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Using undisturbed columns to predict long term behaviour of effluent irrigated soils under field conditions

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Abstract

Soils only have a finite capacity for the removal of wastewater pollutants and with time this capacity could in fact decline. Not all soil types have the capacity to provide adequate treatment and dispersal of sewage effluent. For continued long term application to be successful, it is essential that infiltration and drainage characteristics of soils do not decline. Also it is critical how long term application of nutrients and cations affects the soils and whether any leaching occurs. The research project described in this paper compares the outcomes of detailed field studies with results from an undisturbed soil column study where typical soils in the South East region of Queensland State, Australia have been subjected to sewage effluent application over a period of 12 months. Multivariate analysis helped to classify the influential soil characteristics and to identify relative changes in each soil after the application of effluent. Identification and correlation of influential soil characteristics in field and accelerated column studies confirmed that undisturbed soil column studies can be useful in predicting long term behaviour of effluent irrigated soils.

Introduction

Soil is a medium that supports plant growth, modulates water, nutrients and pollutant transport in a terrestrial environment (Wang et al. 2003). It also serves important ecological functions such as cycling of biochemical essential elements as well as being the ultimate receptor of wastes. Soils only have a finite capacity for the removal of wastewater pollutants and with time this capacity could in fact decline (Halliwell et al. 2001). Once this capacity is exceeded, excessive transmission of pollutant loads to the natural environment is inevitable resulting in environmental and public health impacts. Therefore it is important to investigate the long term behaviour of subsoils under effluent dispersal as effluent application can change soil properties and make the treatment less effective. For example, soil porosity and consequently hydrological properties, soil exchange mechanisms and structural stability are sensitive to treated wastewater compounds (Balks et al. 1998, Coppola et al. 2004).

Not all soil types have the capacity to provide adequate treatment and dispersal of sewage effluent. The soil's capacity to provide adequate treatment is particularly important in the case of septic tank-subsurface effluent dispersal systems which is by far the most common system adopted around the world. The ability of the soil medium to remove pollutants and transmit effluent is one of soils' more important characteristics and one on which a successful on-site sewage treatment system is significantly dependent. On-site wastewater treatment relies on infiltration and percolation of effluent through the soil to achieve satisfactory purification prior to recharge to ground water (Jenssen and Siegrist 1990). The consequences of exposure to inadequately treated effluent from on-site systems include serious environmental and public health impacts (Cliver 2000, Scandura and Sobsey 1997, DeBorde et al. 1998).

For continued long term application to be successful, it is essential that infiltration and drainage characteristics of soils do not decline (Sparling 2001). Also critical is how the long term application of nutrients and cations affect the soils and whether any leaching occurs. Soil column studies are an effective tool that can be used to study soil behaviour under effluent dispersal and have been used by numerous researchers to simulate what happens under field conditions (Van Cuyk et al. 2001, Coppola et al. 2004, Menneer et al. 2001 and Magnesan et al. 1999). The majority of these studies have been used for hydraulic conductivity assessment involving repacked columns due to the difficulty in obtaining undisturbed samples.

To adequately assess a soil's long-term capacity to attenuate effluent pollutants and provide sufficient dispersal capability, hydrological properties and drainage characteristics, as well as the physico-chemical characteristics need to be investigated. Soil sampling and monitoring data at established subsurface effluent disposal systems can be used as a convenient method for evaluating renovation effectiveness and to obtain an insight into renovation mechanisms (Dawes and Goonetilleke 2003). Cation Exchange Capacity (CEC) which provides an indication of the ionic charge of the soil has been identified by Khalil et al. (2004) as an important property in evaluating a soil's ability to renovate effluent. The amount and type of clay present in the soil, pH and organic matter are also important parameters influencing adsorption within the soil matrix. Clays with smectite mineralogy generally have higher CEC levels compared to soils with other clay mineralogy such as kaolinite or illite (Coppin et al. 2002). Individual cations, such as magnesium (Mg), calcium (Ca), potassium (K) and sodium (Na) can also influence the renovation and infiltration of effluent through a soil. High concentrations of cations such as Na and Mg, can cause dispersion of the clay particles and effectively impede water flow through the soil (Dawes and Goonetilleke 2003).

This paper compares the outcomes of detailed field studies (Dawes and Goonetilleke 2003) with physico-chemical data obtained from long term soil column studies. Typical soils of the South East region of Queensland, Australia have been subjected to sewage effluent application over a period of 12 months. Multivariate analytical tools such as Principal Component Analysis (PCA) and Discriminant Analysis (DA) was utilised to allow classification of the influential soil characteristics and to identify relative changes in each soil after the application of effluent. This in turn was used to determine whether correlating results of field studies with soil column data allowed improved prediction of long term treatment potential.

Materials and Methods

Collection of Soil Columns and Setup

Twelve undisturbed cores were obtained representing the major soil types commonly found in the South-East region of Queensland State, Australia. The soil types included Kurosol, Ferrosol, Sodosol, Dermosol, Kandosol, Podosol and Chromosol soil groups (Isbell 2002). Table 1 gives the relevant physical and chemical soil properties of the twelve soil cores and their respective soil classifications based on the Australian Soil Classification and equivalent Soil Taxonomy Order (NRCS 1999), together with a general soil profile description. The undisturbed cores were obtained using an 85mm hollow flite auger and driven to a depth of 1200mm. Whilst in storage in the laboratory, the cores were periodically sprayed with deionised water to prevent the soil from drying out. This was to ensure that no unintentional cracks occurred through the soil structure that may provide preferential flow paths to occur.

Table 1 Soil column physical and chemical properties (original)

Test columns, as depicted in Figure 1, were fabricated using 100mm diameter Perspex tubing capped with a 10mm thick square Perspex base plate. Three effluent sampling points were located along the length of each column at 150, 450 and 800mm from the top and a fourth effluent sampling point was centrally located at the base of the column. Additionally, three soil sample ports were located at the same heights but opposite of the effluent sampling points. Stainless steel tubes (75mm in length and 10mm diameter) with 3mm holes (top and sides) were inserted through the soil at each effluent sampling point to allow percolating effluent to enter and flow out into connected sample bottles. This was to allow percolating effluent to be collected through the effluent sampling points under gravity flow.

Figure 1 Column setup

Prior to inserting each soil core into the prepared columns, the top 350mm was removed. This was to replicate as closely as possible the installation depth of a typical soil absorption system commonly used in Australia (Figure 2). From the remaining section of the soil core, a section between 850 to 900mm in length was separated for installation into columns. A geo-textile membrane was placed at the internal base of the column, to prevent the migration of fine soil particles out of the columns. The gap between the soil core and the column was filled with liquefied petroleum jelly to prevent any preferential flow between the soil core and the column wall and to ensure that all applied effluent would infiltrate through the soil. As vertical flow was only considered in the experiment, partial smearing from the drilling process and minor petroleum jelly intrusion were not considered appreciable to cause any major concerns with effluent flow through the soil. The top surface of the soil core was covered with 20mm gravel to a depth of 30mm to replicate the situation on the subsurface effluent disposal trenches. This gravel layer replicated field conditions and helped distribute the effluent uniformly. The columns were located in a temperature controlled laboratory at 23 degrees C to reduce the effects of evaporation.

Figure 2: Typical setup of an on-site septic tank-soil absorption system commonly adopted in Australia

Soil Sampling and Analysis

Three samples were characterised from each soil column representing different depths down the soil profile. Samples were taken from the soil cores prior to their insertion into the test columns to determine the original physico-chemical characteristics. The results obtained are shown in Table 1. The soil sampling ports on the side of the columns were opened after twelve months of effluent application and three soil samples of 15g were obtained and the windows resealed. The original soil for each column was characterised before effluent application for the following physico-chemical parameters: pH, organic matter content (OM), electrical conductivity (EC), particle size distribution, cation exchange capacity (CEC), effective cation exchange capacity (ECEC) and the soil mineralogy. The individual exchangeable cations (Fe^{2+}, Al^{3+}, Mg^{2+}, Na^{+}, Ca^{2+} and K^{+}) were also investigated and exchangeable sodium percentage (ESP) calculated. The soil test methods adopted for analysis are given in Table 2.

Effluent Application and Sampling

Primary treated effluent collected from a municipal wastewater treatment plant was applied to the top of the column at the rate of 240 mL/day intermittently twice a day until ponding occurred due to the formation of a clogging mat. The application rate was based on typical household effluent flow rates and system sizes and adjusted (scaled) for the cross-sectional area of the soil column. This was to replicate as practically as possible the approach taken in designing the monitored field dispersal areas. AS1547 (1994) was used to determine the loading rate for each of the soil types. Using the Long Term Acceptance Rate (LTAR)/ Permeability relationship curve a conservative rate of 15 to 20 mm/day was chosen as previous researchers have noted that many Australian soils exhibit low permeabilities and are poor for soil absorption. Geary and Gardner (1998) suggest soil based systems relying on soil absorption will fail if loaded in excess of 10 to 20mm/day. Although there were textural differences between the soils, the hydraulic conductivity (k) values in the top section of the soil core were in the same order of magnitude and thus the same application rate was applied to all soils. This was subsequently halved after ponding occurred and the effluent was applied in intermittent doses twice a day.

The primary treated effluent was pre-filtered to remove any large solid matter >75 microns in size to prevent clogging of the soil pores due to large solid material. The reason for the use of primary treated effluent from a municipal treatment plant was that it allowed access to a source of effluent with reasonably uniform quality. The use of septic tank effluent would have been closer to actual situation on the ground, but it was not considered feasible as it would not be possible to obtain a constant quality for the duration of the experiment.

Table 2 Column sample analysis methods

Average quality characteristics of the effluent used is given in Table 3. After effluent ponding had taken place, application rates were reduced and applied when necessary to allow sufficient time for effluent to percolate through the clogging mat and infiltrate into the soil. A reduction in effluent infiltration as a result of the development of a clogging mat occurred over a 3-4 month period before steady state infiltration occurred. Subsequently, a reduction in the soils' permeability also occurred as a result of the clogging mat (Carroll et al. 2005). Effluent application continued over a twelve month period. Effluent which had infiltrated through the soil column was analysed on a fortnightly basis or earlier if the sampling bottles contained more than 20ml of sample. The collected samples were analysed for pH, Electrical Conductivity (EC), Chloride ions, Phosphorus (PO_4^{3-}-P), Nitrates (NO^3), Sulphates (SO_4) and Cations (Al, Fe, Mg, Na, Ca and K) if sufficient sample was available.

Table 3 Average Effluent Characteristics of Applied Effluent

Field Studies

Homogeneous paired soil samples were collected from 34 study sites located in the urban fringe of the local government areas of Brisbane and Logan City Councils in Queensland State, Australia. These regions are adjacent to each other and are currently undergoing significant urbanisation with the development of extensive rural residential allotments which are not serviced by reticulated sewerage facilities. The selected sites consisted of soils that had been subjected to sewage effluent disposal with samples collected from piezometer locations at 1 m and 3m downstream from the edge of the subsurface disposal area and soil samples from control sites that had not received effluent (Dawes et al. 2005). The control samples were needed in order to determine background soil parameters. The piezometers were installed to a maximum depth of 1.5m or to a clay layer of very low permeability in order to collect soil water samples.

Table 4 – Site and soil classification

Site and soil classification and details of the field sites are given in Table 4. Each site was subsequently classified as satisfactorily treating and dispersing effluent or failed due to hydraulic failure or pollutant contamination, based on site, soil and soil water data.

The investigations undertaken involved the analysis of the selected soil profiles for their physical and chemical properties. The soil parameter selection was based on the suite of tests generally carried out in land capability evaluation (Rayment and Higginson 1992). These tests have been developed through extensive agricultural research and are designed to distinguish between deficient, adequate and toxic supply of elements in soil as well as between degraded and non-degraded soil conditions. These criteria are being increasingly used in environmental monitoring (Peverill et al. 1999).

The soil samples were collected by hand auger, air dried, ground and then sieved to 2mm particle diameter and sub-sampled for pH, electrical conductivity (EC), organic matter by weight loss, exchangeable cations using displacement with NH_4Cl and analysed by Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES), concentration of chlorides and nitrates in aqueous solution by colorimetry. Parameters such as exchangeable sodium percentage (ESP), Ca:Mg ratio, cation exchange capacity (CEC) and effective cation exchange capacity (ECEC) were derived from the measured data. Soil texture and drainage class was measured using the field method outlined by McDonald et al. (1998). Particle size analysis was carried out using the hydrometer method described by Loch and Smith (1988), including sample pre-treatment for removal of organic matter where necessary.

Detailed assessment of the sites was carried out to determine treatment performance of each subsurface effluent disposal system. Treatment performance was defined by field observations, soil water sampling results and detailed site history obtained from the householder and surface and sub-surface site conditions noted during the study. This information, together with site conditions and insitu drainage data was utilised in establishing possible site failure mode. Table 5 lists the failure diagnosis for sites classified in terms of type of design boundary failure (USEPA 2002).

Table 5 Failure diagnosis of field sites

Multivariate data analysis

Multivariate analysis constitutes a powerful tool that compliments environmental studies by analysing, describing and interpreting multidimensional observations. Principal Component Analysis (PCA) is a multivariate statistical data analysis technique which reduces a set of raw data into a number of principal components which retain the most variance within the original data in order to identify possible patterns or clusters between objects and variables. Detailed descriptions of PCA can be found elsewhere (Massart et al. 1988, Adams 1995). PCA has been used extensively for various applications related to soil quality. As examples, Sena et al. (2002) used PCA to distinguish between agricultural plots as a function of soil management and determined the most important soil parameters to characterise them. Vance et al. (2003) used PCA to help in classifying soil samples based on exchangeable sodium percentage and spontaneous or mechanical dispersion.

Discriminant analysis (DA) was employed to discriminate between major soil characteristics influencing the relevant processes. Discriminant analysis is a multivariate statistical analysis technique where a data set containing X variables is separated into a number of pre-defined groups using linear combinations of analysed variables. This allows analysis of their spatial relationships and identification of the respective discriminative variables for each group (Wilson 2002). Objects (soil type) that retain similar variances in the analysed variables will have similar discriminant scores and when plotted will cluster together. Likewise, relationships between variables can be easily identified by the respective coefficients. Strongly correlated variables will generally have the same magnitude and orientation when plotted, whereas uncorrelated variables are typically orthogonal to each other. Clusters of object data and their respective relationships with the analysed variable can be clearly seen when respective discriminant scores and coefficients are plotted on a biplot, generally plotting the first two discriminant functions. Visualising these biplots is undertaken in the same manner as the PCA biplot. In soil science studies this method has been applied successfully to classify drainage classes (Kravchenko et al. 2002) and soil classes (Brejda et al. 2000, Carroll et al. 2004)

DA was undertaken to distinguish between the major physico-chemical characteristics of the various soil types used. This was based on a selection of variables employed to evaluate the soil's ability to renovate effluent data and to assess the various changes occurring in the soil columns as a result of long-term effluent application. Data sets were constructed including the original soil data, soil data obtained after effluent application and field data. The variables investigated included, pH, EC, exchangeable cations Ca^{2+} (eCa), Mg^{2+} (eMg), Na^{+} (eNa), and K^{+} (exK), organic matter (%OM), cation exchange capacity (CEC), effective cation exchange capacity (ECEC), exchangeable sodium percentage (ESP), Ca:Mg (C:M), ESP, and percentage clay (%Cl) and type of clay.

All raw data used in the DA and PCA analysis was subjected to pre-treatment to remove or reduce irrelevant sources of variation or 'noise' which may interfere in the analysis (Einax 1998). After pre-treatment, multivariate analysis was conducted on the data set for all soil horizons to determine which soil types were highly correlated with each other and with selected variables to identify possible soil patterns or clusters. Correlations between selected variables were also evaluated allowing identification of the most important parameters when characterising soil behaviour under effluent irrigation. The analysis was performed using statistiXL Version 1.5 (Roberts and Withers 2004).

Results and Discussion

Impact on Soil Properties (Columns)

Tables 6 and 7 show soil textural, drainage, dominant mineralogy and general chemical characteristics, namely site drainage (classified at site where original column was sampled), texture class, percentage clay, pH, Electrical conductivity, organic matter and chemical properties of all twelve soil columns. Original soil properties are presented along with properties after twelve months of effluent application. Values presented in Tables 6 and 7 are average values of duplicate samples and based on dry soil weight. If values differed by more than 10% and enough sample was collected, the test was repeated.

The soil columns investigated in this study fell into seven soil orders (Australian Soil Classification, Isbell 2002) and comprised a range of textural classes ranging from sand to heavy clays. These seven soil orders cover the majority of the soils in South East Queensland with the Chromosols, Kurosols and Sodosols being the most common and distinguished by sharp increases in clay content in their sub-surface layers and a strong texture contrast between A and B horizons. Ferrosols and Dermosols are defined by their lack of texture contrast and are usually deep soils with high iron content. Kandosols are strongly weathered soils with no strong texture contrast. Podosols are characterised by a strongly coherent B horizon and occur along coastal Queensland. The soils ranged from strongly acidic to slightly acidic.

Table 6 Physical and Chemical Properties of Soil Columns
Table 7 Chemical Properties of Soil Columns

Physical Characteristics

Only four columns (Column 3, 8, 10 and 12) were permeable enough to allow effluent to percolate through the entire soil column (collection of percolate at all three sampling points) after twelve months of effluent application. This was expected for the sand textured Column 3 (Podosol). Although related to the soils mineralogy (in particular the type and amount of clay in the soil profile), the extent of clogging mat development on the soil infiltration surface will influence the hydraulic conductivity of the soil. Carroll et al. (2005) highlighted the reduction of hydraulic conductivity in similar soils due to the clogging mat where steady state conditions occurred between 40 and 80 days after effluent application commenced. Hydraulic conductivity values for these soils after 80 days were less than 5mm/day. This reduction could also be caused by clay enrichment down the soil profile (Column 5, 8 and 12) or clogging of soil pores by organic matter which increased in all columns except Column 3. The increase in organic matter resulted in increased CEC in columns which had relatively higher clay content. Menneer et al. (2001) in a study on laboratory and insitu soils in New Zealand found reduced water movement through soils as a result of dispersed clay, thereby blocking the water conducting pores and impeding drainage. There was no evidence of dispersed clay in the leachate that would cause the collapse of soil aggregates and subsequent decrease in hydraulic conductivity in any columns in the twelve months of effluent application.

Columns 1, 3, 7, 9, 10 and 12 exhibited very rapid flow through SP1 (Sample Point 1) and were plugged after two litres of leachate sample was collected. This was done to prevent excessive lateral flow and allow only downward flow though the soil. Columns 5, 6 and 11 were not receiving any effluent below SP1 (no effluent collected in sample bottles). Soil sampling points that did not have substantial flow (> 250mls) of effluent through the soil column were excluded from the multivariate analysis. The effluent infiltration through these soils was very slow, indicating a very low saturated hydraulic conductivity. The possibility of a restrictive layer forming an impermeable barrier and therefore limiting any flow through the soil column may also explain this occurrence. To provide suitable renovation of effluent, infiltration through the soil should be at a rate to provide adequate treatment and also the continued dispersal of the effluent. When the rate is too slow, discharged effluent will not be able to infiltrate through the soil, and ponding will occur. Ponding occurred in all columns except Column 3 (Podosol), and varied from 2 days (Sodosol) after initial effluent application to 76 days (Kandosol). This was dependant on soil texture and clay content through the profile.

Chemical Properties

Very few studies have continuously monitored nutrient and cation leaching from soils over extended periods of time following effluent application. McLaren et al. (2003) in a study on leaching of macronutrients and metals from undisturbed soils treated with spiked metal sulfates sewage sludge found that anion and cation leaching can vary greatly between soils and is dependant on a number of physical and chemical soil properties. These were namely, pH, texture, structure and organic matter. Heng et al. (1999) examined the leaching behaviour of applied cations and anions under contrasting flow conditions on a Red Ferrosol soil and found the leaching process was dominated by the soil's water flow characteristics and showed little influence of surface chemical reactions. Cation exchange reactions occurred in slow flow soil (flux density < 10mm/hr), but not in a fast flow soil. Their study demonstrated that the rate of water movement can influence the soil cation exchange reactions by determining how much of the soils' CEC interacts with the percolating solution. All columns except Column 3 (Podosol) exhibited very slow flow conditions and thus solutes were in significant contact with the soil matrix as effluent percolated through the soil, allowing greater opportunity for chemical reactions to take place.

All soils except in Column 5 (Chromosol) showed a significant increase ($P<0.05$) in pH as a result of effluent application. This is likely to relate to the addition of basic cations and anions found in effluent which is slightly alkaline. These results are similar to the effluent irrigation study by Falkiner and Smith, (1997) on Red Chromosol and Red Kandosol soils, where they found significant increases in soil pH along with significant changes in soil cations Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} after 2 to 4 seasons of irrigation. They found ECEC increased with time and postulated that this was as a result of displacement of H^{+} ions from clay surfaces caused by the addition of cations in irrigation water. Both Column 6 (Sodosol) and Column 8 (Dermosol) support this hypothesis at SP1. Several columns where SP1 was plugged, namely Column 1 (Kurosol), Column 5 (Chromosol) and Column 9 (Dermosol) also showed increased ECEC at SP2. Tillman and Scotter (1991) in a study of movement of solutes through repacked silty loam soils found that the effect of hydrogen ion consumption or production was to raise or lower the effective cation exchange capacity. The majority of soil columns, where flow has occurred, confirm this finding.

Electrical Conductivity (EC) values increased significantly ($P<0.01$) at SP1 for all Columns except 4, 5 and 6 indicating soluble salts were being deposited as a result of effluent ponding. The addition of wastewater effluent to already high EC soils in Columns 4, 5 and 6 led to the redistribution of EC more evenly through the profile even though these soils exhibited very low flow.

Menneer et al. (2001) in a field and laboratory study on sodium rich effluent irrigation of silty loam soils in New Zealand found changes in electrical conductivity, exchangeable sodium and exchangeable sodium percentage up to 0.3m depth with the largest increases at the surface. In this study, Columns 1, 7, 8, 10, 11 and 12 exhibited very similar characteristics. Similar increases in ESP recorded at depth in columns of low CEC enabled small increases in exchangeable sodium to have relatively large effects on ESP. Many researchers (for example, Halliwell et al. 2001, Magesan et al. 1999, Balks et al. 1998) have reported on soil structural deterioration which leads to clay dispersion and subsequent reduction in hydraulic conductivity under effluent application caused by increased ESP. There is still considerable uncertainty about the value at which ESP becomes hazardous. Crescimanno et al. (1995) suggested that a continuum may exist between soil structural properties and ESP, with an ESP as small as 2 to 5 causing adverse effects if low electrolyte concentrations are present in the soil solution. It is expected that ESP will reach equilibrium at shallow depths in the soil columns and will continue to increase in the lower profile with further effluent application.

Exchangeable cation concentrations in all soil columns varied with the application of effluent. All columns except Column 4 and 8 displayed a reduction in exchangeable calcium. Increases in exchangeable sodium, with the majority occurring at the surface, were often accompanied by an increase in exchangeable magnesium. Phillips (2002) states that low CEC soils would not favour large-scale changes in exchangeable cations. The low CEC soil columns in this study (Columns 9, 10, 11 and 12) support this hypothesis except in the case of exchangeable magnesium where large changes in concentrations were adsorbed and leached. These low CEC soils were predominately kaolinite clay except Column 12 which was a mixed mineralogy soil (Kaolinite/Illite). When there is a change in other cations, sodium will compete well for exchange sites (Menneer et al. 2001). The type of clay can determine what exchangeable cations are adsorbed or leached. In a study on illite and montmorillonite clays, Endo et al. (2002) found that illite had a high affinity for sodium and decreased with increasing clay content. In soils with low clay content, sodium adsorption/calcium release in soil colloids was enhanced and ESP increased markedly. Soils with high clay content suppressed sodium adsorption/calcium release. In general significant increases in ESP occurred in soil columns with <30% clay and in the presence of illite clay.

The Ca:Mg ratio in the soil was employed to indicate cation distribution, particularly in the case when the subsoil is dominated by magnesium. Many of the soil columns were dominated by magnesium especially at depth. An excess of one cation may inhibit the uptake of another. Shaw et al. (1997) postulated that low Ca:Mg ratios in conjunction with high ESP indicate enhanced dispersion. Vance et al. (2002) in a study on Sodosol and Chromosol soils found that magnesium dominant soils tended to disperse. Columns 4, 6 and 8 display these characteristics with magnesium and sodium dominant throughout the profiles. The application of effluent improved the Ca:Mg ratio in Columns 2 and 10 and thus increases in exchangeable Sodium were offset by the co-dominance of calcium and magnesium in these soils.

Assessment of Soil Columns with Field Study Sites

The soil columns were collected from similar soil types and profiles to existing field sites. This was to enable assessment in a controlled environment, of a soil's long term ability to effectively attenuate sewage effluent and provide adequate dispersal capacity. Dawes et al. (2005) found that the controlling soil physical and chemical attributes at existing onsite sewage treatment system sites were related to drainage and ion exchange. Significant soil cation exchange capacity and dominance of exchangeable calcium or exchangeable magnesium over exchangeable sodium, low exchangeable sodium, clay type and a minimum depth of 0.4m of potential unsaturated soil before encountering a restrictive horizon were identified as the critical parameters. Field sites (Table 5) were evaluated based on treatment performance and classified according to USEPA (2002) failure diagnosis.

Chromosol (Sites 3, 20 and 34), Kurosol (Site 30) and Sodosol (Site 9) soils where hydraulic failure was diagnosed, were waterlogged for long periods of time throughout the field study. In the soil column study, hydraulic failure occurred rapidly in similar soils; Sodosol (Column 6), Dermosol (Column 8) and Chromosols (Column 5 and 11). The soils in these columns were dominated by either magnesium and/or sodium throughout the soil profile. Calcium was either very low originally or leached from these soils. The ESP of the Chromosol soils increased markedly (Column 5 from 5% to 21% at SP1 and Column 11 from 1% to 7% at SP1) which is likely to lead to soil structural deterioration through dispersion. The Dermosol soil also showed a distinct increase in ESP at SP1 (3% to 13%). The Sodosol soil already had high ESP throughout the profile and soil samples collected from SP2 (depth of soil 0.43m) and SP3 were still dry after 12 months of effluent application. In Columns 2 (Ferrosol) and 4 (Kurosol), moderate to high ESP was offset by the co-dominance of calcium and magnesium. The presence of small amounts of smectite clays in the lower part of these columns could be beneficial in the adsorption of sodium cations.

Several of the field sites had slowly permeable soil at the top of the ‘B’ horizon and lateral flow was observed. In these cases the A-B interface effectively acts as an impermeable barrier to vertical flow. As the ‘A’ horizon becomes saturated, lateral flow of effluent is preferred rather than downward movement. Columns 1, 5, 6, and 9 with the majority of the A horizon removed exhibited these characteristics and were subsequently closed at Sampling Point 1 to allow downward flow.

Similar to many field site soils, the pH in the column soils throughout the profile increased as a result of effluent application. The increase in organic matter and increased pH generally lead to a CEC increase, but was dependant on the type of clay. Minor rearrangement of cations occurred in low CEC soils. Electrical conductivity profiles showed similar variations to the field sites with pulsing of salts through the soil profile (Dawes and Goonetilleke 2003). The build up of salts is dependant on the soils’ hydraulic capacity.

Field sites were categorised by their landscape position and given a drainage classification ranging from well drained to very poorly drained (McDonald et al. 1998). The undisturbed soil columns were also assigned drainage classes based on where they were sampled in the topographic profile. Classifications are given in Tables 4 and 6. Field sites that displayed hydraulic failure (except Site 34 where depth to restrictive horizon was 0.2m) fell within the imperfectly to poorly drained classes. Similarly, the soil columns where hydraulic failure occurred (Column 5 and 6) were classified as imperfectly drained. The hydraulic failure in Column 11 (moderately well drained class) was related to dispersion of the soil caused by an increase in ESP (1% to 7%) in the top half of the profile (SP1).

Multivariate Analysis

Influential soil characteristics

Field Study

The PCA analysis produced some predictable results in relation to the correlations between the variables and soil classifications. The soils with higher clay percentages retained positive scores on PC1, with sandier soils falling directly opposite (mainly A horizon soils). In most sites the A horizon differentiated from the other horizons reflecting a different structure, texture and composition. The majority of A horizon soils have sandy matrices that normally have low sorption capacities. This is reflected in Figure 3 where the cluster of A horizon soils are orthogonal to the CEC vector. The depth to restrictive horizon (Res) was uncorrelated with all other variables as expected. The PC loadings (the lines in Figure 3), show that PC1 is closely associated with the soil parameters of %clay (%Cl), exchangeable sodium percentage (ESP), exchangeable sodium (eNa) and exchangeable magnesium (eMg). Thus the soil ESP was highly correlated with percentage clay and exchangeable sodium and exchangeable magnesium. The second component, PC2 however, is more closely associated with the chemical parameter, exchangeable calcium (eCa). Soils that retained a high CEC value fell positively on PC2, consistent with the samples retaining higher exchangeable calcium values and to a lesser extent with pH.

Figure 3 PCA Biplot of Control Field Soils

Column Study

The principal component analysis of column soil physico-chemical data resulted in 53% of the data variance being explained by principal component 1 (PC1) and 20% being explained by principal component 2 (PC2) (Figure 4). Even though the majority of A horizon soils had been removed before soils were placed in columns, the sandy horizons in Columns 3, 9, 10, 11 and 12 were clearly differentiated and opposite the %clay variable. In Figure 4, the PC loadings show PC1 being closely related with soil parameters, effective cation exchange capacity (ECEC), exchangeable sodium percentage (ESP), exchangeable sodium (eNa) and exchangeable magnesium (eMg) and to a lesser extent, clay content (clay) and CEC. The soil ESP and ECEC were highly correlated with percentage clay and exchangeable sodium and exchangeable magnesium. The second component, PC2 is more closely associated with the chemical parameter of exchangeable calcium (eCa), almost replicating the field study.

Similar correlations and relationships between variables from both field and column studies allow confidence in being able to make predictions on long term soil behaviour based on the selected soil characteristics of controlled soil column experiments.

Figure 4 PCA Biplot of Original Column Soils

Identifying impacts on soil after effluent application

Initially PCA was employed to identify the soil attributes that are most significant in describing variances between original and effluent irrigated soils in the columns. Sparling (2001) in a study on silty loam soils in New Zealand found PCA to show a distinct separation between non-irrigated and irrigated soils. They found biological properties influenced the separation along Factor 1 (PC1) and physical parameters were influential in causing separation along Factor 2 (PC2), despite few significant differences in individual properties. Figure 5 displays the PCA biplot for the column soils before and after effluent irrigation. The PCA biplot does not differentiate between the soils before and after effluent irrigation. As expected, there is good correlation between ESP and exchangeable sodium and exchangeable magnesium and these variables are closely associated with PC1. Correlated soil attributes do not change independently due to changes in soil management, but respond as a group, integrating many complex interactions among chemical and physical soil processes (Brejda et al. 2000). The organic matter increase in effluent irrigated soils has caused this variable to be positively correlated with PC2, whereas in the original soil's organic matter and CEC were highly correlated to PC1. No distinct clustering of soil types or textural contrast was observed using PCA.

Figure 5 PCA Biplot of Control and Effluent irrigated column soils

Discriminant Analysis (DA) was trialled to determine if this method gave an improved overview of the variation between the effluent irrigated and control soils. No variables were excluded. DA clearly separates original and irrigated soil columns as can be seen in Figure 6. It is expected that significant change would occur within the soil matrix due to infiltration of effluent and discriminant analysis has been shown to be sensitive to changes in land management (Brejda et al. 2000). This change would occur due to an increase in organic matter and chemical reactions taking place, individual cations being adsorbed and desorbed. These factors will contribute to the ability of the soil to accept, hold and release nutrients and other chemical constituents.

The original soils are scattered widely on the left hand side of Figure 6 and most of the soil types are represented with only original Ferrosols and both original and effluent irrigated Podosol soils forming recognisable clusters. The effluent irrigated soils lie on the right hand side of Figure 6. There are two distinct clusters, the already sodic soils (ESP>5) correlated with ESP and CEC and soils correlated with EC and exchangeable sodium where only small changes in exchangeable sodium have occurred. These soils have low CEC and low ECEC, and hence small changes in exchangeable sodium can cause large increases in ESP. This in turn may cause clay particles to disperse, consequently reducing the soils’ infiltration capacity and long term effluent treatment capacity. Columns 5, 6, 8 and 11 soils where hydraulic failure occurred rapidly lie within these clusters.

Figure 6 Discriminant Analysis Plot original and effluent irrigated column soils

Prediction of long term behaviour

Field sites were added to the discriminant data analysis shown in Figure 6 in order to identify any common relationships between accelerated soil column studies and field sites. The resultant DA plot excluded exchangeable magnesium from the analysis as it exceeded the grouping tolerance. As exchangeable magnesium was a critical variable in identifying relative changes in soils after effluent application, DA proved ineffective in comparing field and column data. Figure 7 displays the same data using PCA and separates the soils on the basis of their hydraulic performance. The principal component loadings show PC1 being closely related with soil parameters such as exchangeable sodium percentage (ESP), exchangeable sodium (eNa) and exchangeable magnesium (eMg) and to a lesser extent, clay content (clay) and CEC. The second component, PC2 is more closely associated with the chemical parameter of exchangeable calcium (eCa). Soils to the right of the dotted line include all failed field sites and columns 5, 6, 8 an 11 where hydraulic failure has occurred. These can be further classified into soils above the

PC1 line which are highly correlated with exchangeable sodium and exchangeable magnesium (already showing sodic behaviour) and soils below the PC1 line where small increases in exchangeable sodium produce large increases in ESP (low CEC soils). Some original column soils lie in the hydraulic failure zone, but after effluent application they transpose across to the left of the failure line (Column 1 and 12). Soils on the left of the dotted line exhibit a favourable Ca:Mg ratio above PC1 line indicating co-dominance of calcium and magnesium and thus suitable attenuation characteristics. Soils below the PC1 line are characterised by low CEC and low clay content and need to be assessed for treatment failures.

Much of the variance in both the original soils and the effluent treated soils originated from the variations in soil physical attributes. These properties reflect the soils ability to absorb and release water. The change in soil physical attributes can be linked to soil chemistry changes which can lead to soil degradation and subsequently to a reduction in hydraulic conductivity and consequently leading to hydraulic failure. The column study supports findings by Wang et al. (2003) where wastewater irrigation reduced the soil's capacity to hold magnesium. The lower magnesium content of effluent irrigated soils may be an indication that the ability of the soil in retaining nutrients is low. All columns displayed a general trend of reduction in magnesium through part of the soil profile.

Figure 7 PCA Biplot of Field and Column Soils

The most significant aspect highlighted in both field and column studies is that a soil's ability to adequately treat sewage effluent is dependant on a number of factors that all need to be considered together. It is important that significant care is taken in characterising sites using individual soil properties in order to predict how soil behaviour will be affected by a decline in infiltration and drainage characteristics due to long term application of effluent and whether any immobilised nutrients will gradually be leached from the soil.

Conclusions

The major consequences of effluent irrigation are that sodium can induce changes in soil properties with the likelihood of soil ESP increase, leading to decreased hydraulic conductivity of the soil and subsequent hydraulic failure. The type of clay and clay content along with cation exchange capacity, exchangeable magnesium and exchangeable sodium content have the potential to be used as possible indicators of soil degradation under effluent irrigation. This will lead to identification of likely hazards that will aid designers of effluent irrigation systems.

Dynamics of cation movement in soils are important in processes such as waste dispersal and salt removal. Transportation of cations through soil can cause potential increases in salt load not only in the soil profile, but also groundwater or receiving water bodies. A good understanding of the interaction between cations in solution and soils will help in developing better design strategies for effluent irrigation.

Multivariate statistics are useful in understanding treatment differences between soils, even when there is little difference in specific soil properties. The results from this study demonstrate the advantage of principal component analysis and discriminant analysis in identifying and selecting the most appropriate soil parameters for evaluating long term behaviour of soil under effluent application. Identification and correlation of influential soil attributes in field and column studies confirmed that accelerated undisturbed soil column studies can be used to predict long term behaviour of effluent irrigated soils.

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Table 1 Soil column physical and chemical properties (original)

Parameter	Column 1			Column 2			Column 3		
Soil Classification (Isbell 2002)	Yellow Kurosol			Red Ferrosol			Semiaquic Podosol		
Soil Taxonomy (NRCS 1999)	Alfisols or Ultisols			Oxisols			Spodosols		
Soil Profile	Soils with a clear or abrupt textural B horizon Major part of B horizon is strongly acidic			Soils with B horizon with free iron oxide content >5% Fe in fine earth fraction (<2mm).			Soils that have Bs, Bhs or Bh horizons		
Sampling Point	SP1[b,c]	SP2[b,c]	SP3[b,c]	SP1[a]	SP2[b]	SP3[b]	SP1[a]	SP2[a]	SP3[a]
Clay (%)	25.5	45.4	28.8	84.4	88.5	76.4	3.3	0.1	3.4
Silt (%)	19.2	25.3	31.4	1.8	2.4	2.0	2.6	4.0	6.7
Sand (%)	55.3	29.3	39.8	13.8	9.1	21.6	94.1	95.9	89.9
Clay Mineralogy	Kaolinite Some Smectite in lower B horizon, increasing down through the soil profile with 8% Smectite at SP3			Kaolinite Mainly Kaolinite with some Illite in upper soil horizons. 10% Smectite in lower B horizon at SP3			Kaolinite		
pH	6.1	4.7	4.8	5.0	4.4	4.1	5.3	6.4	6.2
EC dS/m	0.17	0.13	0.07	0.05	0.04	0.05	0.02	1.91	0.02
Organic Matter (%)	20.5	7.9	4.7	22.0	18.8	13.2	4.4	0.0	0.3
CEC meq/100g	3.2	6.0	51.2	3.2	27.3	27.3	14.6	7.8	14.6
ECEC meq/100g	3.6	4.8	7.7	3.0	1.0	1.5	1.2	0.6	0.6
Exc Ca meq/100g	1.08	0.18	0.13	1.13	0.35	0.59	0.39	0.30	0.14
Exc Mg meq/100g	2.18	4.22	6.82	1.58	0.37	0.73	0.66	0.18	0.26
Exc Na meq/100g	0.13	0.35	0.54	0.13	0.10	0.14	0.07	0.14	0.13
Exc K meq/100g	0.15	0.04	0.09	0.11	0.07	0.05	0.02	0.05	0.02
ESP (%)	4.0	7.3	7.0	4.5	10	9.3	0.5	1.8	0.9
Ca:Mg	0.50	0.04	0.02	0.72	0.95	0.81	0.59	1.64	0.54

[a] Sampling point located in A horizon of soil core

[b] Sampling point located in B horizon of soil core

[c] Depth from top of column to soil sampling points are 150mm, 450mm and 800mm for SP1, SP2 and SP3 respectively

Table 1 (cont) Soil column physical and chemical properties (original)

Parameter	**Column 4**			**Column 5**			**Column 6**		
Soil Classification (Isbell 2002)	Brown Kurosol			Red Chromosol			Brown Sodosol		
Soil Taxonomy (NRCS 1999)	Alfisols or Ultisols			Ultisols			Alfisols		
Soil Profile	Soils with a clear or abrupt textural B horizon Major part of B horizon is strongly acidic			Soils with a clear and abrupt textural change in B horizon(abrupt increase in clay content)			Soils with clear or abrupt textural B horizon. Upper 0.2m of B2 horizon is highly sodic (ESP >6%)		
Sampling Point	SP1[b]	SP2[b]	SP3[b]	SP1[b]	SP2[b]	SP3[b]	SP1[b]	SP2[b]	SP3[b]
Clay (%)	16.5	28.4	26.1	2.0	7.6	39.1	27.9	18.3	27.8
Silt (%)	14.6	3.2	35.0	23.0	15.5	9.5	10.7	6.3	7.9
Sand (%)	68.9	68.4	38.9	75.0	76.9	51.4	61.4	75.4	64.3
Clay Mineralogy	Kaolinite Minor amounts of Smectite in lower B horizon (<6%)			Kaolinite Small amount Illite (<5%) in lower B Horizon at SP2			Kaolinite Mixed Kaolinite-Illite in upper soil horizons		
pH	4.7	4.8	5.4	5.8	5.7	6.5	4.5	4.5	6.2
EC dS/m	1.82	0.46	0.49	1.13	0.05	0.44	0.79	0.15	0.44
Organic Matter (%)	10.2	6.6	21.0	8.0	3.0	14.6	1.2	5.2	7.1
CEC meq/100g	14.6	27.3	27.3	16.5	24.1	11.3	10.0	14.6	8.8
ECEC meq/100g	2.3	0.1	17.8	5.0	1.4	1.8	5.4	3.4	33.3
Exc Ca meq/100g	0.50	0.01	0.15	1.61	0.09	0.38	0.79	0.32	1.83
Exc Mg meq/100g	1.48	0.03	13.98	3.05	1.03	0.90	4.03	2.52	26.00
Exc Na meq/100g	0.20	0.04	3.49	0.27	0.25	0.25	0.54	0.45	5.30
Exc K meq/100g	0.11	0.02	0.13	0.09	0.04	0.11	0.05	0.07	0.14
ESP (%)	8.6	16.0	19.6	5.2	17.6	15.5	9.9	13.3	15.9
Ca:Mg	0.50	0.30	0.15	0.53	0.09	0.42	0.20	0.13	0.07

[b] Sampling point located in B horizon of soil core

Table 1 (cont) Soil column physical and chemical properties (original)

Parameter	Column 7			Column 8			Column 9		
Soil Classification (Isbell 2002)	Brown Kurosol			Brown Dermosol			Yellow Dermosol		
Soil Taxonomy (NRCS 1999)	Alfisols or Ultisols			Ultisols			Ultisols		
Soil Profile	Soils with a clear or abrupt textural B horizon Major part of B horizon is strongly acidic			Soils with B2 horizon of more developed structure			Soils with B2 horizon of more developed structure		
Sampling Point	SP1[b]	SP2[b]	SP3[b]	SP1[b]	SP2[b]	SP3[b]	SP1[b]	SP2[b]	SP3[b]
Clay (%)	12.0	19.7	43.1	12.4	18.3	27.8	3.2	3.3	15.0
Silt (%)	6.0	4.6	1.1	0.5	6.3	7.9	5.9	2.3	3.0
Sand (%)	82.0	75.7	55.8	87.1	75.4	64.3	90.9	94.4	82.0
Clay Mineralogy	Kaolinite			Kaolinite Mixed Kaolinite-Illite in all soil horizons			Kaolinite Small amount Illite (5%) in lower B Horizon at SP3		
pH	5.8	5.3	4.0	4.3	4.5	6.2	5.12	5.38	5.56
EC dS/m	0.16	0.15	0.15	0.05	0.15	0.44	0.45	1.11	0.32
Organic Matter (%)	3.12	2.89	8.00	10.01	5.20	7.08	2.13	3.26	5.07
CEC meq/100g	14.6	5.3	10	5.3	14.6	14.6	3.7	10.0	4.5
ECEC meq/100g	1.9	2.8	3.7	0.8	4.0	5.8	1.0	0.4	0.2
Exc Ca meq/100g	0.66	0.35	0.06	0.08	0.08	0.11	0.35	0.04	0.01
Exc Mg meq/100g	0.91	2.11	3.30	0.54	3.53	5.10	0.47	0.22	0.08
Exc Na meq/100g	0.14	0.24	0.31	0.16	0.29	0.40	0.10	0.06	0.04
Exc K meq/100g	0.16	0.12	0.06	0.03	0.10	0.14	0.06	0.07	0.08
ESP (%)	1.0	4.5	8.3	3.0	2.0	2.8	2.7	0.6	0.9
Ca:Mg	0.73	0.17	0.02	0.15	0.02	0.02	0.74	0.18	0.13

[b] Sampling point located in B horizon of soil core

Table 1 (cont) Soil column physical and chemical properties (original)

Parameter	Column 10			Column 11			Column 12		
Soil Classification (Isbell 2002)	Yellow Chromosol			Grey Chromosol			Red Kandosol		
Soil Taxonomy (NRCS 1999)	Ultisols			Ultisols			Alfisols or Ultisols		
Soil Profile	Soils with a clear and abrupt textural change in B horizon(abrupt increase in clay content)			Soils with a clear and abrupt textural change in B horizon(abrupt increase in clay content)			Soils with well developed B2 horizon		
Sampling Point	SP1[b]	SP2[b]	SP3[b]	SP1[b]	SP2[b]	SP3[b]	SP1[b]	SP2[b]	SP3[b]
Clay (%)	18.9	15.6	31.0	3.9	4.7	56.8	9.5	40.8	30.1
Silt (%)	1.9	18.1	9.0	5.4	24.4	2.9	2.0	1.8	2.8
Sand (%)	79.2	66.3	60.0	90.7	70.9	40.3	88.5	57.4	67.1
Clay Mineralogy	Kaolinite			Kaolinite Small amount Illite (9%) in lower B Horizon at SP3			Kaolinite Mixed Kaolinite-Illite in all soil horizons		
pH	5.01	5.20	5.60	6.2	6.0	5.9	5.91	6.03	5.65
EC dS/m	0.10	0.07	0.04	0.24	0.16	0.75	0.22	0.24	0.15
Organic Matter (%)	3.9	5.2	6.8	5.0	2.9	11.6	3.0	5.3	11.9
CEC meq/100g	3.7	7.8	7.8	6.0	8.8	3.7	2.8	5.3	3.7
ECEC meq/100g	1.7	0.8	3.2	0.7	1.6	4.7	0.9	2.5	11.1
Exc Ca meq/100g	0.76	0.13	0.12	0.18	0.07	0.07	0.14	0.12	0.13
Exc Mg meq/100g	0.81	0.47	2.89	0.43	1.37	4.36	0.60	2.17	10.51
Exc Na meq/100g	0.10	0.13	0.13	0.06	0.15	0.20	0.09	0.19	0.38
Exc K meq/100g	0.06	0.05	0.09	0.02	0.01	0.02	0.01	0.01	0.04
ESP (%)	2.7	1.7	1.7	1.0	1.7	4.3	3.3	3.6	10.4
Ca:Mg	0.94	0.28	0.04	0.42	0.05	0.02	0.23	0.06	0.01

[b] Sampling point located in B horizon of soil core

Table 2 Column sample analysis methods

Parameter		**Analytical Method**
pH	Soil	4A1: pH of 1:5 soil/water suspension at 25°C (Rayment and Higginson 1992)
	Effluent	TPS-81 pH-conductivity meter
Electrical Conductivity (EC)	Soil	3A1 EC of 1:5 soil/water suspension at 25°C (Rayment and Higginson 1992)
	Effluent	2520-Conductivity (APHA 1999)
Orthophosphate (PO_4^{3-})	Soil	9G2 Acid extractable phosphate 1:200 soil/0.005M H_2SO_4 at 25°C (Rayment and Higginson 1992) and measure using 4500-P C Vanadomolybdophosphoric Acid Colourmetric method (APHA 1999)
Organic Matter (%OM)	Soil	Soil oxidised with 50% H_2O_2 and heated to 1300°C to burn organic matter. Weight loss difference equal to organic matter content
Cation Exchange Capacity (CEC)		Ammonium selective electrode method (Borden and Giese 2001) Ammonia Standards made as per 4500-NH_3 E (APHA 1999)
Effective Cation Exchange Capacity (ECEC)		ECEC = exchangeable cations + exchangeable acidity = (Ca + Mg + Na + K) + (Al + H)
Exchangeable Cations (Al, Fe, Mg, Na, Ca and K)		Measured using Varian AA6 Flame Atomic Absorption Spectrophotometer. Acetylene flame used to measure Fe, propane used to measure Na and K, and nitrous oxide used to measure Ca, Mg and Al
Exchangeable Sodium Percentage (ESP)		ESP = (100 x Exchangeable Na^+)/ECEC
Soil Mineralogy (Clay type)		Samples prepared using method developed by Bish and Post (1989) Mineralogy determined via X-ray diffraction using Phillips PW1050/25 vertical goniometer, with a graphite diffracted beam monochromator
Particle Size Distribution: Percent Clay (%C), Silt (%Si) and Sand (%S)		Determined from Soil mineralogy fractions (%S = % Quartz; %C = $\sum$% Clay fractions eg. %Kaolinite, %Illite, %Smectite) measured using X-ray Diffraction

Table 3 Average Effluent Characteristics of Applied Effluent

Parameter	Concentration
pH	7.88
EC dS/m	0.93
NO_3^- -N mg/L	3.18
TN –mg/L	38.5
PO^{4-} -P mg/L	22.5
Ca mg/L	22.78
Mg mg/L	18.03
Na mg/L	133.3
K mg/L	14.47
SAR	5.21

Table 4 Site and soil classification

Site No.[d]	System age (yr)	Disposal Area (m^2)	Australian Soil Classification[a]	Soil Texture[b] A – A horizon B – B horizon	Soil Drainage[c]	Hyd Loading Rate (mm/day)	Slope (˚)
1	4	56	Red Chromosol	A – Sandy loam B – Clay loam	Moderately well drained	35	>15
3	5	70	Brown Chromosol	A - Sandy loam B – Light Clay	Imperfectly drained	40	<10
4	3	72	Brown Chromosol	A - Sandy loam B- Clay loam	Imperfectly drained	40	<5
7	2.5	60	Red Chromosol	A - Sandy loam B – Sandy clay loam	Moderately well drained	35	>10
8	4	60	Red Sodosol	A - Clay loam B – Heavy clay	Poorly drained	20	<5
9	17	40	Grey Sodosol	A – Clay loam B – Heavy clay	Poorly drained	-	<5
11	4.5	40	Red Kandosol	A - Sandy loam B – Sandy clay loam	Well drained	50	>15
12	19	56	Brown Kurosol	A -Loamy sand B – Sandy clay loam	Moderately well drained	-	>10
14	14	72	Brown Chromosol	A - Loam B – Clay loam	Moderately well drained	-	>15
15	3	48	Red Ferrosol	A - Sandy loam B- Light clay	Moderately well drained	50	>5
16	4	36	Red Ferrosol	A - Clay loam B- Medium clay	Poorly drained	35	<5
17	12	48	Yellow Chromosol	Sandy Loam	Moderately well drained	-	>5
18	8	84	Brown Kurosol	Heavy clay	Very poorly drained	-	<5
19	6	60	Yellow Chromosol	Loamy sand	Moderately well drained	35	>5
20	19	54	Brown Chromosol	A – Loamy sand B – Clay loam	Imperfectly drained	-	<5
21	5	39	Yellow Chromosol	A – Loamy sand B – Clay loam	Well drained	50	>5
22	1	126	Brown Chromosol	A – Loamy sand B – Clay loam	Moderately well drained	35	>5
23	6	72	Brown Chromosol	A – Loamy sand B – Medium clay	Moderately well drained	35	>10
24	18	72	Brown Chromosol	Clay loam	Imperfectly drained	-	>5
25	5	72	Brown Chromosol	Clay loam	Imperfectly drained	20	>5
26	14	126	Brown Chromosol	A – Clayey sand B – Light clay	Imperfectly drained	-	<5
27	12	48	Grey Dermosol	Clay loam	Well drained	-	>15
28	11	72	Brown Kurosol	A – Silty loam B – Medium Clay	Poorly drained	-	>5
29	5	72	Brown Chromosol	Medium clay	Imperfectly drained	20	>10
30	7	144	Brown Kurosol	A - Silty loam B - Medium, clay	Poorly drained	20	<5
31	8	72	Red Chromosol	A - Loamy sand B - Medium clay	Imperfectly drained	-	>5
32	6	72	Brown Chromosol	A - Loamy sand B – Light clay	Moderately well drained	35	>10
33	7	72	Brown Kurosol	A – Sandy loam B – Light clay	Poorly drained	35	<5
34	20	48	Brown Chromosol	A – Clay loam B – Medium clay	Well drained	20	>15

a Australian Soil Classification after Isbell (2002)
b soil texture based on McDonald et al.. (1998)
c classification used complies with AS/NZS 1547:2000 (Standards Australia, 2000), McDonald et al.. (1998)
d missing numbers are sites abandoned due to insufficient soil water sample and unreliable historical site information

Table 5 Failure diagnosis of field sites

Site No[a]	Age (y)	Failure Mode[b]	Depth from surface to Restrictive layer m
3 (BC1)	5	Hydraulic failure (surface ponding) Saturated zone above restrictive horizon	0.5
20 (BC4)	19	Hydraulic failure (waterlogged) Saturated zone above restrictive horizon	0.3
24 (BC7)	18	Pollutant contamination. Inadequate treatment before entering groundwater	0.6
29 (BC10)	5	Pollutant contamination. Inadequate treatment before entering groundwater, rock ledge	0.3
34 (BC12)	20	Hydraulic failure (waterlogged) Saturated zone above restrictive horizon	0.2
30 (BKu3)	7	Hydraulic failure (waterlogged) Saturated zone above restrictive horizon	0.2
18 (BS1)	8	Pollutant contamination. Inadequate treatment before entering groundwater. G/W mounding	0.1
9 (GS1)	17	Hydraulic failure (waterlogged) Saturated zone above restrictive horizon	0.3
8 (RS1)	4	Pollutant contamination. Inadequate treatment before entering groundwater. G/W mounding	0.3
16 (RF2)	4	Hydraulic failure (waterlogged) Saturated zone above restrictive horizon	0.4

[a] BC – Brown Chromosol; GS – Grey Sodosol; RF - Red Ferrosol; BKu – Brown Kurosol; Numbers relate to sequential sites

[b] Failure criteria based on USEPA On-site Wastewater Treatment Manual 2002, Section 5.8

Table 6 Physical and Chemical Properties of Soil Columns

Column No Soil Type[a]	Site Drainage[b]	Sample Point	Texture[c]	% clay	CEC o meq/100g	CEC e meq/100g	ECEC o meq/100g	ECEC e meq/100g	ESP o %	ESP e %	OM o %	OM e %
1 Kurosol	**Well Drained**	**SP1**	**Loam**	25	3.2	35.1	3.6	3.1	4.0	6.5	20.5	16.0
		SP2	**Light Clay**	33	6.0	27.3	4.8	7.9	7.3	7.8	7.9	24.3
		SP3	**Clay Loam**	28	51.2	14.6	7.6	5.6	7.0	13.3	4.7	27.3
2 Ferrosol	**Well Drained**	**SP1**	**Heavy Clay**	85	3.2	27.3	3.0	0.7	4.5	4.5	22.0	31.6
		SP2	**Heavy Clay**	77	27.3	21.2	0.9	1.1	10	10.4	18.8	26.6
		SP3	**Heavy Clay**	75	27.3	16.5	1.5	0.8	9.3	10.2	13.2	24.9
3 Podosol	**Poorly Drained**	**SP1**	**Sand**	3	14.6	10.0	1.2	1.5	0.5	1.0	4.4	1.4
		SP2	**Sand**	1	7.8	7.8	0.6	0.5	1.8	0.8	0.0	0.3
		SP3	**Sand**	3	14.6	51.2	0.6	0.6	0.9	0.2	0.3	3.8
4 Kurosol	**Imperfect Drained**	**SP1**	**Clay Loam**	17	14.6	35.1	2.3	2.0	8.6	14.0	10.2	25.8
		SP2	**Clay Loam**	28	27.3	14.6	0.1	7.8	16.0	16.2	6.6	12.4
		SP3	**Loam**	26	27.3	45.1	17.8	13.5	19.6	20.9	21.0	20.7
5 Chromosol	**Imperfert Drained**	**SP1**	**Loamy Sand**	7	16.5	12.8	5.0	5.0	5.2	21.1	8.0	21.4
		SP2	**Sandy Loam**	11	24.1	35.1	1.4	3.9	17.6	9.9	3.0	21.2
		SP3	**Light Clay**	39	11.3	35.1	1.8	3.3	15.5	12.2	14.6	25.8
6 Sodosol	**Imperfert Drained**	**SP1**	**Clay Loam**	26	10.0	10.0	5.4	8.4	9.9	8.7	1.2	17.8
		SP2	**Sandy Loam**	17	14.6	14.6	3.4	6.0	13.3	14.6	5.2	18.2
		SP3	**Clay Loam**	28	8.8	11.3	33.3	1.4	15.9	10.6	7.1	21.1
7 Kurosol	**Mod well Drained**	**SP1**	**Sandy Loam**	14	14.6	6.9	1.9	1.1	1.0	3.2	3.1	17.9
		SP2	**Sandy Loam**	18	5.3	6.9	2.8	0.9	4.5	1.5	2.9	16.4
		SP3	**Light Clay**	41	10.0	10.0	3.7	2.9	8.3	7.6	8.0	22.2
8 Dermosol	**Poorly Drained**	**SP1**	**Sandy Loam**	16	5.3	2.2	0.8	3.2	3.0	13.1	10.0	22.4
		SP2	**Clay Loam**	25	14.6	8.8	4.0	3.0	2.0	2.9	9.4	27.3
		SP3	**Loam**	21	14.6	8.8	5.2	7.6	2.8	14.3	1.9	24.5
9 Dermosol	**Well Drained**	**SP1**	**Sand**	4	3.7	4.7	1.0	0.5	2.7	1.5	2.1	3.7
		SP2	**Sandy Loam**	10	10.0	6.0	0.4	3.2	0.6	5.1	3.3	18.9
		SP3	**Loam**	20	4.5	4.1	0.2	4.6	0.9	8.4	5.1	29.8
10 Chromosol	**Mod well Drained**	**SP1**	**Sandy Loam**	10	3.7	4.7	1.7	1.5	2.7	4.3	3.9	15.9
		SP2	**Sandy Loam**	13	7.8	6.0	0.8	0.3	1.7	1.2	5.2	22.2
		SP3	**Clay Loam**	31	7.8	4.1	3.2	0.4	1.7	1.0	6.8	25.2
11 Chromosol	**Mod well Drained**	**SP1**	**Sand**	4	6.0	1.5	0.7	0.7	1.0	6.6	5.0	14.5
		SP2	**Loamy Sand**	8	8.8	4.1	1.6	0.8	1.7	2.2	3.0	23.8
		SP3	**Medium Clay**	47	3.7	2.8	4.7	2.8	4.3	5.8	11.6	25.8
12 Kandosol	**Imperfert Drained**	**SP1**	**Loam**	20	2.8	4.1	0.9	0.8	3.3	4.4	3.0	18.7
		SP2	**Clay Loam**	33	5.3	2.5	2.5	2.6	3.6	6.0	5.3	29.4
		SP3	**Clay Loam**	35	3.7	1.5	11.1	3.5	10.4	8.8	11.9	8.4

a Australian Soil Classification after Isbell (2002)
b classification used complies with AS/NZS 1547:2000 (Standards Australia, 2000), McDonald et al.. (1998)
c soil texture based on McDonald et al.. (1998)
o original soil
e after 12 months effluent irrigation

Table 7 Chemical Properties of Soil Columns

Column No Soil Type	Sample Point	pH o	pH e	EC o dS/m	EC e dS/m	ex Na o meq/ 100g	ex Na e meq/ 100g	ex Mg o meq/ 100g	ex Mg e meq/ 100g	ex Ca o meq/ 100g	ex Ca e meq/ 100g	ex K o meq/ 100g	ex K e meq/ 100g
1 Kurosol	**SP1**	6.08	6.17	0.17	1.36	0.13	0.20	2.18	1.48	1.08	1.11	0.15	0.28
	SP2	4.71	5.20	0.13	.39	0.35	0.15	4.22	1.52	0.18	0.22	0.04	0.04
	SP3	4.75	4.90	0.07	.15	0.54	0.74	6.82	4.70	0.13	0.09	0.09	0.02
2 Ferrosol	**SP1**	5.00	4.63	0.05	1.44	0.13	0.20	1.58	0.22	1.13	0.21	0.11	0.02
	SP2	4.36	4.68	0.04	0.44	0.10	0.11	0.37	0.51	0.35	0.43	0.07	0.00
	SP3	4.08	4.18	0.05	0.40	0.14	0.08	0.73	0.45	0.59	0.21	0.05	0.00
3 Podosol	**SP1**	5.27	6.66	0.02	0.43	0.07	0.10	0.66	0.82	0.39	0.54	0.02	0.02
	SP2	6.41	6.32	1.91	0.40	0.14	0.12	0.18	0.22	0.30	0.09	0.05	0.02
	SP3	6.21	5.82	0.02	0.53	0.13	0.10	0.26	0.12	0.14	0.14	0.02	0.02
4 Kurosol	**SP1**	4.65	6.61	1.82	0.43	0.20	0.28	1.48	1.31	0.50	0.35	0.11	0.00
	SP2	4.82	6.17	0.46	1.01	0.04	1.25	0.03	6.16	0.01	0.30	0.02	0.09
	SP3	5.37	4.68	0.49	1.53	3.49	2.81	13.98	10.48	0.15	0.10	0.13	0.04
5 Chromosol	**SP1**	5.82	5.36	1.13	0.64	0.27	1.05	3.05	3.70	1.61	0.13	0.09	0.08
	SP2	5.66	5.12	0.05	0.50	0.25	0.38	1.03	3.35	0.09	0.06	0.04	0.06
	SP3	6.54	6.36	0.44	0.43	0.25	0.40	0.90	3.05	0.38	0.04	0.11	0.02
6 Sodosol	**SP1**	4.47	5.45	0.79	0.46	0.54	0.73	4.03	7.16	0.79	0.43	0.05	0.07
	SP2	4.49	6.10	0.15	0.55	0.45	0.88	2.52	4.70	0.32	0.38	0.07	0.07
	SP3	6.20	6.40	0.44	1.13	5.30	0.15	26.0	1.20	1.83	0.04	0.14	0.04
7 Kurosol	**SP1**	5.81	5.54	0.16	1.56	0.14	0.22	0.91	0.52	0.66	0.26	0.16	0.07
	SP2	5.34	5.98	0.15	1.34	0.24	0.10	2.11	0.61	0.35	0.11	0.12	0.06
	SP3	3.99	4.41	0.15	0.44	0.31	0.22	3.30	2.59	0.06	0.06	0.06	0.06
8 Dermosol	**SP1**	4.30	5.45	0.05	0.46	0.16	0.29	0.54	2.82	0.08	0.04	0.03	0.03
	SP2	4.49	6.10	0.15	0.55	0.29	0.26	3.53	2.60	0.08	0.04	0.10	0.09
	SP3	6.20	6.40	0.44	1.13	0.40	1.26	5.10	5.74	0.11	0.53	0.14	0.04
9 Dermosol	**SP1**	5.12	6.34	0.45	0.48	0.10	0.07	0.47	0.20	0.35	0.13	0.06	0.06
	SP2	5.38	6.08	1.11	0.83	0.06	0.31	0.22	2.81	0.04	0.08	0.07	0.03
	SP3	5.56	5.90	0.32	1.01	0.04	0.35	0.08	4.16	0.01	0.04	0.08	0.06
10 Chromosol	**SP1**	5.01	6.33	0.10	1.20	0.10	0.20	0.81	0.87	0.76	0.39	0.06	0.07
	SP2	5.20	6.22	0.07	1.10	0.13	0.07	0.47	0.16	0.13	0.09	0.05	0.00
	SP3	5.60	6.10	0.04	1.12	0.13	0.04	2.89	0.26	0.12	0.04	0.09	0.02
11 Chromosol	**SP1**	6.22	6.35	0.24	1.09	0.06	0.10	0.43	0.42	0.18	0.10	0.02	0.00
	SP2	6.03	6.16	0.16	1.51	0.15	0.09	1.37	0.63	0.07	0.06	0.01	0.00
	SP3	5.90	4.46	0.75	1.22	0.20	0.16	4.36	2.54	0.07	0.06	0.02	0.01
12 Kandosol	**SP1**	5.91	5.94	0.22	1.66	0.09	0.18	0.60	0.48	0.14	0.07	0.01	0.00
	SP2	6.03	6.50	0.24	0.46	0.19	0.15	2.17	2.45	0.12	0.05	0.01	0.00
	SP3	5.65	5.82	0.15	1.62	0.38	0.13	10.51	3.28	0.13	0.06	0.04	0.01

o Original soil
e After 12 months effluent irrigation

Figure 1 Column Setup

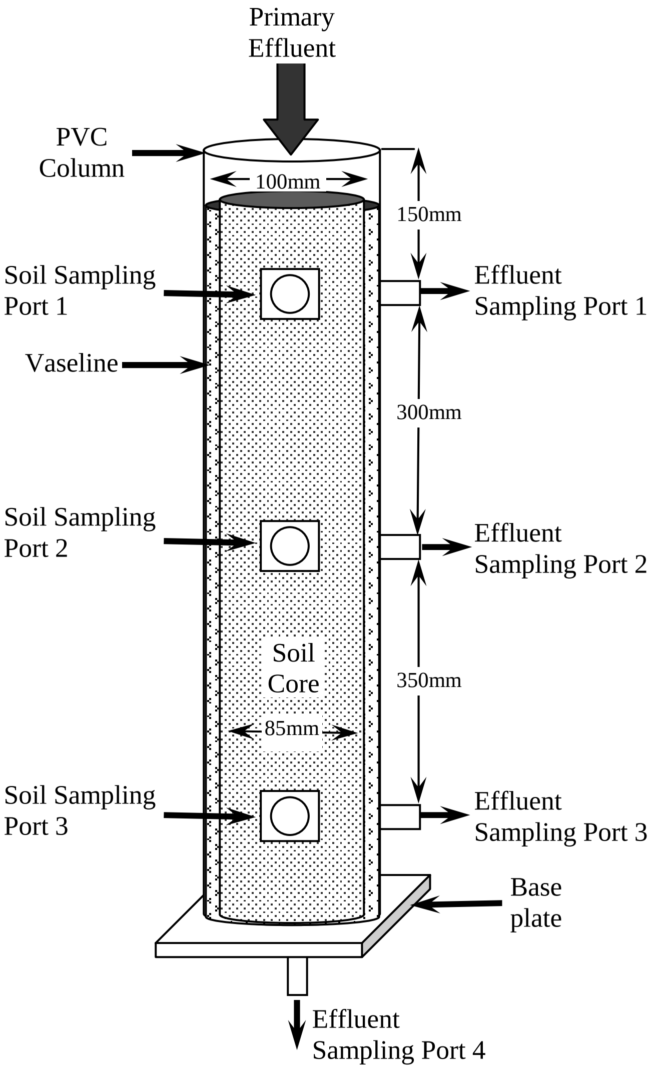

Figure 2 Typical setup of an on-site septic tank-soil absorption system commonly adopted in Australia

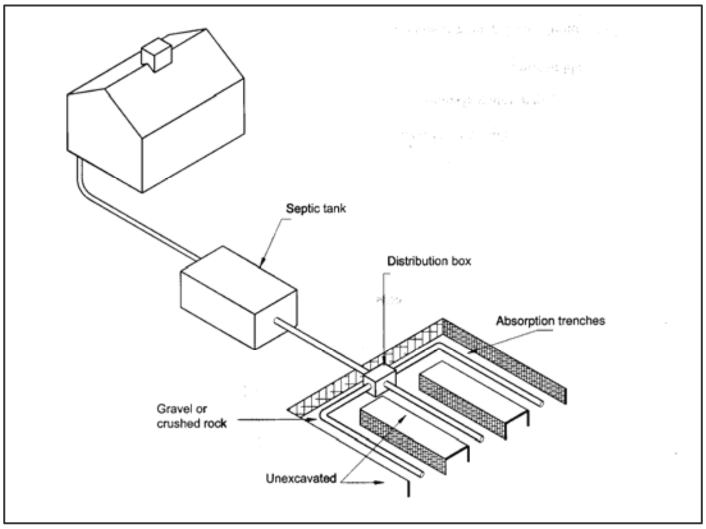

Figure 3 PCA Biplot of Control Field Soils

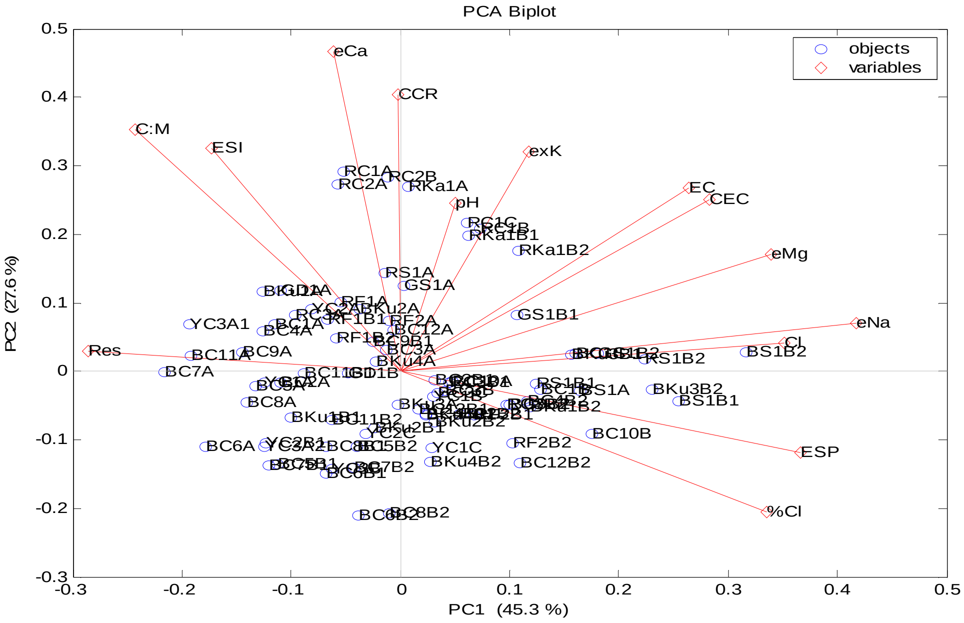

Figure 4 PCA Biplot of Original Column Soils

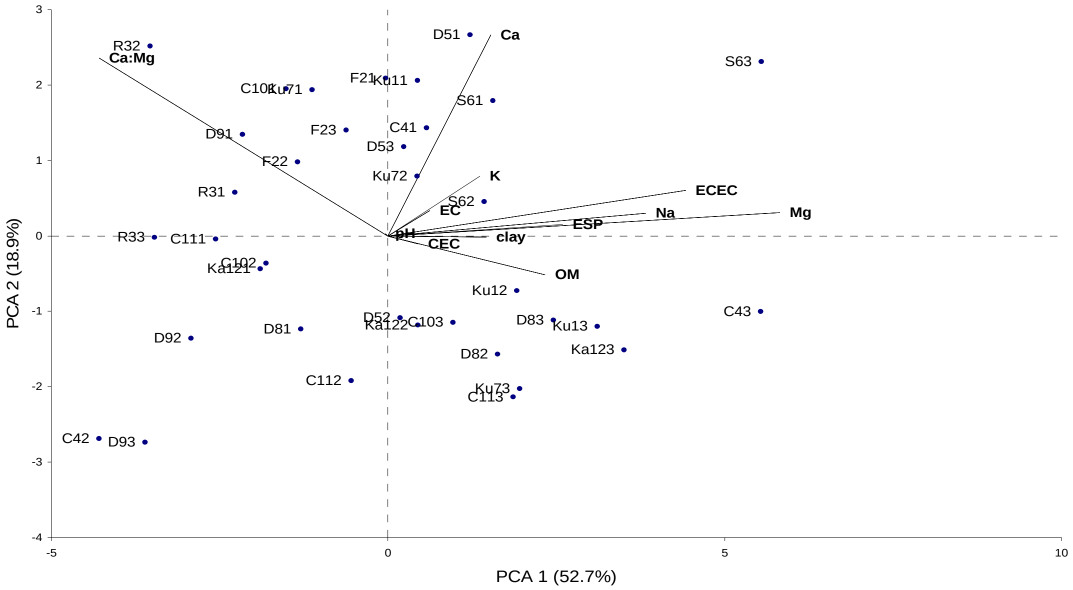

Figure 5 PCA Biplot of Control and Effluent irrigated column soils

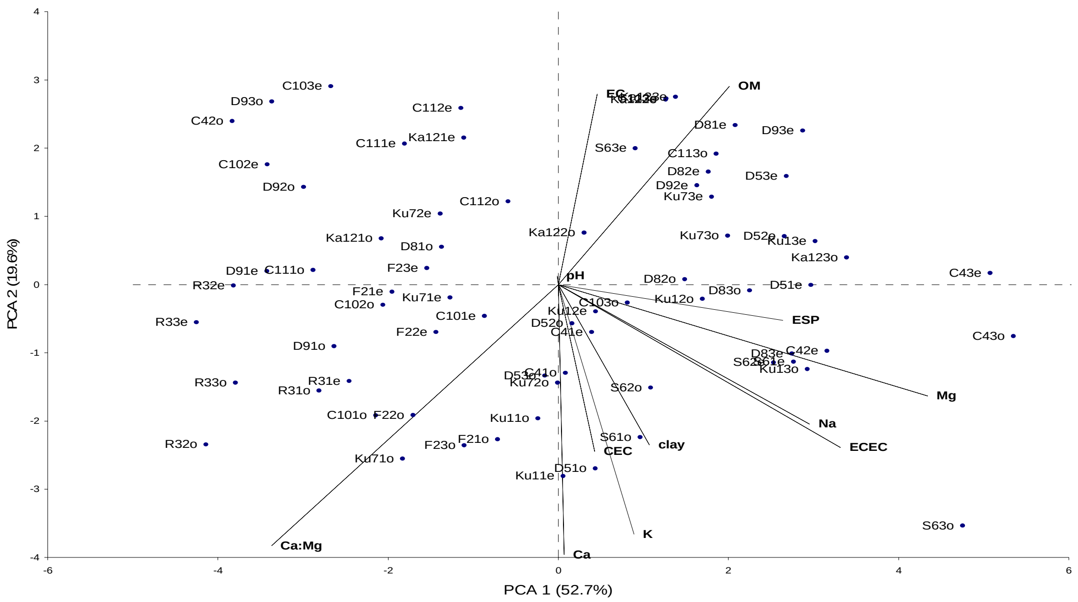

Figure 6 Discriminant Analysis Plot original and effluent irrigated column soils

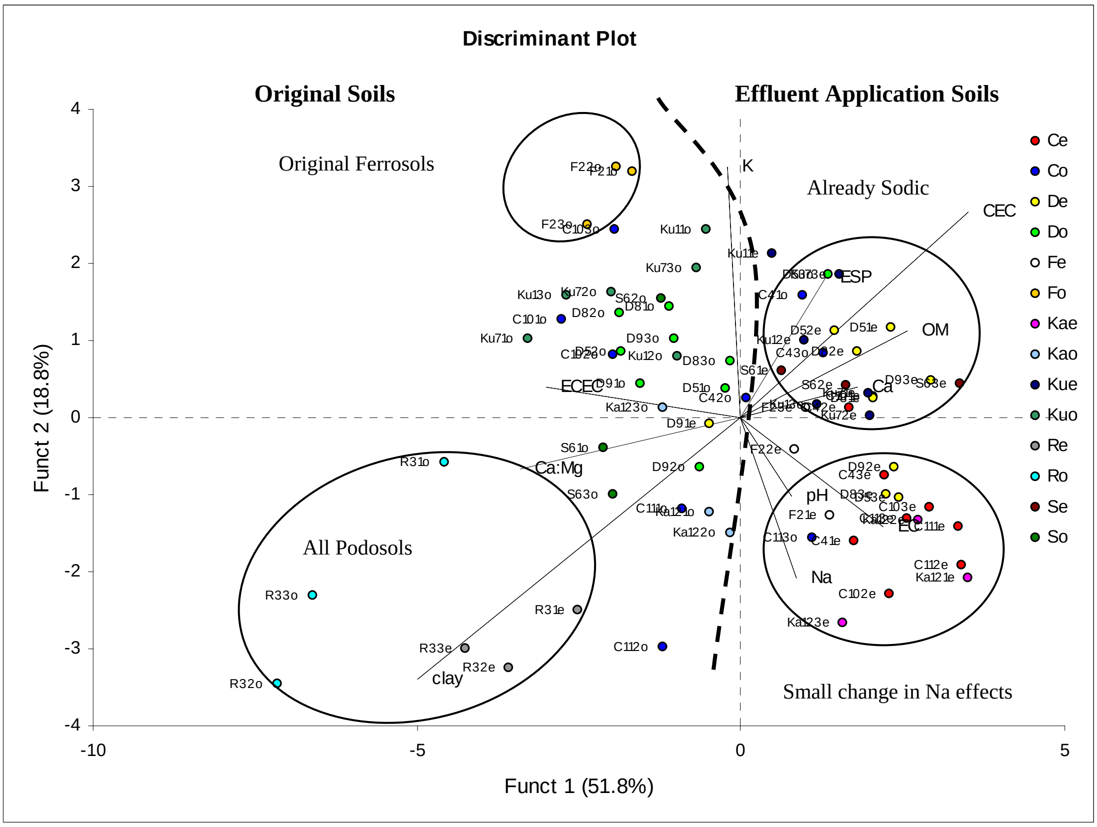

Figure 7 PCA Biplot of Field and Column Soils

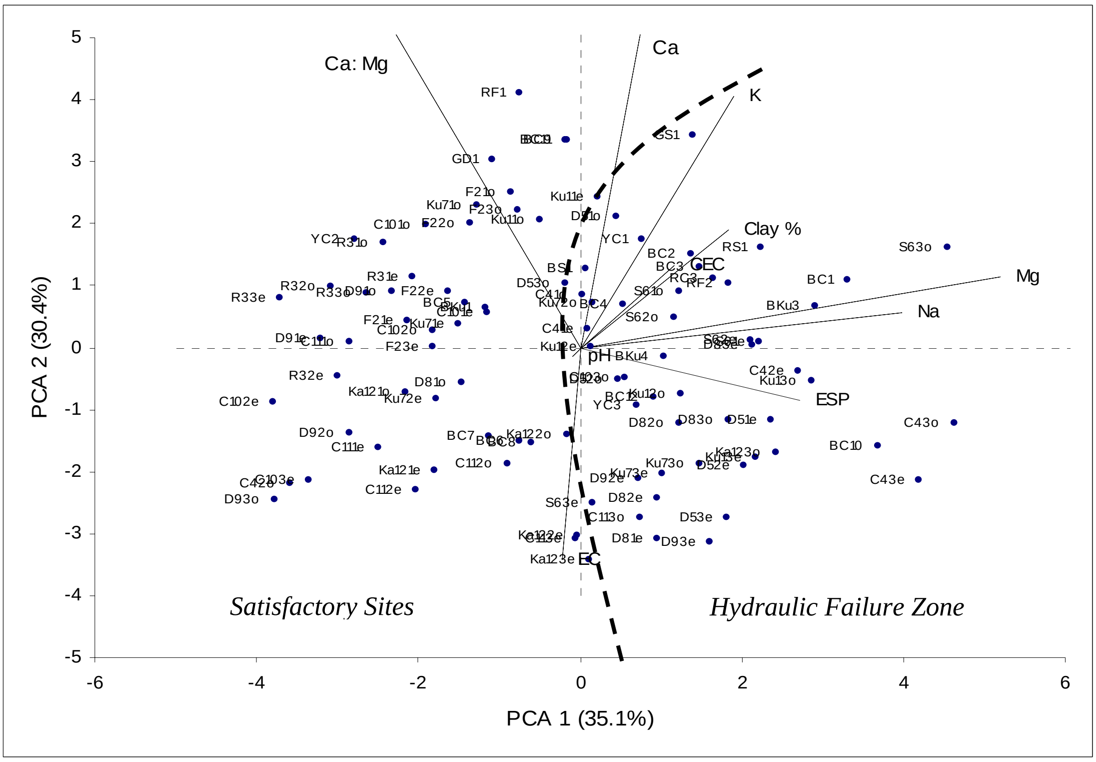

Figure 1 Column Setup
Figure 2 Typical setup of an on-site septic tank-soil absorption system commonly adopted in Australia
Figure 3 PCA Biplot of Control Field Soils
Figure 4 PCA Biplot of Original Column Soils
Figure 5 PCA Biplot of Control and Effluent irrigated column soils

Figure 6 Discriminant Analysis Plot original and effluent irrigated column soils

Figure 7 PCA Biplot of Field and Column Soils