in soils through sorption. This principle could be used in the co-disposal of this material with waste that has a high concentration of heavy metals. There is no evidence that this immobilisation would lead to deficiencies of the trace metals. Manganese appears to the most mobile of the heavy metals investigated following application of the WTR and this may need further investigation.

However, in most of the soils studied Mn decreased in the highly active fraction (soluble and exchangeable) and increased in the inactive amorphous fraction as a result of WTR addition. In addition, evidence from the field experiments (Section 14.5) suggests that laboratory studies overestimate the effects that WTR has on this element's movement in soils.

It is clear that addition of even very high amounts of WTR to a wide range of soils will not result in any increased solubility or mobility of the metals contained in the WTR. Thus it is unlikely that these heavy metals would become available and toxic to plants or become mobile and pollute groundwater.

CHAPTER 17

THE EFFECT OF A WATER TREATMENT RESIDUE ON PHOSPHORUS BEHAVIOUR IN SOILS

17.1 Introduction

Studies on phosphorus in soils have usually been on acid soils, or constituents that dominate these soils. The main reason is the reduced availability of this nutrient under these conditions through sorption, and investigations have centred on developing means of improving its uptake by plants. The determination of sorption isotherms is probably the most common technique for studying P behaviour in soils. These studies can be used to predict the amount of fertiliser P needed to adjust the soil solution P to an optimum for crop growth (Bhuiyan and Sedberry, 1995). However, sorption isotherms are time-consuming to produce and P sorption indices have been proposed as alternatives (Bache and Williams, 1971; Simard *et al*., 1994). Whereas determination of a sorption isotherm requires a range of P concentrations, only one concentration is required to generate the P sorption index. In their experiments, these workers found that the P sorption index of a soil was closely related to its maximum P sorption capacity.

Although not as commonly investigated as sorption, desorption of P is nonetheless important since it essentially governs absorption by plants, leaching and transportation of P in runoff water. Different sorption/desorption models tested by Garcia-Rodeja and Gil-Sotres (1995) established that the concentration of initially desorbable P decreased exponentially with contact time between P and soil, which indicated that desorption is continuous but increasingly slow. These results tend to confirm that sorption and desorption give complementary information as proposed by Quang and Dufey (1997). Furthermore, the results also suggest a need to look at another aspect of 'after-sorption', namely transformation.

The lack of attainment of equilibrium between solution and solid phase (Grant and Heaney, 1997; Quang and Dufey, 1997; Papadopoulos *et al*., 1998) is an indication that either there is an infinite number of sorption sites in a given amount of soil, or that more sorption sites are created as transformation reactions occur in the soil, or both. Of these, the possible creation of sorption sites is the most likely. Sorption of applied P in soil is a form of transformation since P is converted from a highly mobile form to a less mobile or an immobile one. Whereas in sorption experiments the interest has been only on the loss of the element from solution, transformation studies are concerned with which soil constituent the P has associated.

It has been demonstrated that sorption can be correlated with soil constituents like "active" calcium carbonate (Lopez-Pineiro and Navarro, 1997), clay content (Singh and Gilkes, 1991; Lopez-Pineiro and Navarro, 1997) and various Al and Fe species (Singh and Gilkes, 1991; Lopez-Pineiro and Navarro, 1997; Owusu-Bennoah *et al*., 1997). Fractionation of P has been carried out on water treatment residue (WTR) and WTR-treated soils (Jonasson, 1996; Cox *et al*., 1997). Results obtained, although by using different fractionation methods, indicated transformation to Al and Ca forms.

In addition to the agronomic aspects of P behaviour in soils there is also a need to consider the environmental impacts of P should it leach from the soil. Although loss of P is in general not expected to be significant, in coarse-textured soils it can be a problem because of their low number of sorption sites. High concentrations of P in soils are mostly a result of application of fertilisers and if lost by leaching it may pollute water bodies, either via run-off or groundwater (McPharlin *et al*., 1994; Summers and Pech, 1997; Scheffer, 2000; Snars *et al*., 2003; 2004).

Soil conditions should, if practical, be manipulated to favour both the sorption and desorption processes in a quest to balance the demands of plants and to protect the environment.

The objectives of this chapter were as follows:

- to determine the influence of the Midmar WTR on P sorption by soils;
- to study the extractability of P sorbed by WTR-treated soils; and
- to investigate the transformation of P in WTR-treated soils.

17.2 Materials and methods

17.2.1 Determination of optimum sorption time

Five grams of untreated soil or Midmar WTR were allowed to sorb P from 50 mL of 0.005M $CaCl_2$ solution containing an equivalent of 500 µg P g^{-1} sample for the WTR, Hu-M, Ia-C and Sd soils, and 250 µg g^{-1} soil for the Nb-A, Nb-F and Hu-T soils. The source of P was potassium dihydrogen phosphate. Suspensions were shaken for 0, 1, 8, 24 and 48 h in a 100 mL centrifuge tube on an end-over-end shaker. At the end of each incubation time, the suspensions were centrifuged until clear and then filtered through Whatman No. 42 filter paper before analysis by the molybdenum blue method (Murphy and Riley, 1962). From the results it was established that the amount of P sorbed in the 8 h period was almost the same as for the longer times. As a result it was then decided to equilibrate the suspensions for 0, 0.5, 1, 2, 4, 6 and 8 h. Two additional soils, namely the Hu-F and Va were included in the experiment.

17.2.2 Determination of P sorption

The P concentrations used in this experiment were very high and were intended to test to what extent the WTR could be used as an environmental 'cleansing agent' by reducing excessive levels of this element in waste materials, soils or water bodies. In this study, 5 g samples were suspended in different concentrations of P as potassium dihydrogen phosphate in centrifuge tubes containing 50 mL of 0.005M $CaCl_2$. The P concentrations were 0, 200, 400, 600, 800, 1 000, 1 400 and 1 800 mg kg^{-1} for the Hu-F, Hu-M, Ia-C and Sd soils. For the Hu-T, Nb-A, Nb-F, Va and We soils the P levels were 0, 40, 160, 320, 400, 600, 800 and 1 000 mg kg^{-1}. Suspensions were shaken for 6 h, centrifuged, filtered and analysed as before. The Av and Ia-W soils were done subsequently with P concentrations ranging between 0 and 1 800 mg kg^{-1} as in the previous soils, except that 1 g of soil was used. Incubated and non-incubated soil-WTR mixtures, where the WTR was applied at rates of 0, 80, 320 and 1280 Mg ha^{-1} were used in this aspect of the P sorption study.

17.2.3 Fractionation of P

The fractionation of P was carried out by the sequential procedure of Hedley *et al*. (1982), as modified by Zhang and MacKenzie (1997) (but excluding the resin and residual P fractions), on soil samples from both the pot (Chapter 13) and incubation experiments (Chapter 15). This fractionation sequentially extracts readily available, plant available, Al and Fe components, Ca-P and residual P using resin, sodium bicarbonate, sodium hydroxide, hydrochloric acid and a sulphuric acid-hydrogen peroxide mixture, respectively. The resin and sodium bicarbonate fractions are considered biologically available, the hydroxide fraction moderately resistant and the rest unavailable to plants. To estimate the available fractions, a 0.01M $CaCl_2$ solution and an AMBIC extraction (solution of ammonium bicarbonate, EDTA disodium salt and ammonium fluoride at pH 8.0) were used to extract the readily available and plant available P fractions, respectively.

17.2.4 Extraction of P from surface soils of field experiments

Soil samples (0-200 mm depth) from the 0 and 1280 Mg ha^{-1} treatments at both field trials, were extracted with AMBIC solution and analysed for P by the molybdenum blue method (Murphy and Riley, 1962). From the Brookdale site both the mulch and incorporated treatments were included.

17.3 Results and discussion

17.3.1 Determination of sorption time

There was a marked increase in the amount of P sorbed with time up to about 8 h, after which the slope of the curve tended to level off (Figure 17.1). More than 90% of the P sorbed in 48 h was sorbed within the first 8 h. In the other sorption-time curve (Figure 17.2) it can be seen that at 6 h the extent of sorption approximately equalled that at 8 h in almost all soils. Thus for the later experiments 6 h was adopted as the standard equilibration time.

It can also be seen that the Midmar WTR was comparable in terms of the extent of P sorption with the highly weathered Hu-F and Ia-C soils that are known to be highly sorbing soils. This implies that the WTR might be expected to severely reduce the mobility and even plant-availability of P when added to soils.

17.3.2 P sorption in incubated and non-incubated soils

The P isotherm is given as the relationship between the sorbed P and that remaining in solution at the end of the equilibration (shaking) period. Sorbed P is taken as the difference between the initial P concentration in solution and that remaining after shaking. In Figures 17.3 and 17.4 the P remaining in solution at the end of the shaking period is designated the ‘equilibrium’ concentration.

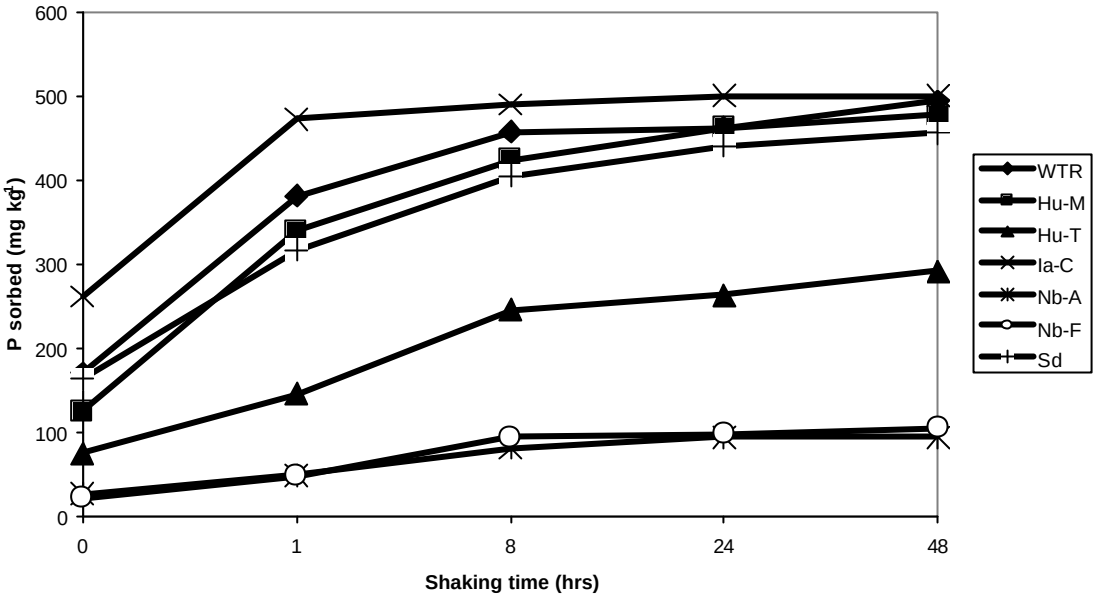


Figure 17.1 Phosphorus sorption at different equilibration times for six soils and the Midmar water treatment residue (WTR).

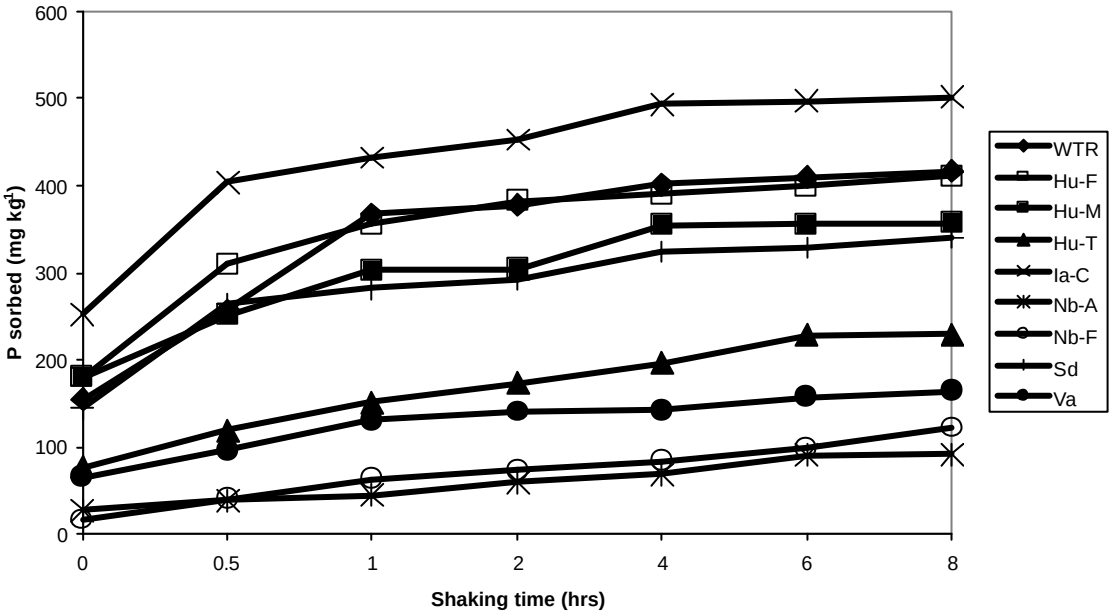


Figure 17.2 Phosphorus sorption at equilibration times up to 8 hours for eight soils and the Midmar water treatment residue (WTR).

In the Av soil (Figure 17.3), the highest sorption was for the non-incubated samples at WTR application rates of 320 and 1280 Mg ha^{-1}. Where samples were incubated, sorption at these rates was similar to that of the 80 Mg ha^{-1} rate in the non-incubated samples. These observations suggest that some constituent of the WTR might be changing with incubation and reducing its P sorption capacity. In general the extent of sorption tended to increase with increasing WTR applied.

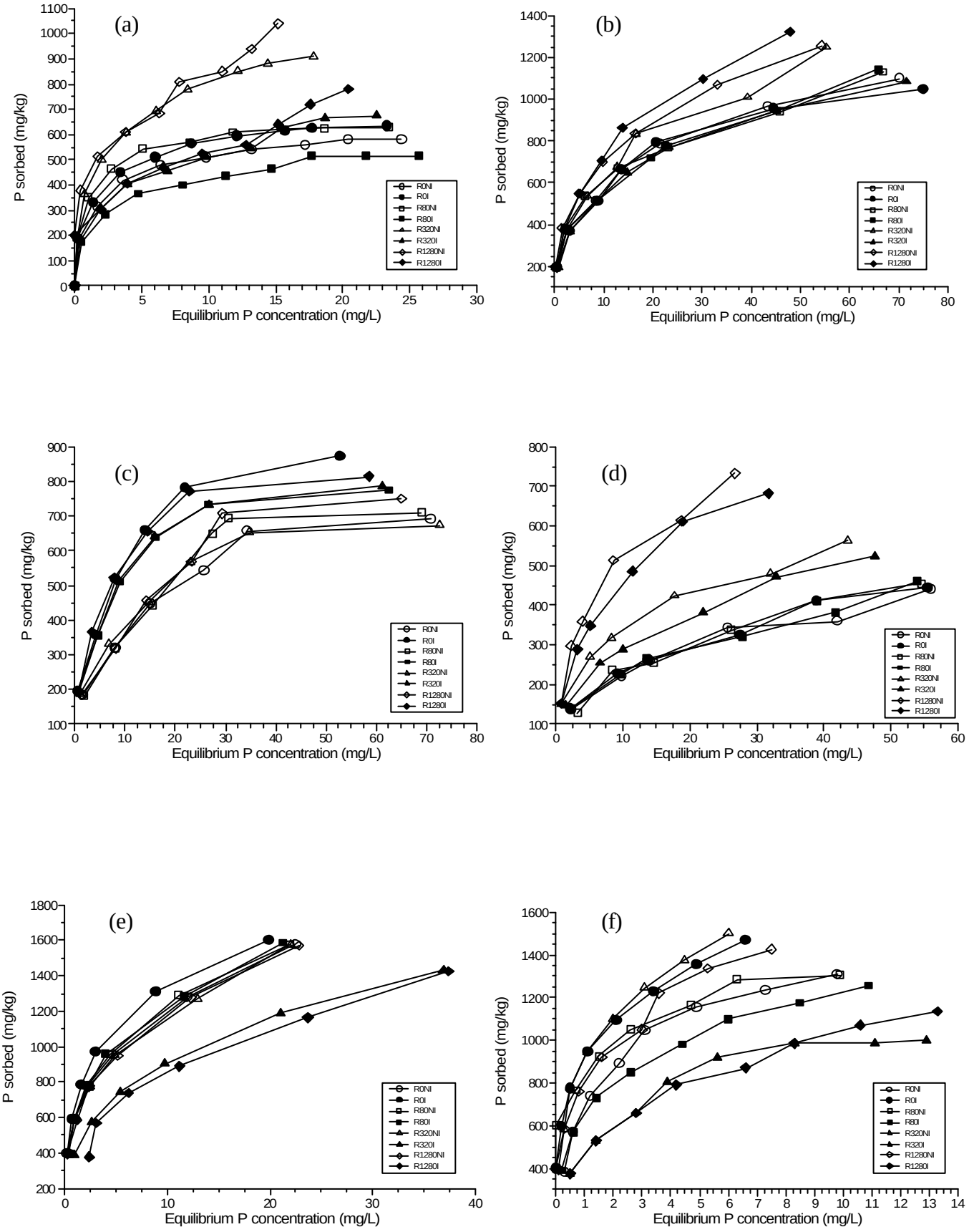


Figure 17.3 P isotherms for (a) Av, (b) Hu-F, (c) Hu-M, (d) Hu-T, (e) Ia-C and (f) Ia-W soils. R - WTR (Mg ha^{-1}); I - incubated; NI - non-incubated.

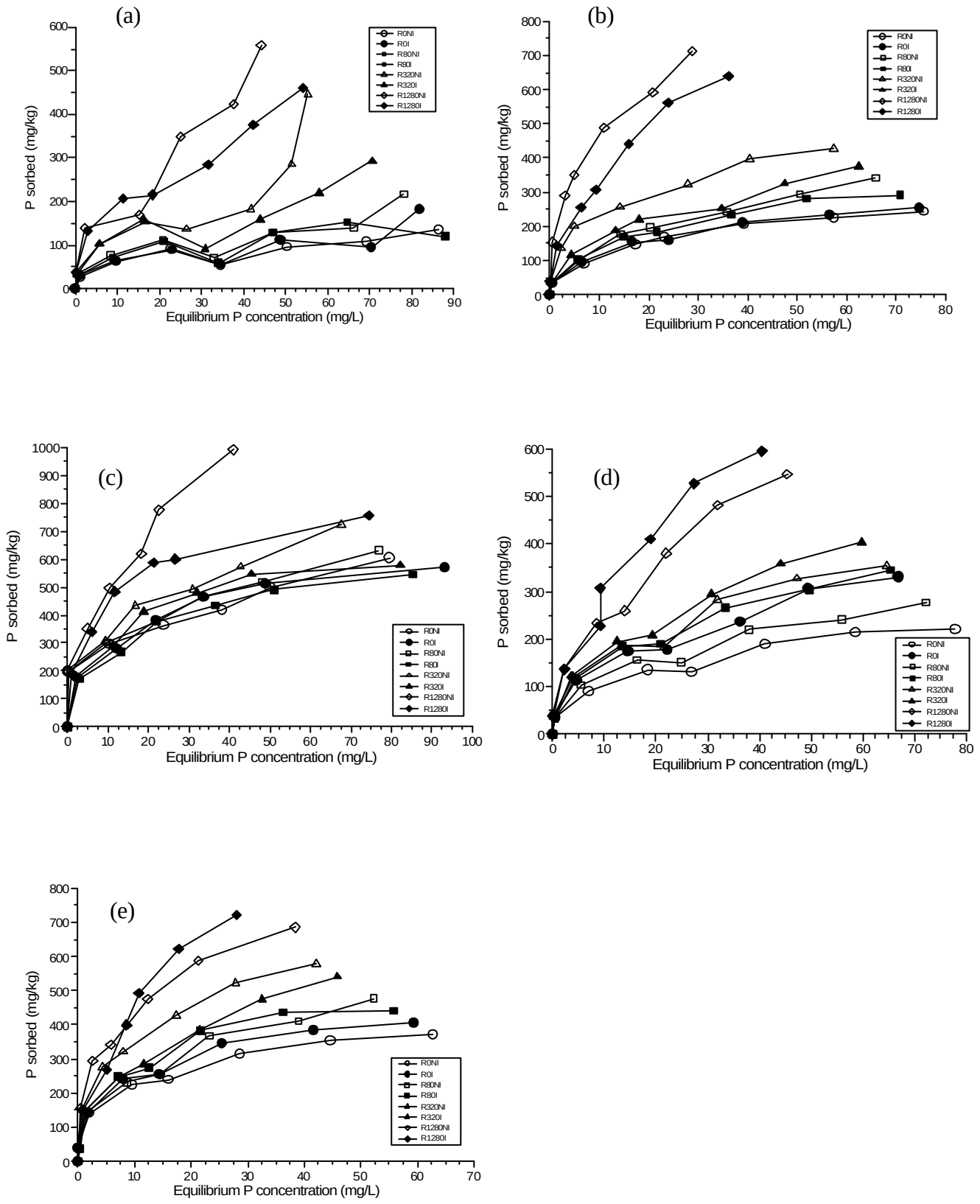


Figure 17.4 P isotherms for (a) Nb-A, (b) Nb-F, (c) Sd, (d) Va and (e) We soils. R - WTR (Mg ha^{-1}); I - incubated; NI - non-incubated.

Other soils in which the sorption capacity increased with application of the WTR, especially at 1280 Mg ha^{-1}, were the Hu-F, Hu-T (Figure 17.3), Nb-A, Nb-F, Sd, Va, and We (Figure 17.4). No common properties between these soils could be identified as the cause of this similar response. Also, if the response was due entirely to the WTR, then all the soils should have behaved similarly. It is probable that, although the results were similar, the mechanisms were not. In all these soils it can be expected that the WTR would reduce labile P and so perhaps induce deficiency in plants, and decrease run-off and leaching losses.

In addition to the Av soil, other soils in which the sorption capacity was higher in non-incubated samples at similar rates of WTR were the Hu-T (Figure 17.3), Nb-A, Nb-F and Sd (Figure 17.4). This observation applies also to the Hu-F soil (Figure 17.3) except for the 1280 Mg ha^{-1} treatment where the incubated sample had the higher sorption capacity. The isotherms of incubated samples coincided where no WTR was applied, suggesting that this behaviour was due more to the WTR than the soil. Again, there was no common feature between these soils that could explain their similar behaviour.

In the Va and We soils (Figure 17.4), incubated samples sorbed more than the corresponding non-incubated samples. It was only in the Ia-C and Ia-W soils (Figure 17.4) that the WTR decreased sorption. These soils thus had a greater sorption capacity than the WTR, and so its application would likely improve P availability.

17.3.3 Phosphorus fractionation

17.3.3.1 Pot experiment soils

Calcium chloride extractions did not exhibit any consistent changes with application of either the WTR or the lime, indicating that amount of solution P was not affected by these treatments (Table 17.1).

Table 17.1 Phosphorus fractions in soil samples from the pot experiment

Soil	Treatment[a]	$CaCl_2$	AMBIC	$NaHCO_3$	NaOH	HCl
		----------(mg kg^{-1})----------				
Hu-M	L0R0	0.4	8.9	13.0	38.0	4.9
	L0R120	0.4	7.3	3.4	153.5	12.9
Hu-T	L0R0	0.4	13.8	3.6	135.8	4.4
	L0R120	0.4	11.2	4.9	113.8	9.7
Ia-C	L0R0	0.2	8.0	16.9	195.2	2.4
	L0R120	0.3	8.1	5.8	185.4	4.0
	L1R0	1.8	5.9	7.7	218.0	3.1
	L1R120	0.5	6.7	7.7	186.0	4.6
Nb-F	L0R0	0.5	105.3	70.2	121.5	12.2
	L0R120	0.8	48.4	52.1	131.1	57.8
	L1R0	1.8	82.1	60.8	113.9	19.9
	L1R120	0.5	45.0	44.6	123.7	55.1
Sd	L0R0	0.9	5.9	0.9	161.9	5.7
	L0R120	1.0	9.2	2.0	189.8	14.1

[a] L is the lime application level and R is the water treatment residue application rate in Mg ha^{-1}.

Application of the WTR did not change the amount of P extracted with the AMBIC solution in the Hu-M, Hu-T and Ia-C soil. In the Nb-F soil this fraction decreased whereas in the Sd soil it increased. The sodium bicarbonate fraction remained almost the same in the Hu-M and Hu-T soils, decreased in the Ia-C and Nb-F soils, and increased in the Sd soil with application of the WTR. In the Ia-C and Nb-F soils application of lime did likewise, which indicated that this reduction could be associated with an increase in pH. Because both of these extractants are used to measure available P a similar behaviour could be expected and this is confirmed here, including samples where lime was added.

The sodium hydroxide extractable fraction greatly increased in the Hu-M soil, only slightly in the Nb-F and Sd soils, and decreased slightly in the Hu-T soil and Ia-C soils. Where the Ia-C soil was limed, no clear pattern was evident whereas in the limed Nb-F soil there was a slight decrease in this fraction. The Ia-C soil was the only one in which the HCl fraction did not increase with application of the WTR. Thus in almost all soils the application of the WTR converted P to the highly reaction-resistant calcium phosphate fraction.

17.3.3.2 Incubation experiment soils

Some differences were found (Table 17.2) compared to samples from the pot experiment.

Table 17.2 Phosphorus fractions in soil samples from the incubation experiment

Soil	Treatment[a]	$CaCl_2$	AMBIC	$NaHCO_3$	NaOH	HCl
		----------(mg kg^{-1})----------				
Hu-F	L0R0	1.0	4.8	4.2	323.3	5.7
	L0R1280	1.0	3.3	4.9	187.6	41.0
	L1R0	0.5	6.2	12.8	419.2	6.2
	L1R1280	0.6	1.7	9.2	218.7	23.2
Hu-M	L0R0	0.6	0.2	6.6	139.2	3.8
	L0R1280	0.4	12.1	5.0	218.8	5.1
Hu-T	L0R0	3.3	4.8	2.1	109.9	2.2
	L0R1280	2.4	54.6	4.2	111.4	43.2
Ia-C	L0R0	0.1	3.2	11.3	146.8	2.9
	L0R1280	0.2	1.6	0.9	109.2	17.7
	L1R0	0.0	2.5	12.2	141.1	5.5
	L1R1280	0.2	2.1	2.0	116.9	12.9
Nb-A	L0R0	1.0	0.3	0.5	27.1	2.5
	L0R1280	0.3	5.4	6.8	67.2	74.6
Nb-F	L0R0	0.6	18.4	37.4	264.0	39.5
	L0R1280	0.8	8.2	13.6	114.0	92.0
Sd	L0R0	0.1	0.2	0.1	117.8	5.7
	L0R1280	0.1	1.2	0.1	118.6	43.4
Va	L0R0	0.7	10.3	10.9	249.8	53.5
	L0R1280	1.0	9.4	9.1	127.9	89.3
We	L0R0	1.1	4.0	1.4	192.7	14.7
	L0R1280	1.1	5.9	5.1	129.5	54.7

[a] L is the lime application level and R is the water treatment residue application rate in Mg ha^{-1}.

For example, in the Hu-M soil, the sodium bicarbonate fraction did not change as compared to a decrease in the sample from the pot experiment. The AMBIC fraction on the other hand decreased as compared to showing no change in the pot experiment samples. In the Hu-T also, these two fractions increased in the incubation samples but were virtually unchanged in the pot samples. It could be that the behaviour of applied P (as in the pot experiment) differed from that of 'native' P (as in the incubation experiment).

There was an increase in P in the sodium hydroxide fraction of the Hu-M and Nb-A soils, a decrease in the Hu-F, Ia-C, Nb-F, Va and We soils, and an unchanged situation in the Hu-T and Sd soils. The calcium chloride and hydrochloric acid fractions gave similar results for all soils, the former with no change and the latter with increases when the WTR was applied.

17.3.4 Phosphorus extracted from field samples

Samples from the Brookdale trial (Table 17.3) show the overall pattern of P increase or decrease with application of the WTR between the years 1998 to 2001. The results showed that the mode of application of the WTR was important. The P extracted from the mulch treatment samples was consistently higher than that extracted from the samples where the WTR had been incorporated. Results of the sorption study (Section 17.3.2) had indicated that application of WTR increased the sorption of P. These field results were thus consistent with the laboratory observations since in the mulch treatment P was applied to the topsoil below the mulch, rather than one to which the WTR had been applied, in other words the incorporated treatment.

Table 17.3 Extractable phosphorus (AMBIC) in selected soil samples from the field experiments at Brookdale and Ukulinga Farms

Field site	Sample year	Treatment (Mg ha^{-1})		
		0	1280[a]	1280[b]
Brookdale	1998	13.0	17.5	12.0
	1999	5.7	6.0	5.5
	2000	13.0	8.2	6.5
	2001	10.5	13.7	7.0
Ukulinga	1999	5.0	na	4.2
	2001	10.5	na	7.2

[a] mulched water treatment residue. [b] incorporated water treatment residue
na not applicable

The Ukulinga samples (Table 17.3) for the years 1999 and 2001 also showed results agreeing with the sorption results for the We soil, namely that there was more sorption of solution P with application of the WTR.

17.4 Conclusions

The determination of P sorption isotherms for a variety of soils has revealed differences between them after addition of the Midmar WTR. Soils with different properties appear to behave similarly suggesting that the operative mechanisms differ between the soils. Changes in P sorption as a result of incubation likewise reveal

differences between the soils although no reasons are obvious from the data obtained in this study. Such results are not unusual since the literature contains many conflicting accounts as regards the soil properties that affect P behaviour in soils. In perhaps the largest study undertaken on P dissolution from fertilisers (Sale *et al.*, 1997) it was found that no single soil factor could adequately predict the dissolution of phosphate rock fertiliser or the subsequent behaviour of the released P at 26 long-term field sites across Australia.

Although it is clear that the WTR is responsible for P sorption the differences in the field between the control plots and those amended with the highest amount of WTR are not great. Further, despite the evidence of both the laboratory experiments and the P extraction data from the field trial soils, at both sites there was no analytical or visual evidence of this sorption causing deficiencies of P that affected the growth of either the perennial ryegrass or the tall fescue (Chapter 14) on these soils. This evidence is in agreement with the studies discussed in Chapter 3 that have observed that P deficiency due to WTR application is restricted to pot experiments. The few field studies that have been conducted have not indicated any substantial problems with P deficiency and have given rise to the possibility that WTRs may act as slow release fertilisers. In addition, from an environmental perspective, the P sorbing capacity of WTRs may be of potential benefit in situations where leaching of P is a problem such as on coarse-textured soils or where over-fertilisation with P on fine-textured soils has exceeded the sorption capacity of the soil.

CHAPTER 18

CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

18.1 Introduction

The research reported is the first to examine water treatment residue (WTR) in South Africa and, from a study of the literature, is one of the most in-depth investigations conducted anywhere on these materials.

As indicated in Section 1.4 the disposal of any waste onto land (as opposed to landfill) can be responsible for a number of possibly adverse environmental effects. Water treatment residue is somewhat unusual compared to many wastes that are land applied in that it is almost entirely inorganic in composition and its source is the catchment of the water source. It therefore consists largely of materials that are locally derived plus the chemicals used during the water treatment process. To find out which chemicals are used in South Africa, the project included a questionnaire survey of water treatment authorities, and a characterisation of some of the major WTRs produced.

Land application of WTR, as with any waste material, was predicted to have effects on soil properties (physical, chemical and microbiological), soil fertility, plant availability of elements, soil water and groundwater. To investigate these aspects, at the initiation of Umgeni Water, two field experiments were set-up to investigate the effect of the WTR produced by the Midmar Water Treatment Works on two contrasting soils, a deep, structurally stable and well-drained Hutton soil at Brookdale Farm, Howick, and a shallow, poorly structured, poorly drained Westleigh soil at Ukulinga Farm near Pietermaritzburg. The results from these field experiments form the core of this report and are supplemented by the use of other soils, both with the Midmar WTR and other WTRs collected from around South Africa, in laboratory and pot experiments.

At a very early planning stage it was decided to divide the project into a number of separate but interlinked sub-projects that would focus on the effect of the Midmar WTR on soil physical properties and soil chemical/fertility/groundwater aspects. Subsequently, with the collection of more WTRs, two other sub-projects were developed i.e., soil microbiological aspects and the prospects for using WTRs from the other two major water suppliers (Rand Water and the City of Cape Town) as amendments for ‘degraded’ lands.

These four investigations have produced a wealth of information and a very consistent result in terms of the prospects for the land disposal (land treatment) of WTRs. The following conclusions and recommendations are based around these sub-projects and the environmental aspects that they were designed to investigate.

18.2 Discussion and conclusions

18.2.1 Soil physical properties

The main reasons for this project were two-fold i.e., there are very few studies on this aspect of WTRs reported in the available international literature and the concern that

should the WTR degrade to its constituent particles (mostly clay and some silt) the effect on soil structure was unknown. By concentrating the disposal of WTR onto a relatively small area of land there may be detrimental effects on soil physical properties due to the blockage of pores with associated problems in terms of changes to hydraulic properties. This project has been able to monitor the effects of the Midmar WTR on the Hutton and Westleigh soils for 5 and 4 yr, respectively. In addition, by laboratory experiments the project was extended to included two other soils with very different properties (a Valsrivier and a Cartref). A wide range of soil physical measurements was taken in the field from all the main applied treatments.

The overwhelming conclusion from all these measurements is that the Midmar WTR actually improved the soil physical properties of both soils shortly after application. With time the soils on the treated plots have gradually reverted to the situation that pertains on the control plots. There is no evidence that even the very high application rate (1280 Mg ha^{-1}) has resulted in any adverse effects on the physical condition of either the structurally stable apedal Hutton or the hard-setting Westleigh soils. Similar conclusions were reached for the Valsrivier and Cartref soils.

18.2.2 Soil chemical and fertility properties

This project utilized the grassed contours at Brookdale and Ukulinga to follow the effects of the Midmar WTR on a test crop (perennial ryegrass/tall fescue) and on the soil chemical properties. In addition, the installation of soil water samplers at Ukulinga, and monitoring of a dam and borehole at Brookdale Farm by Umgeni Water (since 1997) enabled soil water and groundwater data to be collected.

From literature it was clear that three major aspects of WTRs have been most studied i.e., the liming effect, the ability of WTRs to sorb P, and the potential for soil and water pollution by heavy metals within the WTR. The present work has shown that the Midmar WTR does indeed increase soil pH and that this effect is quite long-lasting. In addition, the application of WTR increased extractable Ca and Mg, soluble salt content, cation exchange capacity, chloride and nitrate. Agronomically such effects can be considered to be mainly positive although the increase in nitrate may be a cause for some concern. However, the increase was measured in incubated soils in the laboratory experiment. There was some support for these data from the soil water samplers and the saturated paste soil measurements from the field experiments. Elevated nitrate concentrations were measured on the fallow plots of both experimental sites but the grassed plots showed lower concentrations probably because the vegetation extracted the nitrate before it leached through the soil. Groundwater nitrate concentrations were generally all <0.05 mg N L^{-1} in both dam and borehole samples.

The addition of WTR to a variety of soils increased the yield of ryegrass in a pot experiment, partly due to a liming effect although other factors were clearly also operative. In the field experiments, however, there were no significant differences in grass yield as a result of WTR addition, whether this was by incorporation or as a mulch. Similarly the WTR did not affect the concentrations of heavy metals in the tissue.

In terms of P sorption, this study has shown that, as found by other authors, WTRs have a high P sorption capacity. This was shown dramatically both in the laboratory and pot experiments. A crucial point, however, is that the grass at both field experiments never showed any indication of P deficiency, even on the mulched plots at Brookdale where the grass roots were concentrated within the mulched WTR layer. Similarly, the differences in extractable P between the soils on the control plots compared to the WTR-treated plots were small. Thus the work has confirmed that found by other studies i.e., that laboratory estimates of P sorption greatly overestimate the effect when one considers the effect on plants in the field. In addition, the results show that the WTR-treated soils released less P and so this characteristic of the WTR could be used to positive effect in areas where leaching or loss of P into groundwater or surface water bodies is a problem.

The heavy metal content of the WTR has also been shown not to present any real threat to the environment either by direct leaching (as evidenced by minimal concentrations in the dam and borehole water at Brookdale, and in the soil water collected at Ukulinga) or by uptake by the grass. The study was extended to a range of soils and included an incubation period to estimate the long-term dissolution of the WTR under different soil conditions. Eight metals were analysed and only Mn was measurable in any appreciable quantities. Although the results varied between the soils, overall it seems that application of the Midmar WTR can reduce the amount of soluble metals in soils through sorption and thus lessen the prospect of any pollution danger where this material is land treated.

18.2.3 Use of water treatment residue on 'poor' soil materials

The WTRs from Rand Water and the City of Cape Town were selected partly on the basis of the size of the producing facilities and importantly because of their totally different composition compared to the Midmar WTR. The full characterisation of the materials clearly demonstrates the highly calacareous nature of the Rand WTR and the highly organic composition of that from Cape Town (Faure Water Treatment Plant). As a result of pre-existing contact between Rand Water and a nearby mine this study was based around the prospects for using the Rand WTR as an aid to rehabilitation of coal mine spoil and combustion ash. The pot experiments showed that the response to the WTR was species specific. It appeared that addition of the Rand WTR to the covering soil should only be at the minimum rate and perhaps even lower than tested in this study. Conversely it could be applied at the maximum rate to the spoil material with no effect on yield. For some of the apparently poor performing treatments, the individual harvests indicated that these grasses had a potential to perform better than suggested by the mean total yield data. The high electrical conductivity (EC) and pH of some treatments may have reduced yield. The yield of the perennial grasses tended to improve as they became established, indicating an increased tolerance to the high EC and pH of some treatments. It is considered unlikely that such high EC and pH would be generated in the field and so in some respects the pot experiment produced a worst-case scenario.

The combustion ash proved problematic but it was shown that by adding a thick layer of Rand WTR onto the surface it enabled two species of creeping grasses to become established. Additional fertiliser was shown to improve growth of both species probably as a result of improving the supply of P. *Stenotaphrum secundatum* did not

grow as well as *Cynodon dactylon* but is likely to aid in stabilising the Rand WTR cap. *Cynodon dactylon* would give better cover and would also further stabilise the material as it produces underground rhizomes in addition to the surface stolons.

The Faure Water Treatment Plant, near Somerset West, treats raw water mainly to remove colour and odour, in contrast to the other plants that have large sediment loads to flocculate. The resulting WTR is very different to the Rand and Midmar materials but has the same problems of disposal. The Faure plant is in an area of sandy soils and so it is on such areas that disposal would occur should land treatment prove viable. The pot experiments investigated the growth of dry beans as a test crop with different rates of Faure WTR in a sandy soil. The results were generally encouraging although it was clear that Mn toxicity was a potential problem to achieving maximum growth and yield, especially where high rates of WTR were used with no or low additional fertiliser. The source of the Mn was the brown lime and the coagulant salt used to treat the raw water and so the problem may be entirely overcome by using a 'cleaner' source of these materials. Apparently, Faure will stop using the brown lime in 2004 and it will be replaced by a white lime with presumably much lower Mn content (Mr. P. Flower, pers. comm., 2003). Leaching decreased the Mn concentrations adequately but such a technique would require careful field management. It is considered that the conditions imposed on the pot experiment exacerbated the release of Mn and it is probable that under field conditions leaching would remove the Mn from the root zone. This coupled with oxidising conditions in the sandy soils that may immobilise the Mn would lessen this element's impact on plant growth.

18.2.4 Soil microbiological properties

The concept of 'soil quality' has become popular in recent years and although the data collected from the previous sub-projects can all be considered to reflect this concept, they do so over the longer term. Soil microorganisms will be immediately affected by any change in soil environment such as may occur with addition of a waste material. This part of the investigation therefore centred on the two field trials examining the microbial activity and related characteristics by thorough sampling of the main WTR-treated soils. Although only two sampling times were possible the results of microbial activity showed that differences between treatments were small. There was a clear trend at both sites for microbial activity to peak at a certain depth below the surface (rather than in the topsoil which might be expected). This trend is almost certainly a result of the extremely dry conditions experienced at both field sites (despite irrigation on the grassed plots) during the latter years of the project. The results also showed that the microbial population in the soils is stable – an indicator of good soil quality.

To extend the investigation to include the other WTRs that were collected, a laboratory study was undertaken to measure basal respiration when they were added to the two soils (controls) from the field trial sites. The type of WTR and the application rate greatly affected the basal respiration and, in general, respiration increased with rate of addition of the WTR. The Midmar, Rand, Midvaal and Faure 2 WTRs had the greatest effect on respiration, with the Amatola WTR only having a slight influence on the respiration of the Hutton soil from Brookdale. Increases in respiration became less marked with time. This suggests that such increases will be of short-term duration only and therefore supports the results from the field experiments discussed above. The increase in pH for all treatments due to the lime within all the

WTRs is considered to be a positive influence as it is likely to stimulate microbial growth. Although EC tended to increase with WTR addition there was no effect on microbial activity.

To look in more detail at the microbial population involved in the respiration and activity measurements, the Hutton soil was mixed with the different WTRs (at 15% m/m) and following incubation the microbial population was examined by denaturing gradient gel electrophoresis (DGGE). Although the results showed changes in the microbial community structure of WTR-amended soils after a period of only 5 days the structure had not drastically changed. The original soil bacterial populations were still present though in lesser amounts. The laboratory investigations provided evidence of the competitive and dominant nature of the soil bacterial species, although these were placed under stress by the addition of the WTR. The observed changes are likely to persist for a short period of time, and are unlikely to pose a problem in the long-term. These results indicate that the tested WTRs can be applied to a Hutton soil at an application rate of at least 15% (300 Mg ha^{-1}) without inducing permanent changes to the soil microbial community structure.

18.3 Recommendations

18.3.1 Legislative

18.3.1.1 Declassification of water treatment residue

This investigation has produced a considerable amount of data on the Midmar WTR and by extension all similarly produced polymer WTRs. However, knowledge of the other WTRs investigated is restricted to the reported laboratory and glasshouse studies. The dangers of extrapolation from these to the field situation are indicated by the phosphate and nitrate behaviour of the Midmar WTR, probably the Mn behaviour of the Faure WTR and the high EC measured in the pot experiment using the Rand WTR. The problems with extrapolation to field situations are compounded for WTRs because they vary both spatially and temporally from the same treatment works. However, it is clear that the laboratory and glasshouse experiments exaggerate the problems and reflect worst-case conditions.

Despite this, it is also clear that all aspects of the work reported reveal a highly consistent result i.e., that land application of WTR is safe and is likely to have no negative impacts on soils, vegetation or groundwater even at very high disposal rates that are unlikely to occur in the field. Indeed, it appears that the land application of WTR can have positive effects such as improving water retention in especially coarse-textured soils and increasing hydraulic conductivity in fine-textured soils, reducing P sorption in high P sorbing soils and increasing P sorption in sandy soils, increasing the sorption of heavy metals (thereby reducing their pollution threat) and increasing properties such as cation exchange capacity and plant available Ca and Mg.

Notwithstanding the above, there are some aspects that require further investigation before formalised guidelines for the land disposal of WTR can be fully produced and these are outlined in Section 18.4. However, the positive effects of land disposal of WTR clearly outweigh the assumed negative impacts that were the impetus behind this investigation. Thus, even without formalised guidelines, the results given in this

report offer compelling evidence for the Department of Water Affairs and Forestry to consider declassifying WTR in order that land disposal, with appropriate minimal monitoring of the site, may be an approved option for water treatment authorities.

18.3.1.2 Water treatment residue and biosolids

During the course of this project it became clear that water treatment sludge (as it was originally termed) and wastewater treatment sludge (biosolids) were linked in people's minds. They are, however, completely different materials with drastically different properties with totally different constraints when land application is considered. It was for this reason that the term "water treatment residue" was adopted for this project. It is therefore essential that this term be used in order to distinguish the material from wastewater sludge and that the materials are clearly differentiated in the regulations that govern their disposal.

18.3.2 General

- In terms of the Midmar WTR the information is extensive and an operational management plan for Brookdale Farm was presented to Umgeni Water (Hughes *et al.*, 2000). This involved land treating the WTR as a slurry at a rate not exceeding 320 Mg ha^{-1} using a muck-spreader. This rate was chosen to be on the conservative side and indications from the field data gathered since that time are that this rate could be safely exceeded. However, given the area available for disposal at Brookdale there is no need to increase the application rate, unless or until the treatment plant increases production.
- This study has also considered in some detail the impact of the Midmar WTR on a wide range of soils under laboratory and glasshouse conditions, which as mentioned earlier give the worst-case outcome. These studies have shown no ill-effects on either soils, vegetation or leachates (and thus groundwater), beyond those that might be expected under the imposed conditions. From literature and the questionnaire, the Midmar WTR is typical of all polymer WTRs which, on the basis of the questionnaire results, are the predominant type produced in South Africa. Therefore land disposal recommendations suitable for the Midmar WTR would apply to all such WTRs across a very wide range of soil types.
- The WTRs from Rand Water, Amatola Water, Midvaal and Faure have no long-term impacts on the microbiological properties of the Hutton and Westleigh soils, despite their very different properties. It is therefore likely that such a conclusion could be extended to other soil types and so by this measure of soil quality these types of WTR are unlikely to be damaging and thus can be applied to land at rates up to at least 320 Mg ha^{-1}.
- The Rand Water WTR can be used to rehabilitate the coal mine spoil although the application rate will have to be further investigated by trials on-site. Such trials should include other species.
- The Rand material can also be used as a capping material over the combustion ash especially if a thicker layer is used and fertiliser added. Although not tested in this project the effectiveness of the Rand WTR may be improved by the addition of an organic by-product.
- The Faure WTR was problematic in glasshouse pot experiments. The major problem appeared to be Mn added during the treatment process as a

contaminant in the brown lime and the $Fe_2(SO_4)_3$. As such the obvious solution is for the treatment works to source 'cleaner' additives although the economics of this compared to landfilling the WTR would have to be examined by the plant managers (see earlier comment regarding the change to white lime in 2004). It is also likely that the Mn would be much less of a cause for concern under field conditions (see Section 18.4 for further comments).

- Adequate management must be assured for any land disposal scheme for WTR. This would be especially important where the soils may be naturally sensitive e.g. wet soils or those that display vertic properties.

18.3.3 Techniques

18.3.3.1 Soil physical properties

Field soil cores would probably be the ideal since water retention, hydraulic conductivity, porosity, air permeability and bulk density can be determined on one soil core. In the absence of field experiments then repacked cores should be used though they tended to overestimate the water holding capacity of WTR-amended soils. Water stable aggregation also proved useful to monitor changes in aggregate size distribution.

18.3.3.2 Characterisation of water treatment residues

The $SrCl_2$ extraction worked well, but overestimated Ca (and probably Mg) in some WTRs due to dissolution of Ca from carbonates in the material. Determination of soluble NO_3 and exchangeable NH_4 (2M KCl) with colorimetric determination by continuous flow auto analyser, gave quick estimates of available N. Estimation of P by the AMBIC method was poor and should be used with caution on these materials. Organic carbon seemed variable and this measure is probably not as useful as it is for soils. Determination of calcium carbonate equivalence allows for the prediction of the WTRs liming potential, which may be required under certain types of land application.

Physical analyses were difficult due to the high structural stability of some WTRs while others were less structurally stable. Particle size distribution, together with the double pipette method to determine aggregation, may give a reasonable indication of potential breakdown rates.

X-ray fluorescence spectrometry is a rapid indicator of complete elemental composition. It does not reflect the true toxicity of the WTR since it is a measure of total elements but it may indicate potential toxic elements that require closer investigation. The DTPA and TCLP methods gave conflicting results. It appears that TCLP underestimates metal availability and it is also a tedious method, especially if samples are variable in pH. The DTPA extraction allows for a quicker determination of plant available elements, and seemed to reflect more closely what was observed in the plants used in the pot experiments. The five-step fractionation procedure gives insight into the distribution of the metals in the sample, which could allow predictions on how they may behave under different land application systems. However, the method is tedious and time consuming and the last step requires an appropriate work area and protective clothing (digestion with HF, HNO_3 and $HClO_4$).

Measures of P adsorption by isotherm data appear only to reflect the laboratory environment but do give some idea as to the maximum potential of P sorption by the WTRs. However, all the work in this project has shown that this does not reflect the field environment where the plants showed no indication of P deficiency.

Pot experiments help develop a basic understanding of the behaviour of a WTR when applied to a particular soil or waste for land application purposes. An idea of the parameters that may require further testing can be developed and ultimately a guideline for the establishment of field studies (if needed). They are quicker to develop and establish than field experiments and can give results in a far shorter period of time, offering an economical, relatively quick and simple method of predicting effects on soils and plants. However, they should never be seen as an exact replication of what will occur in the field.

18.3.3.3 Microbiological properties

A simple measurement of microbial activity such as FDA or respiration appears to be suitable. For more detailed information the DGGE technique has great potential to give insight into the microbial population, although it is rather costly, time-consuming and requires highly specialised equipment and personnel. It is thus probably not justified on a regular basis but for individual samples gives information that is unobtainable by more routine methods.

18.3.3.4 Soil chemistry/fertility

The results of this part of the project showed that the Midmar WTR was essentially neutral in its effects on soil properties and plants. This relatively inert behaviour argues in favour of using relatively mild extractants when trying to predict field behaviour. Similar reasoning would apply to other polymer WTRs.

To characterise the Midmar WTR and similar materials that contain reasonable quantities of lime and have a basic pH, the same extractants can be used as for calcareous soils. In terms of predicting the behaviour of WTRs in the field this investigation has only considered the Midmar WTR. However, the similarity between this WTR and others (Chapter 4) suggests that similar conclusions would apply to many WTRs. To establish the amounts of 'immediately reactive' major cations, a single extraction with 0.1M $BaCl_2$ (unbuffered) is convenient. To estimate the movement of these cations in the field, water extracts would be more advisable. With respect to predicting the movement of heavy metals under field conditions, the use of a weak extractant such as 0.05M $CaCl_2$ is suggested. In the current investigation this extractant was used on soils from a pot experiment and on incubated samples to remove soluble plus exchangeable metals. The results predicted the established mobility of metals at the two field sites with reasonable success.

18.4 Future research

As stated above, this investigation has produced a management plan for the land disposal site at Brookdale Farm and has recommended an application rate of 320 Mg ha^{-1} yr^{-1}. Since this site is fully monitored by Umgeni Water, further recommendations have not been given. However, all the evidence suggests that the polymer WTR

produced at the Midmar Water Treatment Works poses no threat to the environment at such levels of disposal. Given this, only minimal monitoring would appear to be required.

The only lime WTR produced in any quantity in South Africa is that from Rand Water and their chosen disposal site is a nearby coal mine. Any further work should therefore be directed at field experimentation based on the outcomes of the laboratory and pot experiments already conducted. In addition, different species should be studied in the field and co-disposal with an organic-rich waste could also be a fruitful line of research to improve the effectiveness of the WTR as an aid to rehabilitation.

The WTR produced at Faure, on the basis of the pot experiment, is also suitable for land disposal with the only problem appearing to be the possibility that Mn may be released and be toxic to plants or contaminate the groundwater. The main source of this Mn is the brown lime used at the treatment plant and from 2004 this is to be replaced with a source of white lime (Mr. P. Flower, pers. comm., 2003). This change will certainly reduce the possible effects of Mn considerably, although it still remains as a contaminant in the $Fe_2(SO_4)_3$ coagulant. In order to investigate the effect of the change of lime further laboratory investigations would be useful. In addition, in order to suggest application rates for land disposal some field experimentation would be required. It is recommended that this could be undertaken at the same time as land disposal of the material, since the likelihood of any adverse effects in the field are minimal.

Of the common types of WTR the only one not studied in this report is that where alum is a major component. However, such WTR is commonly produced overseas and much of the literature is concerned with its effects when disposed of to land. Therefore much of the required information can be gleaned from the literature. This could then be combined with some laboratory studies, and field experimentation along the same lines as for the organic WTR produced at Faure. Since another water treatment plant in Cape Town uses alum, it may be possible to run these field investigations concurrently.

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Journal articles

Moodley, M., Johnston, M.A., Hughes, J.C. and Titshall, L.W. 2004. The effects of a water treatment residue, lime, gypsum, and polyacrylamide on the water retention and hydraulic conductivity of two contrasting soils under field conditions in KwaZulu-Natal, South Africa. Accepted for *Aust. J. Soil Res.* 42 (3). February 2004.

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Appendix 4.1 The questionnaire distributed to water treatment authorities to determine raw water treatment and water treatment residue disposal practices in South Africa. The questionnaire was developed before the decision to use the term 'water treatment residue', hence the use of the term 'sludge'

Questionnaire.

This questionnaire is to obtain information from as many drinking water treatment works as possible. If there is more than one plant under your management or forming part of your organisation, please complete a separate questionnaire for each plant.

Contact person: .....
Details: Address: .....
.....
.....
(Tel) .....
(Fax) .....
(e-mail) .....

1) Where is/are the source/s of abstraction of the facility's raw water? (if more than one, list in order of greatest volume taken).

.....
.....
.....

2) What volume of sludge is produced seasonally?

Winter: .....
Summer: .....
(If possible please also include annual trends)

3) What chemicals and flocculants are added to purify the raw water? (tick where applicable):

Lime: ❒ Bentonite: ❒
$Al_2(SO_4)_3$: ❒
$FeCl_3$: ❒
Polyelectrolytes ❒ Type (please specify): .....
Activated Silica ❒
Other (please specify): .....
.....

4) What are the dosage rates of chemicals added? (Give as ppm or mg/L if possible)

Lime: ..... Bentonite: .....
$Al_2(SO_4)_3$: .....
$FeCl_3$: .....
Polyelectrolytes: .....
Activated Silica: .....
Other (from question 3): .....
.....

5) How is the sludge thickened?

Centrifugation ❒
Chemical additives ❒ (please specify): .....
Settling ponds ❒
Other (please specify): .....

6) What is the approximate solids content of the sludge produced? .....

Appendix 4.1 (cont.) The questionnaire distributed to water treatment authorities to determine raw water treatment and water treatment residue disposal practices in South Africa. The questionnaire was developed before the decision to use the term 'water treatment residue', hence the use of the term 'sludge'

7) How is the sludge currently disposed of?

Landfill ❒ Land treatment ❒ Sewer discharge ❒
River discharge ❒
Other (please specify): .....

8) How is the sludge transported to the disposal site?

Road (truck, trailer, etc.) ❒
Pipeline ❒
On site disposal ❒
Other: .....

9) What is the approximate distance to the disposal site?
.....

10) Have any studies been conducted that are related to the disposal or use of the sludge?

Yes ❒ No ❒

11) If Yes, are these studies available in the public domain?

Yes ❒ No ❒

12) If Yes, where can these studies be accessed?

.....
.....

13) Are there any potential sites for rehabilitation and/or land treatment (amelioration) in the vicinity of the water treatment facility and surrounding areas? (Please give details).
.....
.....
.....
.....

14) Would your company be interested in supporting this study?

Logistically ❒ Financially ❒ Both ❒

15) Would you send us a sample of the requested quantity of waste material?

Yes ❒
Yes, if we arrange transport ❒
No ❒

Appendix 4.2 Method used for particle size analysis (adapted from Gee and Bauder, 1986)

Air-dry (<2 mm) material was dispersed by the addition of 10 mL Calgon (35.7 g sodium hexametaphosphate and 7.9 g sodium carbonate L^{-1}) and 20 mL distilled water with subsequent ultrasound treatment (400 W, Labsonic 2000) for 3 min. The dispersed sample was passed through a 0.053 mm sieve into a 1 L sedimentation cylinder and made up to 1 000 mL with distilled water.

The >0.053 mm fraction (sand) was dried at 105^{o}C and the <0.053 mm fraction in the cylinders was brought into suspension by agitation with a custom-made plunger. The coarse silt (0.02-0.053 mm), fine silt (0.002-0.02 mm) and clay (<0.002 mm) were determined by sedimentation and pipette sampling after appropriate settling times for each size fraction, according to Stokes' Law. The pipetted sample was dried overnight at 105^{o}C. Separate sub-samples of all <2 mm materials were dried at 105^{o}C overnight for moisture content determination. All fractions are given as a mass percentage of oven-dry soil, after correcting for moisture content of air-dry samples. Two replicates were measured on each sample. Texture classes were assigned according to the Soil Classification Working Group (1991).

Appendix 4.3 List of water treatment facilities that returned partially and completely filled questionnaires. Includes source of raw water and chemical dosing rates (where supplied)

Water Authority	Water source	Dosing rates of chemicals (mg L^{-1})[a]								
		Lime	**Ben**	**AlSO**	**FeSO**	**$FeCl_3$**	**LCP**	**ActSi**	**NaAl**	**Other**
Albany Coast Water	Desalinisation Plant									
Amatola Water	Nahoon Dam	8					6-12			
Bloemfontein Water[c]										
Plant 1	Hennie Steyn bridge	7.34				0.8	13.3			
Plant 2	Gariep Dam wall	2.56					4.88			
Plant 3	Sterkfontein bridge	3.43				2	2.9			
Bushbuckridge Water Board[c]										
Plant 1	Shatale River	*						*		
Plant 2	N'warhelo River	*					*			
Plant 3	Edinburgh Dam	*				*	*			
Plant 4	Mutlumuvi/Sand River Pump stations	*					*			
Plant 5	Not specified	*					*			
Plant 6	Sand River canal						*		*	
City of Cape Town[c]										
Blackheath	Theewaterskloof Dam	5.6		1.6						
Brooklands	Kleinplaas/Lewis Gay/Rawson Dams	60		8			0.1			
Constantia Nek	Table Mountain Dams	47.6		5.3				6	3.1	
Faure	Theewaterskloof/Palmiet	40-45			7-15					
Kloofnek	Hely Hutchinson/Woodhead Dams	42		5					2.5	22
Voelvlei	Voelvlei Dam	16.2			4.7-7		0.02-2.25			5.3
Wemmershoek	Wemmershoek/Theewaterskloof Dam	30-36		65						16

Appendix 4.3 (cont.) List of water treatment facilities that returned partially and completely filled questionnaires. Includes source of raw water and chemical dosing rates (where supplied)

Water Authority	Water source	Dosing rates of chemicals (mg L^{-1})[a]								
		Lime	**Ben**	**AlSO**	**FeSO**	**$FeCl_3$**	**LCP**	**ActSi**	**NaAl**	**Other**
Khara Hais Municipality	Orange River	5					0.1-1			5-15
Lepelle Northern Water	Olifants River						0.29			
Midvaal Water Company	Middle Vaal River	15		10		10-23	0.4-10			
Rand Water	Vaal Dam	60-80[b]				1.5-7	8	3		
Rustfontein Water	Modder River	9					2			
Umgeni Water[c]										
Amazimtoti	Niengwane Dam	6-12	0.5-2.5				5-17			
Craigieburn	Umkomaas River	4					1-7			
Durban Heights	Nagle/Inanda Dams	4-6					2-3			
DV Harris	Midmar Dam	8-8.2	3-3.5				1.3			
Hazelmere	Hazelmere Dam	10-12								
Imfume	Boreholes						57			
Ixopo	Solly Bux Dam/borehole	4		33-45						
Midmar	Midmar Dam	5.3-8.2	2.1-2.9				1.1-1.4			
Mtwalume	Mtwalume River	4-7		33			10			
Ogunjini	River abstraction						*			
Umbumbulu	Nugwane Dam	6-12	0.5-2.5				5-17			
Umlaas Rd	Midmar Dam	5.3	2.4-3.4				2.1			
Umzinto	JG Smith Dam/Umzinto River	10-12					8-14			
Wiggins	Inanda Dam	2-2.5	1-2				1.5-2			

[a] Lime - lime, Ben – bentonite, AlSO - $Al_2(SO_4)_3.14H_2O$, FeSO - $Fe_2(SO_4)_3$, $FeCl_3$ - $FeCl_3$, LCP – long-chain organic polymer, ActSi - activated silica, NaAl - sodium aluminate, Other - activated charcoal and CO_2.

[b] Added as CaO (Rand Water). [c] Water treatment authorities with more than one water treatment facility.

* These treatment facilities indicated the use of these chemicals, but did not supply dosing rates.

Appendix 4.4 X-ray fluorescence analysis of the water treatment residues, the spoil, soil and ash (Chapters 7 and 8), and the Longlands sand (Chapter 9)

Sample	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Total	LOI[a]
	(%)											
Midmar[b]	52.30	23.93	13.91	0.84	1.36	4.65	0.11	1.60	0.81	0.32	99.83	22.90
Midmar[c]	54.57	22.60	11.95	1.53	1.92	4.20	0.15	1.47	0.86	0.24	99.49	23.91
Midvaal	53.07	22.36	14.24	0.41	1.83	4.45	0.33	1.89	0.74	0.47	99.79	27.70
Amatola	52.59	29.06	10.31	0.07	1.82	1.55	0.43	2.98	0.86	0.12	99.79	25.63
Rand	24.36	9.89	4.85	0.66	5.25	53.19	0.61	0.82	0.31	0.09	100.03	36.93
Faure 1	29.93	8.70	53.80	0.96	0.72	3.15	bd	0.93	0.78	0.39	99.36	43.07
Faure 2	37.96	17.78	32.13	2.31	1.54	3.35	0.49	1.86	0.62	0.37	98.40	55.28
Spoil	73.02	19.00	2.82	0.03	0.59	1.39	0.33	1.09	1.03	0.09	99.57	26.93
Soil	87.65	7.16	2.32	0.03	0.22	0.19	0.35	1.41	0.36	0.01	99.70	4.52
Ash	56.14	29.93	3.87	0.03	1.27	5.55	0.24	0.78	1.51	0.38	99.70	1.61
Lo[d]	89.91	2.59	3.84	0.07	0.08	0.16	bd	0.16	2.80	0.03	99.64	2.81

Sample	Cd	Co	Cr	Cu	Ni	Pb	Zn	S	Sr	As	V	U
	($mg\ kg^{-1}$)											
Midmar[b]	nd	45.0	138.0	42.0	56.0	17.0	101.0	810	157.0	20.0	205.0	2.0
Midmar[c]	4.00	39.0	161.0	44.0	53.0	37.0	84.0	720	71.0	17.0	154.0	bd
Midvaal	nd	32.0	246.6	53.2	117.7	26.0	142.1	2402	66.2	5.0	187.8	0.2
Amatola	nd	19.0	134.3	23.0	39.7	36.0	84.5	911	91.4	11.0	175.8	3.8
Rand	nd	3.5	77.3	5.4	22.9	5.8	33.1	700	273.4	1.7	61.1	2.1
Faure 1	nd	nd	43.0	bd	21.0	nd	182.0	2500	nd	nd	93.0	nd
Faure 2	nd	nd	70.0	11.0	27.0	nd	124.0	2500	nd	nd	134.0	nd
Spoil	nd	22.1	248.6	34.4	52.1	14.0	51.6	10800	164.3	13.8	222.4	2.5
Soil	nd	12.6	152.3	15.4	25.7	6.9	30.8	100	48.4	5.1	98.1	0.5
Ash	nd	12.6	201.5	49.8	47.4	45.9	40.3	2900	990.0	24.0	151.7	12.2
Lo[d]	nd	nd	146.0	4.0	4.0	nd	16.0	235	nd	nd	nd	nd

Sample	Nb	Ce	Nd	Zr	Y	Sc	Th	Ba	La	Rb	Ga
	($mg\ kg^{-1}$)										
Midmar[b]	nd	88.0	31.0	123.0	29.0	40.0	17.0	891.0	34.0	104.0	18.0
Midmar[c]	11.0	96.0	25.0	126.0	27.0	33.0	10.0	1007.0	19.0	94.0	20.0
Midvaal	7.8	51.0	24.0	101.6	23.1	30.7	7.9	438.7	5.4	109.2	19.0
Amatola	10.6	71.0	38.0	105.1	29.4	30.1	16.1	705.7	30.6	171.5	23.0
Rand	2.7	5.1	bd	32.2	38.1	13.5	5.0	398.4	bd	38.1	8.9
Faure 1	nd	nd	nd	nd	nd	nd	nd	nd	38.0	nd	nd
Faure 2	nd	nd	nd	nd	nd	nd	nd	nd	26.0	nd	nd
Spoil	12.3	95.0	36.5	196.6	24.2	34.6	15.3	538.7	30.8	33.2	14.9
Soil	5.1	36.8	13.5	230.1	14.5	20.0	9.6	448.4	31.2	58.4	9.3
Ash	34.6	169.5	76.9	389.1	71.7	36.5	45.8	1117.4	100.6	40.5	38.7
Lo[d]	nd	nd	nd	nd	nd	nd	nd	nd	10.0	nd	nd

[a] loss on ignition. [b] Midmar WTR sampled in May 1998 and [c] sampled in August 2000.
[d] Longlands sand. bd below detection. nd not determined.

Appendix 5.1a Soil profile description of the Hutton soil at Brookdale Farm

Soil code: Hu 3100
Soil Form: Hutton
Soil Family: Stella
Location: Brookdale Farm, Howick
Parent material: Dolerite
Land use: Dryland cropping

Horizon	Depth (m)	Description
A	0 - 0.38	Very dark brown (10YR 2/2); clay; weak crumb; dry; firm; many fine roots; gradual transition to B1.
B1	0.38 - 0.60	Dark brown (7.5YR 3/2); clay; weak, subangular blocky; moist, friable; gradual transition to B2.
B2	0.60 - 1.20+	Dark red (2.5YR 3/6); weak, subangular blocky; moist, firm.

Horizon	Particle size distribution (%)					
	----------Sand----------			----------Silt----------		Clay
	Coarse	Medium	Fine	Coarse	Fine	
	0.5 - 2.0 mm	0.25 - 0.5 mm	0.053 - 0.25 mm	0.02 - 0.053 mm	0.002 - 0.02 mm	<0.002 mm
A	7	2	5	16	18	52
B1	6	1	6	20	11	56
B2	8	2	6	8	13	63

Horizon	pH		Exchangeable cations ----------($cmol_c\ kg^{-1}$)-------				Exch. acidity ($cmol_c\ kg^{-1}$)	Organic carbon ($g\ kg^{-1}$)
	(KCl)	(H_2O)	Ca	Mg	Na	K		
A	4.22	5.21	5.57	2.29	0.10	0.17	0.37	33.5
B1	4.14	5.50	4.38	2.60	0.24	2.17	0.40	23.2
B2	4.04	5.82	5.34	1.95	0.12	1.00	1.42	15.2

Appendix 5.1b Soil profile description of the Westleigh soil at Ukulinga Farm

Soil code: We 1000
Soil Form: Westleigh
Soil Family: Helena
Location: Ukulinga Farm, Mkondeni, Pietermaritzburg
Parent material: Ecca shale
Land use: Pasture

Horizon	Depth (m)	Description
A	0 - 0.26	Very dark brown (10YR 2/2); silty clay loam; weak, crumb; hard when dry; gradual transition to B.
B	0.26 - 0.55	Dark reddish gray (5YR 4/2); gravelly silty clay loam; moderate, subangular blocky; very hard when dry; numerous yellowish-brown mottles; hardpan concretions.

Horizon	Particle size distribution (%)					
	----------Sand----------			----------Silt----------		Clay
	Coarse	Medium	Fine	Coarse	Fine	
	0.5 - 2.0 mm	0.25 - 0.5 mm	0.053 - 0.25 mm	0.02 - 0.053 mm	0.002 - 0.02 mm	<0.002 mm
A	9	2	6	25	25	33
B	not determined					

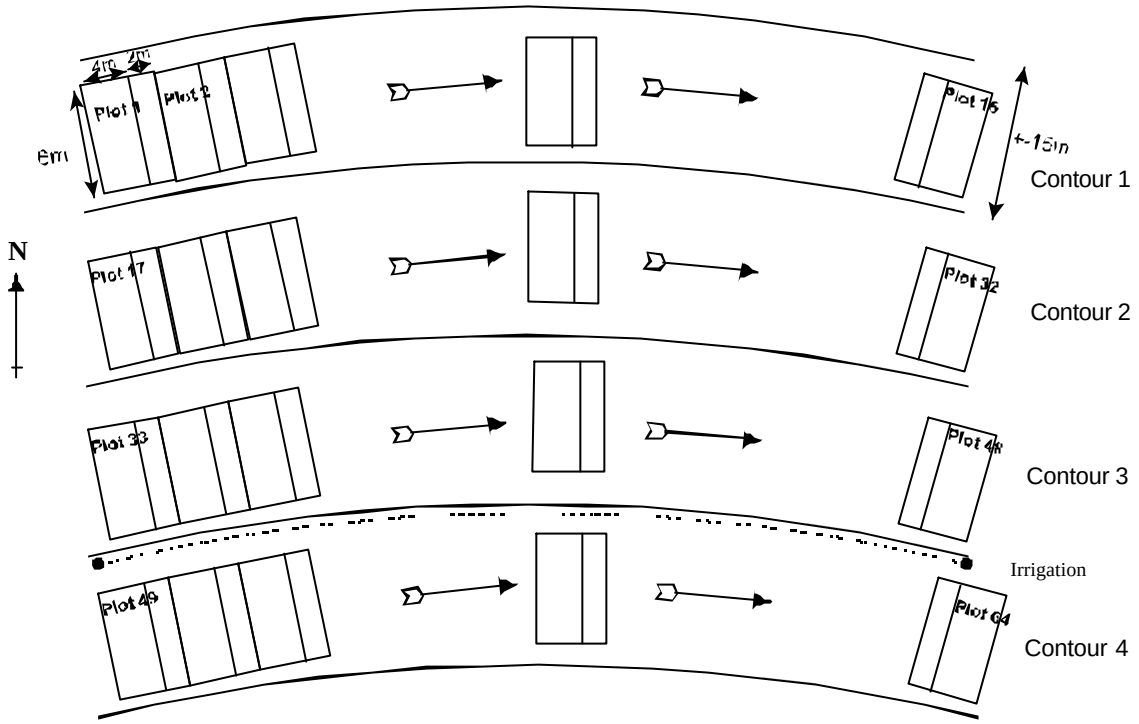
Horizon	pH		Exchangeable cations ----------($cmol_c\ kg^{-1}$)--------				Exch. acidity ($cmol_c\ kg^{-1}$)	Organic carbon ($g\ kg^{-1}$)
	(KCl)	(H_2O)	Ca	Mg	Na	K		
A	4.90	5.91	6.24	3.06	0.14	0.17	0.06	21.70
B	not determined							

Appendix 5.2a Treatments investigated at Brookdale Farm

----------Fallow----------		----------Grassed----------	
Plot	**Treatment**	**Plot**	**Treatment**
1	P15	33	Control
2	L2	34	P15
3	1280	35	40
4	G10	36	L2
5	M320	37	160
6	40	38	320
7	G5	39	M1280
8	1280	40	L10
9	M640	41	P30
10	M1280	42	160
11	L2	43	640
12	320	44	M320
13	80	45	Control
14	P30	46	P15
15	Control	47	G10
16	160	48	40
17	640	49	P30
18	80	50	320
19	160	51	G5
20	Control	52	G5
21	640	53	80
22	L2	54	L10
23	M640	55	M320
24	G5	56	G10
25	320	57	640
26	40	58	80
27	M320	59	L2
28	P15	60	1280
29	G10	61	M640
30	P30	62	M1280
31	M1280	63	M640
32	L10	64	1280

Codes used in Table above	**Description of treatment**
L2	Lime applied at 2 Mg ha^{-1}. Incorporated with the top 0.2 m of the soil by discing.
L10	Lime applied at 10 Mg ha^{-1}. Incorporated with the top 0.2 m of the soil by discing.
G5	Gypsum applied at 5 Mg ha^{-1}. Incorporated with the top 0.2 m of the soil by discing.
G10	Gypsum applied at 10 Mg ha^{-1}. Incorporated with the top 0.2 m of the soil by discing.
P15	Anionic polyacrylamide applied at 15 kg ha^{-1}. Sprayed onto the plot surface as a 0.1 g L^{-1} solution.
P30	Anionic polyacrylamide applied at 30 kg ha^{-1}. Sprayed onto the plot surface as a 0.1g L^{-1} solution.
40, 80, 160, 320, 640, 1280	WTR content (Mg ha^{-1}). Incorporated with the top 0.2 m of the soil by discing or applied as a mulch (M).

Appendix 5.2b Layout of the field experiment at Brookdale Farm

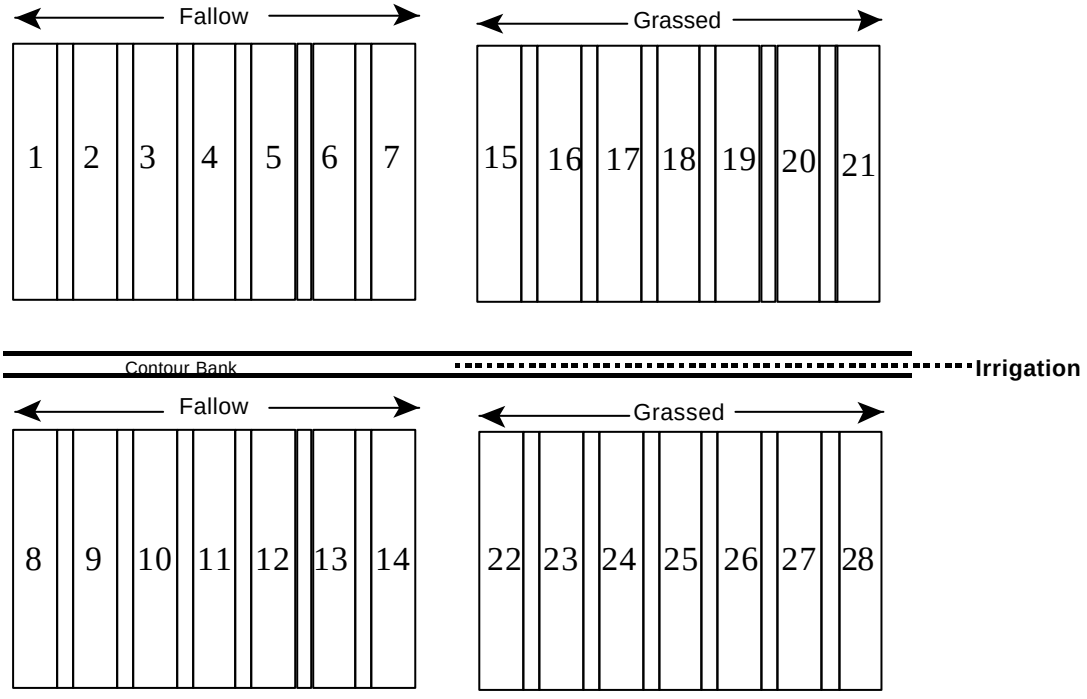


Note : Contours 1 and 2 were maintained fallow; Contours 3 and 4 were planted initially to perennial ryegrass (*Lolium perenne*) and then to Dovey tall fescue (*Festuca arundinaceae*) as explained in the text (Section 5.3.1). The 6 x 4 m plots were separated by 6 x 2 m buffer strips.

Appendix 5.3 Treatments investigated and layout at the Ukulinga Farm field experiment

----------Fallow----------		----------Grassed----------	
Plot	**Treatment**	**Plot**	**Treatment**
1	Control	15	80
2	320	16	P30
3	G10	17	80
4	1280	18	320
5	L10	19	1280
6	320	20	G10
7	P30	21	Control
8	80	22	1280
9	G10	23	L10
10	1280	24	320
11	P30	25	L10
12	80	26	Control
13	L10	27	G10
14	Control	28	P30

Codes used in Table above	**Description of treatment**
L10	Lime applied at 10 Mg ha^{-1}. Incorporated with the top 0.2 m of the soil by discing.
G10	Gypsum applied at 10 Mg ha^{-1}. Incorporated with the top 0.2 m of the soil by discing.
P30	Anionic polyacrylamide applied at 30 kg ha^{-1}. Sprayed onto the plot surface as a 0.1g L^{-1} solution.
80, 320, 1280	WTR content (Mg ha^{-1}). Incorporated with the top 0.2 m of the soil by discing.



Appendix 6.1 Summary ANOVA statistics for the effect of water treatment residue (WTR) applied at rates of 0, 80, 320 and 1280 Mg ha^{-1}, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (PAM) on volumetric water content (m^3 m^{-3}) at selected matric potentials in the Hutton soil at Brookdale Farm

Date	Matric potential (-kPa)	WTR application rate (Mg ha^{-1}) 0	80	320	1280	Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
	0	0.572	0.571	0.556	0.576	0.544	0.564	nd	NS	1.63	0.256
Feb	10	0.394	0.355	0.354	0.358	0.383	0.363	nd	NS	2.84	0.118
1999	30	0.331	0.303	0.305	0.319	0.347	0.312	nd	NS	1.08	0.454
	100	0.281	0.259	0.279	0.289	0.319	0.284	nd	NS	1.05	0.469
	0	0.534b*	0.554ab	0.539b	0.564a	nd	nd	nd	0.0226	3.79	0.047
Apr	10	0.359bc	0.373ab	0.347c	0.380a	nd	nd	nd	0.0151	9.90	0.002
1999	30	0.317	0.319	0.322	0.356	nd	nd	nd	NS	3.24	0.069
	100	0.273b	0.274b	0.280b	0.314a	nd	nd	nd	0.0282	4.62	0.028
	0	0.499bc	0.512ab	0.524a	0.524ab	0.519ab	0.503abc	0.483c	0.0251	3.21	0.021
June	10	0.323	0.332	0.338	0.329	0.336	0.330	0.325	NS	0.64	0.700
1999	30	0.292	0.296	0.303	0.300	0.300	0.292	0.283	NS	2.10	0.097
	100	0.271	0.269	0.276	0.283	0.274	0.265	0.266	NS	1.14	0.376
	0	0.480e	0.503cd	0.495de	0.529a	0.516bc	0.486de	0.522ab	0.0177	10.21	<0.001
Nov	10	0.326d	0.343c	0.348bc	0.372a	0.360ab	0.343c	0.342c	0.0138	10.27	<0.001
1999	30	0.289	0.302	0.302	0.308	0.301	0.294	0.287	NS	1.67	0.202
	100	0.255	0.265	0.262	0.271	0.246	0.259	0.242	NS	1.82	0.167
	0	0.506b	0.508b	0.508b	0.547a	0.512b	0.543a	0.538a	0.0205	7.12	<0.001
Apr	10	0.317b	0.324b	0.322b	0.336ab	0.357a	0.339ab	0.349ab	0.0230	3.58	0.013
2000	30	0.293	0.288	0.285	0.304	0.310	0.287	0.306	NS	2.01	0.110
	100	0.258ab	0.255ab	0.254b	0.266ab	0.279a	0.221c	0.261ab	0.0238	4.84	0.003
	0	0.531bc	0.544abc	0.556ab	0.563a	0.547ab	0.555ab	0.518c	0.0262	3.09	0.025
June	10	0.347c	0.355c	0.359c	0.382b	0.417a	0.356c	0.352c	0.0232	9.81	<0.001
2000	30	0.316cd	0.318bc	0.326ab	0.337a	0.322ab	0.298d	0.303cd	0.0174	4.97	0.003
	100	0.299ab	0.300a	0.305a	0.311a	0.293ab	0.265c	0.278bc	0.0225	4.56	0.004
	0	0.554	0.554	0.539	0.571	nd	nd	nd	NS	2.43	0.116
Feb	10	0.341	0.337	0.349	0.348	nd	nd	nd	NS	1.51	0.261
2001	30	0.295	0.296	0.306	0.304	nd	nd	nd	NS	1.85	0.137
	100	0.271	0.277	0.276	0.274	nd	nd	nd	NS	0.68	0.581
	0	0.567	0.561	0.576	0.588	0.566	0.575	0.582	NS	0.89	0.522
Sept	10	0.363	0.356	0.368	0.361	0.367	0.372	0.374	NS	0.93	0.496
2001	30	0.311	0.310	0.314	0.320	0.324	0.317	0.309	NS	1.80	0.147
	100	0.275bc	0.275bc	0.276bc	0.285ab	0.292a	0.271c	0.263c	0.0153	3.20	0.022
	0	0.563d	0.572b	0.556cd	0.586a	0.570b	0.563bc	0.563bc	0.0138	4.37	0.005
Oct	10	0.342	0.336	0.341	0.364	0.345	0.332	0.324	NS	2.28	0.075
2002	30	0.295	0.297	0.310	0.320	0.298	0.299	0.306	NS	0.93	0.496
	100	0.262abc	0.268ab	0.281ab	0.288a	0.268ab	0.255bc	0.236c	0.0294	2.98	0.029
	0	0.510c	0.510c	0.513c	0.540a	0.533ab	0.528bc	0.522c	0.0194	3.24	0.020
June	10	0.325	0.333	0.335	0.333	0.336	0.331	0.322	NS	1.53	0.218
2003	30	0.285	0.297	0.287	0.295	0.297	0.291	0.277	NS	1.85	0.137
	100	0.251	0.265	0.252	0.263	0.261	0.254	0.242	NS	1.97	0.117

* Letters that are different indicate significant differences between means.

nd not determined.

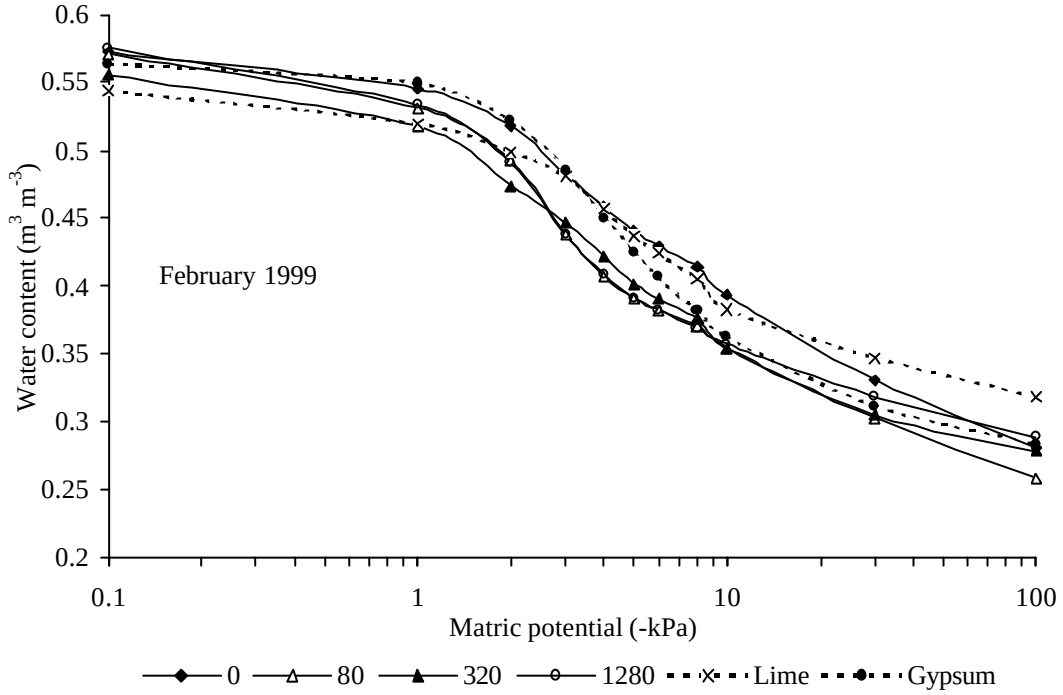
NS non-significant F-statistic.

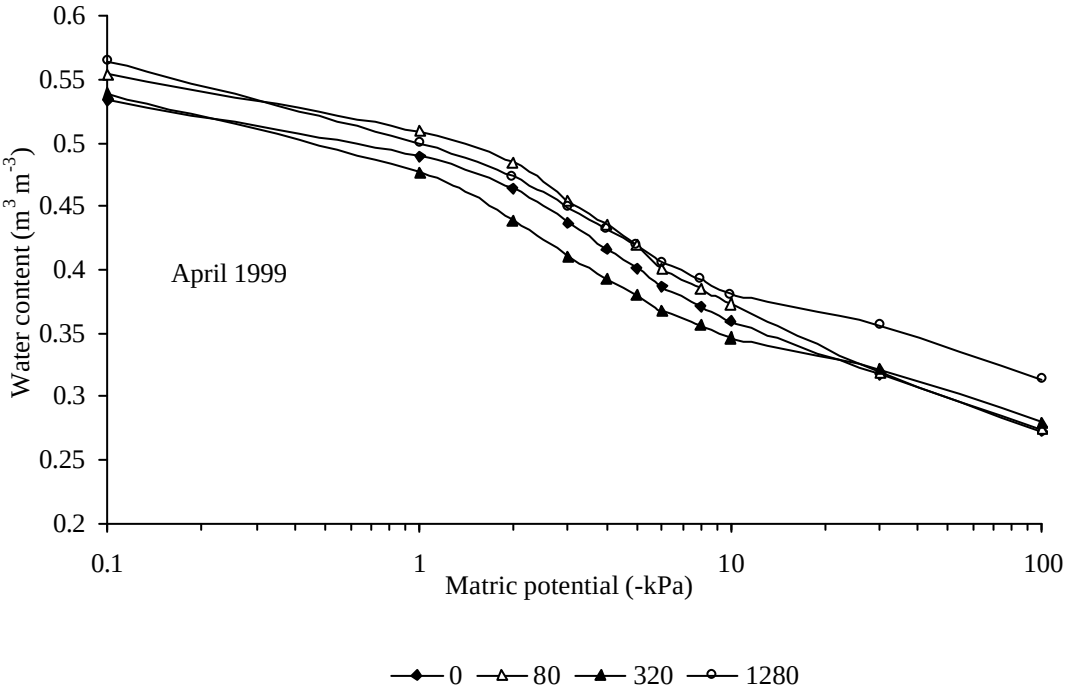
Appendix 6.2 Summary ANOVA statistics for the effect of water treatment residue (WTR) applied at rates of 0, 80, 320 and 1280 Mg ha^{-1}, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (PAM) on the readily available water content (m^3 m^{-3}) over time in the Hutton soil at Brookdale Farm

Date	WTR application rate (Mg ha^{-1})				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})
	0	80	320	1280			
Feb 1999	0.0897a*	0.0730bcd	0.0598b	0.0528cd	0.0598b	0.0602e	nd
Apr 1999	0.0864a	0.0936a	0.0942b	0.0730bc	nd	nd	nd
June 1999	0.0518c	0.0638bcd	0.0626a	0.0455d	0.0624b	0.0649de	0.0591e
Nov 1999	0.0710abc	0.0782bc	0.0864a	0.1007a	0.1132a	0.0847de	0.1000ab
Apr 2000	0.0595bc	0.0685bcd	0.0678b	0.0694bc	0.0786b	0.1181a	0.0884bc
June 2000	0.0482c	0.0551d	0.0538b	0.0712b	0.1239a	0.0913bc	0.0741cd
Feb 2001	0.0708abc	0.0601cd	0.0726a	0.0711bc	nd	nd	nd
Sept 2001	0.0878a	0.0812ab	0.0922a	0.0763b	0.0751b	0.1001ab	0.1110a
Oct 2002	0.0800ab	0.0681bcd	0.0602b	0.0755b	0.0771b	0.0767cde	0.0878bc
June 2003	0.0741ab	0.0672bcd	0.0833a	0.0690bc	0.0741b	0.0771bcde	0.0795c
$LSD_{5\%}$	0.0240	0.0183	0.0236	0.0205	0.0224	0.0257	0.0198
VR	3.23	3.89	2.48	4.26	9.26	4.68	6.41
F-Pr	0.010	0.003	0.033	0.002	<0.001	0.003	<0.001

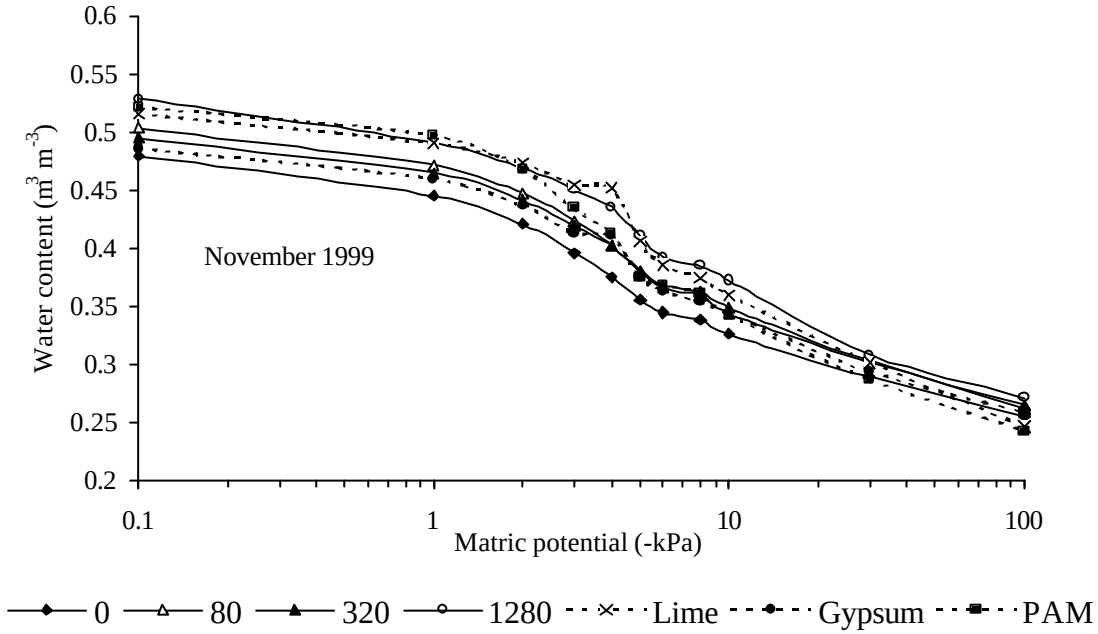
* Letters that are different indicate significant differences between means within any one treatment.
nd not determined.

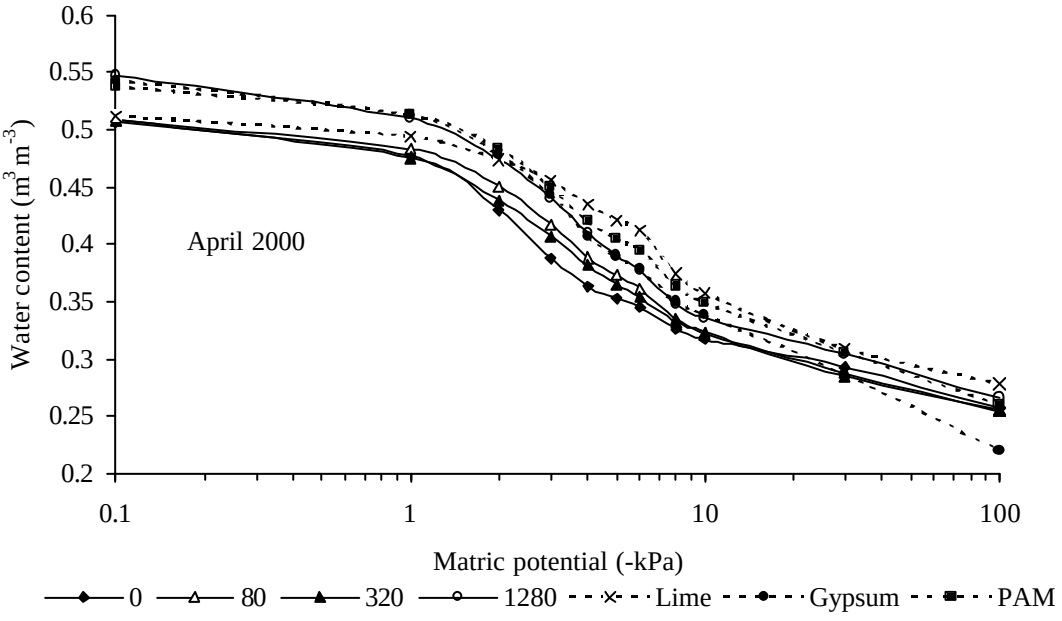
Appendix 6.3 Water retention curves for February 1999, April 1999, November 1999, April 2000 and February 2001 samples collected from Brookdale Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, and in some instances, the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)



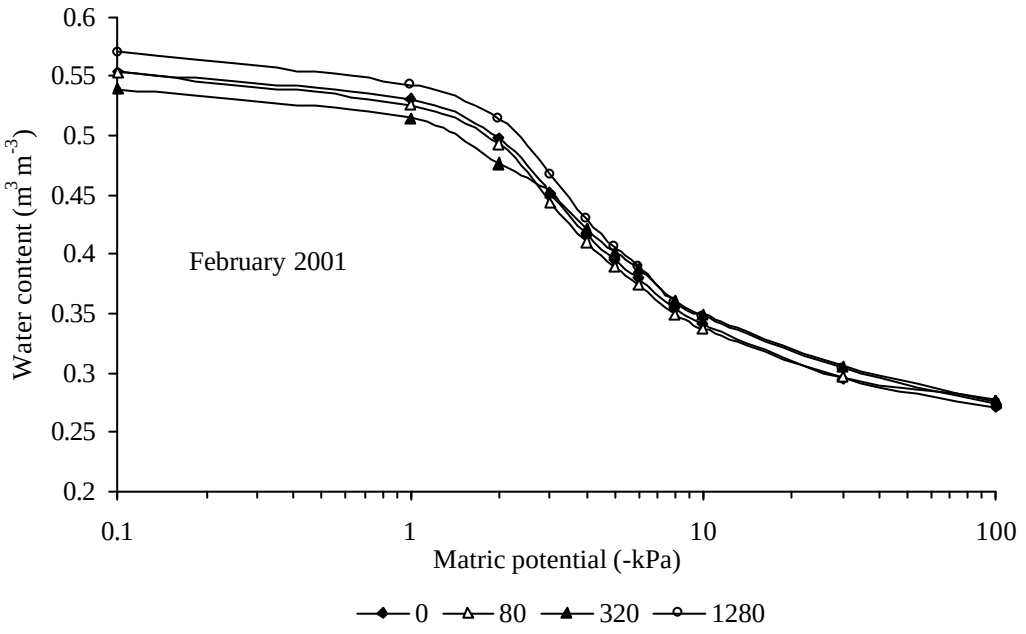


Appendix 6.3 (cont.) Water retention curves for February 1999, April 1999, November 1999, April 2000 and February 2001 samples collected from Brookdale Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, and in some instances, the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)





Appendix 6.3 (cont.) Water retention curves for February 1999, April 1999, November 1999, April 2000 and February 2001 samples collected from Brookdale Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, and in some instances, the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)



Appendix 6.4 Summary ANOVA statistics for the effect of water treatment residue (WTR) applied at rates of 0, 80, 320 and 1280 Mg ha^{-1}, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (PAM) on volumetric water content (m^3 m^{-3}) at selected matric potentials in the Westleigh soil at Ukulinga Farm

Date	Matric Potential (-kPa)	WTR application rate (Mg ha^{-1}) 0	80	320	1280	Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
Dec 1999	0	0.506b*	0.507b	0.530ab	0.555a	nd	nd	nd	0.0327	5.34	0.026
	10	0.302b	0.305b	0.313b	0.356a	nd	nd	nd	0.0166	23.96	<0.001
	30	0.255c	0.256c	0.269b	0.320a	nd	nd	nd	0.0106	88.37	<0.001
	100	0.209b	0.214b	0.212b	0.292a	nd	nd	nd	0.0300	19.33	<0.001
Apr 2000	0	0.489d	0.519bc	0.553a	0.563a	0.503b	0.509c	nd	0.0180	23.63	<0.001
	10	0.324b	0.311b	0.326b	0.357a	0.325b	0.312b	nd	0.0232	4.55	0.008
	30	0.281b	0.271b	0.295b	0.327a	0.293b	0.285b	nd	0.0253	5.14	0.005
	100	0.246b	0.235b	0.258b	0.308a	0.260b	0.240b	nd	0.0285	7.73	<0.001
Aug 2000	0	0.436e	0.468d	0.518b	0.589a	0.471cd	0.481bc	0.424e	0.0220	54.97	<0.001
	10	0.325b	0.320b	0.338b	0.365a	0.323b	0.324b	0.324b	0.0243	3.72	0.011
	30	0.292b	0.285b	0.297b	0.340a	0.291b	0.288b	0.301b	0.0223	6.18	<0.001
	100	0.250bc	0.251bc	0.251bc	0.316a	0.250bc	0.243c	0.267b	0.0231	10.43	<0.001
Feb 2001	0	0.476c	0.489c	0.531b	0.578a	0.486c	0.496c	0.479c	0.0242	20.06	<0.001
	10	0.313bc	0.305bc	0.321b	0.346a	0.302c	0.308bc	0.300c	0.0189	6.18	<0.001
	30	0.288b	0.282b	0.294b	0.331a	0.286b	0.289b	0.281b	0.0213	5.78	0.001
	100	0.265bc	0.263bc	0.274b	0.311a	0.255bc	0.253bc	0.251c	0.0223	7.53	<0.001
Sept 2001	0	0.475e	0.516c	0.564b	0.598a	0.503cd	0.512cd	0.475de	0.0233	32.74	<0.001
	10	0.311c	0.310c	0.330b	0.363a	0.309c	0.315bc	0.317bc	0.0165	11.87	<0.001
	30	0.285bc	0.273c	0.295b	0.335a	0.286bc	0.291b	0.297b	0.0177	10.32	<0.001
	100	0.252bc	0.249c	0.268b	0.315a	0.253bc	0.251bc	0.268b	0.0184	13.97	<0.001
Oct 2002	0	0.467c	0.462c	0.510b	0.549a	0.467c	0.449c	0.448c	0.0233	22.18	<0.001
	10	0.305c	0.310bc	0.324b	0.359a	0.310bc	0.323b	0.311bc	0.0151	13.06	<0.001
	30	0.276c	0.285bc	0.293bc	0.339a	0.291bc	0.298b	0.302b	0.0203	8.43	<0.001
	100	0.244d	0.248cd	0.260bcd	0.311a	0.258bcd	0.269b	0.263bc	0.0182	12.69	<0.001
June 2003	0	0.444	0.471	0.504	0.536	0.459	0.466	0.435	NS	2.12	0.094
	10	0.309bc	0.292c	0.321b	0.361a	0.305bc	0.316b	0.322b	0.0170	13.86	<0.001
	30	0.283bc	0.266c	0.293b	0.340a	0.275bc	0.285b	0.293b	0.0184	14.39	<0.001
	100	0.252b	0.232c	0.258b	0.313a	0.238bc	0.244bc	0.250bc	0.0202	15.29	<0.001

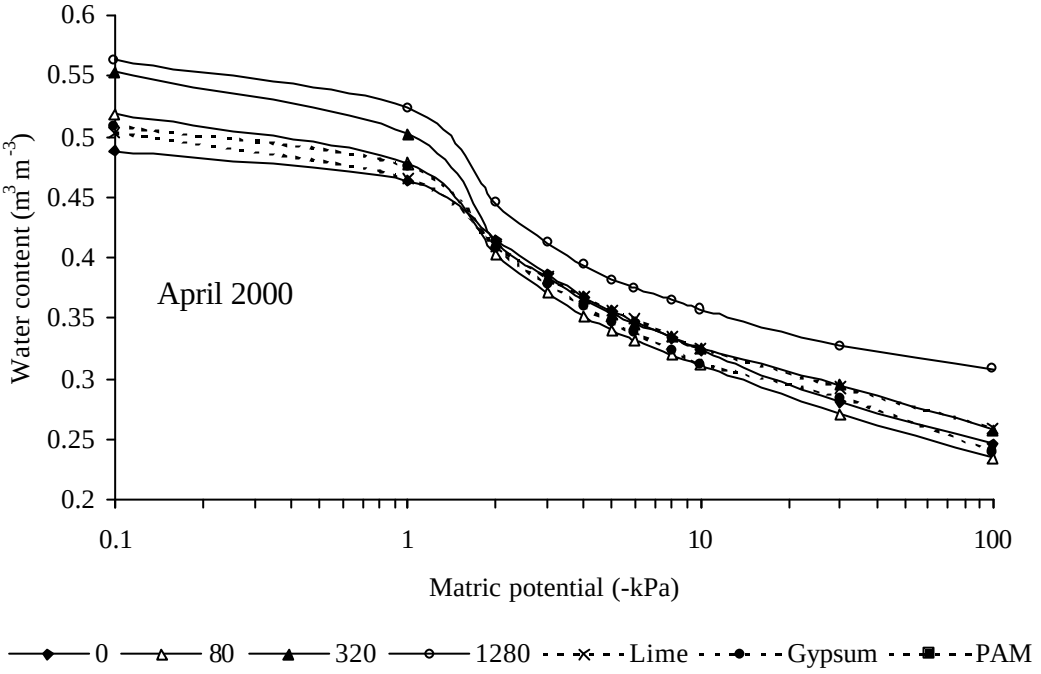
* Letters that are different indicate significant differences between means.
nd not determined.
NS non-significant F-statistic.

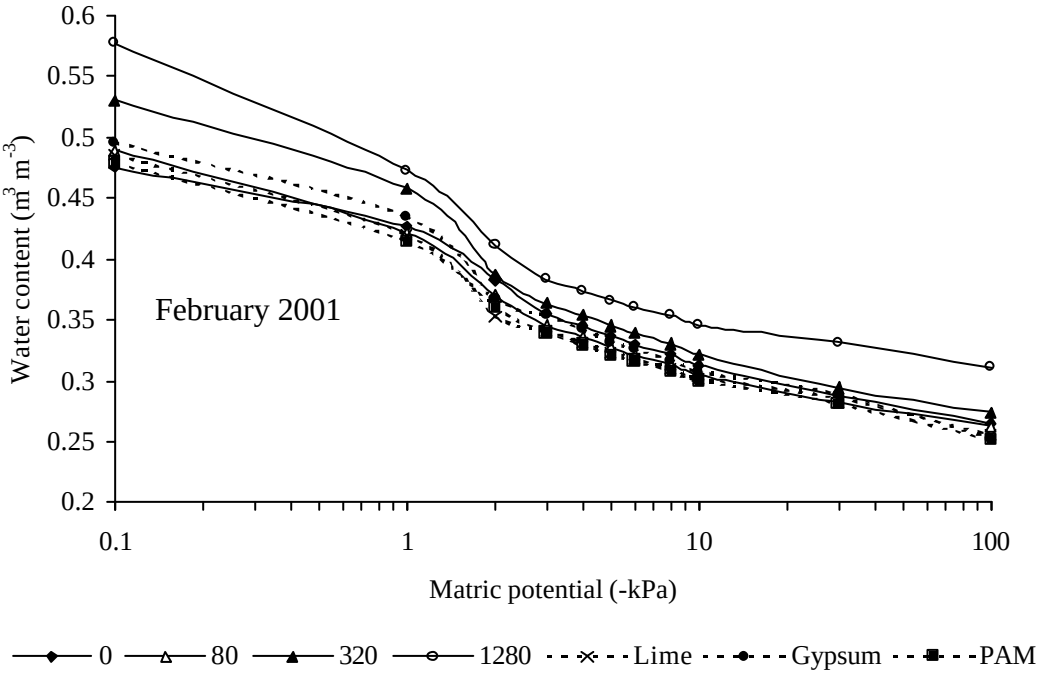
Appendix 6.5 Summary ANOVA statistics of the effect of water treatment residue (WTR) applied at rates of 0, 80, 320 and 1280 Mg ha^{-1}, 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (PAM) on the readily available water content (m^3 m^{-3}) over time in the Westleigh soil at Ukulinga Farm

Date	WTR application rate (Mg ha^{-1})				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})
	0	80	320	1280			
Dec 1999	0.0928a	0.0910a	0.1015a	0.0633a	nd	nd	nd
Apr 2000	0.0774ab	0.0762ab	0.0678bc	0.0488ab	0.0655ab	0.0724ab	nd
Aug 2000	0.0748bc	0.0689b	0.0868ab	0.0483b	0.0725a	0.0802a	0.0570bc
Feb 2001	0.0474d	0.0421c	0.0476d	0.0345b	0.0467c	0.0548bc	0.0485c
Sept 2001	0.0591d	0.0610bc	0.0620cd	0.0477b	0.0556abc	0.0520c	0.0665abc
Oct 2002	0.0613cd	0.0627b	0.0635c	0.0486b	0.0635abc	0.0543c	0.0727a
June 2003	0.0566d	0.0607bc	0.0630cd	0.0480b	0.0490bc	0.0480c	0.0719ab
$LSD_{5\%}$	0.0174	0.0182	0.0186	0.0149	0.0170	0.0171	0.0149
VR	6.78	6.02	8.10	2.74	3.11	5.00	4.39
F-Pr	<0.001	<0.001	<0.001	0.043	0.034	0.005	0.015

* Letters that are different indicate significant differences between means within any one treatment.
nd not determined.

Appendix 6.6 Water retention curves for samples collected in April 2000 and February 2001 from Ukulinga Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue, and the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)





Appendix 6.7 Mean bulk densities (kg m^{-3}) for the treatments investigated at (a) Brookdale Farm and (b) Ukulinga Farm for different sampling dates

(a)

Date	WTR application rate ----------(Mg ha^{-1})----------				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})
	0	80	320	1280[a]			
Feb 1999	1170	1220	1190	1170	1290	1180	nd
Apr 1999	1120	1110	1080	1060	nd	nd	nd
June 1999	1090	1110	1100	1050	1110	1130	1060
Nov 1999	1190	1140	1150	1110	1140	1180	1110
Apr 2000	1200	1200	1200	1100	1190	1140	1140
June 2000	1160	1150	1130	1100	1170	1110	1130
Feb 2001	1140	1150	1200	1100	nd	nd	nd
Sept 2001	1190	1190	1170	1150	1190	1190	1180
Oct 2002	1170	1150	1160	1100	1140	1160	1130
June 2003	1130	1180	1180	1100	1160	1120	1130

[a] incorporated treatment
nd not determined

(b)

Date	WTR application rate ----------(Mg ha^{-1})----------				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})
	0	80	320	1280			
Dec 1999	1170	1170	1110	1100	nd	nd	nd
Apr 2000	1250	1180	1090	1030	1210	1190	nd
Aug 2000	1310	1220	1160	1030	1270	1250	1370
Feb 2001	1310	1260	1200	1040	1320	1260	1300
Sept 2001	1350	1260	1170	1080	1300	1270	1360
Oct 2002	1310	1330	1230	1130	1300	1350	1350
June 2003	1300	1230	1190	1080	1260	1310	1370

nd not determined.

Appendix 6.8 Mean (n=4) air-filled porosity (m^3 m^{-3}), calculated for the -5, -10, -30 and -100 kPa matric potentials, of the Hutton soil amended with 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue (WTR), 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (PAM) at Brookdale Farm

Date	Matric potential (-kPa)	WTR application rate (Mg ha^{-1}) 0	80	320	1280	Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
Feb 1999	0	0.142	0.139	0.152	0.175	0.075	0.141	nd	NS	1.00	0.489
	10	0.179	0.164	0.193	0.200	0.107	0.181	nd	NS	0.66	0.670
	30	0.227	0.200	0.225	0.227	0.138	0.217	nd	NS	2.71	0.092
	100	0.269	0.237	0.253	0.253	0.167	0.242	nd	NS	0.48	0.782
Apr 1999	0	0.176b*	0.161b	0.211a	0.182b	nd	nd	nd	0.029	5.41	0.018
	10	0.218	0.207	0.244	0.221	nd	nd	nd	NS	2.93	0.086
	30	0.260	0.261	0.270	0.245	nd	nd	nd	NS	0.66	0.594
	100	0.304	0.306	0.311	0.288	nd	nd	nd	NS	1.85	0.201
June 1999	0	0.230	0.215	0.211	0.232	0.199	0.203	0.229	NS	0.83	0.59
	10	0.264	0.250	0.248	0.275	0.244	0.246	0.273	NS	1.04	0.430
	30	0.295	0.287	0.283	0.303	0.280	0.283	0.315	NS	1.36	0.275
	100	0.316	0.314	0.310	0.320	0.306	0.311	0.332	NS	0.54	0.775
Nov 1999	0	0.147	0.142	0.139	0.128	0.124	0.134	0.154	NS	1.58	0.226
	10	0.168	0.169	0.163	0.157	0.158	0.158	0.179	NS	1.05	0.434
	30	0.196	0.200	0.197	0.205	0.202	0.195	0.221	NS	0.94	0.495
	100	0.221	0.228	0.227	0.233	0.243	0.222	0.254	NS	1.57	0.228
Apr 2000	0	0.195	0.176	0.182	0.196	0.131	0.182	0.165	NS	2.05	0.104
	10	0.231	0.225	0.225	0.251	0.195	0.232	0.221	NS	1.44	0.245
	30	0.255	0.261	0.262	0.282	0.243	0.284	0.264	NS	1.32	0.294
	100	0.291b	0.294b	0.293b	0.320ab	0.274c	0.350a	0.309bc	0.037	3.91	0.009
June 2000	0	0.184a	0.167a	0.174a	0.161a	0.171a	0.106b	0.181a	0.034	5.40	0.002
	10	0.214a	0.209a	0.215a	0.202a	0.223a	0.141b	0.223a	0.038	4.95	0.003
	30	0.245	0.246	0.248	0.248	0.272	0.236	0.281	NS	2.17	0.087
	100	0.262c	0.264bc	0.269bc	0.273bc	0.297ab	0.265bc	0.315a	0.035	2.83	0.035
Feb 2001	0	0.175	0.177	0.146	0.180	nd	nd	nd	NS	3.00	0.073
	10	0.228	0.229	0.199	0.235	nd	nd	nd	NS	3.39	0.054
	30	0.274	0.270	0.242	0.277	nd	nd	nd	NS	2.71	0.092
	100	0.299	0.289	0.272	0.306	nd	nd	nd	NS	2.19	0.142
Sept 2001	0	0.136	0.149	0.142	0.158	0.138	0.125	0.126	NS	0.76	0.608
	10	0.187	0.195	0.189	0.204	0.182	0.180	0.180	NS	0.40	0.869
	30	0.239	0.241	0.243	0.245	0.225	0.234	0.246	NS	0.31	0.922
	100	0.275	0.276	0.281	0.281	0.257	0.280	0.291	NS	0.58	0.742
Oct 2002	0	0.174	0.191	0.179	0.174	0.180	0.190	0.213	NS	0.52	0.788
	10	0.218	0.229	0.220	0.220	0.224	0.232	0.251	NS	0.54	0.770
	30	0.265	0.269	0.251	0.263	0.272	0.264	0.268	NS	0.18	0.980
	100	0.298	0.298	0.280	0.295	0.301	0.309	0.338	NS	1.29	0.303
June 2003	0	0.208	0.187	0.179	0.215	0.188	0.192	0.210	NS	1.64	0.186
	10	0.247	0.221	0.221	0.254	0.226	0.245	0.254	NS	1.61	0.193
	30	0.287	0.257	0.269	0.292	0.265	0.285	0.298	NS	1.35	0.279
	100	0.321	0.288	0.304	0.323	0.301	0.322	0.333	NS	1.32	0.291

* Letters that are different indicate significant differences between means at a particular matric potential.

nd not determined.

NS non-significant F-statistic.

Appendix 6.9 Mean (n=4) air-filled porosity (m^3 m^{-3}), calculated for the -5, -10, -30 and -100 kPa matric potentials, of the Westleigh soil amended with 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue (WTR), 10 Mg ha^{-1} lime and gypsum and 30 kg ha^{-1} polyacrylamide (PAM) at Ukulinga Farm

Date	Matric Potential (-kPa)	WTR application rate (Mg ha^{-1}) 0	80	320	1280	Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
Dec 1999	0	0.225	0.218	0.235	0.197	nd	nd	nd	NS	1.74	0.237
	10	0.258	0.254	0.269	0.230	nd	nd	nd	NS	2.69	0.117
	30	0.304b	0.302b	0.313a	0.266b	nd	nd	nd	0.027	6.42	0.016
	100	0.351b	0.345b	0.370a	0.293b	nd	nd	nd	0.033	10.30	0.004
Apr 2000	0	0.172c	0.215ab	0.235a	0.228a	0.186b	0.206ab	nd	0.033	4.92	0.006
	10	0.204c	0.244ab	0.263a	0.252a	0.217bc	0.240ab	nd	0.033	4.02	0.014
	30	0.247b	0.284a	0.293a	0.282a	0.250b	0.268ab	nd	0.033	3.09	0.036
	100	0.281	0.320	0.330	0.301	0.283	0.313	nd	NS	2.79	0.051
Aug 2000	0	0.151	0.189	0.189	0.214	0.172	0.173	0.128	NS	2.05	0.104
	10	0.181	0.220	0.224	0.248	0.200	0.206	0.157	NS	2.39	0.065
	30	0.214b	0.256ab	0.265ab	0.273a	0.232abc	0.242ab	0.180c	0.056	2.85	0.034
	100	0.256bc	0.289ab	0.310a	0.297ab	0.272ab	0.286ab	0.214c	0.053	3.13	0.024
Feb 2001	0	0.168b	0.197b	0.203ab	0.243a	0.180b	0.193b	0.188b	0.041	2.94	0.031
	10	0.192b	0.220b	0.227ab	0.263a	0.201b	0.218b	0.209b	0.041	2.73	0.040
	30	0.216	0.242	0.254	0.278	0.218	0.237	0.228	NS	2.25	0.078
	100	0.239	0.262	0.275	0.298	0.248	0.273	0.258	NS	1.89	0.129
Sept 2001	0	0.155bc	0.191ab	0.205a	0.208a	0.179abc	0.178abc	0.149c	0.040	2.88	0.033
	10	0.181bc	0.215ab	0.228a	0.230a	0.202abc	0.205abc	0.172c	0.040	2.77	0.038
	30	0.20b7	0.251a	0.263a	0.258a	0.225ab	0.229ab	0.191b	0.040	3.87	0.009
	100	0.240bc	0.276ab	0.290a	0.278ab	0.258abc	0.269ab	0.221c	0.040	3.28	0.019
Oct 2002	0	0.187	0.172	0.193	0.201	0.182	0.152	0.165	NS	2.45	0.059
	10	0.200ab	0.187abc	0.211a	0.216a	0.198abc	0.169c	0.179b	0.031	2.59	0.049
	30	0.229a	0.213ab	0.242a	0.236a	0.218ab	0.193b	0.188b	0.032	3.52	0.014
	100	0.261a	0.250ab	0.275a	0.264a	0.251ab	0.223b	0.227b	0.028	4.11	0.007
June 2003	0	0.182abc	0.221a	0.207ab	0.213a	0.200ab	0.163bc	0.141c	0.047	3.36	0.018
	10	0.202abc	0.243a	0.230ab	0.230ab	0.222ab	0.188bc	0.162c	0.047	3.36	0.018
	30	0.227abc	0.270a	0.258ab	0.251ab	0.251ab	0.219bc	0.190c	0.046	3.07	0.026
	100	0.258	0.304	0.293	0.278	0.288	0.260	0.233	NS	2.53	0.053

* Letters that are different indicate significant differences between means at a particular matric potential.

nd not determined.

NS non-significant F-statistic.

Appendix 6.10 Mean weight diameters (mm) from dry aggregate size distribution of treatments investigated at (a) Brookdale Farm and (b) Ukulinga Farm

(a)

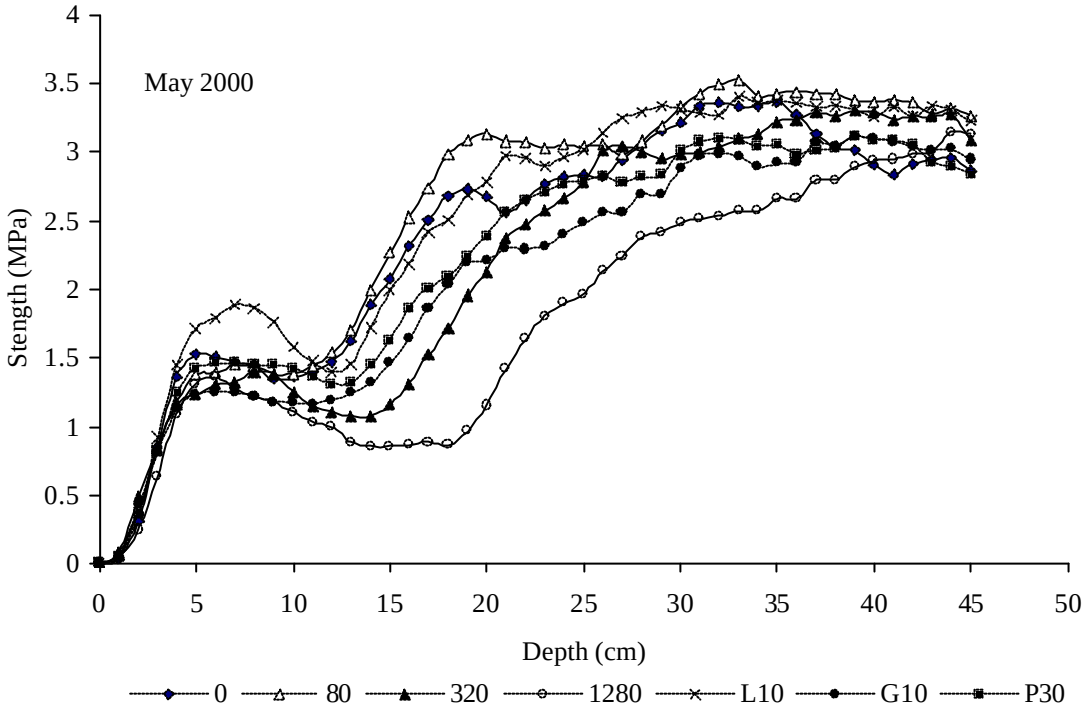
Date	WTR application rate (Mg ha^{-1})				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
	0	80	320	1280						
Feb 1999	8.59ab*	4.61c	6.68bc	5.25c	9.96a	6.58bc	4.69c	2.46	6.27	0.002
Sept 1999	4.19	4.12	5.47	4.33	4.02	5.43	3.75	NS	0.78	0.601
Nov 1999	7.93a	6.89ab	7.67a	6.50abc	5.09bcd	4.82cd	3.99c	1.85	6.11	0.003
Feb 2000	3.16	4.35	2.64	4.93	3.99	3.40	2.90	NS	1.83	0.164
Feb 2001	3.68	4.30	3.86	3.31	nd	nd	nd	NS	0.63	0.618
Sept 2001	2.47	4.37	4.54	5.06	3.30	4.74	4.98	NS	2.26	0.098
Oct 2002	5.12	4.59	4.02	3.47	3.76	3.73	4.84	NS	0.99	0.468
June 2003	4.62	3.87	4.36	4.00	6.14	5.51	3.55	NS	1.09	0.413

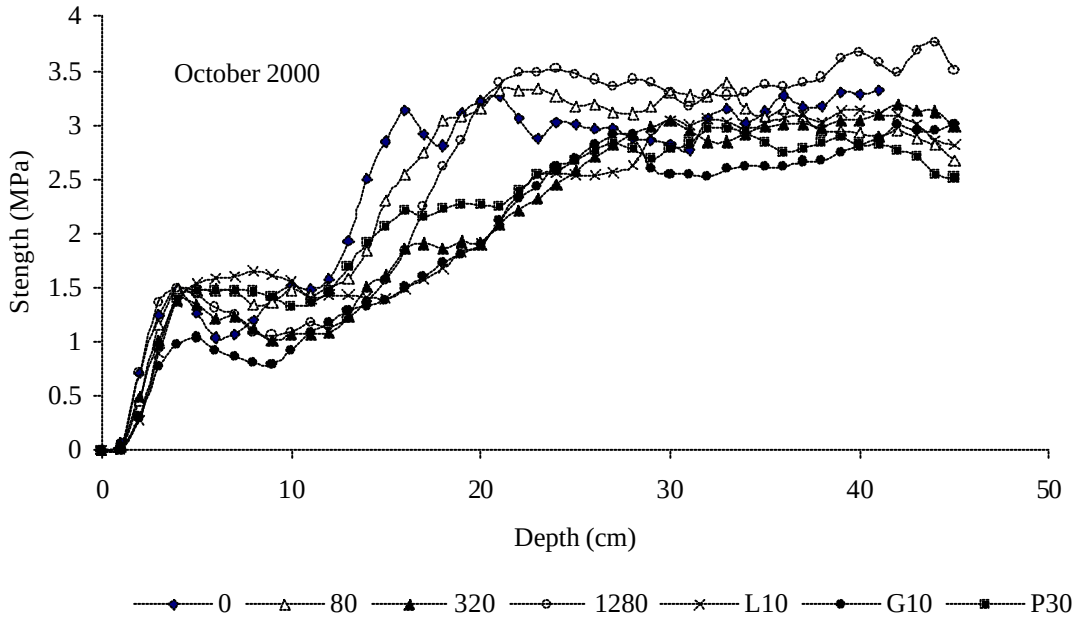
(b)

Date	WTR application rate (Mg ha^{-1})				Lime 10 (Mg ha^{-1})	Gypsum 10 (Mg ha^{-1})	PAM 30 (kg ha^{-1})	$LSD_{5\%}$	VR	F-Pr
	0	80	320	1280						
Nov 1999	4.35	3.94	3.80	5.24	3.68	3.53	nd	NS	1.62	0.229
Apr 2000	3.84	3.99	4.59	5.52	4.41	3.68	nd	NS	2.38	0.101
Oct 2000	4.60	3.80	3.58	4.85	3.96	3.58	4.28	NS	1.39	0.286
Feb 2001	5.48	3.91	5.37	4.63	4.98	4.65	5.00	NS	0.53	0.780
Sept 2001	3.66c	5.72ab	3.98bc	6.09a	6.68a	5.80ab	5.67ab	1.94	3.05	0.040
Oct 2002	3.64	5.32	3.94	6.43	3.82	4.31	5.68	NS	2.13	0.115
June 2003	5.82	3.20	4.02	5.25	4.49	3.46	3.75	NS	2.52	0.072

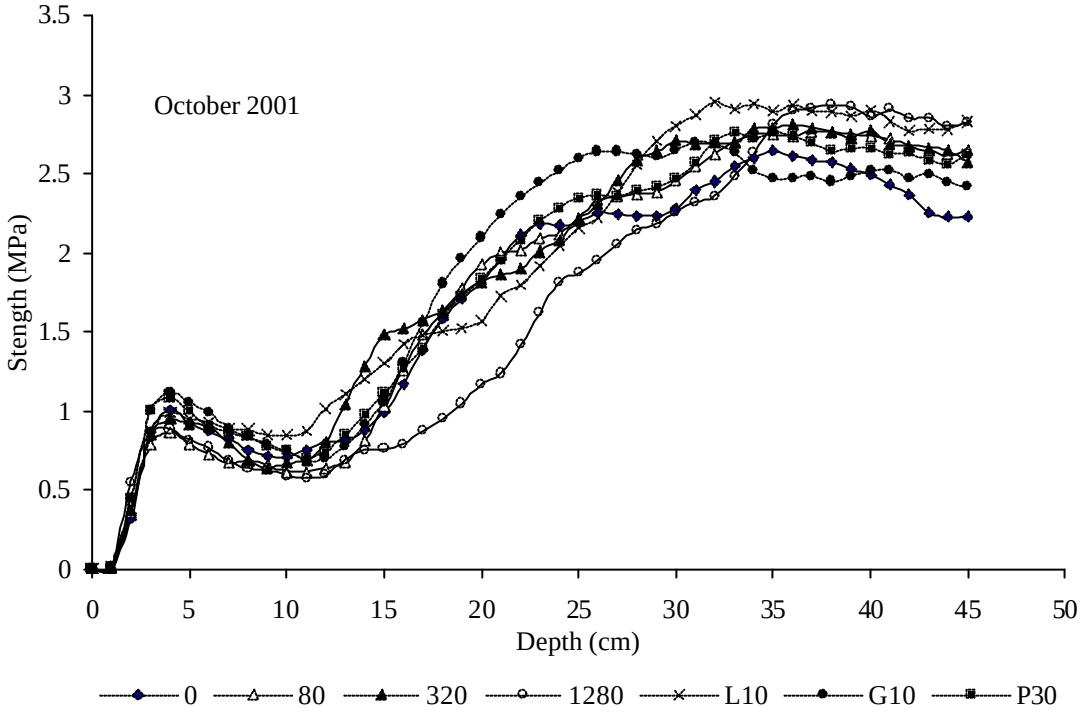
* Letters that are different indicate significant differences between means.
NS non-significant F-statistic.
nd not determined.

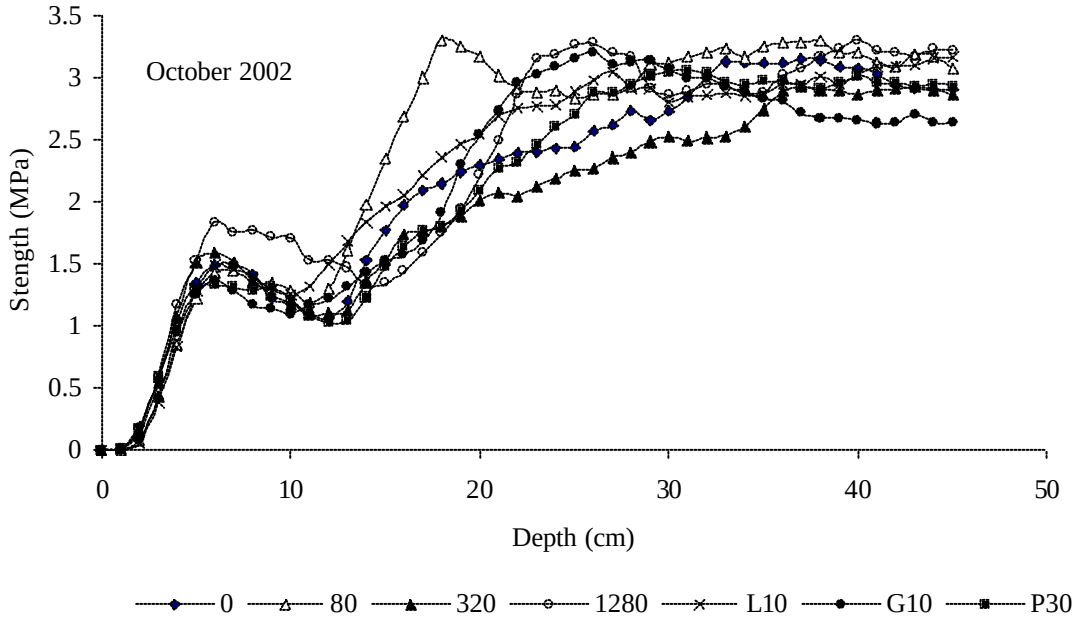
Appendix 6.11 Penetrometer soil strength profiles for May 2000, October 2000, 2001 and 2002 from Brookdale Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue and the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)



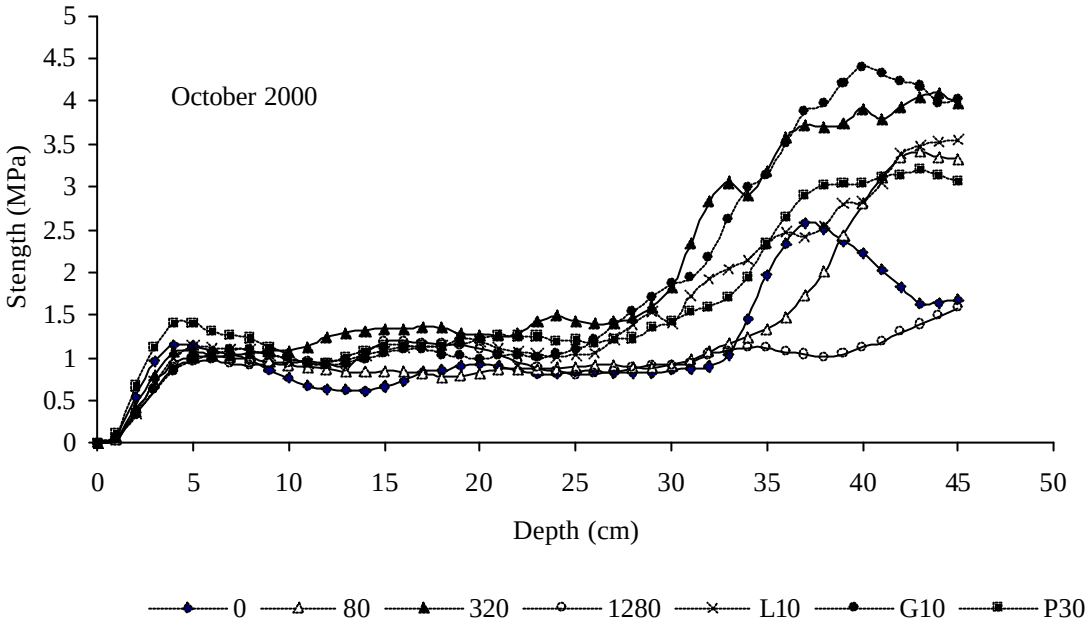


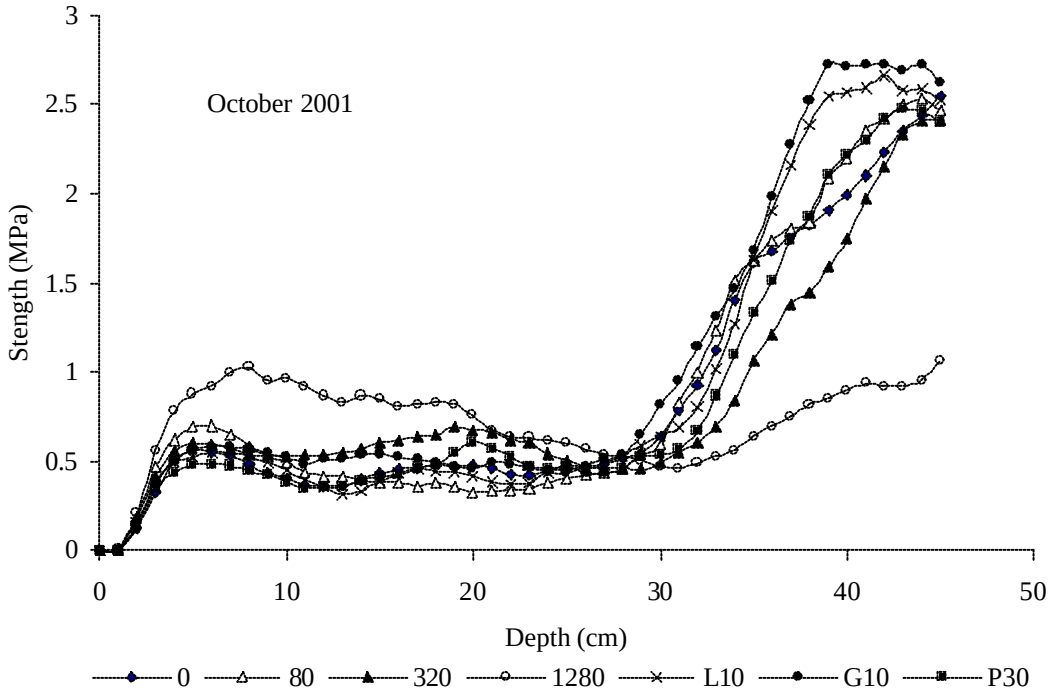
Appendix 6.11 (cont.) Penetrometer soil strength profiles for May 2000, October 2000, 2001 and 2002 from Brookdale Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue and the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)



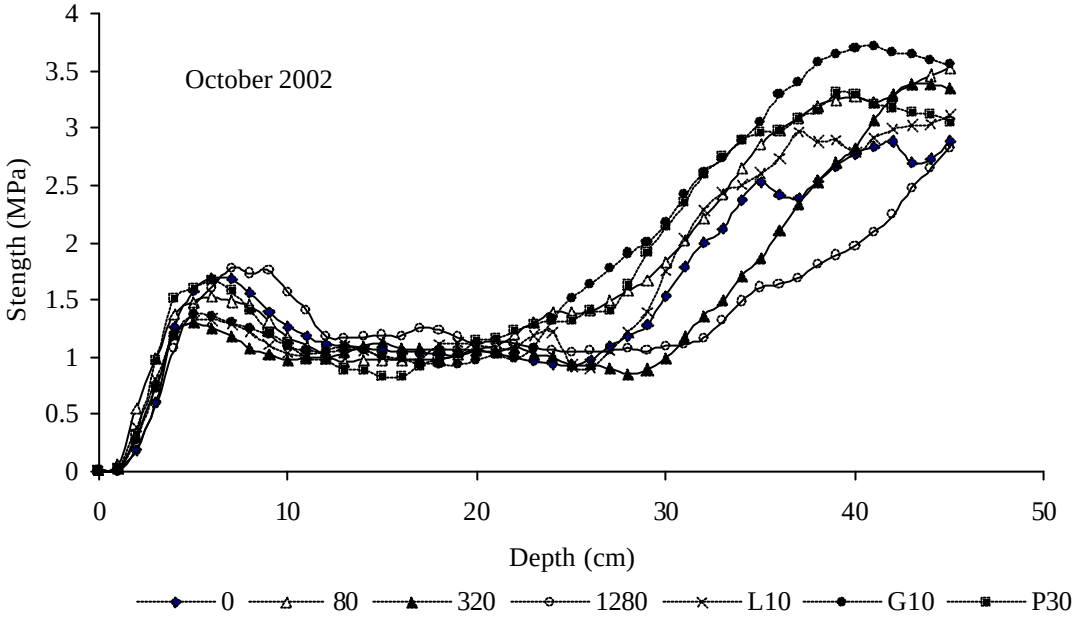


Appendix 6.12 Penetrometer soil strength profiles for October 2000, 2001 and 2002 from Ukulinga Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue and the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)





Appendix 6.12 (cont.) Penetrometer soil strength profiles for October 2000, 2001 and 2002 from Ukulinga Farm showing the effect of 0, 80, 320 and 1280 Mg ha^{-1} water treatment residue and the application of 10 Mg ha^{-1} of lime and gypsum and 30 kg ha^{-1} of polyacrylamide (PAM)



Appendix 7.1 Mean (n=3) electrical conductivity (mS m^{-1}) and pH for the first, second and third leachates collected from the soil and spoil treatments at Rand water treatment residue (RWTR) application rates of 0, 50, 100, 200 and 400 g kg^{-1}. Coefficient of variation (%) values are given for pH and EC for each leachate

Waste	Grass	RWTR rate (g kg^{-1})	Leachate 1		Leachate 2		Leachate 3	
			EC	pH	EC	pH	EC	pH
Soil	*E.teff*	0	91.5	7.03	87.6	7.29	152.3	6.40
Soil	*E.teff*	50	100.9	7.50	318.0	7.92	458.3	8.08
Soil	*E.teff*	100	127.5	7.99	155.3	7.29	408.3	7.62
Soil	*E.teff*	200	143.0	7.87	192.6	8.28	650.0	8.19
Soil	*E.teff*	400	275.0	7.36	288.3	8.21	519.6	8.08
		CV(%)	11.3	1.6	11.6	1.8	12.5	2.0
Soil	*D.eriantha*	0	76.2	6.62	46.3	5.69	57.0	5.40
Soil	*D.eriantha*	50	231.3	7.82	314.6	7.92	492.0	8.26
Soil	*D.eriantha*	100	289.0	7.39	336.0	7.98	624.3	8.24
Soil	*D.eriantha*	200	319.0	7.89	708.3	7.75	850.6	8.23
Soil	*D.eriantha*	400	411.6	7.59	550.3	7.98	704.3	8.32
		CV(%)	9.1	1.2	16.4	0.8	14.9	1.8
Soil	*C.ciliaris*	0	114.8	6.09	166.3	5.86	202.3	5.86
Soil	*C.ciliaris*	50	122.7	7.84	273.6	7.97	594.0	7.66
Soil	*C.ciliaris*	100	215.6	7.99	287.0	8.14	700.0	7.82
Soil	*C.ciliaris*	200	254.3	7.78	356.6	8.15	767.0	7.88
Soil	*C.ciliaris*	400	282.2	7.93	371.0	8.19	657.0	8.62
		CV(%)	13.3	2.1	30.1	0.4	18.0	3.5
Spoil	*E.teff*	0	281.3	7.27	275.0	6.92	343.6	6.69
Spoil	*E.teff*	50	351.3	7.20	446.0	7.45	402.3	7.98
Spoil	*E.teff*	100	492.6	7.41	621.0	7.56	563.6	8.01
Spoil	*E.teff*	200	665.3	7.60	680.0	7.93	653.0	7.92
Spoil	*E.teff*	400	632.0	7.94	779.3	7.93	619.3	8.23
		CV(%)	7.8	1.9	3.1	2.0	21.0	0.8
Spoil	*D.eriantha*	0	265.3	7.22	309.0	6.77	221.3	6.53
Spoil	*D.eriantha*	50	401.6	7.51	529.3	7.57	498.3	7.32
Spoil	*D.eriantha*	100	392.0	7.68	688.0	7.62	636.6	8.03
Spoil	*D.eriantha*	200	445.0	7.61	730.3	7.61	665.3	8.26
Spoil	*D.eriantha*	400	473.6	7.47	846.0	7.67	827.3	8.13
		CV(%)	6.4	3.0	5.4	0.5	14.2	3.3
Spoil	*C.ciliaris*	0	289.0	7.39	261.3	6.89	237.0	6.37
Spoil	*C.ciliaris*	50	327.6	7.60	387.3	7.62	434.0	8.05
Spoil	*C.ciliaris*	100	467.6	7.66	512.0	7.77	459.0	8.21
Spoil	*C.ciliaris*	200	619.0	7.88	824.6	7.87	745.0	8.04
Spoil	*C.ciliaris*	400	607.6	7.54	1086.6	7.63	945.3	7.84
		CV(%)	7.9	2.3	10.0	1.4	23.5	0.6

Appendix 7.2 ANOVA tables for (a) *Eragrostis teff*, (b) *Digitaria eriantha* and (c) *Cenchrus ciliaris* grown in the soil material and (d) *Eragrostis teff*, (e) *Digitaria eriantha* and (f) *Cenchrus ciliaris* grown in the spoil material when treated with Rand water treatment residue (RWTR) at application rates of 0, 50, 100, 200 and 400 g kg^{-1}

(a)

Source of variation	d.f.[a]	SS[b]	MS[c]	VR[d]	F Probability
Block (replicate)	2	13.25	6.62	1.16	
RWTR application rate	4	605.27	151.32	16.61	<0.001
Residual	8	45.50	5.69		
Total	14	664.01			
Coefficient of variation (%)	8.7				

(b)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	31.37	15.68	2.03	
RWTR application rate	4	546.80	136.70	17.72	<0.001
Residual	8	61.72	7.72		
Total	14	639.89			
Coefficient of variation (%)	17.2				

(c)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	4.78	2.39	0.36	
RWTR application rate	4	231.13	57.78	8.62	0.005
Residual	8	53.64	6.71		
Total	14	289.55			
Coefficient of variation (%)	4.8				

(d)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	62.47	31.23	2.74	
RWTR application rate	4	38.55	9.64	0.85	0.534
Residual	8	91.23	11.40		
Total	14	192.25			
Coefficient of variation (%)	19.4				

(e)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	38.35	19.17	1.19	
RWTR application rate	4	125.19	31.30	1.94	0.197
Residual	8	128.94	16.12		
Total	14	292.48			
Coefficient of variation (%)	8.1				

(f)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	85.60	42.80	0.64	
RWTR application rate	4	286.99	71.75	1.07	0.430
Residual	8	535.48	66.93		
Total	14	908.06			
Coefficient of variation (%)	11.5				

[a] degrees of freedom. [b] sum of squares.
[c] mean sum of squares. [d] variance ratio.

Appendix 7.3 Mean yields (±SE, 3 replicates) for the first, second and third harvests for *Eragrostis teff*, *Digitaria eriantha* and *Cenchrus ciliaris* grown in the soil and spoil treated with Rand water treatment residue (RWTR) at application rates of 0, 50, 100, 200 and 400 g kg^{-1}

Waste	Grass	RWTR rate (g kg^{-1})	Harvest 1		Harvest 2		Harvest 3	
			(g pot^{-1})					
			mean	SE	mean	SE	mean	SE
Soil	*E. teff*	0	10.16a*	0.41	12.24a	4.40	2.46a	0.70
Soil	*E. teff*	50	8.56ab	1.79	3.16b	0.88	2.47a	1.31
Soil	*E. teff*	100	7.80ab	2.50	1.14b	0.89	2.17a	1.32
Soil	*E. teff*	200	7.10bc	1.18	0.88b	0.46	1.52ab	0.49
Soil	*E. teff*	400	4.65c	0.92	1.20b	0.37	0.50b	0.41
		$LSD_{5\%}$	2.53		4.00		1.16	
		CV(%)	12.5		21.6		41.3	
Soil	*D. eriantha*	0	4.11a	0.81	10.65a	1.29	7.26a	0.54
Soil	*D. eriantha*	50	1.87b	1.02	3.84b	3.41	2.23b	1.45
Soil	*D. eriantha*	100	0.11c	0.19	5.09b	2.67	2.56b	2.15
Soil	*D. eriantha*	200	0.31c	0.16	5.02b	0.41	3.77b	2.28
Soil	*D. eriantha*	400	0.00c	0.00	2.13b	0.76	2.55b	1.40
		$LSD_{5\%}$	1.24		3.89		3.00	
		CV(%)	4.7		17		24.5	
Soil	*C. ciliaris*	0	7.08a	0.24	6.97	1.79	6.11	0.66
Soil	*C. ciliaris*	50	5.51ab	0.93	4.13	2.66	6.49	0.73
Soil	*C. ciliaris*	100	4.54abc	3.19	3.44	0.77	5.31	1.78
Soil	*C. ciliaris*	200	3.19bc	2.95	5.36	5.20	6.09	3.27
Soil	*C. ciliaris*	400	1.72c	0.27	3.47	1.63	2.92	1.29
		$LSD_{5\%}$	3.38		NS		NS	
		CV	26.9		16.5		10.4	
Spoil	*E. teff*	0	2.00a	1.01	7.98	1.93	3.01	1.47
Spoil	*E. teff*	50	2.52a	0.69	8.73	3.71	2.05	1.11
Spoil	*E. teff*	100	2.77a	0.28	11.10	3.12	1.69	0.94
Spoil	*E. teff*	200	4.30b	1.00	5.62	2.50	1.29	0.37
Spoil	*E. teff*	400	4.21b	0.83	5.93	4.35	1.08	0.64
		$LSD_{5\%}$	1.43		NS		NS	
		CV(%)	13.8		24.4		41.4	
Spoil	*D. eriantha*	0	0.46a	0.25	9.91	1.62	16.54	2.04
Spoil	*D. eriantha*	50	0.41a	0.25	9.30	1.57	17.34	3.43
Spoil	*D. eriantha*	100	0.72a	0.05	9.48	1.65	14.79	4.29
Spoil	*D. eriantha*	200	0.49a	0.41	9.73	1.39	10.52	6.33
Spoil	*D. eriantha*	400	0.10b	0.18	9.95	1.02	10.43	3.40
		$LSD_{5\%}$	0.31		NS		NS	
		CV(%)	48.0		12.0		20.7	
Spoil	*C. ciliaris*	0	0.77a	0.34	9.68	3.97	12.43	5.56
Spoil	*C. ciliaris*	50	1.58b	0.19	11.00	3.10	9.32	3.64
Spoil	*C. ciliaris*	100	1.92b	0.11	9.22	4.22	10.81	6.61
Spoil	*C. ciliaris*	200	2.94c	0.51	11.56	5.04	12.72	7.92
Spoil	*C. ciliaris*	400	2.24bc	0.62	17.20	1.09	13.83	2.67
		$LSD_{5\%}$	0.73		NS		NS	
		CV(%)	10.9		15.9		9.9	

* Letters that are different indicate significant differences ($p<0.05$) within a single harvest for a treatment and grass type. NS non significant F-statistic.

Appendix 7.4 Fertility analysis for *Eragrostis teff, Digitaria eriantha* and *Cenchrus ciliaris* grown in the soil and spoil treated with Rand water treatment residue (RWTR) at application rates of 0, 50 100, 200 and 400 g kg^{-1}. The numbers 1, 2 and 3 refer to the first, second and third harvests, respectively. Typical nutrient levels for turf grasses (Bennett, 1993) and *Festuca arundinacea* and *Eragrostis curvula* (Miles, undated) are given where available

Waste	Grass	RWTR rate (g kg^{-1})	Ca (%)			Mg (%)			K (%)			Na (%)			P (%)			N (%)		
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Soil	*E. teff*	0	0.29	0.35	0.26	0.18	0.28	0.28	1.76	1.75	2.29	0.023	0.023	0.025	0.42	1.18	1.56	1.30	2.59	2.80
		50	0.46	0.41	0.52	0.30	0.42	0.51	1.42	1.74	2.70	0.021	0.031	0.053	0.39	0.44	0.75	1.36	2.86	3.71
		100	0.37	0.37	0.46	0.35	0.71	0.69	1.41	1.69	2.95	0.030	0.047	0.065	0.34	0.63	0.75	1.26	3.17	3.93
		200	0.41	0.35	0.33	0.45	0.75	0.79	1.89	1.64	2.99	0.032	0.023	0.027	0.36	0.57	0.73	1.93	3.01	3.79
		400	0.35	0.23	0.28	0.75	0.90	1.08	2.53	1.55	2.57	0.037	0.049	0.058	0.45	0.34	0.68	3.51	3.05	nd
Soil	*D. eriantha*	0	0.73	0.55	0.41	0.39	0.56	0.55	3.76	3.29	4.09	0.035	0.025	0.049	0.97	1.80	0.69	2.49	2.54	3.22
		50	0.66	0.72	0.77	1.19	1.29	0.94	3.83	4.21	4.62	0.039	0.044	0.075	0.71	2.42	1.38	3.21	2.77	3.71
		100	1.68	0.67	0.63	1.50	1.72	1.28	3.89	4.24	4.55	0.066	0.033	0.048	0.62	2.70	1.52	nd	2.53	3.69
		200	0.77	0.38	0.28	1.38	1.66	1.27	3.23	3.60	3.92	0.033	0.023	0.038	0.52	1.77	1.02	nd	2.70	3.44
		400	nd	0.33	0.72	nd	2.17	1.85	nd	3.66	3.65	nd	0.025	0.029	nd	2.30	1.29	nd	2.96	3.44
Soil	*C. ciliaris*	0	0.13	0.21	0.18	0.07	0.33	0.27	3.19	3.06	4.06	0.025	0.026	0.023	0.67	1.81	0.61	1.24	2.28	3.05
		50	0.17	0.53	0.46	0.25	0.70	0.61	4.19	3.88	4.85	0.095	0.074	0.024	0.40	0.54	0.53	1.67	2.64	3.12
		100	0.23	0.38	0.26	0.29	0.71	0.66	3.91	3.54	4.68	0.102	0.143	0.039	0.32	0.37	0.53	1.97	2.33	2.95
		200	0.16	0.31	0.16	0.30	0.73	0.78	4.12	3.57	4.54	0.086	0.043	0.053	0.27	0.29	0.59	2.66	1.77	2.84
		400	0.16	0.18	0.13	0.56	0.80	0.92	5.89	3.80	4.85	0.087	0.040	0.064	0.34	0.21	0.49	4.42	1.72	2.73
Spoil	*E. teff*	0	0.45	0.67	0.56	0.24	0.44	0.35	1.67	2.58	3.51	0.027	0.038	0.078	0.70	0.97	0.85	1.61	3.54	4.15
		50	0.36	0.55	0.61	0.29	0.56	0.57	1.66	2.34	3.29	0.028	0.024	0.058	0.56	0.88	0.77	1.45	3.08	4.06
		100	0.33	0.42	0.48	0.28	0.65	0.69	1.42	2.51	2.99	0.017	0.018	0.063	0.50	0.81	0.77	1.69	3.22	4.05
		200	0.33	0.32	0.36	0.35	0.63	0.77	1.94	1.90	2.91	0.021	0.023	0.066	0.55	0.48	0.66	1.74	3.05	3.91
		400	0.34	0.29	0.26	0.56	0.86	0.96	2.11	2.06	2.96	0.032	0.012	0.047	0.42	0.62	0.85	3.14	3.38	4.20
Spoil	*D. eriantha*	0	0.35	0.47	0.49	0.27	0.51	0.53	2.94	4.11	3.71	0.028	0.030	0.055	0.92	0.71	0.82	2.14	2.74	2.71
		50	0.97	0.41	0.41	0.88	0.84	0.97	3.34	3.84	3.64	0.024	0.014	0.060	0.48	0.63	0.54	nd	3.18	2.57
		100	0.82	0.31	0.36	0.88	1.15	0.91	3.29	3.67	3.58	0.035	0.014	0.058	0.37	0.74	0.47	2.47	3.17	2.55
		200	0.81	0.25	0.2	1.33	1.13	0.79	3.41	3.18	3.57	0.024	0.012	0.033	0.35	0.60	0.39	3.89	2.85	2.52
		400	1.38	0.26	0.14	1.80	1.22	1.11	2.94	3.15	3.37	0.049	0.014	0.051	0.28	0.61	0.47	nd	2.96	2.38
Spoil	*C. ciliaris*	0	0.41	0.24	0.36	0.29	0.28	0.31	5.02	3.87	4.23	0.087	0.047	0.061	0.86	0.60	0.59	1.73	2.55	2.74
		50	0.22	0.18	0.28	0.30	0.36	0.37	4.73	3.18	3.82	0.080	0.031	0.069	0.52	0.39	0.27	1.55	2.41	2.62
		100	0.21	0.24	0.21	0.31	0.48	0.52	4.58	3.30	3.79	0.081	0.035	0.055	0.42	0.33	0.42	1.54	2.44	2.58
		200	0.20	0.16	0.18	0.38	0.55	0.69	4.73	3.32	3.72	0.075	0.025	0.029	0.31	0.35	0.45	1.83	2.15	2.70
		400	0.22	0.13	0.11	0.59	0.68	0.77	6.47	3.56	3.31	0.115	0.020	0.027	0.34	0.38	0.44	4.01	2.72	2.50
Bennett (1993)			0.50 - 1.20			0.20 – 0.60			1.00 – 2.50			-			0.10 – 0.40			2.80 – 3.50		
Miles (undated)	*E. curvula*		0.22 - 0.31			0.07 – 0.14			0.90 – 1.60			-			0.16 – 0.21			1.80 – 2.30		
	F. arundinacea		0.10 - 0.25			0.20 – 0.36			2.20 – 3.50			-			0.25 – 0.35			2.80 – 3.50		

Appendix 7.4 (cont.) Fertility analysis for *Eragrostis teff*, *Digitaria eriantha* and *Cenchrus ciliaris* grown in the soil and spoil treated with Rand water treatment residue (RWTR) at application rates of 0, 50 100, 200 and 400 g kg^{-1}. The numbers 1, 2 and 3 refer to the first, second and third harvests, respectively. Typical nutrient levels for turf grasses (Bennett, 1993) and *Festuca arundinacea* and *Eragrostis curvula* (Miles, undated) are given where available

Waste	Grass	RWTR rate (g kg^{-1})	Zn			Cu			Mn			Fe			B		
			(mg kg^{-1})														
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Soil	*E. teff*	0	33	31	42	4	10	11	536	639	436	67	128	48	38	4	4
		50	19	14	23	4	4	6	98	51	69	143	94	130	36	4	4
		100	23	16	23	6	6	9	74	72	80	114	142	169	42	4	4
		200	25	12	19	11	8	16	89	99	93	148	258	237	42	6	6
		400	23	10	21	23	14	15	140	80	155	283	303	405	43	8	13
Soil	*D. eriantha*	0	46	19	41	13	8	8	310	481	631	191	124	76	nd	8	4
		50	34	10	19	17	10	9	93	77	88	151	164	144	nd	12	8
		100	41	10	29	33	16	10	140	99	96	769	311	196	nd	14	13
		200	22	10	50	29	16	12	117	66	71	312	174	130	nd	8	6
		400	nd	12	29	nd	27	18	nd	78	61	nd	217	162	nd	8	8
Soil	*C. ciliaris*	0	32	12	18	6	4	5	148	165	223	82	108	170	46	6	4
		50	19	10	16	8	6	6	70	53	53	136	338	95	36	8	6
		100	30	25	18	11	6	7	60	53	39	192	227	119	43	8	6
		200	34	12	12	13	8	8	73	71	43	198	590	117	nd	8	8
		400	33	12	12	17	6	12	107	67	50	405	263	161	nd	6	6
Spoil	*E. teff*	0	78	89	90	8	12	12	195	220	174	76	85	94	nd	71	63
		50	64	61	62	4	8	10	109	59	62	66	77	97	nd	53	79
		100	67	51	55	6	10	6	84	60	51	69	99	101	nd	33	57
		200	57	37	36	8	8	7	59	43	38	70	82	99	nd	25	30
		400	34	31	32	11	12	8	49	43	55	104	117	140	36	10	19
Spoil	*D. eriantha*	0	67	55	47	11	9	10	143	183	257	124	115	81	nd	224	95
		50	52	45	43	13	6	7	96	69	85	96	143	80	nd	175	76
		100	57	35	33	13	8	5	83	71	58	94	149	89	nd	88	79
		200	66	39	18	15	6	3	81	53	31	134	125	63	nd	74	43
		400	54	31	20	19	8	6	88	51	47	224	133	86	nd	63	18
Spoil	*C. ciliaris*	0	43	31	42	9	4	6	139	72	84	93	110	90	30	94	63
		50	41	29	40	9	4	2	93	41	29	83	108	92	35	49	42
		100	38	24	40	9	4	4	66	35	29	89	222	86	49	47	27
		200	30	25	29	9	4	5	39	29	27	99	104	84	35	22	29
		400	35	20	23	11	6	4	35	22	20	128	122	113	39	10	8
Bennett (1993)			-			5 - 20			25 - 150			35 - 100			10 - 60		

nd not determined.

Appendix 7.5 Overview of possible causes and mechanisms of grass nutrient uptake and responses when grown in Rand water treatment residue (RWTR) mixed with spoil or soil (expanded from Section 7.4.4)

In some instances Ca uptake appeared to be associated with low yield, possibly due to a concentration effect, although this trend was not consistent enough to be shown conclusively. Bennett (1993) reports an adequate Ca concentration of from 0.5 to 1.2% for turf grasses. This is generally higher than the levels reported here, but can be viewed in the light of the nature of these grasses. Turf grasses typically require higher nutrient levels due to continuous herbage removal (mowing). Although there appears to be little information on sufficiency levels for grasses other than those found in cropping systems, Miles (undated) has reported an adequate range for *Eragrostis curvula* to be from 0.1 to 0.25%, and 0.22 to 0.31% for *Festuca arundinacea*. These values suggest that the Ca concentrations reported here may be adequate. Furthermore, there was little visual indication of Ca deficiencies during the course of the pot experiment.

A clear pattern for Mg uptake was evident; in almost all cases there was an increase with increasing application rate of RWTR. Bennett (1993) indicates that generally Mg concentrations are lower than Ca in grasses. This trend is reversed for these data, with the treatments with higher RWTR application rates tending to have higher Mg:Ca ratios. Marschner (1986) reports that when two nutrients are near the deficiency range, an increase of one nutrient may stimulate growth, leading to a deficiency of the other induced by the dilution effect. While it may be plausible that in some instances the elevated concentrations of Mg induced low levels of Ca, frequently high levels of Mg were not associated with improved yield of a particular treatment or grass. In addition it would appear that generally Ca was at adequate concentrations to prevent this effect.

Concentrations of K tended to be high. Wilkinson *et al*. (2000) report that excessive K uptake may inhibit Mg translocation to aerial tissue in plants, due to competitive effects in the roots of plants. It would appear that this has not occurred here, due to adequate Mg and K, even in the control treatments.

Uptake of Na tended to show marginal increases with increasing RWTR additions, but concentrations were negligible. While some authors have reported on essentiality of Na by some plants species, halophytes in particular (Marschner, 1986), little evidence exists for its necessity in grasses and adequacy values are not available. It has also been reported that under certain conditions Na may substitute for K in plant tissue (Marschner, 1986). Of more concern in this discussion is the potential of Na to induce deficiencies of other elements. Levy (2000) reports that Na may induce K, Mn, Zn and Cu deficiencies in plants, as well as creating unsuitable growing environments, such as under sodic conditions.

As P was added to the pots, it was unlikely that P deficiencies would occur, even though it was indicated that the RWTR has a high P sorbing capacity. Apart from additional fertiliser added at 80 days after establishment to correct apparent N and P deficiencies, the plants did not show typical P deficiency symptoms, indicating that adequate P was available.

Appendix 7.5 (cont.) Overview of possible causes and mechanisms of grass nutrient uptake and responses when grown in Rand water treatment residue (RWTR) mixed with spoil or soil (expanded from Section 7.4.4)

Nitrogen concentrations did not show a consistent pattern for any of the treatments. Generally the second and third harvests showed higher N uptake, but this was probably due to increased N applications after the first harvest to correct for apparent deficiencies. *Eragrostis teff* grown in the spoil showed high N concentrations for the third harvest. This is attributed to a very poor yield, leading to a concentration effect. A similar comment could be made about *E. teff* grown in the soil, although it is not as evident as for the spoil treatment. The increase in uptake by *Cenchrus ciliaris* and *Digitaria eriantha* may be due to the plants being able to access more nutrients as root mass increased within the pots.

Trace nutrient uptake was variable. Zinc uptake tended to decrease with increasing RWTR additions regardless of treatment. Changes across the harvests were not clear, though. The decrease with increasing RWTR additions may be associated with an increase in pH, where Zn is immobilised and becomes plant unavailable (Mortvedt, 2000). This effect is also reported for Cu, Mn and Fe (Mortvedt, 2000).

Manganese uptake showed a similar pattern to that of Zn, but the concentrations were considerably greater. *Eragrostis teff* grown in the soil showed markedly high Mn concentrations (>400 mg kg^{-1}), but this decreased considerably with RWTR additions. The other grasses and those grown in the spoil did not show such high control concentrations, but the same pattern was evident. While it is unlikely that the ranges found in this investigation would be problematic, they may lead to imbalances and antagonistic effects of other elements essential for plant growth.

Iron concentrations showed a sharp increase in tissue concentrations, especially for the soil treatments. While it is reported that Fe deficiencies may occur in calcareous (or over-limed) media (Mortvedt, 2000), it was not apparent here. A number of possibilities exist that may help explain this behaviour. Firstly, both the RWTR and spoil show moderate levels of plant available Fe, even though the pH was high for both materials. The RWTR has $FeCl_3$ added during treatment, while coal spoil typically has a high Fe content (pyritic materials). Another possibility is the widely reported interaction between Fe and Mn (Pendias and Pendias, 1984; Adriano, 1986). These authors indicate that Fe and Mn are generally interrelated in their metabolic functions and that a Fe/Mn ratio of 1.5 to 2.5 should exist for healthy plant growth. It is reported that high levels of Mn may antagonise and reduce Fe uptake in plants. This may be what was observed in the control treatments for the soil and spoil. When RWTR is added, Mn availability may be reduced due to an increase in pH. As the RWTR has moderate concentrations of available Fe, the availability of this element may be improved, hence increasing the uptake by the grasses. While the Fe/Mn ratio of from 1.5 to 2.5 was seldom observed for these grasses, there was little evidence of either Mn or Fe toxicity when the ratio was below 1.5 or over 2.5. It may be argued that the apparent N deficiencies were rather a result of Fe chlorosis, but this was discounted as N applications remedied the symptoms.

Appendix 7.5 (cont.) Overview of possible causes and mechanisms of grass nutrient uptake and responses when grown in Rand water treatment residue (RWTR) mixed with spoil or soil (expanded from Section 7.4.4)

Copper concentrations in the grasses tended to increase with increasing RWTR additions in the soil material. This trend was apparent only for the first and second harvest in the spoil material, and then showed a reverse trend for the third harvest. It was expected that plant uptake of Cu would decrease with increasing RWTR additions, due to increasing pH, but the reverse pattern of uptake was evident.

Boron uptake was variable, and the first harvest was missing a number of data due to inadequate sample size. Generally the soil treatments had low B concentrations, especially the second and third harvests. The reduction in uptake with increasing RWTR additions is probably associated with an increase in pH, reducing availability (Adriano, 1986). The high concentrations seen for some of the control spoil treatments were of some concern. However, no toxicity symptoms were seen. The upper limit for toxicity to plants is variable and dependant on species and cultivars (Pendias and Pendias, 1984). Adriano (1986) reports a value of >800 mg B kg^{-1} as being toxic to pasture grasses, which is above the values reported here.

Appendix 8.1 ANOVA results for (a) aboveground yield, (b) root biomass in the Rand water treatment residue (RWTR) layers and (c) root biomass in the ash layer of *Cynodon dactylon* and *Stenotaphrum secundatum* grown in the 20, 40 and 60 mm layers of RWTR over a coal combustion ash with two rates of fertiliser

(a)

Source of variation	d.f.[a]	SS[b]	MS[c]	VR[d]	F Probability
Block (replicate)	2	18.23	9.11	4.02	
Fertiliser application rate	1	38.50	38.50	16.96	<0.001
Grass species	1	31.04	31.04	13.68	0.001
RWTR application rate	2	79.37	39.69	17.48	<0.001
Fertiliser x grass	1	36.26	36.26	15.98	<0.001
Fertiliser x RWTR	2	5.50	2.75	1.21	0.317
Grass x fertiliser	2	2.84	1.42	0.63	0.544
Fertiliser x RWTR x grass	2	0.40	0.20	0.09	0.916
Residual	22	49.93	2.27		
Total	35	262.08			
Coefficient of variation (%)	15.3				

(b)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	0.32	0.16	0.38	
Fertiliser application rate	1	0.17	0.17	0.41	0.526
Grass species	1	0.53	0.53	1.27	0.273
RWTR application rate	2	9.35	4.68	11.27	<0.001
Fertiliser x grass	1	0.63	0.63	1.51	0.232
Fertiliser x RWTR	2	2.59	1.30	3.12	0.064
Grass x fertiliser	2	4.37	2.19	5.26	0.014
Fertiliser x RWTR x grass	2	0.24	0.12	0.28	0.756
Residual	22	9.13	0.42		
Total	35	27.32			
Coefficient of variation (%)	5.1				

(c)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	0.02	0.01	0.34	
Fertiliser application rate	1	0.01	0.01	0.49	0.493
Grass species	1	0.00	0.00	0.01	0.933
RWTR application rate	2	0.06	0.03	1.12	0.344
Fertiliser x grass	1	0.01	0.01	0.52	0.480
Fertiliser x RWTR	2	0.03	0.01	0.67	0.524
Grass x fertiliser	2	0.01	0.01	0.27	0.770
Fertiliser x RWTR x grass	2	0.07	0.03	1.34	0.282
Residual	22	0.55	0.02		
Total	35	0.76			
Coefficient of variation (%)	53.9				

[a] degrees of freedom. [b] sum of squares.
[c] mean sum of squares. [d] variance ratio.

Appendix 9.1 ANOVA results for (a) number of seeds, (b) number of pods and (c) mass of seeds of dry beans (*Phaseolus vulgaris*) grown in a Longlands sand treated with Faure water treatment residue (FWTR) at application rates of 0, 50, 100, 200 and 400 g kg^{1} with fertiliser rates of 0, 25, 50, 100 and 150%

(a)

Source of variation	d.f.[a]	SS[b]	MS[c]	VR[d]	F Probability
Block (replicate)	2	76.88	38.44	3.80	
Fertiliser application rate	4	1788.75	447.19	11.19	<0.001
FWTR application rate	4	127.28	31.82	3.14	0.022
Fertiliser x FWTR	16	178.99	11.19	1.11	0.377
Residual	48	485.79	10.12		
Total	74	2657.68			
Coefficient of variation (%)	7.9				

(b)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	10.91	5.45	1.70	
Fertiliser application rate	4	461.12	115.28	35.83	<0.001
FWTR application rate	4	121.39	30.35	9.43	<0.001
Fertiliser x FWTR	16	71.15	4.45	1.38	0.191
Residual	48	154.43	3.22		
Total	74	818.99			
Coefficient of variation (%)	5.8				

(c)

Source of variation	d.f.	SS	MS	VR	F Probability
Block (replicate)	2	6.65	3.33	3.11	
Fertiliser application rate	4	223.85	55.96	52.36	<0.001
FWTR application rate	4	37.45	9.36	8.76	<0.001
Fertiliser x FWTR	16	18.37	1.15	1.07	0.404
Residual	48	51.31	1.07		
Total	74	337.63			
Coefficient of variation (%)	6.8				

a degrees of freedom. b sum of squares.
c mean sum of squares. d variance ratio.

Appendix 9.2 Nutrient concentrations of bean seed grown in a Longlands sand with Faure water treatment residue (FWTR) at application rates of 0, 50, 100, 200 and 400 g kg^{-1} with fertiliser levels of 0, 25, 50, 100 and 150%

FWTR rate (g kg^{-1})	Fertiliser rate (%)	Ca	Mg	K	Na	P	Zn	Cu	Mn	Fe
		(%)					(mg kg^{-1})			
0	0	0.17	0.17	1.37	0.017	0.34	36	14	28	94
50		0.14	0.19	1.36	0.013	0.31	31	10	30	85
100		0.18	0.20	1.41	0.015	0.35	37	12	35	93
200		0.19	0.18	1.29	0.014	0.25	33	11	35	81
400		0.15	0.17	1.31	0.015	0.27	40	12	40	107
0	25	0.13	0.20	1.32	0.010	0.34	32	12	23	74
50		0.17	0.21	1.25	0.013	0.33	28	3	24	78
100		0.14	0.19	1.28	0.018	0.34	33	6	26	85
200		0.16	0.21	1.37	0.019	0.32	31	5	27	87
400		0.13	0.20	1.43	0.016	0.35	31	9	32	92
0	50	0.16	0.22	1.38	0.018	0.41	34	9	32	89
50		0.13	0.22	1.46	0.021	0.35	32	8	29	89
100		0.15	0.20	1.40	0.012	0.37	32	9	27	92
200		0.16	0.20	1.37	0.009	0.33	29	9	26	80
400		0.12	0.20	1.41	0.021	0.36	28	9	28	84
0	100	0.18	0.20	1.39	0.006	0.43	33	3	37	78
50		0.14	0.20	1.40	0.006	0.43	39	8	37	74
100		0.17	0.19	1.38	0.007	0.37	37	8	31	96
200		0.14	0.19	1.42	0.010	0.40	37	9	31	96
400		0.12	0.18	1.47	0.009	0.35	46	10	38	80
0	150	0.15	0.20	1.38	0.007	0.45	45	11	33	93
50		0.12	0.20	1.45	0.006	0.48	48	10	44	79
100		0.17	0.21	1.54	0.007	0.46	51	9	41	82
200		0.12	0.22	1.60	0.010	0.48	40	9	46	90
400		0.09	0.22	1.60	0.015	0.47	43	13	63	92

Appendix 10.1 ANOVA results of organic carbon as affected by water treatment residue (WTR), status and soil depth at Ukulinga Farm and Brookdale Farm sampled in September 2001 and May 2002

Ukulinga	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	3	334	<0.001***	3	96	0.042*
Depth	4	773	<0.001***	4	362	<0.001***
Interactions						
Status.WTR	3	184	0.004**	3	38	0.209NS
Status.Depth	4	14	0.021*	4	31	0.002**
WTR.Depth	12	62	<0.001***	12	9	0.188NS
Status.WTR.Depth	11(1)	31	<0.001***	12	4	0.702NS

Brookdale	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	5	141	0.107NS	5	111	0.020*
Depth	7	7271	<0.001***	7	6080	<0.001***
Interactions						
Status.WTR	5	67	0.389NS	5	36	0.278NS
Status.Depth	7	24	0.010**	7	30	0.363NS
WTR.Depth	35	23	<0.001***	35	52	0.008**
Status.WTR.Depth	35	6	0.903NS	34(1)	19	0.852NS

Status - condition of plots i.e. grassed or fallow; WTR - water treatment residue.
NS non-significant (P>0.05); * significant (P=0.05); ** highly significant (P=0.01);
*** very highly significant (P=0.001).

Appendix 10.2 The effect of water treatment residue (WTR) and depth on mean soil organic carbon (mg kg^{-1}; n=6) at Ukulinga Farm sampled in September 2001 and May 2002

September 2001

WTR	Mean depth (mm)					
(Mg ha^{-1})	**50**	**150**	**250**	**350**	**450**	**Means***
0	23.0	18.4	13.9	9.1	6.4	14.2a
80	21.9	20.2	19.6	17.1	17.9	19.4b
320	22.0	20.2	19.5	17.2	13.2	18.4b
1280	24.1	20.7	19.1	17.4	12.1	18.7b
Means*	22.7a	19.9b	18.0c	15.2d	12.4e	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	1.6	0.80	2.0
d.f	6	31	22.91

May 2002

WTR	Mean depth (mm)					
(Mg ha^{-1})	**50**	**150**	**250**	**350**	**450**	**Means***
0	22.1	20.0	19.0	16.4	12.7	18.1a
80	21.4	19.5	19.6	19.2	15.8	19.1a
320	22.0	20.1	19.9	17.3	15.3	18.9a
1280	24.9	22.3	20.8	19.8	17.3	21.1b
Means*	22.6a	20.5b	19.9b	18.1c	15.3d	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	1.9	1.0	2.4
d.f	6	32	23.65

* Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.3 The effect of water treatment residue (WTR) and depth on mean soil organic carbon (mg kg^{-1}; n=6) at Brookdale Farm sampled in September 2001 and May 2002

September 2001

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	33.3	33.4	28.9	24.0	20.4	14.7	10.3	6.4	21.4
80	32.3	30.1	27.5	23.5	19.1	10.3	7.6	5.8	19.5
320	31.1	29.7	25.5	21.3	18.5	10.5	7.0	5.2	18.6
M320	32.2	29.8	29.5	26.9	20.4	15.9	9.3	6.7	21.3
1280	33.8	32.3	30.6	25.4	20.5	12.5	9.1	7.4	21.4
M1280	31.2	30.9	28.8	26.4	19.9	13.8	8.8	5.5	19.8
Means*	32.3a	32.5a	28.5b	24.6c	19.8d	12.9e	8.7f	6.2g	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR*DEPTH
rep.	96	72	12
l.s.d.	2.4	0.90	3.2
d.f	10	82	36.45

May 2002

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	31.6	31.6	29.5	24.6	18.8	14.5	10.7	9.4	2.32a
80	32.3	31.6	30.1	27.2	21.3	14.3	9.5	7.7	2.18ab
320	32.6	30.8	28.9	22.7	18.6	12.9	9.0	8.3	2.05b
M320	32.2	30.5	28.1	24.5	19.5	13.1	8.9	7.5	2.05b
1280	32.1	30.8	29.9	28.6	22.5	17.6	11.5	7.5	2.26a
M1280	32.6	31.1	30.6	26.4	21.6	15.1	10.3	7.9	2.20ab
Means*	32.3a	31.1ab	29.5b	25.7c	20.4d	14.6e	10.7f	9.7f	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR*DEPTH
rep.	96	72	12
l.s.d.	1.6	1.7	4.2
d.f	10	83	92.95

*Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.4 ANOVA results of pH as affected by water treatment residue (WTR), status and soil depth at Ukulinga Farm and Brookdale Farm sampled in September 2001 and May 2002

Ukulinga	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	3	1.51	0.171^{NS}	3	5.12	<0.001***
Depth	4	1.07	<0.001***	4	2.18	<0.001***
Interactions						
Status.WTR	3	0.61	0.472^{NS}	3	0.09	0.398^{NS}
Status.Depth	4	1.22	<0.001***	4	0.49	<0.001***
WTR.Depth	12	0.47	<0.001***	12	1.60	<0.001***
Status.WTR.Depth	11(1)	0.35	<0.001***	12	0.11	0.076^{NS}

Brookdale	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	5	3.54	0.092^{NS}	5	3.35	0.066^{NS}
Depth	7	2.46	<0.001***	7	2.46	<0.001***
Interactions						
Status.WTR	5	3.36	0.104^{NS}	5	1.18	0.439^{NS}
Status.Depth	7	0.36	0.024*	7	0.36	0.552^{NS}
WTR.Depth	35	0.52	<0.001***	35	0.52	<0.001***
Status.WTR.Depth	35	0.20	0.123^{NS}	34(1)	0.20	0.558^{NS}

Status - condition of plots i.e. grassed or fallow; WTR - water treatment residue.
NS non-significant (P>0.05); * significant (P=0.05); ** highly significant (P=0.01);
*** very highly significant (P=0.001).

Appendix 10.5 The effect of water treatment residue (WTR) and depth on mean soil pH (n=6) at Ukulinga Farm sampled in September 2001 and May 2002

September 2001

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	450	Means*
0	6.12	6.15	6.21	6.34	6.48	6.27
80	6.04	5.83	5.94	6.17	6.42	6.41
320	6.68	6.39	6.09	6.42	6.52	6.42
1280	6.83	6.52	6.13	6.15	6.42	6.08
Means*	6.42a	6.22b	6.09c	6.29b	6.46a	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	0.36	0.07	0.36
d.f	6	31	8.40

May 2002

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	450	Means*
0	5.74	5.90	6.01	6.27	6.38	6.06a
80	6.39	6.08	6.01	6.18	6.29	6.19b
320	6.99	6.67	6.14	6.29	6.45	6.51c
1280	7.41	7.31	6.24	6.10	6.44	6.70c
Means*	6.63a	6.49b	6.10c	6.21d	6.39e	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	0.13	0.10	0.21
d.f	6	32	35.33

* Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.6 The effect of water treatment residue (WTR) and depth on mean soil pH (n=6) at Brookdale Farm sampled in September 2001 and May 2002

September 2001

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	5.23	5.36	5.62	5.77	5.84	5.82	5.89	5.86	5.68
80	5.98	5.66	5.26	5.55	5.68	5.79	5.53	5.26	5.56
320	5.42	5.28	5.41	5.58	5.59	5.56	5.24	5.25	5.42
M320	5.72	5.45	5.50	5.88	5.96	6.04	6.07	5.96	5.82
1280	6.86	6.68	5.51	5.56	5.70	5.77	5.55	5.45	5.89
M1280	6.61	6.28	5.89	5.85	6.04	6.07	5.98	5.93	6.08
Means*	5.97a	5.79bc	5.53e	5.70cd	5.80b	5.84ab	5.71bcd	5.62de	

Least significant differences of means (5% level)

	DEPTH	WTR*DEPTH
rep.	72	12
l.s.d.	0.13	0.45
d.f	82	28.89

May 2002

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	4.87	5.04	5.34	5.49	5.67	5.64	5.66	5.59	5.41
80	5.02	5.37	5.31	5.64	5.60	5.71	5.78	5.74	5.52
320	5.33	5.36	5.63	5.80	5.90	5.92	5.87	5.84	5.71
M320	5.12	5.31	5.37	5.64	5.69	5.55	5.27	5.27	5.40
1280	5.24	5.14	5.42	5.77	5.92	5.87	5.90	5.96	5.65
M1280	5.53	5.21	5.38	5.56	5.71	5.85	5.83	5.62	5.58
Means*	5.19a	5.24a	5.41b	5.65c	5.75c	5.76c	5.72c	5.67c	

Least significant differences of means (5% level)

	DEPTH	WTR*DEPTH
rep.	72	12
l.s.d.	0.13	0.43
d.f	83	32.80

* Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.7 ANOVA results of electrical conductivity as affected by water treatment residue (WTR), status and soil depth at Ukulinga Farm and Brookdale Farm sampled in September 2001 and May 2002

Ukulinga	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	3	1123.201	<0.001***	3	76.294	0.112^{NS}
Depth	4	29.630	0.001**	4	139.379	<0.001***
Interactions						
Status.WTR	3	67.667	0.244^{NS}	3	4.168	0.914^{NS}
Status.Depth	4	1.997	0.806^{NS}	4	53.219	<0.001***
WTR.Depth	12	16.715	0.003**	12	8.123	0.480^{NS}
Status.WTR.Depth	11(1)	12.445	0.022*	12	4.655	0.852^{NS}

Brookdale	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	5	1099.138	<0.001***	5	248.418	0.003**
Depth	7	90.762	<0.001***	7	128.020	<0.001***
Interactions						
Status.WTR	5	135.011	0.074^{NS}	5	64.533	0.169^{NS}
Status.Depth	7	80.490	<0.001***	7	11.275	0.172^{NS}
WTR.Depth	35	95.282	<0.001***	35	34.625	<0.001***
Status.WTR.Depth	35	23.136	0.040*	34(1)	6.504	0.659^{NS}

Status - condition of plots i.e. grassed or fallow; WTR - water treatment residue.
NS non-significant (P>0.05); * significant (P=0.05); ** highly significant (P=0.01);
*** very highly significant (P=0.001).

Appendix 10.8 The effect of water treatment residue (WTR) and depth on mean soil electrical conductivity (mS m^{-1}; n=6) at Ukulinga Farm sampled in September 2001 and May 2002

September 2001

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	450	Means*
0	9.874	10.482	10.650	10.812	10.716	10.507a
80	6.414	5.808	5.540	4.414	5.446	5.525b
320	6.998	6.599	6.691	5.437	4.922	6.129b
1280	18.433	14.991	13.307	12.514	14.827	14.814c
Means*	10.430a	9.470b	9.047bc	8.294c	8.978bc	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	2.725	0.928	2.971
d.f	6	31	13.37

May 2002

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	450	Means*
0	6.299	3.086	2.862	2.208	3.063	3.504
80	6.861	4.840	4.228	3.929	3.832	4.688
320	7.138	5.071	4.338	3.439	3.832	4.764
1280	9.983	8.185	4.798	4.650	3.666	6.256
Means*	7.570a	5.295b	4.056c	3.557c	3.536c	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	2.223	1.192	2.858
d.f	6	32	24.44

* Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.9 The effect of water treatment residue (WTR) and depth on mean soil electrical conductivity (mS m^{-1}; n=6) at Brookdale Farm sampled in September 2001 and May 2002

September 2001

WTR ($Mgha^{-1}$)	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	6.69	8.15	6.70	6.93	7.81	8.91	6.89	5.78	7.23a
80	4.21	5.08	8.74	7.13	7.13	6.54	6.64	6.43	6.49a
320	5.88	8.05	8.14	8.31	7.62	8.33	7.37	5.43	7.39a
M320	6.83	12.15	9.67	9.45	9.54	11.67	10.84	8.45	9.83b
1280	6.10	7.57	8.64	8.97	7.31	7.88	5.15	6.05	7.20a
M1280	10.33	11.47	10.55	11.27	13.00	14.50	14.80	13.50	15.43c
Means*	6.67a	87.4b	8.74b	8.68b	8.73b	10.09c	10.32c	9.46bc	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR*DEPTH
rep.	96	72	12
l.s.d.	2.210	1.256	3.505
d.f	10	82	63.04

May 2002

WTR ($Mgha^{-1}$)	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	6.692	4.533	3.870	4.073	4.433	5.743	5.675	5.174	5.024ab
80	6.080	5.263	5.467	5.609	6.483	7.792	7.857	8.517	6.633b
320	3.758	4.244	4.218	6.378	5.571	7.810	6.983	7.023	5.748ab
M320	5.676	3.745	3.947	4.253	4.934	5.544	5.458	4.666	4.778a
1280	8.118	8.285	6.495	5.362	4.848	7.668	8.950	11.20	9.036c
M1280	5.433	4.600	3.890	4.208	4.362	5.961	5.854	6.408	5.090ab
Means*	5.959bc	5.112ac	4.648a	4.980a	5.105ac	6.753b	7.847d	8.008d	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR*DEPTH
rep.	96	72	12
l.s.d.	1.840	0.903	2.666
d.f	10	83	51.33

*Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.10 ANOVA results of microbial activity as affected by water treatment residue (WTR), status and soil depth at Ukulinga and Brookdale Farm sampled in September 2001 and May 2002

Ukulinga	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	3	0.03	0.868^{NS}	3	0.34	0.134^{NS}
Depth	4	0.07	0.083^{NS}	4	0.18	<0.001***
Interactions						
Status.WTR	3	0.06	0.711^{NS}	3	0.07	0.679^{NS}
Status.Depth	4	0.06	0.105^{NS}	4	0.15	<0.001***
WTR.Depth	12	0.04	0.282^{NS}	12	0.02	0.269^{NS}
Status.WTR.Depth	11(1)	0.06	0.071^{NS}	12	0.01	0.521^{NS}

Brookdale	**----------September 2001----------**			**----------May 2002----------**		
Stratum	degrees of freedom	mean square	Probability	degrees of freedom	mean square	Probability
Main effects						
WTR	5	0.932	<0.001***	5	0.590	0.092^{NS}
Depth	7	10.60	<0.001***	7	3.87	<0.001***
Interactions						
Status.WTR	5	0.319	0.005**	5	1.600	0.004**
Status.Depth	7	0.32	<0.001***	7	0.08	0.110^{NS}
WTR.Depth	35	0.42	<0.001***	35	0.16	<0.001***
Status.WTR.Depth	35	0.13	<0.001***	34(1)	0.19	<0.001***

Status - condition of plots i.e. grassed or fallow; WTR - water treatment residue.
NS non-significant (P>0.05); * significant (P=0.05); ** highly significant (P=0.01);
*** very highly significant (P=0.001).

Appendix 10.11 The effect of water treatment residue (WTR) and depth on mean microbial activity (µMol g^{-1} h^{-1}; n=6) at Ukulinga Farm sampled in September 2001 and May 2002

September 2001

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	450	Means*
0	0.22	0.21	0.38	0.26	0.17	0.25
80	0.20	0.20	0.25	0.33	0.25	0.25
320	0.24	0.26	0.31	0.36	0.27	0.29
1280	0.26	0.25	0.23	0.29	0.37	0.28
Means*	0.23	0.23	0.29	0.31	0.26	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	0.16	0.07	0.19
d.f	6	31	18.94

May 2002

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	450	Means*
0	0.27	0.24	0.25	0.33	0.25	0.27
80	0.31	0.29	0.39	0.42	0.45	0.37
320	0.29	0.24	0.37	0.46	0.37	0.35
1280	0.14	0.13	0.19	0.28	0.30	0.21
Means*	0.25ac	0.23a	0.30bc	0.37d	0.34bd	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR * DEPTH
rep.	60	48	12
l.s.d.	0.16	0.05	0.17
d.f	6	32	12

* Means with the same letter are not significantly different at the 5% level of probability.

Appendix 10.12 The effect of water treatment residue (WTR) and depth on mean microbial activity (µMol g^{-1} h^{-1}; n=6) at Brookdale Farm sampled in September 2001 and May 2002

September 2001

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	0.75	0.73	0.99	1.36	1.32	0.89	0.51	0.31	0.86a
80	0.73	0.99	1.40	2.03	1.21	0.50	0.37	0.25	0.94b
320	0.61	0.75	0.85	1.07	1.15	0.87	0.21	0.10	0.70c
M320	0.78	0.85	1.10	1.42	1.35	0.86	0.34	0.22	0.86a
1280	0.69	0.71	0.80	1.39	1.17	0.62	0.48	0.38	0.78d
M1280	0.57	0.55	0.56	0.98	1.17	1.10	0.34	0.24	0.69c
Means*	0.69a	0.76b	0.95c	1.37d	1.23d	0.81e	0.38f	0.25g	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR*DEPTH
rep.	96	72	12
l.s.d.	0.07	0.04	0.11
d.f	10	82	68.23

May 2002

WTR (Mg ha^{-1})	Mean depth (mm) 50	150	250	350	500	700	900	1100	Means*
0	0.40	0.35	0.41	0.72	1.08	0.47	0.14	0.05	0.45
80	0.39	0.39	0.53	0.90	1.23	0.67	0.22	0.13	0.56
320	0.31	0.36	0.36	0.58	0.57	0.38	0.12	0.11	0.35
M320	0.37	0.43	0.31	0.57	0.67	0.38	0.19	0.08	0.37
1280	0.31	0.26	0.30	0.43	0.67	0.75	0.13	0.10	0.37
M1280	0.30	0.35	0.38	0.48	0.66	0.52	0.23	0.13	0.38
Means*	0.35a	0.3571a	0.38a	0.61b	0.81c	0.53d	0.17e	0.10f	

Least significant differences of means (5% level)

	WTR	DEPTH	WTR*DEPTH
rep.	96	72	12
l.s.d.	0.15	0.07	0.21
d.f	10	83	46.21

* Means with the same letter are not significantly different at the 5% level of probability.

Appendix 11.1 ANOVA results of respiration as affected by Faure 1, Midmar and Rand water treatment residues (WTR)

Source of variation	Degrees of freedom	Mean square	F probability[a]
CONTROL	2	11155.2	<0.001***
CONTROL.RATE	2	7028.1	<0.001***
CONTROL.WTR	2	36502	<0.001***
CONTROL.SOIL	1	5544.4	<0.001***
CONTROL.DATE	9	2074.9	<0.001***
CONTROL.RATE.WTR	4	719.8	0.007**
CONTROL.RATE.SOIL	2	537.0	0.066^{NS}
CONTROL.WTR.SOIL	2	5386.6	<0.001***
CONTROL.RATE.DATE	6	41.4	0.971^{NS}
CONTROL.WTR.DATE	6	677.1	0.003**
CONTROL.SOIL.DATE	3	454.6	0.075^{NS}
CONTROL.RATE.WTR.SOIL	4	236.0	0.303^{NS}
CONTROL.RATE.WTR.DATE	12	59.9	0.986^{NS}
CONTROL.RATE.SOIL.DATE	6	25.8	0.992^{NS}
CONTROL.WTR.SOIL.DATE	6	657.0	0.004**
CONTROL.RATE.WTR.SOIL.DATE	12	55.2	0.990^{NS}

[a] NS non-significant (P>0.05); * significant (P=0.05); ** highly significant (P=0.01); *** very highly significant (P=0.001).

Appendix 11.2 ANOVA results of respiration as affected by Faure 2, Amatola and Midvaal water treatment residues (WTR)

Source of variation	Degrees of freedom	Mean square	F probability[a]
CONTROL	2	3143.64	<0.001***
CONTROL.RATE	1	12513.58	<0.001***
CONTROL.WTR	2	7952.39	<0.001***
CONTROL.SOIL	1	86.75	0.184^{NS}
CONTROL.DATE	9	322.82	<0.001***
CONTROL.RATE.WTR	2	2459.64	0.001***
CONTROL.RATE.SOIL	1	189.62	0.051^{NS}
CONTROL.WTR.SOIL	2	10.66	0.801^{NS}
CONTROL.RATE.DATE	3	133.91	0.048^{NS}
CONTROL.WTR.DATE	6	257.86	0.001**
CONTROL.SOIL.DATE	3	21.73	0.715^{NS}
CONTROL.RATE.WTR.SOIL	2	68.39	0.248^{NS}
CONTROL.RATE.WTR.DATE	6	64.76	0.249^{NS}
CONTROL.RATE.SOIL.DATE	3	140.86	0.041^{NS}
CONTROL.WTR.SOIL.DATE	6	55.68	0.339**
CONTROL.RATE.WTR.SOIL.DATE	6	70.94	0.201^{NS}

[a] NS non-significant (P>0.05); * significant (P= 0.05); ** highly significant (P = 0.01); *** very highly significant (P= 0.001)

Appendix 12.1 Preparation of solutions used in microbial community analysis

10% APS: Make a 10% (w/v) solution in Milli-Q (1 g in 10 mL) and store 0.5 mL aliquots at -20°C.

10M NaOH: Dissolve 400 g NaOH in 450 mL water and add water to make up to 1 L.

0.5M EDTA: Dissolve 186.1 g $Na_2EDTA.2H_2O$ in 700 mL water and adjust pH to 8 with 10M NaOH. Make volume up to 1 L, autoclave for 20 min at 120°C and store at room temperature.

50x TAE buffer: Mix 242 g Tris-base (final concentration of 2M), 57.1 mL acetic acid, and 200 mL 0.5M EDTA or 37.2 g $Na_2EDTA.2H_2O$ (final concentration of 0.1M). Adjust volume to 1 L (solution pH 8). Autoclave for 20 min at 120°C and store at room temperature.

1x TAE running buffer: Mix 20 mL 50X TAE with 980 mL water.

Gel-dye: Mix 0.05 g bromophenol blue in 10 mL 1x TAE.

Loading buffer: Mix 0.05% (w/v) bromophenol blue (0.05 g), 40% sucrose (40 g), 0.1M EDTA (20 mL 0.5M EDTA), and 0.5% SDS (0.5 g) and adjust to 100 mL.

Ethidium bromide: Mix 10 mg ethidium bromide in 1 mL water.

Appendix 12.2 Silver staining of DNA polyacrylgels

Solutions required:
Fixation solution: 10% ethanol and 0.5% acetic acid in water
Part of developing solution: 1.5% NaOH
Stop mix: 0.75% Na_2CO_3
Freshly prepared: 250 mL of 0.1% $AgNO_3$
Developing solution: 25 mg $NaBH_4$, 1 mL formaldehyde in 250 mL 1.5% NaOH

Procedure: Use two clean trays.

In Tray 1:

- Destain an ethidium bromide stained gel on a glass plate by agitation in ultrapure distilled water for 30 min.
- Fixate the gel for 2 x 3 min (at least) with fixation solution (100-200 mL), with gentle agitation.
- Remove fixation solution. Rinse gel with ultrapure distilled water. Add 250 mL of freshly prepared 0.1% $AgNO_3$ solution and agitate in the dark for 15 min.
- Remove solution and rinse with ultrapure distilled water. Fill tray with amount of ultrapure distilled water and position the gel well on the glass plate. Transfer the glass plate with gel to second tray.

In Tray 2:

- Develop the gel by agitation with 250 mL of developing solution for about 30 min in the dark, in a daylight-protected tray. Directly after addition, shake the solution well for uniform development. Monitor the development and, if necessary, stop the development earlier.

Remove developing solution and rinse with ultrapure distilled water. Add 200 mL stop mix and agitate for at least 10 min. Capture image and store sealed in plastic.

Appendix 13.1 Ryegrass analysis from Cuts 2, 4, 6 and 8 of the pot experiment using different rates of water treatment residue (WTR) and lime in five soils

CUT 2

Soil	Lime level	WTR (Mg ha^{-1})	Ca	K	Mg	N	Na	P	Cu	Fe	Mn	Zn
			----------(%)----------						----------(mg kg^{-1})--------			
Hu-M	0	0	0.53	2.97	0.55	4.53	0.70	0.31	15	117	198	61
		40	0.63	3.30	0.52	5.90	0.78	0.36	16	126	140	55
		80	0.66	3.27	0.64	5.30	0.94	0.30	17	114	96	55
		120	0.79	3.12	0.63	5.65	0.95	0.28	17	115	89	58
Hu-T	0	0	0.42	3.96	0.48	2.38	0.46	0.51	10	122	686	87
		40	0.57	3.93	0.47	3.42	0.57	0.43	13	163	442	86
		80	0.61	4.02	0.47	4.80	0.61	0.43	14	101	216	83
		120	0.60	3.84	0.56	3.42	0.67	0.34	16	100	192	82
Ia-C	0	0	0.34	4.58	0.38	3.88	0.51	0.33	15	112	215	48
		40	0.57	3.73	0.5	3.45	0.53	0.25	13	169	296	47
		80	0.54	3.83	0.36	5.15	0.52	0.31	13	114	214	42
		120	0.67	4.16	0.39	3.45	0.57	0.31	16	116	182	42
	1	0	0.55	4.46	0.46	3.23	0.47	0.30	18	111	170	51
		40	0.60	4.02	0.39	2.65	0.40	0.30	13	115	206	49
		80	0.61	3.83	0.40	3.23	0.50	0.37	14	151	159	49
		120	0.72	3.74	0.38	2.75	0.48	0.31	15	100	169	47
	2	0	0.69	3.65	0.43	4.50	0.55	0.34	15	138	106	47
		40	0.71	3.68	0.40	5.15	0.51	0.37	15	149	142	46
		80	0.68	3.78	0.39	4.45	0.61	0.28	15	141	164	38
		120	0.96	4.01	0.40	3.88	0.63	0.26	16	234	210	41
Nb-F	0	0	0.25	3.41	0.39	3.69	0.19	0.72	9	112	162	36
		40	0.97	3.12	0.61	4.05	0.31	0.62	10	120	384	58
		80	0.82	3.25	0.47	3.25	0.28	0.59	7	95	559	45
		120	1.05	2.96	0.48	3.51	0.46	0.53	10	192	404	47
	1	0	0.8	3.19	0.50	2.87	0.15	0.71	11	111	260	69
		40	1.00	2.95	0.39	2.71	0.19	0.57	11	126	448	47
		80	1.07	2.74	0.44	2.79	0.31	0.52	10	106	405	36
		120	1.07	3.01	0.42	3.00	0.33	0.55	12	86	268	43
	2	0	0.91	3.47	0.46	2.64	0.13	0.65	9	101	153	58
		40	0.82	3.31	0.40	2.77	0.18	0.59	9	105	515	54
		80	1.00	2.56	0.48	2.10	0.22	0.54	5	102	315	39
		120	1.01	3.00	0.49	5.60	0.34	0.49	9	100	294	40
Sd	0	0	0.43	3.88	0.45	2.87	0.48	0.43	11	164	476	60
		40	0.58	3.8	0.58	3.86	0.85	0.37	13	91	310	72
		80	0.56	3.88	0.51	2.75	0.79	0.40	14	136	149	64
		120	0.55	3.89	0.55	2.82	0.94	0.40	15	118	174	62

Appendix 13.1 (cont.) Ryegrass analysis from Cuts 2, 4, 6 and 8 of the pot experiment using different rates of water treatment residue (WTR) and lime in five soils

CUT 4

Soil	Lime level	WTR (Mg ha^{-1})	Ca	K	Mg	N	Na	P	Cu	Fe	Mn	Zn
			----------(%)----------						----------(mg kg^{-1})--------			
Hu-M	0	0	0.74	1.11	0.81	nd	0.37	0.26	7	nd	459	42
		40	0.83	1.43	0.7	nd	0.26	0.32	4	nd	170	40
		80	0.96	1.54	0.83	nd	0.38	0.33	7	nd	101	46
		120	0.99	1.35	0.72	nd	0.36	0.19	7	nd	72	40
Hu-T	0	0	0.45	1.91	0.52	nd	0.27	0.29	5	nd	465	58
		40	0.79	2.00	0.65	nd	0.28	0.33	5	nd	419	62
		80	1.00	1.97	0.73	nd	0.34	0.28	7	nd	220	74
		120	1.07	1.82	0.84	nd	0.41	0.22	9	nd	340	85
Ia-C	0	0	1.14	2.24	0.40	nd	0.30	0.20	9	nd	534	45
		40	1.30	1.28	0.81	nd	0.63	0.24	7	nd	576	50
		80	1.31	1.18	0.75	nd	0.64	0.20	8	nd	391	49
		120	1.05	1.56	0.71	nd	0.54	0.17	8	nd	233	44
	1	0	1.22	2.97	0.50	nd	0.10	0.19	12	nd	276	44
		40	0.90	1.86	0.40	nd	0.09	0.20	11	nd	273	43
		80	1.12	2.42	0.46	nd	0.11	0.17	14	nd	246	45
		120	1.34	2.17	0.64	nd	0.08	0.17	11	nd	223	51
	2	0	0.72	0.99	0.56	nd	0.35	0.23	10	nd	153	42
		40	0.81	1.82	0.52	nd	0.55	0.19	10	nd	167	36
		80	1.14	2.80	0.29	nd	0.24	0.14	13	nd	230	41
		120	1.15	3.05	0.29	nd	0.12	0.17	15	nd	149	37
Nb-F	0	0	0.42	2.10	0.46	nd	0.26	0.62	7	nd	179	52
		40	1.19	1.99	0.77	nd	0.10	0.80	7	nd	1033	54
		80	0.98	2.13	0.54	nd	0.13	0.55	8	nd	1061	41
		120	1.53	1.54	0.91	nd	0.26	0.66	9	nd	1441	46
	1	0	1.01	2.25	0.58	nd	0.15	0.80	9	nd	188	48
		40	1.13	2.21	0.59	nd	0.11	0.62	7	nd	823	44
		80	1.64	1.84	0.68	nd	0.10	0.47	5	nd	1764	42
		120	1.77	1.65	0.64	nd		0.46	6	nd	1066	33
	2	0	1.38	1.89	0.93	nd	0.75	0.62	8	nd	150	41
		40	1.14	1.44	0.75	nd	0.64	0.55	7	nd	766	33
		80	1.31	1.2	0.72	nd	0.87	0.58	8	nd	974	27
		120	0.77	0.61	0.70	nd	0.58	0.41	8	nd	783	28
Sd	0	0	0.59	1.86	0.57	nd	0.35	0.41	7	nd	448	55
		40	0.65	1.89	0.65	nd	0.28	0.40	7	nd	272	40
		80	0.75	2.07	0.71	nd	0.32	0.44	6	nd	129	57
		120	0.94	1.77	0.86	nd	0.37	0.36	4	nd	247	52

Appendix 13.1 (cont.) Ryegrass analysis from Cuts 2, 4, 6 and 8 of the pot experiment using different rates of water treatment residue (WTR) and lime in five soils

CUT 6

Soil	Lime level	WTR (Mg ha^{-1})	Ca	K	Mg	N	Na	P	Cu	Fe	Mn	Zn
			----------(%)----------						----------(mg kg^{-1})--------			
Hu-M	0	0	0.64	2.74	0.47	4.05	0.36	0.40	11	199	175	55
		40	0.73	2.61	0.48	4.06	0.39	0.41	14	168	134	52
		80	0.59	2.76	0.48	3.90	0.42	0.42	11	136	68	53
		120	0.70	2.28	0.52	4.34	0.44	0.40	11	163	68	81
Hu-T	0	0	0.57	3.12	0.39	3.60	0.30	0.54	13	218	164	87
		40	0.75	2.72	0.42	3.70	0.45	0.51	12	219	194	88
		80	0.84	2.51	0.39	3.40	0.42	0.53	12	166	126	72
		120	0.83	2.25	0.45	3.55	0.48	0.51	12	193	103	65
Ia-C	0	0	0.56	2.67	0.34	3.70	0.33	0.40	9	216	130	43
		40	0.75	2.47	0.45	2.94	0.37	0.39	11	122	198	57
		80	0.95	2.46	0.43	3.31	0.34	0.40	12	135	141	72
		120	0.96	2.27	0.45	3.05	0.46	0.42	12	120	163	62
	1	0	1.44	2.74	0.45	2.85	0.42	0.41	16	169	129	61
		40	1.05	2.67	0.46	2.99	0.47	0.52	12	179	120	115
		80	1.12	2.54	0.39	3.81	0.43	0.43	10	185	75	51
		120	1.21	2.09	0.47	3.36	0.30	0.37	8	143	99	62
	2	0	0.96	2.27	0.42	3.50	0.39	0.37	16	175	53	71
		40	1.10	2.24	0.51	3.10	0.38	0.38	16	156	57	66
		80	1.06	2.26	0.48	3.67	0.42	0.39	13	164	69	65
		120	1.06	2.30	0.50	3.14	0.37	0.41	18	168	77	67
Nb-F	0	0	0.35	3.29	0.27	3.87	0.13	0.68	12	197	139	75
		40	0.79	2.82	0.34	3.22	0.21	0.51	12	164	144	65
		80	0.94	2.33	0.37	2.91	0.27	0.56	13	278	306	83
		120	1.03	2.38	0.42	5.14	0.29	0.56	9	182	287	76
	1	0	0.93	2.64	0.23	3.49	0.17	0.75	13	168	108	95
		40	1.24	2.26	0.33	3.84	0.19	0.53	11	161	225	79
		80	1.03	2.42	0.35	4.20	0.29	0.50	13	174	194	53
		120	0.96	2.41	0.36	3.41	0.26	0.50	13	147	158	58
	2	0	1.01	2.72	0.24	3.78	0.15	0.64	13	211	62	80
		40	1.61	2.20	0.31	3.50	0.21	0.56	13	153	142	62
		80	1.25	2.34	0.36	3.74	0.33	0.59	13	167	120	56
		120	1.06	2.51	0.38	5.43	0.23	0.52	16	207	111	58
Sd	0	0	0.48	2.51	0.48	3.30	0.86	0.40	11	179	281	114
		40	0.49	2.49	0.45	3.20	0.68	0.43	11	138	170	54
		80	0.53	2.79	0.41	3.60	0.80	0.37	13	135	91	65
		120	0.65	2.41	0.49	3.45	0.82	0.42	12	205	107	79

Appendix 13.1 (cont.) Ryegrass analysis from Cuts 2, 4, 6 and 8 of the pot experiment using different rates of water treatment residue (WTR) and lime in five soils

CUT 8

Soil	Lime level	WTR (Mg ha^{-1})	Ca	K	Mg	N	Na	P	Cu	Fe	Mn	Zn
			----------(%)----------						----------(mg kg^{-1})---------			
Hu-M	0	0	0.85	1.61	0.64	3.10	0.15	0.47	6	160	806	44
		40	0.94	1.65	0.70	3.13	0.16	0.56	6	198	455	34
		80	0.94	1.60	0.68	3.57	0.15	0.58	6	188	188	21
		120	1.34	1.35	0.62	2.08	0.18	0.42	4	143	346	46
Hu-T	0	0	0.60	1.60	0.55	3.74	0.17	0.52	7	215	442	35
		40	0.84	1.50	0.62	3.07	0.19	0.51	4	188	321	29
		80	1.02	1.55	0.52	3.37	0.16	0.53	5	356	85	41
		120	1.12	1.41	0.51	2.78	0.15	0.40	4	74	321	45
Ia-C	0	0	1.11	1.36	0.65	3.84	0.25	0.52	10	196	773	80
		40	1.36	1.29	0.64	3.56	0.20	0.49	7	258	898	81
		80	1.54	1.19	0.62	3.69	0.18	0.44	5	209	613	66
		120	1.43	1.26	0.71	2.25	0.16	0.49	8	159	477	49
	1	0	1.70	1.55	0.69	2.76	0.18	0.60	11	273	646	69
		40	1.44	1.25	0.73	2.60	0.17	0.45	5	464	372	55
		80	1.46	1.15	0.73	2.84	0.16	0.39	4	200	373	50
		120	1.37	1.08	0.73	3.32	0.12	0.31	5	187	467	45
	2	0	2.30	1.29	0.71	2.79	0.18	0.58	17	165	373	40
		40	2.24	1.10	0.71	2.17	0.20	0.46	19	467	507	49
		80	2.05	1.11	0.65	2.98	0.14	0.43	11	282	581	40
		120	1.96	1.26	0.63	3.22	0.17	0.35	8	146	822	35
Nb-F	0	0	0.84	2.07	0.55	2.69	0.22	0.88	5	1065	514	64
		40	1.40	1.39	0.56	2.33	0.38	0.84	7	823	197	78
		80	1.50	1.33	0.50	3.37	0.20	0.69	7	128	503	46
		120	1.70	1.19	0.62	2.91	0.24	0.74	9	178	1593	58
	1	0	1.29	1.90	0.48	3.04	0.19	0.95	5	252	287	60
		40	1.61	1.53	0.49	3.22	0.16	0.61	8	115	422	41
		80	1.77	1.29	0.66	2.96	0.20	0.64	10	159	794	45
		120	1.77	1.40	0.63	2.51	0.34	0.77	10	469	752	41
	2	0	1.51	2.16	0.48	2.98	0.18	1.02	8	143	139	49
		40	1.62	1.63	0.51	2.19	0.22	0.84	8	145	343	35
		80	1.96	1.50	0.61	2.10	0.31	1.07	9	116	476	32
		120	2.03	1.37	0.55	2.89	0.17	0.93	9	158	275	36
Sd	0	0	0.79	1.65	0.67	3.68	0.34	0.41	5	237	1213	34
		40	0.78	1.39	0.57	3.34	0.26	0.40	4	135	388	25
		80	0.86	1.50	0.59	3.22	0.23	0.44	6	146	258	31
		120	1.01	1.34	0.66	3.51	0.22	0.46	5	185	296	39

Appendix 14.1 Analysis* of the water from the dam at Brookdale Farm (as supplied by Umgeni Water)

Date	pH	EC (mS m^{-1})	Alk.[a] (mg L^{-1})	Ca	Mg	Na	K	Fe	Mn	TDS[b]	SS[c]
				---(mg L^{-1})---							
11/12/1997	nd	12.6	nd	9.8	6.6	10.3	<1	0.35	0.06	nd	nd
26/3/1998	nd	nd	nd	9.6	6	9.3	<1	0.44	0.04	nd	53.6
4/6/1998	8.43	13	70.8	8.8	6.2	10.1	<1	0.22	<0.01	81.6	<4
10/9/1998	nd	16	72.3	10.4	8.1	12.1	4.8	<0.02	<0.01	89.8	11.2
3/12/1998	nd	10.9	47.1	7.2	4.3	8.8	<1	0.22	0.01	56	<4
6/5/1999	7.8	14.8	67.2	10.2	7.3	11.3	<1	0.38	0.02	75.8	7.2
3/6/1999	7.7	18.3	88.4	13.4	9.1	12.9	<1	1.05	0.07	109	14
2/9/1999	nd	15.7	69.9	10.1	6.6	14.2	<1	2.52	0.07	115	22.8
2/12/1999	6.7	13.2	46.9	6.4	3.6	12	<1	0.66	0.03	73.6	8.4
30/3/2000	7.3	11.2	49.1	7.1	4.5	7.3	2.2	0.97	0.06	75.8	7.2
8/6/2000	nd	10.5	46.8	8.3	5.4	8.3	1.6	0.4	0.02	82.2	6.8
7/9/2000	9.63	12	60.3	9.6	5.7	9.6	<1	0.19	0.02	77.6	10.4
10/4/2001	nd	13	52	8.3	5.7	9.3	<1	0.67	0.06	nd	nd
7/6/2001	9.2	13.7	nd	10.1	7.1	11.1	<1	0.15	<0.01	nd	nd
7/9/2001	9.6	14.9	59.9	11.6	7.5	11.7	<1	0.36	0.03	nd	nd
4/4/2002	nd	13.6	59.3	nd	nd	nd	nd	nd	nd	nd	nd
13/6/2002	9.7	13.4	63.2	10.6	6.7	10.6	<1	0.14	<0.01	91	<4
12/9/2002	9.7	14.1	64.3	10.9	6.9	10.1	<1	0.45	0.02	99	<4

Date	NO_3	NH_3	Cl	SO_4	Total Al	Total P	D.R. P[d]	F	Cr	Hg	Dissolved O_2
	--(mg N L^{-1})--		---(mg L^{-1})---		---(µg L^{-1})---						(mg L^{-1})
11/12/1997	nd	nd	nd	nd	nd	nd	nd	nd	<3	<0.5	nd
26/3/1998	<0.05	0.19	8.4	0.66	61.7	105	nd	nd	5.3	<0.5	nd
4/6/1998	<0.05	0.07	8.33	0.7	<10	20.4	<3	<100	4.8	<0.5	7
10/9/1998	<0.05	0.05	9.55	0.65	22.1	33	<3	<100	<3	<0.5	nd
3/12/1998	<0.05	0.08	8.37	1.05	nd	43.6	4.51	131	<3	<0.5	nd
6/5/1999	0.08	0.05	11.1	0.13	35.9	22.6	<3	nd	<3	<0.5	3.5
3/6/1999	<0.05	0.07	12.6	0.11	13.1	16.4	<3	135	<3	<0.5	nd
2/9/1999	nd	0.06	nd	nd	110	46.2	34.8	137	<3	<0.5	nd
2/12/1999	<0.05	0.04	8.96	2.01	57.3	37	3.43	131	<3	<0.5	6.5
30/3/2000	<0.05	0.09	8.86	0.15	64.7	32.6	nd	<100	<3	<0.5	6.9
8/6/2000	<0.05	0.04	9.58	0.17	11.7	<15	3.86	nd	<3	<0.5	nd
7/9/2000	<0.05	0.09	6.66	0.42	30.1	30.9	13.9	<100	<3	<0.5	14.3
10/4/2001	<0.05	<0.01	8.87	<0.16	143	nd	nd	<100	<3	<0.5	nd
7/6/2001	<0.05	nd	7.37	0.19	107	nd	nd	nd	<3	nd	nd
7/9/2001	<0.05	0.05	8.24	0.34	70.7	16.5	<3	<100	<3	<0.5	nd
4/4/2002	nd	nd	nd	nd	nd	21.6	15.8	nd	<3	<0.5	nd
13/6/2002	<0.05	0.06	8.2	0.84	32.2	15.5	6.59	<100	<3	<0.5	nd
12/9/2002	<0.05	0.04	7.98	<0.12	80.4	<15	<3	<100	<3	<0.5	nd

Appendix 14.1 (cont.) Analysis* of the water from the dam at Brookdale Farm (as supplied by Umgeni Water)

Date	Coliforms	*E. coli*	Colour	Turbidity	Atrazine
	----------(100 mL^{-1})----------		(Hazen)	(NTU)	(ng L^{-1})
11/12/1997	500	292	8.1	6	11.5
26/3/1998	196	192	6.4	27.8	<5
4/6/1998	102	70	5.54	3.11	<5
10/9/1998	12	12	10	6.33	<5
3/12/1998	270	270	12.2	9.77	nd
6/5/1999	24	18	7.3	2.72	<5
3/6/1999	520	170	16.3	15.5	<5
2/9/1999	210	210	21.2	23	nd
2/12/1999	nd	nd	21.2	6	nd
30/3/2000	2	2	18.7	4.75	nd
8/6/2000	8	4	16	2.39	nd
7/9/2000	nd	2	14.6	2.23	nd
10/4/2001	36	30	nd	nd	nd
7/6/2001	14	4	nd	nd	nd
7/9/2001	2	2	12	3.04	nd
4/4/2002	14	6	10.6	4.26	nd
13/6/2002	0	0	8.2	2.08	nd
12/9/2002	2	0	6.8	2.43	nd

[a] alkalinity as $CaCO_3$. [b] total dissolved solids. [c] suspended solids.
[d] dissolved reactive phosphate (orthophosphate).

* NO_2 (all < 0.05 mg N L^{-1}); Cu (all <0.05 mg L^{-1}); Zn (all <0.03 mg L^{-1}); Pb (all <4 µg L^{-1}); As (all <2 µg L^{-1}); Cd and Se (all <1 µg L^{-1}).

Appendix 14.2 Analysis* of the water from the borehole at Brookdale Farm (as supplied by Umgeni Water)

Date	pH	EC ($mS\ m^{-1}$)	Alk.[a] ($mg\ L^{-1}$)	Ca	Mg	Na	K	Fe	Mn	TDS[b]	SS[c]
				----------				($mg\ L^{-1}$)			----------
4/12/1997	nd	13	nd	10.1	5.6	10.2	<1	0.03	0.02	88	4
26/3/1998	nd	20.9	121	21	7.2	15	<1	<0.02	0.04	164	<4
4/6/1998	6.9	27.5	124	21	10	14.2	<1	0.13	<0.01	184	<4
10/9/1998	7.7	22.8	112	23	7.4	16	<1	0.11	0.04	154	5.6
3/12/1998	nd	22.1	118	20	7.1	14.7	<1	<0.02	<0.01	nd	<4
6/5/1999	7.7	21.7	112	20.3	8	16	<1	0.2	0.05	138	6.4
3/6/1999	7.7	22.4	117	22	8.1	16	<1	0.03	0.04	148	5.6
2/12/1999	8.2	22.6	123	22	7.6	15	<1	0.03	0.04	150	<4
30/3/2000	7.4	13.2	62.1	9.3	6.2	8.9	<1	0.08	<0.01		5.6
8/6/2000	nd	16.4	79.8	16	7.6	11.1	<1	<0.02	<0.01	113	<4
7/9/2000	7.01	18.2	89.2	17	6.8	11.7	<1	1.77	0.24	114	18.4
10/4/2001	nd	12.1	48.5	6.2	6.5	8.9	<1	1.52	0.09	nd	nd
7/6/2001	6.7	13.4	nd	8.2	7.8	10.4	<1	1.09	0.03	nd	nd
7/9/2001	7.8	19	78.8	19	7.4	13.4	<1	0.02	<0.01	160	<4
13/6/2002	7.2	15.1	64	11.5	6.3	10.2	<1	0.38	0.13	101	<4
12/9/2002	7.4	17.7	85.3	15.9	7.0	12.2	<1	0.08	<0.01	119	<4

Date	NO_3	NH_3	Cl	SO_4	Total Al	Total P	D.R. P[d]	F	Cr	Hg	Si
	---($mg\ N\ L^{-1}$)--		----($mg\ L^{-1}$)----		----------		($\mu g\ L^{-1}$)	----------			($mg\ L^{-1}$)
4/12/1997	<0.05	0.06	9.3	0.89	31	24.7	6.06	<100	<3	<0.5	7.2
26/3/1998	<0.05	0.13	6.98	1.86	43.9	25.6	nd	161	22	<0.5	15
4/6/1998	1.78	0.04	12.36	1.84	<10	21.9	20.7	<100	<3	0.5	23
10/9/1998	0.05	0.07	5.68	2.43	<10	19.7	16.8	172	3.6	<0.5	15
3/12/1998	0.19	0.19	5.14	2.06	1114	21.9	21.4	163	<3	<0.5	15.6
6/5/1999	<0.05	0.03	6.53	2.16	23.9	25.4	22.4	nd	<3	<0.5	17
3/6/1999	0.06	0.04	6.11	1.94	<10	20.8	19	172	<3	<0.5	17
2/12/1999	<0.05	0.03	6.91	2.16	12	22.4	nd	161	<3	<0.5	16
30/3/2000	<0.05	0.05	8.97	1.21	962	<15	nd	<100	<3	<0.5	5.9
8/6/2000	<0.05	0.02	8.94	1.22	<10	<15	nd	143	<3	<0.5	8.6
7/9/2000	<0.05	0.03	7.49	1.44	46.4	nd	nd	<100	<3	<0.5	10.4
10/4/2001	<0.05	0.02	8.1	<0.16	58.4	nd	nd	<100	<3	<0.5	5.7
7/6/2001	<0.05	nd	7.98	0.63	133	nd	nd	nd	<3	<0.5	6.5
7/9/2001	<0.05	0.05	6.4	2.41	<10	<15	nd	<100	<3	<0.5	11.1
13/6/2002	<0.05	0.08	8.66	1.37	52.9	19.2	nd	<100	<3	<0.5	7.84
12/9/2002	<0.05	0.05	7.68	1.66	69.2	<15	nd	<100	<3	<0.5	9.68

Appendix 14.2 (cont.) Analysis* of the water from the borehole at Brookdale Farm (as supplied by Umgeni Water)

Date	Coliforms	*E.coli*	Turbidity	Phenols	Atrazine	Zn	Pb	Cd
	-----(100 mL^{-1})-----		(NTU)	($\mu g\ L^{-1}$)	($ng\ L^{-1}$)	($mg\ L^{-1}$)	---($\mu g\ L^{-1}$)---	
4/12/1997	102	0	1.9	<5	nd	<0.02	<4	<1
26/3/1998	0	0	0.9	nd	<5	<0.02	<4	<1
4/6/1998	34	18	2.57	<5	<5	0.1	<4	<1
10/9/1998	0	0	0.65	<5	<5	<0.03	<4	<1
3/12/1998	2	0	0.19	<5	nd	0.1	5	<1
6/5/1999	0	0	1.81	<5	<5	<0.03	<4	<1
3/6/1999	nd	nd	0.48	nd	<5	<0.03	<4	<3
2/12/1999	0	0	0.12	<5	nd	<0.03	<4	<1
30/3/2000	36	20	2.02	<5	nd	0.2	<4	<1
8/6/2000	31	19	0.36	<5	nd	0.3	<4	<1
7/9/2000	4	0	10.7	<5	nd	<0.03	<4	<1
10/4/2001	0	0	15.8	<5	nd	<0.03	<4	<1
7/6/2001	0	0	nd	nd	nd	2.3	<4	<1
7/9/2001	0	0	0.33	<5	nd	<0.03	<4	<1
13/6/2002	1240[e]	1240[e]	6.46	<5	nd	0.7	<4	<1
12/9/2002	22	6	0.64	<5	nd	0.2	<4	<1

[a] alkalinity as $CaCO_3$. [b] total dissolved solids. [c] suspended solids.
[d] dissolved reactive phosphate (orthophosphate). [e] external contamination.
* NO_2 and Cu (all below detection); As (all <2 $\mu g\ L^{-1}$); Se (all <1 $\mu g\ L^{-1}$); Ni (all <3 $\mu g\ L^{-1}$).

Appendix 15.1 Changes in pH (H_2O and KCl) with time following application of water treatment residue (WTR), and lime for two soils, during the incubation experiment

Hu-F	WTR							Hu-F	WTR						
(H_2O)	----------(Mg ha^{-1})----------						Lime	(KCl)	----------(Mg ha^{-1})----------						Lime
Day	0	40	80	120	320	1280		Day	0	40	80	120	320	1280	
1	5.20	5.21	5.22	5.24	5.38	5.66	5.43	1	4.19	4.21	4.27	4.34	4.49	4.93	4.27
3	5.41	5.52	5.72	5.72	5.77	6.44	5.07	3	4.25	4.28	4.39	4.47	4.85	5.76	4.26
6	5.34	5.47	5.51	5.68	5.89	6.46	5.35	6	4.36	4.39	4.43	4.50	5.08	5.96	4.25
14	5.21	5.25	5.44	5.47	5.87	6.96	5.19	14	4.29	4.30	4.40	4.52	5.01	6.28	4.26
21	5.05	5.18	5.34	5.42	6.09	6.99	5.07	21	4.21	4.23	4.39	4.46	4.97	6.18	4.19
28	5.08	5.11	5.20	5.23	5.73	6.66	5.11	28	4.32	4.36	4.38	4.43	5.07	6.23	4.18
35	5.15	5.17	5.31	5.37	5.92	6.61	5.07	35	4.19	4.29	4.46	4.58	5.10	6.15	4.25
42	5.16	5.30	5.35	5.43	5.96	6.63	5.10	42	4.13	4.18	4.38	4.49	5.11	6.14	4.19
49	5.11	5.14	5.30	5.32	5.81	6.59	5.45	49	4.05	4.16	4.31	4.43	5.04	6.13	4.20
56	5.08	5.12	5.22	5.33	6.12	6.89	4.90	56	4.08	4.23	4.37	4.49	5.12	6.27	4.20
63	5.16	5.01	5.13	5.35	5.81	6.74	4.88	63	4.21	4.35	4.50	4.62	5.27	6.58	4.29
70	5.05	4.94	5.08	5.10	5.86	6.91	4.84	70	4.12	4.25	4.40	4.53	5.23	6.56	4.19
84	4.99	4.83	4.96	5.05	5.64	6.84	4.73	84	4.11	4.16	4.31	4.44	5.10	6.48	4.13
98	4.91	4.81	4.96	5.03	5.58	6.74	4.82	98	4.16	4.29	4.43	4.55	5.15	6.59	4.20
140	4.88	4.90	4.95	4.97	5.58	6.57	4.76	140	4.12	4.25	4.38	4.49	5.15	6.53	4.20
Ia-C	WTR							Ia-C	WTR						
(H_2O)	----------(Mg ha^{-1})----------						Lime	(KCl)	----------(Mg ha^{-1})----------						Lime
Day	0	40	80	120	320	1280		Day	0	40	80	120	320	1280	
1	4.49	4.53	4.65	4.69	5.05	5.74	4.71	1	4.08	4.18	4.22	4.50	4.75	4.82	4.50
3	4.78	4.84	5.03	5.09	5.51	6.36	4.97	3	4.17	4.29	4.40	4.63	4.64	4.75	4.63
6	4.68	4.87	5.10	5.27	5.74	6.55	4.99	6	4.26	4.33	4.46	4.47	4.68	4.85	4.47
14	4.77	4.89	5.35	5.38	6.12	6.93	4.85	14	4.23	4.32	4.48	4.53	4.74	4.85	4.48
21	4.55	4.86	5.08	5.35	6.13	6.88	4.94	21	4.18	4.30	4.49	4.52	4.80	4.88	4.52
28	4.62	4.91	5.12	5.32	5.95	7.08	4.88	28	4.21	4.33	4.44	4.52	4.69	4.94	4.44
35	4.59	4.91	4.94	5.24	6.16	7.02	5.20	35	4.16	4.28	4.47	4.55	4.88	5.07	4.47
42	4.42	4.92	5.07	5.07	6.07	6.70	4.93	42	4.09	4.27	4.41	4.45	4.73	4.86	4.41
49	4.47	4.70	5.14	4.99	5.75	6.62	4.88	49	4.05	4.18	4.37	4.41	4.65	4.72	4.41
56	4.43	4.57	4.70	4.88	5.75	6.60	4.75	56	4.06	4.11	4.26	4.33	4.57	4.60	4.26
63	4.53	4.65	4.86	4.87	5.62	6.73	4.98	63	4.20	4.31	4.45	4.51	4.59	4.74	4.51
70	4.37	4.51	4.55	4.75	5.50	6.69	4.66	70	4.12	4.17	4.25	4.32	4.52	4.68	4.32
84	4.20	4.26	4.48	4.66	5.38	6.73	4.68	84	3.98	4.04	4.22	4.25	4.38	4.65	4.25
98	4.28	4.31	4.53	4.70	5.35	6.62	4.62	98	4.19	4.31	4.35	4.42	4.55	4.68	4.42
140	4.30	4.33	4.54	4.67	5.29	6.66	4.63	140	4.12	4.15	4.25	4.33	4.61	4.63	4.33
Hu-M	WTR							Hu-M	WTR						
(H_2O)	----------(Mg ha^{-1})----------							(KCl)	----------(Mg ha^{-1})----------						
Day	0	40	80	120	320	1280		Day	0	40	80	120	320	1280	
1	5.79	5.90	6.01	6.02	6.03	6.23		1	4.65	4.66	4.72	4.75	4.83	4.87	
3	5.98	6.19	6.21	6.27	6.29	6.34		3	4.71	4.82	4.83	4.85	4.88	4.96	
6	6.08	6.32	6.34	6.46	6.49	6.73		6	4.80	4.81	4.88	4.88	4.89	4.96	
14	6.05	6.35	6.37	6.38	6.42	6.60		14	4.94	4.94	5.06	5.09	5.09	5.16	
21	6.06	6.38	6.52	6.59	6.65	6.68		21	4.87	4.93	5.03	5.04	5.12	5.16	
28	6.03	6.24	6.25	6.27	6.31	6.41		28	5.06	5.07	5.08	5.10	5.15	5.28	
35	6.04	6.18	6.30	6.40	6.47	6.56		35	4.95	4.97	4.99	5.14	5.20	5.21	
42	5.20	5.51	5.56	5.61	5.73	6.03		42	4.59	4.63	4.70	4.77	4.95	5.20	
49	5.13	5.15	5.30	5.30	5.43	5.75		49	4.40	4.40	4.42	4.48	4.59	4.82	
56	5.14	5.18	5.19	5.25	5.34	5.67		56	4.39	4.42	4.51	4.53	4.69	4.94	
63	5.07	5.13	5.22	5.37	5.47	5.62		63	4.38	4.56	4.57	4.59	4.75	4.95	
70	4.91	5.01	5.03	5.05	5.18	5.51		70	4.35	4.43	4.46	4.49	4.64	4.84	
84	5.03	5.01	5.03	4.95	5.05	5.26		84	4.21	4.28	4.35	4.35	4.48	4.70	
98	5.03	5.01	5.03	4.95	5.05	5.26		98	4.35	4.41	4.49	4.49	4.60	4.71	
140	5.04	5.08	5.09	4.92	4.94	5.04		140	4.32	4.37	4.43	4.44	4.55	4.56	

Appendix 15.1 (cont.) Changes in pH (H_2O and KCl) with time following application of water treatment residue (WTR), and lime for two soils, during the incubation experiment

Hu-T	WTR						Hu-T	WTR					
(H_2O)	----------(Mg ha^{-1})----------						(KCl)	----------(Mg ha^{-1})----------					
Day	0	40	80	120	320	1280	Day	0	40	80	120	320	1280
1	5.59	5.61	5.67	5.69	5.98	6.41	1	4.39	4.46	4.56	4.76	5.22	6.11
3	5.83	5.90	6.08	6.18	6.49	6.97	3	4.54	4.61	4.87	5.02	5.50	6.25
6	5.54	5.88	5.99	6.11	6.49	6.95	6	4.45	4.70	4.87	5.17	5.76	6.50
14	5.50	5.65	5.74	6.12	6.58	7.20	14	4.42	4.55	4.80	5.07	5.93	6.78
21	5.28	5.41	5.54	5.78	6.49	7.09	21	4.31	4.44	4.62	4.92	5.82	6.66
28	5.18	5.25	5.44	5.63	6.26	7.04	28	4.32	4.35	4.48	4.77	5.86	6.33
35	5.33	5.47	5.59	5.68	6.31	6.66	35	4.22	4.41	4.68	4.93	5.82	6.37
42	5.04	5.22	5.49	5.67	6.36	6.79	42	4.14	4.36	4.65	4.96	5.76	6.40
49	5.14	5.21	5.39	5.67	6.43	6.71	49	4.08	4.21	4.53	4.78	5.87	6.35
56	4.86	5.10	5.33	5.64	6.32	6.78	56	4.11	4.37	4.61	4.93	5.85	6.40
63	4.81	5.27	5.33	5.55	6.66	6.95	63	4.22	4.45	4.73	5.04	5.97	6.83
70	4.74	4.95	5.24	5.47	6.42	6.91	70	4.13	4.36	4.61	4.92	5.88	6.71
84	4.67	4.81	5.05	5.30	6.08	6.78	84	4.04	4.22	4.64	4.76	5.74	6.75
98	4.81	4.84	5.08	5.29	6.03	6.76	98	4.22	4.36	4.61	4.89	5.82	6.75
140	4.74	4.79	5.01	5.23	6.07	6.69	140	4.19	4.31	4.54	4.83	5.76	6.70
Nb-A	WTR						Nb-A	WTR					
(H_2O)	----------(Mg ha^{-1})----------						(KCl)	----------(Mg ha^{-1})----------					
Day	0	40	80	120	320	1280	Day	0	40	80	120	320	1280
1	6.05	6.08	6.20	6.39	6.39	6.73	1	4.61	4.88	5.11	5.27	5.99	6.84
3	6.45	6.46	6.60	6.66	6.89	7.32	3	4.66	5.03	5.36	5.57	6.26	6.83
6	6.67	6.67	6.70	6.85	7.17	7.20	6	4.77	5.18	5.56	5.77	6.46	6.93
14	6.48	6.60	6.90	7.07	7.70	7.91	14	4.58	5.27	5.64	6.01	6.80	7.45
21	6.19	6.45	6.80	7.06	7.49	7.70	21	4.53	5.23	5.79	6.15	6.82	7.15
28	5.92	6.48	6.79	7.37	7.76	8.03	28	4.75	5.22	5.61	6.20	6.63	7.17
35	5.91	6.42	6.76	7.16	7.18	7.39	35	4.54	5.25	5.81	6.20	6.52	6.96
42	5.74	5.94	6.52	6.76	7.11	7.16	42	4.50	5.23	5.69	6.02	6.55	6.79
49	5.74	6.18	6.40	6.81	6.98	7.14	49	4.51	5.28	5.59	5.76	6.38	6.71
56	5.85	6.17	6.40	6.61	7.10	7.13	56	4.47	5.16	5.71	6.00	6.47	6.69
63	5.79	6.20	6.51	6.75	7.15	7.16	63	4.58	5.39	5.88	6.27	6.94	7.01
70	5.61	6.06	6.47	6.73	7.21	7.32	70	4.45	5.27	5.87	6.25	6.95	7.14
84	5.46	5.92	6.29	6.55	7.07	7.17	84	4.34	5.28	5.63	6.27	6.95	7.13
98	5.47	6.03	6.44	6.69	7.05	7.17	98	4.45	5.27	5.78	6.19	6.96	7.12
140	5.43	6.05	6.34	6.64	7.11	7.14	140	4.43	5.44	5.82	6.24	6.82	6.99
Nb-F	WTR						Nb-F	WTR					
(H_2O)	----------(Mg ha^{-1})----------						(KCl)	----------(Mg ha^{-1})----------					
Day	0	40	80	120	320	1280	Day	0	40	80	120	320	1280
1	5.71	5.75	5.79	5.81	5.91	6.60	1	4.46	4.59	4.69	4.90	5.22	6.37
3	6.05	6.08	6.18	6.26	6.32	6.87	3	4.59	4.72	4.91	5.11	5.63	6.55
6	6.19	6.30	6.31	6.41	6.54	7.17	6	4.65	4.92	5.09	5.33	5.64	6.84
14	6.16	6.22	6.22	6.43	6.76	7.43	14	4.65	5.00	5.28	5.47	6.13	7.00
21	5.99	6.11	6.30	6.32	6.79	7.16	21	4.56	4.89	5.20	5.50	6.32	6.94
28	5.85	5.91	6.05	6.23	6.69	6.80	28	5.09	5.10	5.11	5.32	6.07	6.54
35	5.75	5.93	6.15	6.23	6.82	6.90	35	4.49	4.89	5.19	5.50	6.15	6.54
42	5.66	5.94	6.04	6.36	6.72	6.96	42	4.46	4.90	5.20	5.21	6.15	6.63
49	5.58	5.88	6.07	6.30	6.72	6.82	49	4.32	4.71	5.12	5.41	6.11	6.62
56	5.76	5.82	6.16	6.37	6.82	7.10	56	4.44	4.86	5.32	5.52	6.20	6.67
63	5.59	5.87	6.04	6.22	6.84	7.05	63	4.49	4.95	5.36	5.66	6.47	6.96
70	5.34	5.78	5.92	6.17	6.70	7.13	70	4.39	4.86	5.24	5.50	6.43	6.94
84	5.23	5.53	5.79	5.99	6.55	7.02	84	4.33	4.81	5.21	5.55	6.43	6.92
98	5.28	5.54	5.86	6.01	6.63	6.92	98	4.44	4.88	5.24	5.52	6.43	6.95
140	5.25	5.48	5.77	6.02	6.70	6.84	140	4.38	4.87	5.26	5.54	6.43	6.94

Appendix 15.1 (cont.) Changes in pH (H_2O and KCl) with time following application of water treatment residue (WTR), and lime for two soils, during the incubation experiment

Sd	WTR						Sd	WTR					
(H_2O)	----------(Mg ha^{-1})----------						(KCl)	----------(Mg ha^{-1})----------					
Day	0	40	80	120	320	1280	Day	0	40	80	120	320	1280
1	5.81	5.81	5.85	5.91	6.03	6.32	1	4.56	4.72	4.86	4.98	5.48	6.13
3	5.83	5.96	6.17	6.36	6.40	6.65	3	4.73	4.86	5.01	5.16	5.50	6.17
6	6.31	6.37	6.45	6.46	6.60	6.90	6	4.97	5.08	5.22	5.28	5.73	6.42
14	6.01	6.13	6.19	6.34	6.78	7.22	14	4.73	4.94	5.08	5.19	5.78	6.57
21	5.82	5.96	6.06	6.27	6.60	7.08	21	4.63	4.77	5.04	5.14	5.73	6.45
28	5.73	5.83	5.97	6.19	6.62	7.36	28	4.66	4.72	4.96	5.25	5.82	6.57
35	5.74	5.75	5.98	6.05	6.51	7.18	35	4.68	4.85	5.03	5.20	5.73	6.50
42	5.44	5.56	5.82	5.96	6.50	6.90	42	4.60	4.65	4.84	5.03	5.68	6.39
49	5.51	5.62	5.71	5.79	6.44	6.71	49	4.38	4.56	4.68	4.87	5.47	6.19
56	5.51	5.56	5.60	5.79	6.20	6.86	56	4.27	4.51	4.61	4.78	5.26	6.20
63	5.51	5.56	5.58	5.71	6.09	7.00	63	4.48	4.57	4.68	4.84	5.52	6.62
70	5.13	5.13	5.17	5.36	5.99	7.06	70	4.31	4.40	4.53	4.71	5.41	6.64
84	4.87	5.18	5.01	5.18	5.88	6.95	84	4.21	4.20	4.44	4.63	5.38	6.68
98	4.89	5.01	5.13	5.20	5.86	6.98	98	4.23	4.35	4.55	4.74	5.34	6.63
140	4.91	5.37	5.08	5.27	5.88	6.93	140	4.11	4.28	4.49	4.66	5.38	6.55
Va	WTR						Va	WTR					
(H_2O)	----------(Mg ha^{-1})----------						(KCl)	----------(Mg ha^{-1})----------					
Day	0	40	80	120	320	1280	Day	0	40	80	120	320	1280
1	7.07	7.15	7.17	7.17	7.30	7.35	1	5.97	6.02	6.11	6.16	6.34	6.84
3	7.33	7.37	7.39	7.40	7.42	7.48	3	5.87	5.99	6.03	6.14	6.36	6.73
6	7.43	7.44	7.46	7.50	7.54	7.55	6	6.05	6.07	6.16	6.25	6.50	6.90
14	7.42	7.43	7.43	7.45	7.53	7.54	14	5.85	6.13	6.14	6.21	6.53	6.92
21	7.20	7.22	7.26	7.26	7.28	7.34	21	6.10	6.12	6.26	6.28	6.49	6.74
28	7.23	7.27	7.45	7.45	7.47	7.64	28	6.14	6.16	6.22	6.25	6.43	6.61
35	7.22	7.37	7.44	7.44	7.48	7.54	35	6.05	6.12	6.17	6.29	6.52	6.71
42	7.28	7.39	7.40	7.47	7.49	7.50	42	5.94	6.09	6.21	6.32	6.53	6.71
49	7.09	7.16	7.24	7.31	7.33	7.37	49	6.03	6.04	6.10	6.33	6.56	6.67
56	7.32	7.32	7.40	7.45	7.53	7.60	56	5.96	6.07	6.19	6.35	6.41	6.65
63	7.24	7.26	7.31	7.32	7.33	7.44	63	6.09	6.29	6.41	6.59	6.84	7.04
70	7.23	7.25	7.30	7.31	7.36	7.39	70	5.97	6.22	6.40	6.55	6.82	6.97
84	6.93	7.07	7.12	7.16	7.18	7.21	84	6.20	6.26	6.40	6.53	6.82	7.01
98	7.07	7.16	7.18	7.30	7.31	7.33	98	6.08	6.22	6.39	6.54	6.82	6.97
140	7.06	7.08	7.14	7.21	7.24	7.30	140	6.09	6.22	6.31	6.48	6.75	7.01
We	WTR						We	WTR					
(H_2O)	----------(Mg ha^{-1})----------						(KCl)	----------(Mg ha^{-1})----------					
Day	0	40	80	120	320	1280	Day	0	40	80	120	320	1280
1	6.11	6.14	6.17	6.21	6.24	6.50	1	5.06	5.12	5.15	5.24	5.53	6.07
3	6.23	6.25	6.37	6.42	6.64	7.07	3	5.19	5.22	5.27	5.39	5.59	6.42
6	6.08	6.32	6.36	6.72	6.83	7.12	6	5.16	5.20	5.32	5.38	5.81	6.62
14	6.11	6.13	6.14	6.39	6.69	7.23	14	5.17	5.24	5.36	5.46	5.82	6.79
21	6.29	6.32	6.48	6.53	6.83	7.20	21	5.06	5.22	5.36	5.41	5.76	6.61
28	6.01	6.02	6.22	6.24	6.64	7.29	28	5.35	5.36	5.40	5.52	5.62	6.14
35	6.29	6.45	6.47	6.54	6.91	7.28	35	5.12	5.27	5.45	5.52	5.97	6.60
42	6.13	6.14	6.41	6.54	6.75	7.28	42	5.09	5.26	5.49	5.55	6.04	6.55
49	6.01	6.11	6.24	6.28	6.67	7.01	49	5.06	5.18	5.38	5.60	5.98	6.53
56	5.98	6.23	6.34	6.49	6.79	7.10	56	5.07	5.23	5.45	5.67	6.22	6.72
63	6.05	6.06	6.22	6.50	6.84	7.16	63	5.18	5.32	5.55	5.69	6.32	6.90
70	5.90	6.02	6.21	6.30	6.73	7.09	70	5.05	5.24	5.53	5.62	6.24	6.84
84	5.87	5.93	5.93	6.12	6.65	7.12	84	5.18	5.18	5.38	5.53	6.22	6.94
98	5.85	5.91	6.06	6.14	6.57	6.98	98	5.11	5.22	5.46	5.59	6.22	6.83
140	5.86	6.03	6.07	6.21	6.51	6.99	140	5.22	5.24	5.41	5.48	6.13	6.81

Appendix 15.2 Changes in pH (H_2O and KCl) with time in the Av and Ia-W soils following application of water treatment residue (WTR) and lime during the incubation experiment

Av	WTR										
(H_2O)	----------(Mg ha^{-1})----------									Lime	
Day	0	20	40	60	80	100	120	320	1280	L1	L2
0	3.93	4.10	4.23	4.30	4.39	4.44	4.56	5.33	7.00	5.07	5.65
3	3.95	4.31	4.50	4.76	4.86	5.11	5.43	6.74	7.39	5.03	6.37
6	3.98	4.34	4.60	4.86	5.03	5.41	5.82	6.95	7.59	5.32	6.49
9	3.99	4.31	4.57	4.86	5.05	5.40	5.76	6.91	7.51	5.22	6.42
12	4.00	4.28	4.57	4.84	5.07	5.43	5.82	6.98	7.50	5.25	6.41
15	3.95	4.30	4.56	4.86	5.03	5.42	5.88	7.06	7.62	5.39	6.52
30	3.95	4.30	4.60	4.88	5.05	5.46	5.79	6.97	7.51	5.51	6.65
60	4.08	4.51	4.70	5.32	5.66	5.86	6.07	7.02	7.41	6.26	7.07
Av	WTR										
(KCl)	----------(Mg ha^{-1})----------									Lime	
Day	0	20	40	60	80	100	120	320	1280	L1	L2
0	3.84	3.93	4.03	4.18	4.33	4.36	4.53	5.55	6.85	4.18	4.46
3	3.85	3.95	4.09	4.24	4.46	4.60	4.90	6.30	7.32	4.42	5.78
6	3.86	3.96	4.11	4.33	4.63	4.91	5.28	6.60	7.47	4.72	6.02
9	3.85	3.95	4.09	4.32	4.59	4.84	5.18	6.53	7.43	4.57	5.88
12	3.83	3.96	4.09	4.29	4.60	5.10	5.23	6.57	7.42	4.56	5.96
15	3.84	3.94	4.11	4.32	4.56	4.87	5.30	6.73	7.42	4.79	5.93
30	3.83	3.96	4.12	4.37	4.72	5.02	5.35	6.80	7.42	4.97	6.43
60	3.86	3.99	4.18	4.53	4.84	5.12	5.45	6.78	7.49	5.36	6.63
Ia-W	WTR										
(H_2O)	----------(Mg ha^{-1})----------									Lime	
Day	0	20	40	60	80	100	120	320	1280	L1	L2
0	3.99	4.02	4.03	4.05	4.16	4.18	4.30	4.77	5.78	4.67	4.78
3	3.99	4.16	4.37	4.45	4.52	4.66	4.85	5.46	6.80	4.76	5.41
6	3.96	4.22	4.46	4.58	4.65	4.88	5.10	6.02	7.25	4.82	5.29
9	4.00	4.19	4.44	4.62	4.62	4.86	5.04	5.95	7.09	4.75	5.36
12	4.02	4.18	4.41	4.63	4.63	4.88	5.07	5.98	7.06	4.69	5.76
15	4.01	4.18	4.40	4.62	4.64	4.85	5.01	6.08	7.12	4.67	5.61
30	3.99	4.06	4.33	4.46	4.55	4.78	5.00	6.13	7.00	4.58	5.60
60	4.01	4.10	4.33	4.54	4.61	4.85	4.98	6.03	7.12	5.02	5.81
Ia-W	WTR										
(KCl)	----------(Mg ha^{-1})----------									Lime	
Day	0	20	40	60	80	100	120	320	1280	L1	L2
0	3.76	3.84	3.93	4.00	4.03	4.09	4.24	4.86	6.20	4.09	4.42
3	3.85	3.92	4.04	4.10	4.23	4.36	4.47	5.31	6.89	4.13	4.55
6	3.85	3.98	4.05	4.23	4.37	4.53	4.73	5.71	7.08	4.26	4.72
9	3.84	3.93	4.06	4.20	4.33	4.50	4.70	5.64	7.00	4.20	4.72
12	3.83	3.95	4.06	4.21	4.33	4.53	4.70	5.75	7.00	4.14	4.65
15	3.84	3.95	4.05	4.21	4.34	4.50	4.70	5.80	7.13	4.18	4.70
30	3.83	3.94	4.05	4.22	4.35	4.54	4.73	6.03	7.08	4.20	5.02
60	3.82	3.91	4.03	4.19	4.29	4.47	4.65	5.87	7.09	4.20	5.05

Appendix 15.3 Changes in extractable acidity (1M KCl) with time in the Av and Ia-W soils following application of water treatment residue (WTR) and lime during the incubation experiment

Av	WTR										
	----------(Mg ha^{-1})----------									Lime	
Day	0	20	40	60	80	100	120	320	1280	L1	L2
1	3.60	2.96	2.04	1.53	0.87	0.78	0.44	0.05	0.04	1.92	0.94
3	3.65	2.35	1.40	0.74	0.31	0.19	0.09	0.03	0.02	0.54	0.40
6	3.74	2.18	1.00	0.42	0.12	0.07	0.05	0.04	0.00	0.16	0.02
9	3.52	2.25	1.10	0.48	0.15	0.07	0.06	0.04	0.00	0.24	0.03
12	3.42	2.14	1.14	0.52	0.16	0.08	0.05	0.04	0.00	0.26	0.03
15	3.63	2.23	1.10	0.46	0.17	0.08	0.04	0.03	0.00	0.12	0.02
30	3.72	2.09	1.00	0.38	0.11	0.06	0.05	0.03	0.00	0.09	0.02
60	3.64	2.00	0.89	0.18	0.07	0.06	0.04	0.03	0.00	0.03	0.02
Ia-W	WTR										
	----------(Mg ha^{-1})----------									Lime	
Day	0	20	40	60	80	100	120	320	1280	L1	L2
1	3.80	3.18	2.58	2.14	1.94	1.54	0.91	0.12	0.04	2.11	0.94
3	3.66	2.58	1.70	1.21	0.81	0.46	0.35	0.09	0.00	1.50	0.38
6	3.66	2.31	1.45	0.83	0.46	0.26	0.18	0.09	0.00	1.10	0.24
9	3.86	2.66	1.46	1.02	0.62	0.36	0.22	0.09	0.00	1.16	0.24
12	4.00	2.23	1.44	0.74	0.50	0.25	0.22	0.06	0.00	1.14	0.21
15	3.47	2.22	1.36	0.70	0.45	0.27	0.17	0.08	0.00	1.03	0.18
30	3.63	2.44	1.46	0.74	0.47	0.23	0.14	0.08	0.00	0.82	0.04
60	3.96	2.70	1.42	0.88	0.52	0.27	0.17	0.06	0.00	0.82	0.06