Carroll, Steven, Goonetilleke, Ashantha and Dawes, Les (2004)
Framework for soil suitability evaluation for sewage effluent renovation.
Environmental Geology 46(2): pp. 195-208

FRAMEWORK FOR SOIL SUITABILITY EVALUATION FOR SEWAGE EFFLUENT RENOVATION

STEVEN CARROLL, ASHANTHA GOONETILLEKE AND LES DAWES

School of Civil Engineering,
Queensland University of Technology

Abstract Current methods of establishing suitable locations for onsite wastewater treatment systems (OWTS) are inadequate, particularly in light of the numerous cases of onsite system failure and the resulting adverse consequences. The development of a soil suitability framework for assessing soil suitability for OWTS allows a more practical means of assessment. The use of multivariate statistical analysis techniques, including Principal Component Analysis (PCA) and multi-criteria decision aids of PROMETHEE and GAIA, enabled the identification suitable soils for effluent renovation. The outcome of the multivariate analysis, together with soil permeability and drainage characteristics permitted the establishment of a framework for assessing soil suitability based on three main soil functions: (1) the ability of the soil to provide suitable effluent renovation, (2) the permeability of the soil, and (3) the soil's drainage characteristics. The developed framework was subsequently applied to the research area, Gold Coast, Queensland, Australia, and the use of standard scoring functions were utilised to provide a scoring system to signify which soils were more suitable for effluent renovation processes. From the assessment, it was found that Chromosol and Kurosol soils provided the highest level of effluent renovation, closely followed by Ferrosol and Dermosol, Kandosol and Rudosol soil types. Tenosol and Podosol soil types were found to have a significantly lower suitability, with Hydrosol soils proving the least suitable for renovating effluent from OWTS.

Keywords: Effluent renovation, Onsite wastewater treatment, Risk, Soil suitability, Queensland, Australia

Introduction

The poor performance of onsite wastewater treatment systems (OWTS) is common and is of significant concern to regulatory authorities worldwide (Siegrist and others 2000). The consequences of exposure to inadequately treated effluent from onsite systems include serious environmental and public health impacts (Cliver 2000, Gold and Sims 2000). Approximately 17% of Australian households are currently serviced by OWTS (O'Keefe 2001), with the most common form being the septic tank-subsurface soil adsorption systems. Similar trends are evident in the United States with over 25% of the population utilising onsite systems (Seigrist 2001). A typical septic tank treatment system is depicted in Figure 1. The septic tank itself only provides primary treatment of wastewater, with the final treatment and ultimate disposal performed by the subsurface disposal trenches and surrounding soil. Therefore the satisfactory performance of onsite wastewater treatment systems, in particular septic systems, depends mainly on the underlying soil to renovate or suitably remove or absorb effluent pollutants, and transmit the discharged effluent. Though other forms of effluent disposal, such as mounds and evapotranspiration systems are becoming more popular, subsurface disposal trenches remain the most widely used approach. Additionally, even though secondary treatment systems, such as aerobic wastewater treatment systems (AWTS) are becoming increasingly common, septic tanks far outnumber them.

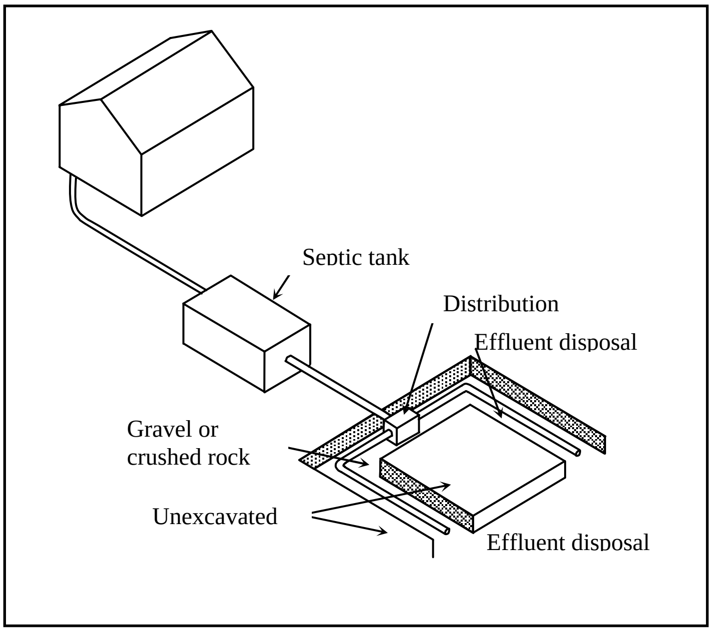

Figure 1 Typical setup of an onsite septic tank-soil adsorption system commonly adopted in Australia

Contamination of the surrounding environment due to poor OWTS performance is not a recent issue. Numerous cases of contamination of groundwater and surface water have been reported over the years (for example Hagedorn and others 1981; Harris 1995; Hoxley and Dudding 1994). Similarly, from a public health perspective, numerous incidents of disease outbreaks have been traced back to poor treatment performance of these systems (Cliver 2000). This is compounded by the fact that large clusters of onsite systems will inevitably increase the severity of contamination

(Hampton and Yahner 1984; Paul and others 1997; Yates 1985). Due to the widely recognised environmental and public health issues resulting from poor OWTS performance, performance based standards and guidelines are commonly adopted for system siting, design and management. Unfortunately, these performance based standards do not necessarily achieve their intended objectives for two primary reasons. Firstly, the influence of soil and site factors in effluent treatment are not completely understood (Dawes and Goonetilleke 2003). Secondly, most standards and codes commonly focus on individual systems, with little regard to the impact of clustering of systems (US EPA 1997).

In determining site suitability for OWTS, understanding the soil's ability to accept, treat and dispose of discharged effluent is crucial. Due to its heterogeneous nature, the assessment of a single soil parameter cannot provide a comprehensive overview of its suitability for a particular purpose (Diack and Stott 2001). As an example, the simple soil permeability test traditionally used as a means of assessment for effluent disposal, will indicate the soil's ability to absorb effluent, but will not show if the effluent will undergo sufficient treatment prior to percolating into the groundwater. Therefore there is a crucial need for more scientifically rigorous procedure for assessing soil suitability for sewage effluent renovation through the removal of important pollutants.

The primary focus of the research undertaken was to develop methodology based on physico-chemical data to evaluate the sewage effluent renovation ability of different soil types. Multivariate analysis to define soil capability rankings, together with permeability and drainage classifications were employed to develop a suitability framework to assess three specific soil functions: (1) the ability of the soil to provide suitable effluent renovation, (2) the permeability of the soil, and (3) the soil's drainage characteristics. Ranking of soil data is widely used for assessing soil quality for agricultural purposes. As examples Diack and Stott (2001) and Karlen and others (1994) have discussed methods for assessing soil quality and developing soil quality indices. However, there has been very limited research undertaken on providing a method for ranking soil suitability for effluent renovation. Khalil and others (2004) have undertaken research in assessing soil suitability based on physico-chemical data utilising multi-criteria decision aids for a number of sites in Southeast Queensland.

However, ranking was established for site locations rather than for soil type, which is the main focus of this research.

Materials and methods

Project area

The project area encompassed the Gold Coast region, in Southeast of Queensland State, Australia, covering approximately 1500 km^2. The region currently has over 15,000 onsite wastewater treatment systems with a majority of them being conventional septic tank-soil absorption systems. Large clusters of OWTS exist in various locations, and their cumulative effect has become a major concern for the region’s local government. This region is a major tourist destination, with significant ecosystems such as, World Heritage sites, important water resources and Ramsar wetland sites. Additionally, the region is one of the most rapidly urbanising areas in Australia. Due to the escalating cost of infrastructure, onsite systems are the most economical and accepted means of wastewater treatment within these areas. However, the current performance of onsite systems throughout the study area is a concern. The majority of onsite systems throughout the study area are low technology septic systems. Several areas which have high failure rates due to inadequate soil conditions and have subsequently moved away from subsurface disposal systems in favour of more advance treatment systems such as AWTS have been identified by the local authority.

Soil sample collection

The Gold Coast region has a variety of soil and landscape characteristics, ranging from flat sandy coastal plains to steep mountainous terrain. The soil types throughout the region were classified according to the Australian Soil Classification (Isbell 1996). Soil descriptions for the fourteen soil types under the Australian Soil Classification are described in Table 1. Soil classifications developed through the Soil Taxonomy Order classification (NRCS 1999) are provided for comparison.

Physico-chemical data used for establishing the suitability of soil for effluent renovation was collected from 28 sampling sites within the project area and supplemented with data already available. Sampling sites were selected based on areas that rated poorly in relation to the three specific criteria: (1) soil drainage, (2) planning conditions related to minimum lot size specified in the Town Plan and (3) environmental sensitivity or proximity to environmentally sensitive ecosystems such as waterways, reservoirs and wetlands. Soil samples were collected from the B horizon to a maximum depth of 1200 mm from each of the sampling sites. This was to ensure the samples would be representative of the '*zone of influence*' of a typical subsurface treatment field. As subsurface disposal trenches are typically installed at a depth of approximately 450 mm, the soil most predominant in renovating effluent is the B horizon. Samples were obtained by hand auger, and approximately one kilogram of the representative soil was collected, mixed thoroughly to obtain homogeneous samples and sealed in marked plastic bags for transport back to the laboratory.

Table 1: Soil definitions of soils classified under the Australian Soil Classification (Isbell 1996)

Australian Soil Classification	**Connotation**		**Equivalent Soil Taxonomy Order (NRCS 1999)**
Anthroposols	'*man-made*' soils	Soils resulting from human activities, causing a profound modification to the soil material	
Calcarosols	calcareous throughout	Soils that are calcareous throughout the solum – or at least directly below the A1 horizon or to a depth of 0.2m if the A1 horizon is weakly developed.	Aridisols or Alfisols
Chromosols	often brightly coloured	Soils with a clear and abrupt textural B horizon (abrupt increase in clay content) in which the major part[1] of the upper 0.2m of the B2 horizon is strongly acidic.	Alfisols
Dermosols	often with clay skins or ped faces	Soils with B2 horizon that have more developed structure than weak throughout major part[1] of horizon	Utisols
Ferrosols	high iron content	Soils with B2 horizon in which the major part[1] has free iron oxide content >5% Fe in fine earth fraction (<2mm).	Oxisols
Hydrosols	wet (saturated) soils	Soils that are saturated in the major part[1] of the solum for at least 2-3months in most years (including tidal waters)	Ultisols or Inceptisols
Kandosols		Soils that have, well developed B2 horizons in which major part[1] is massive or has weak grade of structure and have a maximum clay content in B2 which exceeds 15%.	Alfisols or Ultisols[2]
Kurosols	extremely acidic soils	Soils with a clear or abrupt textural B horizon and in which the major part of B2 horizon is strongly acidic	Alfisols or Ultisols[2]
Organosols	dominated by organic material	Soils that have more than upper 0.4m of organic material within upper 0.8m or have organic materials extending from surface to a minimum depth of 0.1m that either directly overly rock, weathered rock or hard layers , in which the interstices are filled or partially filled with organic material.	Histols
Podosols	podzols	Soils that have Bs, Bhs or Bh horizons.	Spodosols
Rudosols	rudimentary soil development	Soils with negligible (*rudimentary*) pedilogical organisation apart form minimum development of A1 horizon or presence of less than 10% of B horizon material in fissures in parent rock. Soil is only weakly developed in A1 horizon with little or no texture or colour change with depth.	Entisols
Sodosols	sodic soils	Soils with clear or abrupt textural B horizon in which major part[1] of upper 0.2m of B2 horizon is sodic (ESP >6%) and is not strongly sub-plastic.	Alfisols
Tenosols	weakly developed soils	Soils with generally weak pedologic organisation apart from A horizon	Inceptisols or Entisols
Vertosols	shrink-swell clays	Soils that have a clay texture or 35% more clay throughout solum except for thin surface crusty horizons and, unless too moist, have open cracks at some time in most years that are at least 5mm wide. Slickensides and/or lenticular peds are identifiable at some depth.	Vertisols

[1] *'Major part'* – requirement must be met over more than half the specified thickness.
[2] Classification is dependent upon the quantities of base cations

Soil analysis

Soil samples were tested for pH, electrical conductivity (EC), chloride concentration (Cl^-), cation exchange capacity (CEC), organic content (%OC) and particle size distribution (percent sand (%S) and percent clay (%C)). The soil parameter selection was based on the suite of tests generally carried out in land resource evaluation (Rayment and Higginson 1992). These tests have been developed through extensive agricultural research and are designed to distinguish between deficient, adequate and toxic availability of elements in soil and between degraded and non-degraded soil conditions. Additionally, the CEC/Clay ratio (CCR) (Shaw and others 1998) was calculated from the derived parameters. CCR provides an indication of the type of clay present in the soil sample. Ratios < 0.2 represent kaolinite clays 0.3-0.5 indicate illite clays and >0.8 indicate smectite clays. Values in between represent clays of mixed mineralogy. Soil permeability and drainage characteristics, assessed using soil particle size analysis and soil texture characteristics, were also assessed for each soil sample. Although both describe a means by which water and effluent moves through soil, permeability and drainage are two different characteristics that must be addressed. For example, a soil having a high permeability may also possess poor drainage, particularly in the case of hydrosols (permanently saturated soils). Similarly, a soil with low permeability may have good drainage, depending on its location in the soil catena.

The soil parameters selected for analysis also provided an indication of a soil's ability to provide suitable renovation of applied effluent, particularly in relation to the removal of nutrients and pathogenic organisms. pH, EC and Cl^- are good indicators of effluent movement through the soil matrix. Typically, for soils in South East Queensland, an increase in these parameters are generally observed where effluent has been applied, thereby allowing the extent of effluent movement to be traced through the soil. CEC and %OM are both influential in determining soil renovation ability. Higher levels of both parameters can appreciably influence the renovation process (Khalil and others 2004). In most soils, a higher amount of organic matter can significantly increase the CEC. However, CEC is also dependent on the CEC/Clay ratio and the amount of clay present in the soil, which in turn can affect the drainage and permeability of the soil. As an example, smectite clays provide higher CEC values, but due to their shrink/swell characteristics they have very low permeability values.

The soil samples were air dried and ground to < 2mm. Parameters such as pH, EC, Cl^- and %OC were determined using the methods outlined by Rayment and Higginson (1992). pH and EC were measured from a 1:5 soil:water suspension using a combined pH/Conductivity meter. Chloride concentration (Cl^-) was analysed by the ferric thiocyanate colourmetric method (APHA 1999). Cation Exchange Capacity was determined by the method outlined in Borden and Giese (2001), where all available exchange sites are saturated with exchangeable ammonia and measured using the ammonia selective electrode method. This included the available exchange sites contained in the soil particles and the organic material. This is important as organics provide significant adsorption and cation exchange ability in addition to the soil particles, which therefore produces higher CEC levels. In fact, the CEC value of most soils is highly influenced by the organic content, and high CEC values (>100 meq 100 g^{-1}) are more likely resultant from the influence of the organics rather than the amount or type of clay. Organosol soils are a typical example of this. Organic content (%OC) was determined by the Walkey-Black method with the soil organic matter first oxidised using 30% hydrogen peroxide and combusted at 1300˚C. Particle size distribution (for %C and %S) was determined using a Malvern Mastersizer S particle size analyser. CCR was calculated by dividing the CEC value by the %C (Shaw and others 1998). As soil permeability (K) data was not available for most of the soil types investigated, it was assessed based on the formula developed by Krumbien and Monk (1943). This method calculates permeability from predetermined values of a soil's particle size distribution. Soil drainage classifications for the soil samples were established using soil textural and particle size distribution data. This information was used to classify the soil into appropriate drainage classifications as outlined by (McDonald and others 1998).

Soil suitability framework

The results of the assessment of the soil's ability for effluent renovation, together with permeability and drainage characteristics, were integrated into a framework to assess a site's suitability for locating an onsite wastewater treatment system. To develop the soil suitability framework, due consideration was given to the physical and chemical characteristics of the various soil types. Multivariate data analysis including Principal Component Analysis (PCA) and multi-criteria decision-making techniques of PROMETHEE and GAIA, were used to evaluate the physico-chemical data of collected soil samples. The resulting rankings, coupled with the permeability and drainage characteristics, were used to establish the appropriate suitability rankings. These ranking were determined by utilising standard scoring functions (SSF) based on 'more is better', 'less is better', or optimum functions as described by Karlen and others (1994).

Data analysis

Soil data extracted from the resulting soil information consisted of 98 soil samples, including the variables of %C, K, pH, EC, Cl^-, CEC and CCR and %OC. A Principal Component Analysis (PCA) was conducted on the data sets to determine which soil types were highly correlated with each other and the selected variables. PCA was performed using MATLAB 6.5 Release 13 (The Mathworks Inc 2002). The results from the PCA analysis were used to structure the preference functions and threshold information for use with the multi-criteria decision-aid methods of PROMETHEE and GAIA, using Decision Lab 2000 v1.01 (Visual Decision Inc. 1999).

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 to identify possible patterns or clusters between objects and variables. Detailed descriptions of PCA can be found elsewhere (Massart and others 1988, Adams 1995; Kokot and others 1998), and therefore will not be discussed in detail in this paper. PCA has been used extensively for various applications related to soil characteristics or soil quality. As examples, Carlon and others (2001) used PCA and Kriging techniques for the analysis of data in performing a risk-based characterisation of soil at a contaminated industrial site. Vance and others (2003) used PCA to help in classifying soil samples based on exchangeable sodium percentage and spontaneous or mechanical dispersion.

All raw data used in the PCA analysis was subjected to pre-treatment to remove or reduce extraneous sources of variation or ‘noise’ which may interfere in the analysis (Adams 1995). Firstly, the raw data was log transformed to reduce data heterogeneity. Following this, the transformed data was column-centered (column-means subtracted from each element in their respective columns) and standardised (individual column values divided by the column standard deviations). PCA was undertaken on the transformed data to identify possible patterns or clusters. Correlations between selected variables were also obtained allowing identification of the most important parameters that should be considered when deciding site suitability for onsite wastewater treatment.

PROMETHEE and GAIA

PROMETHEE and GAIA are multivariate decision aids that rank actions according to specific criteria and thresholds. The details of PROMETHEE and GAIA are described elsewhere (Visual Decision Inc. 1999; Keller and others 1991), and therefore only a brief summary of the methods is provided here. The PROMETHEE method uses a pair-wise comparison system in which each action (soil sample) is compared to all other actions one-by-one defined by the preference functions, with thresholds and weights adopted by the decision-maker (Visual Decision Inc. 1999). PROMETHEE establishes preference flows (Φ) for each action and ranks these based on the preference flows. Partial ranking (*PROMETHEE I*) utilises the Φ^+ and Φ^- preference flows for ranking the actions. The positive flow, Φ^+, determines the degree to which each soil sample is preferred over other samples, with higher positive values receiving a higher rank. The negative flow Φ^- determines the degree to which other soil samples are preferred over a particular sample. However, if samples have conflicting flows or preferences, they are considered incomparable in the *PROMETHEE I* ranking (Visual Decision Inc. 1999). The net flow Φ ($\Phi = \Phi^+ - \Phi^-$), also called the *Pi* score, represents the complete ranking (*PROMETHEE II*) of samples, with higher flow values ranked more highly. Both *PROMETHEE I* and *II* rankings were analysed to establish which soils were more suitable for effluent renovation.

GAIA provides a diagrammatic representation of the ranking methods of PROMETHEE, utilising a PCA technique. PCA is applied to the net preference flows (Φ), and a biplot or GAIA plane, of the first two PCs is developed. Although no initial pre-treatment of data is needed to be undertaken, the preference functions established by PROMETHEE act to normalise the data, thereby providing some pre-treatment of the initial data. An additional feature of the GAIA plane is the incorporation of the *Pi* decision axis. The orientation of the *Pi* axis emphasises which criteria and actions are more dominant in the analysis (Visual Decision Inc. 1999).

To obtain suitable rankings for the soil data, specific preference functions and threshold values need to be selected and identified for the analysis. Six different preference functions are available in Decision Lab 2000 software. However, only the *v-shape* and *linear* functions, as depicted in Figure 2 were found suitable for the envisaged analysis. Both functions depend on two preference thresholds, an indifference threshold *Q*, and preference threshold *P*. The *Q* threshold represents the largest deviation considered as negligible (preference of 0) by the decision-maker. The *P* threshold, on the other hand provides the smallest deviation considered as decisive (preference of 1) (Visual Decision Inc. 1999). Table 2 depicts the variables and the selected preference functions and thresholds used in the two analyses. For EC, Cl^- and CEC, a *v-shape* function was used as these variables only required a simple linear ranking system, with higher values generally receiving a preference of 1. For EC and Cl^-, however, rankings were minimised for the analysis as lower values for these parameters were considered more suitable. This was based on the fact that higher EC and Cl^- values in natural soil conditions would function poorly under effluent application rather than soils with lower levels. Preference thresholds *P*, for these variables were determined by subtracting the smallest data value from a maximum threshold value considered as providing the highest level of performance. As an example, a CEC value greater than 100 meq 100 g^{-1} was considered as extremely high, and therefore a value larger than this was given a preference of 1. %C, pH, %OC and CCR were ranked based on *linear* preference functions with upper (*P*) and lower (*Q*) thresholds for these variables selected as described in Table 2. *P* thresholds where established by the same means as for the *v-shape* functions. The *Q* threshold, however, was taken as an appropriate level at which any difference below the threshold was considered as negligible. As an example, a difference of 10% for %C was considered as negligible, and therefore received a preference of 0. Finally, all criteria were equally weighted to remove any bias towards a particular variable over the remaining variables.

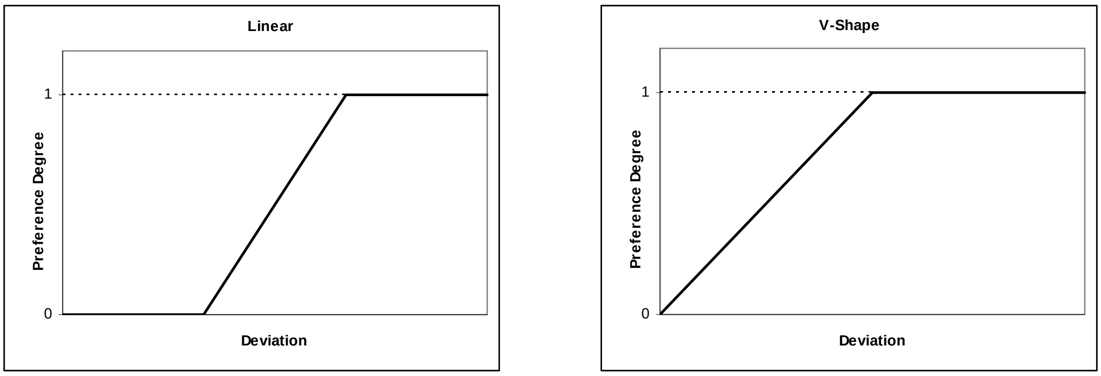

Figure 2 Preference Functions used for multivariate analysis (Visual Decision Inc, 1999)

Table 2: Preference Functions, threshold values and general statistics used in PROMETHEE analysis

	%C	**k**	**pH**	**EC**	**Cl^-**	**CEC**	**OC%**	**CCR**
Function	linear	linear	linear	v-shape	v-shape	v-shape	linear	linear
Min/Max	Max	Min	Min	Min	Min	Max	Max	Max
P	50	1	3	1000	500	100	50	5
Q	10	0.001	0.1	1	1	1	10	0.2
Unit	%	m/day		uS/cm	mg/Kg	meq/100g	%	
Weight	1	1	1	1	1	1	1	1

In the case of permeability, values used for the required preference thresholds were focused specifically on the adsorption processes of the soil, with lower permeability values considered more suitable by allowing more time for cation exchange processes to take place (Hartmann and others 1998), and therefore a better renovation ability is achieved. However, for a soil to renovate effluent, the effluent must be able to percolate through the soil at a satisfactory rate, while still providing suitable time for adsorption processes to occur. Therefore, values higher than 1m/day or lower than 0.001m/day were considered unsuitable for effluent renovation. The preference thresholds, *P* and *Q* were set to ensure that K values exceeding these levels would receive a preference of 0 while the remaining values in between these thresholds would be ranked with higher values considered more suitable.

Results and Discussion

PCA, PROMETHEE and GAIA

PCA was conducted using the variables of %C, K, pH, EC, Cl^-, CEC and CCR and %OC. Although %OC was initially included in the multivariate analysis, it was later removed due to an analytical bias towards Organosol soil. Organosols by nature have significantly high organic content, and as such the Organosol samples were observed to retain most, if not all of the data variance associated with %OC in the initial analysis. Therefore, to allow a more unbiased analysis between the Organosols and the other parameters, %OC was removed. The PCA of the physico-chemical data set resulted in 77.4% of the data variance being contained in the first three components. Therefore, the first three PC's were retained. This was based on the Scree test (Cattell 1966) which confirmed that the first three PC's were significant as depicted in Figure 3, with the remaining components considered to only contribute 'noise' to the overall data variance. Figure 4 provides a scores, loadings and biplot of the PCA analysis. The scores plot provides a graphical representation of clusters of soils with similar physico-chemical properties. The respective loadings or 'weights', and loadings plot of the analysed soils provide an indication of the correlations between the different variables. Table 3 gives the PC loadings for the seven variables. From these loadings, the correlations between specific variables can be identified, and this is shown graphically in the loadings plot in Figure 4b. Vectors situated closely together represent variables that are highly correlated while orthogonal vectors represent variables that are uncorrelated.

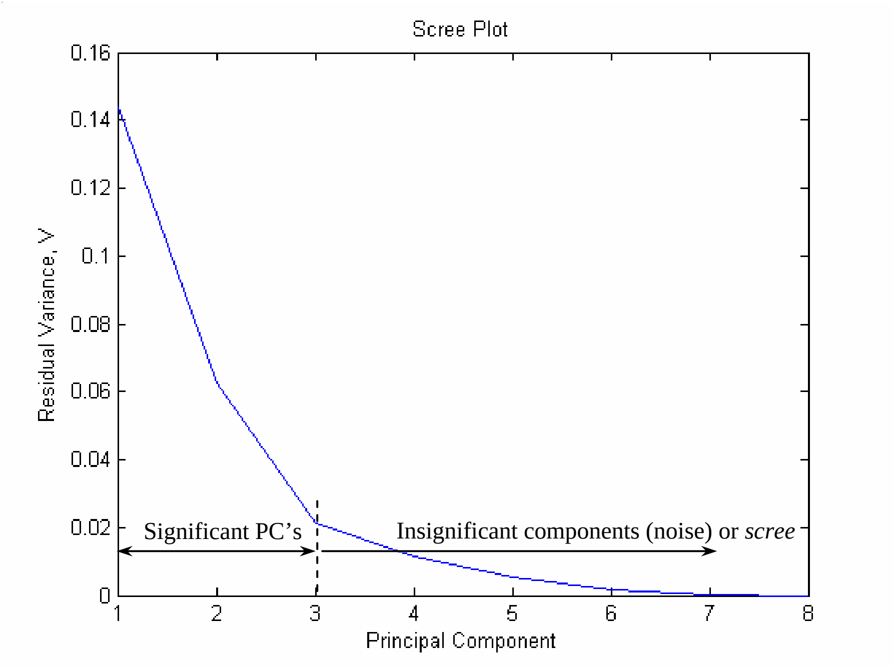

Figure 3: Scree Plot for determining significant number components for PCA analysis

The PCA analysis produced some typical results in relation to the correlations between the variables and soil classifications. As shown in Figure 4a and 4c, the soils with higher clay content retained positive scores on PC1, with sandier soils falling directly opposite. Soils that retained a high CEC value fell positively on PC2, consistent with the samples retaining higher EC and Cl^- values. The permeability K, of the soil is shown to be closely correlated with the %S negatively correlated with %C. This is not surprising as the chlorides and other cations will adsorb to exchangeable sites, increasing the level of exchangeable ions contained in the soil. With high levels of salt ions in the soil (in this case chloride ions), it is evident that the EC level will also increase.

Fig 4a

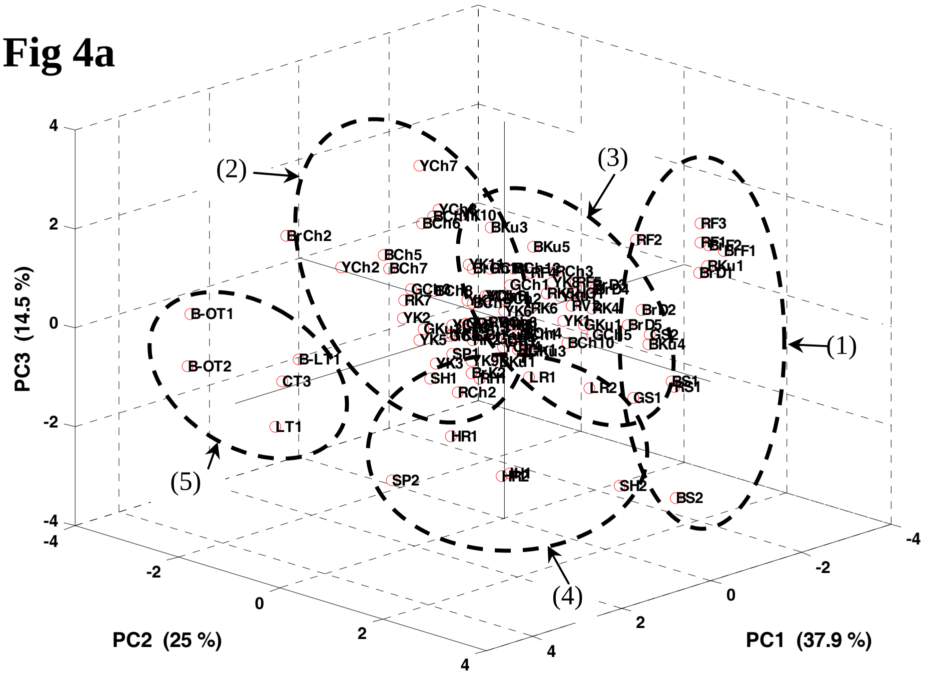
PC3 (14.5 %)
PC2 (25 %)
PC1 (37.9 %)
4
2
0
-2
-4
-4
-2
0
2
4
-4
-2
0
2
4
(1)
(2)
(3)
(4)
(5)
YCh7
BCh6
BKu3
BKu5
RF2
RF3
RF1
BrF2
BrF1
BKu1
BrD1
BrCh2
BCh5
YCh2
BCh7
GCh1
RK7
YK2
YK5
YK6
RK6
RK4
YK1
GKu1
BrD5
BrD2
GS2
BKu4
GCh5
BCh10
SP1
YK3
SH1
YK9
LR1
LR2
GS1
BS1
RS1
RCh2
HR1
SP2
SH2
BS2
B-OT1
B-OT2
B-LT1
CT3
LT1

Fig. 4b

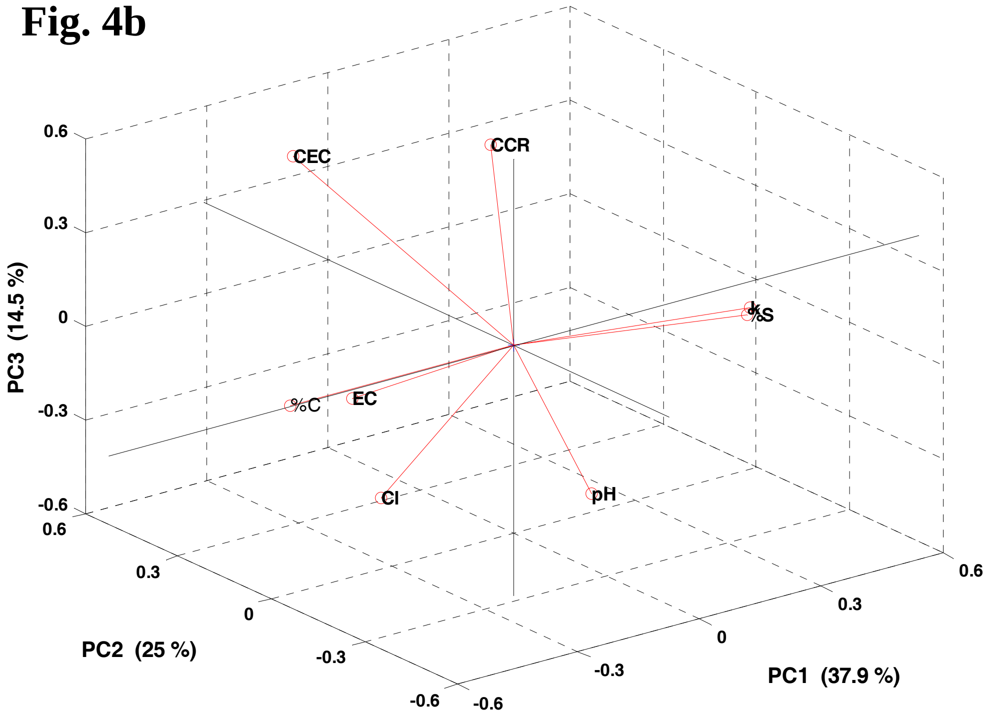
PC3 (14.5 %)
PC2 (25 %)
PC1 (37.9 %)
0.6
0.3
0
-0.3
-0.6
0.6
0.3
0
-0.3
-0.6
-0.6
-0.3
0
0.3
0.6
CEC
CCR
k
%S
%C
EC
Cl
pH

Fig 4c

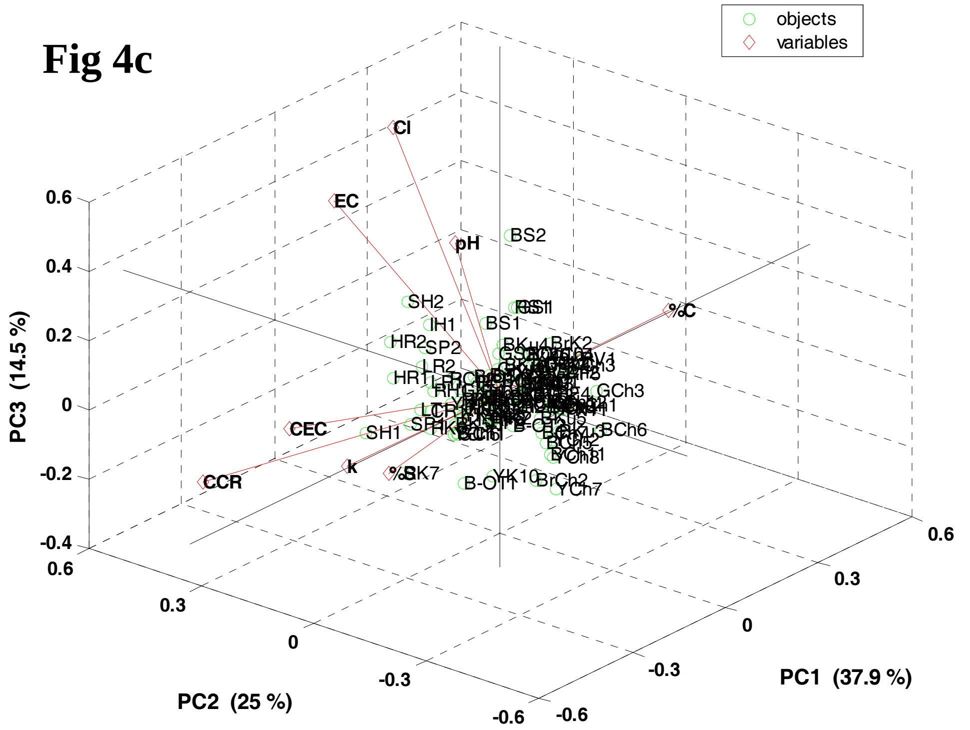

Figure 4: Results of PCA analysis for derived soil data; a) Scores plot of soil samples showing developed clusters, b) Loadings plot of analysed variables, and c) Biplot of PC1 versus PC2. Legend: (#) Developed Soil Clusters Notation: Final letter in soil notation refers to greater soil group as follows: (F) Ferrosol; (D) Dermosol; (S) Sodosol; (Ch) Chromosol; (K) Kandosol; (Ku) Kurosol; (R) Rudosol; (T) Tenosol; (P) Podosol; (H) Hydrosol; (O) Organosol; (V) Vertosol.

The PC loadings highlighted in Table 3 (shown in bold), shows that PC1 is closely associated with the soil physical parameters of %S, %C, K, and to a lesser extent pH, although %C is negatively correlated with these variables. The second component PC2 however, is more closely associated with the chemical parameters of EC, Cl$^-$, CEC and CCR. The resulting biplot (Fig 4c) shows the relationship between particular soil types and the variables analysed. Appropriately, %S is highly correlated with the Tenosol group, as they possess the highest content of sand. Likewise, %C is correlated with the Ferrosol, Dermosol, Vertosol, Sodosol groups. CCR is shown to be highly correlated with the Hydrosol and Podosol groups. This is mainly due to these soils having average CEC values and very low clay percentages, which in turn provides large CCR values for these soils. However, as CCR is related to the clay type, it is possible that the small percentage of clay contained in the Podosol and

Hydrosol soils are smectite-type clays which do have higher adsorption ability and will therefore produce a higher CEC value. However, it would be more likely that these soils retain a mixed clay mineralogy consisting of smectites and kaolinite clays.

Table 3: PC loadings from principal component analysis

Variable	**PC1**	**PC2**	**PC3**
%S	**0.4932**	-0.1107	-0.0253
%C	**-0.5493**	0.0040	-0.0017
K	**0.5493**	-0.0475	-0.0470
pH	0.1743	-0.0249	**-0.5215**
EC	-0.0374	**0.4728**	-0.3701
Cl-	-0.0670	0.3389	**-0.6170**
CEC	-0.0704	**0.6195**	0.3495
CCR	0.3345	**0.5123**	0.2919

The major outcome derived from the PCA analysis in relation to soil ability to renovate effluent are the clusters developed between soils that retain similar properties and characteristics, as depicted in the scores plot in Figure 4a. Major soil clusters developed through the PCA analysis include: (1) Ferrosols, Dermosols and Sodosols, (2) Chromosols and Vertosols, (3) Kandosols, Kurosols and Rudosols, (4) Hydrosols and Podosols and (5) Tenosols. The Kandosol and Kurosol soils, however, are widely scattered, having a much higher variance on PC2 than other soils. This is primarily related to the varying content of clay generally present in these soils. The organosol soil is closely related to the Kandosols, but as the %OC was not removed in this analysis; the other physical and chemical characteristics associated with the soils indicated that the organosol was similar to the Kandosol soil group. However, due to the high CEC value of the organosol soil as a result of its high organic content, it is shown to be highly correlated with CEC. The Chromosol soil group (cluster (4)) is highly variable on PC2. This is related to the varying CEC levels and %C typically common to this soil type. Chromosol soils are essentially identified by abrupt changes in the amount of clay through the soil profile. The small grouping of Chromosol soils on the bottom of the scores plot represents the Chromosol soils with very low CEC values. Correlations between specific soil clusters and the variables can also be identified in the biplot. CEC, EC and Cl^- are highly correlated with clusters (1) and

(4), although the %C, which is highly correlated with clusters (1) and (2), does reduce the correlation of CEC with these clusters to a minor extent.

From the PROMETHEE analysis, patterns or clusters in the ranking were identified, and to a lesser extent these followed similar patterns as obtained through the PCA analysis, although some minor variations were obvious. Variables that were found to be correlated through the PCA analysis and utilised for the PROMETHEE analysis also provided similar correlations. However, some differences are obvious, and these are related to the preference functions and threshold values adopted. As an example, permeability is shown to be highly correlated with %C, as it was minimised to account for the fact that lesser permeable soils are considered to provide higher renovation ability than very highly permeable soils. Therefore, from the ranking of the soil data, specific soil types can be seen to function more appropriately in terms of effluent renovation than others. Table 4 provides the partial and complete rankings determined from the preference flows produced from the PROMETHEE analysis. From the *PROMETHEE II* complete ranking (Φ_{net}), and *PROMETHEE I* partial ranking (Φ^+ and Φ^-), specific clusters of soils are shown to be more highly ranked than others. Although the *PROMETHEE II* complete ranking provides a rank for each soil sample, the partial ranking determined via *PROMETHEE I* provided more beneficial results by highlighting clusters of soils that are similarly ranked as well as soils which are considered not comparable with other soils.

The GAIA plot shown in Figure 5 provides a graphical representation of the various clusters formed through the data analysis. The *Pi* axis shown in the GAIA plane represents the direction of the more highly ranked soils, and therefore more suitable soils for effluent renovation. Ferrosol and Dermosol soils are the most highly ranked, and therefore they cluster closely towards the *Pi* axis. In contrast, the Tenosol group clearly clusters in the opposite direction. The soil clusters identified through the PROMETHEE analysis in order of their preference are as follows: (1) Ferrosols and Dermosols; (2) Chromosols; (3) Kandosols, Kurosols and Rudosols; (4) Organosols; (5) Vertosols and Sodosols; (6) Podosols and Tenosols; and (7) Hydrosols.

Table 4: Partial and complete preference flows and rankings for the first data set
Notation: Refer to Figure 4

Soil Sample	Phi Plus	Phi Minus	Phi Net	Ranking	Soil Sample	Phi Plus	Phi Minus	Phi Net	Ranking
SH1	0.2264	0.2409	-0.0145	**48**	BKu3	0.1112	0.0733	0.038	**30**
B-OT1	0.1083	0.302	-0.1937	**92**	BCh10	0.1119	0.1015	0.0104	**40**
LT1	0.145	0.3057	-0.1608	**90**	BKu4	0.1066	0.1431	-0.0365	**67**
GCh1	0.1714	0.055	0.1164	**17**	RCh3	0.1097	0.0612	0.0485	**28**
RF1	0.2401	0.054	0.1862	**6**	BCh11	0.089	0.0829	0.0061	**42**
RF2	0.1672	0.0452	0.1219	**14**	BKu5	0.1431	0.067	0.0761	**23**
YKu1	0.157	0.0594	0.0976	**20**	BCh12	0.1079	0.0724	0.0355	**31**
LR1	0.1273	0.1208	0.0065	**41**	YCh3	0.0666	0.1024	-0.0359	**66**
HR1	0.1802	0.2051	-0.0249	**57**	GCh2	0.0642	0.1012	-0.037	**68**
HR2	0.1654	0.3135	-0.148	**89**	GCh3	0.1096	0.086	0.0237	**37**
GKu1	0.1389	0.0712	0.0676	**25**	GCh4	0.0721	0.1016	-0.0295	**59**
SH2	0.0814	0.3306	-0.2492	**96**	RK2	0.0543	0.135	-0.0807	**82**
RH1	0.0953	0.1704	-0.0751	**79**	BrD3	0.1338	0.0642	0.0696	**24**
IH1	0.0572	0.3089	-0.2517	**97**	GKu2	0.0628	0.1092	-0.0465	**72**
BrD1	0.2382	0.0557	0.1825	**7**	YK2	0.0669	0.1457	-0.0788	**81**
BS1	0.1329	0.1701	-0.0372	**69**	YK3	0.0507	0.1356	-0.0848	**83**
YK1	0.1624	0.0615	0.101	**19**	RV1	0.0967	0.1182	-0.0215	**55**
LR2	0.2484	0.1208	0.1276	**13**	YCh4	0.0578	0.1108	-0.053	**75**
RF3	0.3239	0.0186	0.3053	**1**	B-LT1	0.091	0.2797	-0.1887	**91**
RKu1	0.3169	0.0448	0.2721	**3**	YK4	0.0527	0.1309	-0.0782	**80**
BrF1	0.2952	0.0295	0.2658	**4**	YK5	0.0653	0.116	-0.0507	**73**
BrF2	0.3125	0.0268	0.2857	**2**	YCh5	0.0632	0.0946	-0.0314	**61**
BrD2	0.1668	0.0604	0.1063	**18**	BrD4	0.1639	0.0465	0.1173	**16**
HO1	0.2066	0.0695	0.1371	**12**	RK3	0.0899	0.1023	-0.0124	**47**
SP1	0.1847	0.3258	-0.1411	**88**	YK6	0.0756	0.1074	-0.0319	**63**
SP2	0.0563	0.3001	-0.2438	**94**	YCh6	0.1848	0.0651	0.1197	**15**
B-OT2	0.0465	0.2937	-0.2471	**95**	RV2	0.114	0.0792	0.0348	**32**
CT3	0.0623	0.2736	-0.2113	**93**	YK7	0.0794	0.1002	-0.0208	**53**
RCh1	0.1034	0.1427	-0.0393	**70**	CR1	0.2216	0.0844	0.1372	**11**
BCh1	0.0822	0.0901	-0.0079	**46**	GCh5	0.0698	0.0978	-0.028	**58**
BCh2	0.0949	0.0816	0.0133	**39**	RK4	0.1986	0.043	0.1556	**9**
RCh2	0.097	0.1866	-0.0896	**84**	RK5	0.2145	0.047	0.1675	**8**
RS1	0.121	0.2516	-0.1306	**86**	RK6	0.2818	0.0595	0.2222	**5**
GS1	0.0749	0.2061	-0.1313	**87**	YK8	0.1216	0.062	0.0595	**26**
RK1	0.131	0.1018	0.0292	**33**	YK9	0.0532	0.1168	-0.0636	**77**
BKu1	0.0552	0.1083	-0.0531	**76**	YK10	0.1433	0.064	0.0792	**22**
BCh3	0.0696	0.0873	-0.0177	**49**	GS2	0.1111	0.0821	0.0291	**34**
RF4	0.1121	0.0847	0.0274	**36**	YCh7	0.0897	0.0762	0.0135	**38**
RF5	0.1651	0.0774	0.0877	**21**	RK7	0.2393	0.0905	0.1487	**10**
YCh1	0.0837	0.0786	0.0051	**43**	BrD5	0.1577	0.0994	0.0584	**27**
BS2	0.1377	0.4006	-0.263	**98**	BrKu1	0.0592	0.1295	-0.0702	**78**
BCh4	0.0831	0.0887	-0.0056	**45**	LR3	0.071	0.0908	-0.0198	**52**
YCh2	0.0692	0.1027	-0.0335	**64**	BrK2	0.0642	0.1911	-0.1269	**85**
BCh5	0.0717	0.093	-0.0213	**54**	GKu3	0.0721	0.103	-0.0309	**60**
BCh6	0.1252	0.0787	0.0465	**29**	YK11	0.0729	0.1075	-0.0346	**65**
BCh7	0.0677	0.1076	-0.0399	**71**	YCh8	0.0709	0.0903	-0.0195	**51**
BCh8	0.0729	0.0923	-0.0194	**50**	BrCh1	0.0714	0.0942	-0.0227	**56**
BCh9	0.1012	0.0725	0.0287	**35**	RCh4	0.0815	0.0813	0.0002	**44**
GD1	0.067	0.0987	-0.0317	**62**	BrCh2	0.0699	0.1213	-0.0514	**74**

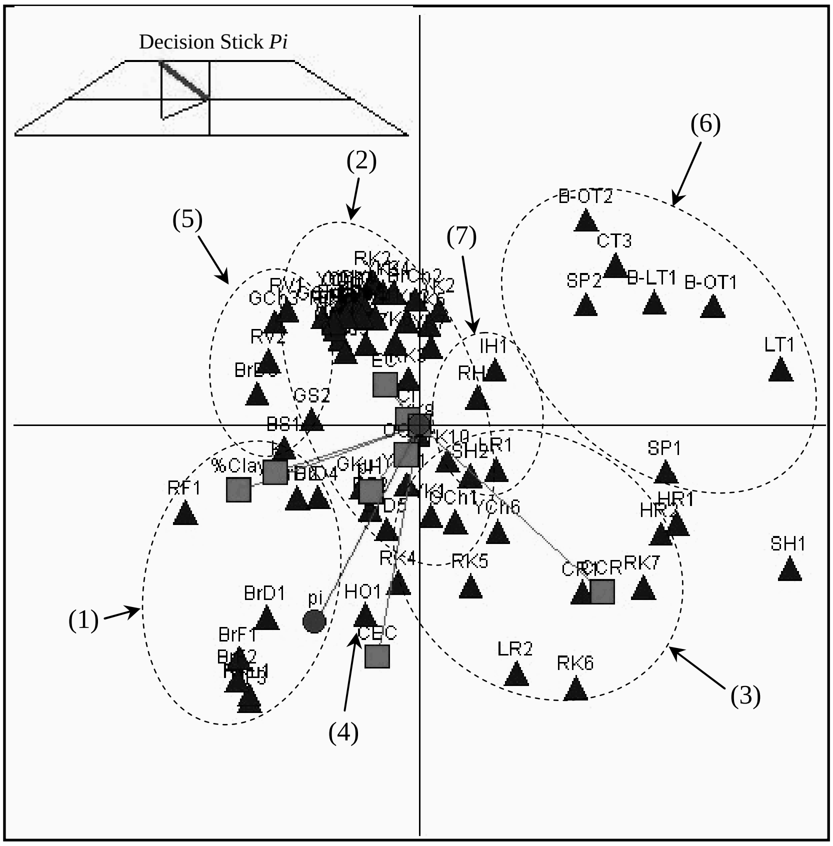

Figure 5: GAIA plot of PROMETHEE analysis highlighting seven major soil clusters. Legend: (▲) Soil Samples; (■) Analysed variables; (#) Developed soil clusters; For soil notation refer to Figure 4

As the results of the PCA and PROMETHEE analysis provided similar patterns, a ranking outlining which soil types perform best in regard to effluent renovation was consequently established. From the multivariate analysis, Ferrosol and Dermosol soils provided the most evidence of suitability for locating OWTS due to their high renovation ability. This relates to their high CEC values and clay content, which typically consist of smectite type clays (CCR >0.8) (Baker and Eldershaw 1993) which are suitable by providing greater cation exchange and therefore contaminant adsorption characteristics. As such, the suitability of a soil for renovating effluent is mostly dependent on the CEC, which in turn relies on the type of clay (represented by the CCR factor) as well as the organic content. This is shown through the PCA analysis where CEC and %OC are highly correlated, with both showing some correlation with the CCR value.

However, care must be taken in considering soil which retains high organics, such as Organosols, as high levels of organic content can be water repulsive, thus reducing the drainage ability (Harper and others 2000; Ferreira and others 2000). Chromosol soils provide the next most significant ranking, due to the amount of clay available. Kandosol, Kurosol and Rudosol soils also ranked quite high, although their distribution on both PC1 and PC2 are fairly scattered. However, in assessing these soils, the %C needs to be determined as these soils can have varying amounts of clay, as shown by the large distribution around the %C variable. The most significant of these soils, however, are the Kurosols. Kurosols are typically acidic soils, and therefore have significant characteristics in relation to soils renovation ability. Due to the lower soil pH arising from the acidic conditions, Kurosols can provide higher CEC values as a result of the increase in aluminium and iron content (Edwards 1985). This will largely depend on the percentage of clay in the soil, and those with higher percentages will be more suitable. Podosol and Tenosol soils ranked significantly lower than the other soils due to the relatively higher percentage of sand and permeability rates. Therefore, these soils will act more like filters, filtering out larger suspended matter, with the least ability for high levels of adsorption of mobile effluent pollutants. Lastly, Hydrosol soils ranked lower than all other soil types. This results from the permanent or seasonally saturated soil conditions typical of Hydrosols. This not only increases the risk of contamination from OWTS, but also increases desorption of already adsorbed pollutants.

Permeability and drainage

To classify permeability K, average values for each specific soil classification were adopted as a generalised value to establish an initial suitability level for each soil. As permeability is not only strongly related to soil characteristics, but also to site conditions, it is difficult to provide a specific range of values for particular soil types. Variations in soil conditions, such as cracks and animal burrows, soil depth and large pores can significantly influence permeability, making it difficult to predict accurate K values from one site to another. Table 5 presents the general statistics and characteristics used for the permeability for each soil type based on available data. Soil drainage classifications used for assessing soil suitability were adopted from

McDonald and others (1998). These were established for the respective soil classifications based on soil texture and particle size distribution data.

Table 5: General statistic for permeability (K) classifications

Soil Type	K mean m/day	K St. Dev. m/day	K max m/day	K min m/day
Ferrosol	8.386E-04	2.202E-03	7.980E-03	1.596E-05
Dermosol	1.339E-04	1.617E-04	5.229E-04	1.894E-05
Chromosol	4.495E-02	1.677E-01	1.322E+00	5.724E-05
Kandosol	8.782E-02	5.638E-01	3.870E+00	4.775E-05
Kurosol	4.061E-02	1.929E-01	1.059E+00	1.498E-05
Rudosol	1.066E-01	2.314E-01	7.861E-01	1.211E-03
Organosol	3.706E-04	3.161E-04	5.941E-04	1.471E-04
Sodosol	2.028E-03	5.766E-03	1.839E-02	2.620E-05
Vertosol	8.426E-05	6.538E-05	1.819E-04	4.405E-05
Podosol	1.046E+00	7.186E-01	2.037E+00	2.020E-02
Tenosol	4.819E+00	1.340E+00	5.905E+00	2.141E+00
Hydrosol	4.745E-01	7.098E-01	2.261E+00	3.868E-03

Soil suitability ranking

The established classifications for effluent renovation ability, permeability and drainage formed the basis for developing the framework for determining the degree of suitability of specific soils for sewage effluent renovation. The framework process has been developed such that once the necessary information required is determined, the suitability can be established by the use of standard scoring systems as described by Karlen and others (1994). Figure 6 illustrates the framework developed. For the different types of soil in the study region, a *less is better* function was adopted, where each value is divided by the highest possible value such that the highest value will receive a score of 1 (Andrews and others 2002). Similarly, a *less is better* scoring function was adopted for the scoring of typical drainage characteristics according to soil type. However, for permeability, the *optimum* function was adopted. This was in view of the fact that lower soil permeability will provide better effluent renovation processes than very highly permeable soils as more time is available for contact with soil particles and therefore enhanced opportunities for cation exchanges to take place (Hartmann and others 1998). Higher K values on the other hand, only allow sufficient time for fast surface exchange processes to occur, resulting in reduced ability for effluent renovation.

Soil Type	Ability	Criteria
Ferrosol Dermosol	1	Soils with a high renovation ability due to high CEC values and clay contents.
Chromosol	2	Soils with a good renovation ability due to medium CEC values. Percentage clay must be determined, as these soils can have highly variable percentages, with abrupt increases through the profile. Chromosol soils with small clay percentages will provide less renovation ability due to lower CEC, and may fall into lower categories.
Kandosol Kurosol Rudosol	3	Soils with medium renovation ability, generally due to slightly higher sand contents, but still retain a suitable CEC. Care must be taken with Rudosol soils to ensure there is adequate soil depth to provide sufficient renovation ability.
Organosol	4	Soils with high renovation ability, primarily due to organic content. However, high levels of organic material can repel water, lowering the drainage, and therefore renovation ability. Nutrient levels are also commonly high due to the organic material
Sodosol Vertosol	5	Soils with low renovation ability due to the sodic conditions causing soil dispersion (Sodosol) or extremely high plastic shrink/swell clays (Vertosol) that result in poor permeability and drainage ability.
Podosol Tenosol	6	Soils with poor renovation ability due to low CEC values and clay contents. Typically coarse grained sandy soils that have good drainage and permeability, resulting in poor exchange processes with effluent constituents.
Hydrosol	7	Soils with very poor renovation ability, with low CEC and clay content. Renovation ability is severely worsened due to shallow groundwater.

Permeability	Suitability	Criteria
Very Slow Ks < 0.005 m/day	3	Permeability of water vertically through soil horizon very slow. Usually a clay or silty clay texture. Very poorly suited for effluent renovation as water can not percolate through soil, therefore not providing adequate exchange ability between soil and discharged effluent.
Slow Ks = 0.005-0.05 m/day	1	Permeability of water is slow with vertical percolation taking a week or more to dissipate. Soil structure usually massive or moderate grade, with a clay or silty clay texture. Soil provide a moderate renovation ability, increasing as the permeability increases as a better exchange capacity (CEC) is available as water move more easily through soil. As such, higher permeability's (up to 0.05m/day) will provide more suitable conditions for effluent renovation.
Moderate Ks = 0.05-0.5 m/day	2	Permeability of water is moderate only required a number of days to dissipate through the soil profile. Soil has a moderate structure with visible pores and channels. Soil permeability is suitable for effluent renovation, providing suitable time for exchange processes to occur reducing the amount of mobile contaminants. However, ability reduces as permeability increases, as higher permeability's will provide only surface exchange sites as water passes more quickly, and not inter-aggregate sites.
High Ks > 0.5 m/day	3	Permeability of soil is high, requiring a few hours to allow water to permeate through the profile. Soil texture is usually sandy, with visible pores and cracks. Soil effluent renovation ability is significantly reduced as the permeability increases.

Drainage	Suitability	Criteria
Rapid	1	Water is drained rapidly, with water moving rapidly to underlying highly permeable material. Soils are coarse textured, or shallow or both. Soil only remains wet for several hours.
Well	2	Water is readily, but not rapidly drained from the soil. Excess water flows vertically with much resistance into underlying moderately permeable material. Soils have a medium texture and remain wet only for several days.
Moderate	3	Drainage of water is moderate, due to a low permeability, lack of gradient or a shallow water table, or a combination of these. Soil are typically coarse-textured and remain wet for approximately only one week
Imperfect	4	Water is drained only slowly, with soils remaining wet for several weeks. Soils may be mottled or possess rusty appearance.
Poor	5	Water is drained very slowly in relation to the supply. Soil horizons may be gleyed, mottled or possess rusty appearances. Soil remains wet for periods of months.
Very Poor	6	Drainage of water is so slow, that water table remains at or near the surface for most of the year.

Overall Soil Suitability for Effluent Renovation

Figure 6 Established framework for soil suitability for effluent renovation

The overall soil suitability scoring for the different soils types in the study area are outlined in Table 6. From these results, Chromosol and Kurosol soils were found to be more suitable for effluent renovation than the Ferrosol and Dermosol soils. However, there was only a minor difference in suitability between the first six soil types, following which a sharp decrease in overall renovation ability was evident. Hydrosol and Vertosol soils were found to provide the worst overall suitability for effluent renovation.

Table 6: Soil Suitability Rankings for Effluent Renovation

Soil Classification	Soil Suitability	Description
Chromosols Kurosols	1	Good renovation ability with medium permeability and well drained soils.
Ferrosols Dermosols	2	Good renovation ability with poor to medium permeability and well drained soil
Kandosols Rudosols	3	Medium renovation ability with medium to high permeability and moderately well drained soil
Podosols Tenosols	4	Low - medium renovation ability with high permeability and poor to moderately well drained soil
Organosols	5	Very good renovation ability with slow permeability and poorly drained soil
Vertosols Sodosols	6	Good renovation ability with slow to medium permeability and poorly drained soil
Hydrosols	7	Low renovation ability with rapid permeability in permanently saturated conditions.

The most important aspect highlighted by the soil suitability framework is that a soil’s ability to both renovate and adequately dispose of discharge effluent is dependent on a number of factors that all need to be considered together. Consequently, along with the soil’s ability for effluent renovation, both permeability and drainage characteristics are also highly significant in determining soil suitability. The permeability values used for assessing soil suitability in the study region with the developed framework considers both rapid and very slowly permeable soils least suitable in renovating wastewater. Accordingly, values higher than 1m/day and lower than 0.001m/day were considered unsuitable and received a zero score. The optimum value which was taken as the median value of the range between the extremes was given a score of 1, with all other values scored on either a *more is better* or *less is better* scenario. Both soil suitability and drainage were assessed using the *more is better* scoring function.

Although the Ferrosol and Dermosol soils were found to be the most capable for effluent renovation, their overall suitability can significantly reduce according to their permeability and drainage classifications. Likewise, for the Chromosol soils, although their renovation ability is slightly less, their overall rating was found to be more suitable than all the other soils. These findings agree with research undertaken by Dawes and Goonetilleke (2003) where it was found that Ferrosol, Dermosol and Chromosol soils provided better treatment of effluent in relation to pollutant attenuation and removal. However, care must be taken with Chromosol soils due to the abrupt textural changes common of this soil type. Soils with high %C can create a restrictive horizon, subsequently reducing infiltration through the soil causing effluent to move laterally. Soils with a restrictive horizon less than 0.4m from the surface do not provide adequate purification of effluent (Dawes and Goonetilleke 2003). This in essence, underlies the need to ensure adequate assessment of the underlying soil conditions before identifying a site as suitable for an OWTS.

Conclusions

The ranking of the various soil types provided a means of assessment of ability for effluent renovation. These rankings, coupled with permeability and drainage soil factors, have been employed to develop a soil suitability framework for siting and designing OWTS. The use of PCA and the multi-criteria decision aids PROMETHEE and GAIA, has enabled correlations between different soil types to be assessed and therefore allowing clusters of soils with similar physico-chemical characteristics to be identified. It is evident from the multivariate statistical analysis that a strong correlation exists between CEC, %C and %OC, which are the primary parameters shown to influence the effluent renovation ability of a soil. The permeability characteristics of different soil types are also significant, as this influences not only how rapidly the discharged effluent percolates through the soil matrix, but also has an important role in the cation exchange and adsorption processes. Likewise, adequate drainage is required for the soil to function as an effluent renovation media. From the developed framework, it was found that although Ferrosol and Dermosol soils have the highest renovation ability, the permeability and drainage characteristics reduced their overall suitability. Chromosol soils were found to have the best overall renovation ability, followed closely by the Ferrosol and Dermosol soils, and the Kurosol, Kandosol and Rudosol soils. The sandy soils were found to have the least ability, with Hydrosols having the least overall renovation ability. However, from the assessment of the three major soil functions in relation to effluent renovation suitability; (1) soil effluent renovation ability, (2) permeability and (3) drainage characteristics, it can be concluded that these characteristics play a major role in the overall suitability rankings. It is necessary for the assessment of site suitability to consider the effects of these primary soil functions, and not predict the soils suitability based on a single soil function.

Acknowledgements

The authors would like to thank Gold Coast City Council and Queensland University of Technology for funding this research project.

References

Adams MJ (1995) Chemometrics in analytical spectroscopy. Springer Verlag, New York

Andrews SS, Karlen DL, Mitchell JP (2002) A comparison of soil quality indexing methods for vegetable production systems in North California. Agriculture *Ecosystems and Environment*, 90: 25-45

APHA (1999) Standard methods for the examination of water and wastewater - 20th Edition. American Public Health Association, American Water Works Association and Water Environment Federation, Washington, DC

Baker DE, Eldershaw VJ (1993) Interpreting soil analyses - for agricultural land use in Queensland. Division of Land Use and Fisheries, Department of Primary Industries, Brisbane

Borden D, Giese RF (2001) Baseline studies of the clay minerals society source clays: cation exchange capacity measurements by the ammonia-electrode method. *Clays and Clay Minerals*, 49:(5) 444-45

Carlon C, Critto A, Marcomini A, Nathanail P (2001) Risk-based characterisation of contaminated industrial site using multivariate and geostatistical tools. *Environmental Pollution*, 111: 417-27

Cattell RB (1966) The scree test for the number of factors. *Multivariate Behavioral Research*, 1: 245-76

Cliver DO (2000) Research needs in decentralised wastewater treatment and management: fate and transport of pathogens. In: National Research Needs Conference Proceedings: Risk-Based Decision Making for Onsite Wastewater Treatment. EPRI, Palo Alto, CA, U.S. Environmental Protection Agency, National Decentralized Water Resources Capacity Development Project, 1001446, pp. 1-31

Dawes L, Goonetilleke A (2003) An Investigation into the role of site and soil characteristics in onsite sewage treatment. *Environmental Geology*, 44:(4) 467-77

Diack M, Stott DE (2001) Development of a soil quality index for the Chalmers silty clay loam from midwest USA. In: Stott DE, Mohtar RH, Steinhardt GC (eds) 10th International Soil Conservation Organisation Meeting, May 24-29 1999, Purdue University, USDA-ARS National Soil Erosion Research Laboratory, pp. 550-55

Edwards DG (1985) Diagnosing toxicity, In: Identification of Soils and Interpretation of Soil Data. ASSSI Qld Branch, Brisbane

Ferreira AJD, Coelho COA, Walsh RPD, Shakesby RA, Ceballos A, Doerr SH (2000) Hydrological implications of soil water-repellency in eucalyptus globulus forests, North-Central Portugal. *Journal of Hydrology*, 231-232: 165-77

Gold AJ, Sims JT (2000) Research needs in decentralized wastewater treatment and management: a risk-based approach to nutrient contamination. In: National Research Needs Conference Proceedings: Risk-Based Decision Making for Onsite Wastewater Treatment. EPRI, Palo Alto, CA, U.S. Environmental Protection Agency, National Decentralized Water Resources Capacity Development Project, 1001446, pp. 1-43

Hagedorn C, McCoy EL, Rahe TM (1981) The potential for ground water contamination from septic tanks. *Journal of Environmental Quality*, 10:(1) 1-8

Hampton MJ, Yahner JE (1984) Cluster systems in a rural lake community. In: Proceedings of the Fourth National Symposium on Individual and Small Community Sewerage Systems, New Orleans, Louisiana, American Society of Agricultural Engineers, pp. 165-68

Harper RJ, McKissock I, Gilkes RJ, Carter DJ, Blackwell PS (2000) A multivariate framework for interpreting the effects of soil properties, soil management and landuse on water repellency. *Journal of Hydrology*, 231-232: 371-83

Harris PJ (1995) Water quality impacts from on-site waste disposal systems to coastal areas through groundwater discharge. *Environmental Geology,* 26:262-68

Hartmann A, Gräsle W, Horn R (1998) Cation exchange processes in structured soils at various hydraulic properties. Soil and Tillage Research, 47: 67-72

Hoxley G, Dudding M (1994) Groundwater contamination by septic tank effluent: two case studies in Victoria, Australia. In: Proceedings of the Conference Water Down Under '94, Adelaide, Australia, pp. 145-52

Isbell RF (1996) The Australian Soil Classification. CSIRO Publishing, Collingwood, Victoria, Australia

Karlen DL, Wollenhaupt NC, Erbach DC, Berry EC, Swan JB, Eash NS, Johdahl, JL (1994) Crop residue effect on soil quality following 10-years of no-till corn. *Soil and Tillage Research*, 31: 149-67

Keller HR, Massart DL, Brands JP (1991) Multicriteria decision making: a case study. *Chemometrics and Intelligent Laboratory Systems*, 11: 175-89

Khalil WA, Goonetilleke A, Kokot S, Carroll S (2004) Use of chemometric methods and multicriteria decision-making for site selection for sustainable on-site sewage effluent disposal. *Analytical Chimica Acta*, 504: (1) 41-56

Kokot S, Grigg M, Panayiotou H, Dong Phuong T (1998) Data interpretation by some common chemometrics methods. *Electroanalysis*, 10:(16) 1081-88

Krumbein WC, Monk GD (1943) Permeability as a function of the size parameters of unconsolidated sand. *Transaction of the American Institute of Mining, Metallurgical and Petroleum Engineers*, 151: 153-63

Massart DL, Vandeginste BGM, Deming SM, Michotte Y, Kaufman L (1988) Chemometrics - a text book. Elsevier, Amsterdam

McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins, MS (1998) Australian soil and land survey - field handbook, 2nd Edition. Canberra, Australia

NRCS (1999) Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys - 2nd edition. Agriculture Handbook No.436, United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC

O'Keefe N (2001) Accreditation of on-site wastewater treatment systems - installation and maintenance personnel. In: Patterson RA, Jones MJ (eds), Proceedings of On-Site '01 Conference: Advancing On-Site Wastewater Systems, Armidale, Lanfax Laboratories, pp. 295-99

Paul JH, Rose JB, Jiang SC, Zhou X, Cochran P, Kellogg C, Kang JB, Griffin D, Farrah SA, Lukasik J (1997) evidence for groundwater and surface marine water contamination by waste disposal wells in the Florida Keys. *Water Research*, 31:(6) 1448-54

Rayment GE, Higginson FR (1992) Australian laboratory handbook of soil and water chemical methods - Australian soil and land survey handbook. Inkata Press, Sydney

Shaw RJ, Coughlan KJ, Bell LC (1998) Root zone sodicity, In: Summer ME, Naidu R (eds), Sodic Soils: Distribution, Properties, Management and Environment Consequences., Oxford University Press, New York

Siegrist RL (2001) Advancing the science and engineering of onsite wastewater systems. Onsite Wastewater Treatment. In: Mancl K (ed) Proceedings of the Ninth National Symposium on Individual and Small Community Sewage Systems, St Josephs, MI, ASAE, pp. 1-10

Siegrist RL, Tyler EJ, Jenssen PD (2000) Design and performance of onsite wastewater treatment soil adsorption systems. In: National Research Needs Conference Proceedings: Risk-Based Decision Making for Onsite Wastewater Treatment. EPRI, Palo Alto, CA, U.S. Environmental Protection Agency, National Decentralized Water Resources Capacity Development Project, 1001446, pp. 1-48

The MathWorks Inc. (2002) MATLAB Ver6.5 Release 13, The MathWorks, Natick, MA

US EPA (1997) Response to Congress on use of decentralized wastewater treatment systems. United States Environmental Protection Agency, EPA 832-R-97-001b

Vance WH, McKenzie BM, Tisdall, JM (2003) The stability of soils used for cropping in Northern Victoria and Southern New South Wales. *Australian Journal of Soil Research*, 40:(4) 615-24

Visual Decision Inc. (1999) Decision Lab 2000 Executive Edition, Visual Decision Inc., Montreal, Quebec, Canada

Yates MV, (1985) Septic tank density and ground-water contamination. *Ground Water*, 31:(6) 884-89