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**DAWES, L and GOONETILLEKE, A (2005) Using multivariate analysis to predict the behaviour of soils under effluent irrigation. *Water, Air and Soil Pollution*.**

**Abstract:**

Onsite wastewater treatment systems aim to assimilate domestic effluent into the environment. Unfortunately failure of such systems is common and inadequate effluent treatment can have serious environmental implications. The capacity of a particular soil to treat wastewater will change over time. The physical properties influence the rate of effluent movement through the soil and its chemical properties dictate the ability to renovate effluent. A research project was undertaken to determine the role that physical and chemical soil properties play in predicting the long-term behaviour of soil under effluent irrigation and to determine if they have a potential function as early indicators of adverse effects of effluent irrigation on treatment sustainability. Principal Component Analysis (PCA) and Cluster Analysis grouped the soils independently of their soil classifications and allowed us to distinguish the most suitable soils for sustainable long term effluent irrigation and determine the most influential soil parameters to characterise them.

## 1. Introduction

Approximately 17% of the Australian population, or more than two million people, are not serviced by reticulated sewerage facilities (O’Keefe 2001) and rely wholly on on-site systems for the treatment and disposal of domestic wastewater. In the United States this percentage is over 25% (Seigrist and Van Cuyk 2001). Septic tanks are by far the most common form of onsite wastewater treatment and the associated sub-surface effluent disposal area is a crucial part of the treatment train. The treatment efficiency of the soil disposal area and the adjoining buffer zones are essential to prevent the contamination of surface and groundwater resources by sewage effluent (Dawes and Goonetilleke 2003). 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 depends mainly on the underlying soil to renovate and transmit the discharged effluent. The consequences of exposure to inadequately treated effluent from onsite systems include serious environmental and public health impacts (Cliver 2000).

Despite the seemingly low technology of septic systems, failure is common. In many cases this can lead to adverse public health and environmental impacts (Whitehead and Geary 2000). Onsite wastewater treatment systems have traditionally relied on soil properties to remove contaminants as effluent percolates through the soil. Soil can be an excellent treatment medium provided it has appropriate physico-chemical characteristics and the duration of effluent/soil contact is sufficient. However the ability of the soil to purify effluent is not completely understood. Numerous researchers (for example Levine et al. 1980; Brouwer and Bugeja 1983; Schipper et al. 1996; Seigrist and Van Cuyk *et al*. 2001; Whitehead and Geary 2000) have noted the current lack of in-depth knowledge of the processes taking place within the soil matrix. In determining site suitability for effluent irrigation, 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 factual overview of its suitability for a particular purpose (Diack and Stott 2001). There is a crucial need for more scientifically rigorous procedures for assessing soil behaviour under sewage irrigation.

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

The complexity and large amount and variance of environmental data sets limit the use of univariate statistical methods for the assessment of a soils ability to remove contaminants. Multivariate statistical methods are able to detect similarities between variables and allow a more profound interpretation of relevant data (Gallego et al., 2002; Einax and Soldt, 1998: Carlon et al., 2001). Relationships between several variables can be examined by means of multivariate analysis methods such as Principal Component Analysis and Cluster Analysis. These techniques are able to identify similarities in the data and can assist in characterising suitable soils for effluent disposal which otherwise would be extremely difficult to detect using univariate statistical methods. In the research study undertaken, multivariate statistical methods were utilised to evaluate the changes to physico-chemical properties of common sub-tropical soils of South East Queensland under sewage effluent irrigation and to determine their long-term effluent treatment capabilities.

## 2. Materials and Methods

### *Site selection and sampling*

A total of 34 study sites were selected in the urban fringe of the local government areas of Brisbane and Logan City Councils in Queensland State, Australia. This region is currently undergoing significant urbanisation with the development of extensive rural residential allotments which are not serviced by reticulated sewerage facilities. A representative sample of study sites having septic tanks and sub-surface effluent disposal areas was selected for detailed investigations. The site selection was based on the proportionate area of urban development in the region and distributed across different sub-tropical soil types common to southeast Queensland together with a mix of system ages. The slope of the effluent disposal fields varied from relatively flat (<5% slope) to significantly sloping (>15% slope).

Homogeneous paired soil samples were collected from each site. This 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. 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. Five sites were subsequently rejected due to insufficient soil water samples and/or lack of reliable historical information about the system and site. Site and soil classification and site details for the sample sites are given in Table 1.

**Table 1 – Site and soil classification**

*Soil analysis*

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 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 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 and were air dried, ground and then sieved to 2mm particle diameter and sub-sampled for pH, electrical conductivity (EC), concentration of chlorides in a 1:5 soil: water suspension, exchangeable cations using displacement with $NH_4Cl$ and analysed by Inductively Coupled Plasma (ICP), concentration of chlorides and nitrates in aqueous solution by colorimetry. Parameters such as exchangeable sodium percentage (ESP), Ca:Mg ratio, clay activity ratio (CCR), cation exchange capacity (CEC) and effective cation exchange capacity (ECEC) were derived from the measured data.

Additionally, the electrochemical stability index (ESI) which is calculated as $EC_{1:5}$ divided by ESP was also derived. ESI (critical value below 0.05) is used in land use management as a tool for determining soil structural stability diagnosis in conjunction with ESP (Hughes, 1999). Soil texture and drainage class was measured by the field method outlined by McDonald et al. (1990). 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.

*Classification of soil and sampling sites*

Soil samples collected were classified, noting features such as parent material and profile description. Soil profile descriptions including colour, texture, structure and biological activity were recorded in depth increments of 100mm. The soil types located throughout the region have been classified according to the Australian Soil Classification (Isbell 1996). The dominant soils were Red and Brown Chromosols, which generally exhibit a strong texture and contrast between the A and B horizons.

Site conditions such as topography, slope and drainage characteristics were described in detail at the soil sampling points. Insitu drainage information collected included the presence of preferential flow paths and redoximorphic features. Additionally, information on water table depth, presence of effluent flows, depth to soil horizons and depth to the impermeable soil layer were recorded. This information was utilised in establishing site failure mode as shown in the site diagnosis given in Table 2.

**Table 2 Failure Diagnosis of sites**

Detailed assessments of the sites were 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. Table 2 lists the failure diagnosis for sites classified in terms of type of design boundary failure (USEPA, 2002). At the time of sampling, the remaining 19 sites were classified as showing satisfactory treatment performance.

*Statistical analysis*

Prior to multivariate analysis, some univariate statistical analysis was initially undertaken to evaluate the variability in the sampling and to detect any anomalies that could distort the final outcomes. Univariate methods are more appropriate when one variable is systematically measured for numerous samples. Multivariate analysis tools give a better understanding of the soil ecosystem processes which necessitates collection of various properties (Sena et al., 2002).

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 (Wold et al, 1987, Massart et al, 1988, Adams 1995;). PCA has been used extensively for various applications related to soil quality and contamination. As examples, Critto et al. (2003) used PCA and kriging techniques for the analysis of data in characterisation of soil and groundwater surrounding an illegal landfill site. 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.

Unsupervised methods of multivariate statistics such as principal component analysis (PCA) and fuzzy k-means cluster analysis (FCA) take into account the correlations among several variables that are simultaneously analysed, thus allowing interpretation of better summarized information. In cluster analysis, data points are split into a given number of groups. In the conventional hierarchical approach each case is completely allocated to a single cluster, thus assuming well defined boundaries between clusters. The fuzzy approach calculates the similarity of a case for all clusters. Therefore gradual changes between clusters can be described. Soil composition depends on many geological and environmental processes producing gradual transitions between soil types and a wide range of contamination stages. The fuzzy approach traces these gradual changes and is considered more appropriate than the conventional approach (Hanesch et al. 2001).

All raw data used in the PCA analysis was subjected to pre-treatment in order to remove or reduce irrelevant sources of variation or ‘noise’ which may interfere in the analysis (Einax 1998). Firstly, the raw data was log transformed to reduce data heterogeneity. Following this, the transformed data was column-centred (column-means subtracted from each element in their respective columns) and standardised (individual column values divided by the column standard deviations).

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. The analysis undertaken included principal component analysis (PCA) and fuzzy cluster analysis (FCA). PCA was undertaken on the transformed data to identify possible soil patterns or clusters. Correlations between selected variables were also obtained allowing identification of the most important parameters when characterising soil behaviour under effluent irrigation. The analysis was performed using MATLAB 6.5 Release 13 (The Mathworks Inc 2002). The variables investigated included, pH, EC, chloride concentration (Cl), exchangeable cations $Ca^{2+}$ (eCa), $Mg^{2+}$ (eMg), $Na^{+}$ (eNa), and $K^{+}$ (exK), CEC, Ca:Mg (C:M), ESI, ESP, CCR and percentage clay (%Cl) and depth to restrictive horizon (Res) on observed treatment performance, drainage class, sodicity, soil type and type of clay.

## 3. Results

### *Soil and Site Characteristics*

Table 3 reports the clay type, dominant mineralogy and general characteristics, namely pH, Electrical conductivity and chemical properties of the soils at the top of the B horizon. As most subsurface effluent disposal trenches in Australia are excavated to a depth of 450mm, the soil most predominant in renovating effluent is typically contained in the B horizon. Additionally it is the B horizon which will control the flow of effluent through the soil.

The 29 sites investigated in this study fell into six soil orders (Australia Soil Classification, Isbell 1996) and comprised a range of textural classes ranging from loamy sand to heavy clays. These six 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. Most of the soils were acidic to neutral except for soil BS1 (pH 7.5) which was slightly alkaline.

**Table 3 Soil Characteristics at top of B horizon**

### *Principal component analysis*

The principal component analysis of the physico-chemical data for all soils resulted in 73% of the data variance being contained in the first two components. Therefore, the first two principal components (PC) were retained. This was based on the Scree test (Cattell 1966) where the first two PC’s were shown to be significant with the remaining components considered to only contribute ‘noise’ to the overall data variance. Figure 2(a) and 2(b) provides a scores and biplot of the PCA analysis for all soils in both A and B horizons using the first two principal components. 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. Vectors situated closely together represent variables that are highly correlated while orthogonal vectors represent variables that are uncorrelated.

**Figure 2(a) Scores plot of all soil samples**

**Figure 2(b) Biplot of PC1 vs PC2**

### *Correlations and contrasting variables*

The combined plot of scores and loadings (Figure 2(b)) (Biplot) shows the relationship between particular soil types and the variables analysed. If a variable is close to an object, it will have a high direct influence on it. 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). It is noteworthy that 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 2(b) where the cluster of A horizon soils are orthogonal to CEC vector. Soils that retained a high CEC value fell positively on PC2, consistent with the samples retaining higher exchangeable Ca values and to a lesser extent with pH. The depth to restrictive horizon was uncorrelated with all other variables as expected.

The PC loadings, the lines in Figure 2(b), show that PC1 is closely associated with the soil parameters of %Clay (%Cl), exchangeable sodium percentage (ESP), exchangeable sodium content (eNa) and chloride concentration (Cl). The second component, PC2 however, is more closely associated with the chemical parameters of exchangeable calcium (eCa) and clay activity ratio (CCR). Figure 2(b) also shows the relationship between particular soil horizons and the different variables analysed. Appropriately, %clay is correlated with the heavier clay soils Sodosols and some Kurosol groups. CCR is shown to be highly correlated with the soils having high smectite clay. These soils include Kandosols and Red Chromosols. Smectite clays have higher adsorption ability and exhibit a higher CEC value.

The major findings determined from the principal component analysis are the clusters developed between soils that retain similar properties and characteristics, as depicted in the PCA biplot of B horizon soils (Figure 3). By confining the multivariate analysis to B Horizon soils, the major soil clusters developed through the PCA and Cluster analysis include:

[1] High CEC soils including Kandosol and Red Chromosol soils,
[2] High clay percentage soils with high exchangeable sodium content Sodosol and Chromosol soils
[3] Low CEC soils including Kurosol and Chromosol soils.

The Kurosol soils are widely scattered, having a much higher variance on PC1 than other soils. Correlations between specific soil clusters and the variables can also be identified in the PCA biplot. CEC, exchangeable $Ca^{2+}$ are highly correlated within cluster [1], and the %clay, exchangeable sodium percentage, exchangeable sodium content, electrical conductivity and chloride concentration is highly correlated within cluster [2]. Cluster [3] exhibits low cation exchange capacity (CEC) and does not correlate with any variable.

**Figure 3 Biplot PCI vs PC2 B Horizon soils**

## 4. Discussion

*Role of exchangeable cations in effluent disposal*

Soil cation exchange capacity is a measure of the negative electrical charge available to hold nutrients on the soil particle surface. The interaction of these surfaces with water and species dissolved in water are most critical for soil behaviour. Cations are positively charged and soil storage occurs largely by adsorption on the negatively charged soil surfaces. There is a continual process of adsorption/desorption taking place with similar cations held in solution. These cations are referred to as exchangeable cations. In the case of the exchangeable cations in a soil being predominantly $Ca^{2+}$ or $Mg^{2+}$, the clay particles interact or repel each other only to a limited extent and as such the particle separations are not large. However, when the proportion of $Na^{+}$ ions is appreciable, considerably greater swelling is encountered. This leads to a diminution of the favourable characteristics conferred on a soil by its macroporosity (Quirk 1971). Emerson (1983) supports these findings noting that exchangeable $Ca^{2+}$ has the important effect of flocculating individual clay particles and imparting a stable structure to the soil through interparticle and interaggregate bonds. This structure creates pore space that allows the movement of water and air through the soil.

Principal component analysis and Cluster analysis of the soil characteristics distinctly separated the soil samples in the B horizon based on their exchange capacity and sodicity. The soils in cluster [1] consist of smectite type clays (CCR >0.8) (Baker and Eldershaw 1993).This was confirmed by X Ray diffraction analysis. These soils are co-dominated by exchangeable $Ca^{2+}$ and $Mg^{2+}$ over exchangeable $Na^{+}$ and provide greater cation exchange capacity and therefore adsorption characteristics. These soils also exhibit high Ca:Mg ratio which indicates cation distribution, particularly in the case when the subsoil is dominated by $Mg^{2+}$. An excess of one cation may inhibit the uptake of another. Emerson (1977) found that Ca:Mg ratios less than 0.5 are associated with soil dispersion. This is supported by Shaw et al. (1994) who postulated that low Ca:Mg ratios in conjunction with high ESP indicate enhanced dispersion. All soils in cluster [1] exhibit these characteristics.

Cluster [2] consists of mainly mixed mineralogy soils that exhibit a co-dominance of exchangeable $Na^{+}$and $Mg^{2+}$ over exchangeable $Ca^{2+}$. When sodium dominates the exchange complex of the clay, the width of the diffuse double layer increases. This allows the repulsive forces between the clay colloids to dominate and gives soils a greater tendency to disperse (Sumner 1993). Magnesium has a great affinity for water with the hydration energy of magnesium being 20% higher than for calcium. Thus magnesium dominant soils also have a tendency to disperse (Bakker et al.1973). Curtin et al. (1994) in a study of prairie soils in Canada found that these soils had a stronger tendency to accumulate exchangeable $Na^+$when $Mg^{2+}$ was the complimentary cation. In this study exchangeable $Mg^{2+}$ has a significant effect on cluster [2] soils signified by its positive correlation with PC1 in Figure 3. This cluster corresponds to all hydraulically failed soils as described in site failure diagnosis in Table 2.

Soils in cluster [3] are predominately kaolinite clays with very low CEC. Having low CEC mostly less than 6 meq/100g will not favour large scale changes in exchangeable cation composition. Kaolinite clays are least sensitive to a physico-chemical response, while illite and mixed mineralogy soils are most sensitive to sodium (Shaw 1998).

The most significant aspect highlighted 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 long-term application of effluent and whether any immobilised nutrients will gradually be leached from the soil. For example clay soils can be quite stable even with high ESP, balanced by low pH (<5.0), organic content, co-domination of $Ca^{2+}$ and $Mg^{2+}$. Drainage characteristics and landscape position can also play an important role. This has been discussed in detail elsewhere (Dawes and Goonetilleke 2003).

### *Sodic soils in effluent disposal*

There is much debate about the establishment of a critical ESP threshold for soil structure degradation which would cause the blocking of water conducting soil pores with dispersed clay particles, leading to reduced water and air movement. Numerous researchers have characterised sodic soils as having an exchangeable sodium percentage of at least 6% in the Australian environment (Northcote and Skene, 1972 and Ford et al. 1993). However, Sumner (1993) and Balks et al. (1998) concluded that there is considerable uncertainty about the value at which ESP becomes hazardous. Balks et al. (1998) found that continued irrigation with wastewater will result in an increase in soil sodicity. This increased sodicity will result in an increased tendency of the soil to disperse for all soil textures. Thus the value of 6% ESP should not be taken absolutely as other factors such as pH, clay mineralogy, clay content and organic matter may enhance or limit the soils potential to disperse.

Principal component analysis of the soil characteristics separated the soil samples in the B horizon between those classified as sodic and non-sodic based on the commonly used criteria of ESP of at least 6%. Figure 4 shows differentiation between sodicity classes for the same data shown in Figure 3. The biplot indicates that sodic soils have a higher ESP, EC, exchangeable sodium content, chloride concentration and clay content with non-Sodic soils being characterised by low exchange capacity and dominance of kaolinite clay. These findings agree with previous research that sodium has a direct effect on the ESP of soils giving the soils a greater tendency to disperse (Sumner 1993, Vance et al. 2002). Crescimanno et al. (1995) suggested that a continuum may exist between soil structural properties and ESP, with an ESP as small as 2 – 5% causing adverse effects if low electrolytic concentrations are present in the soil solution.

**Figure 4 PCI vs PC2 B Horizon soils Sodic/Non-Sodic soils**

It is difficult to define between sodicity classes in Figure 4 and not all sites, classified as being below ESP 6% were diagnosed as having failed hydraulically in terms of treatment performance under effluent irrigation (Table 2). Further exploration of soil degradation was required to predict how a particular soil will behave under long-term effluent irrigation. Investigating the entire soil profile in sites BC4 and BC12 where hydraulic failure was diagnosed, the B2 horizon was found to have ESP values of 8% and 10% respectively. This implies that ESP has reached equilibrium in the upper soil layers but will continue to increase at greater depths with further irrigation. Figure 5 confirms this and clearly shows the cluster of B horizon soils that exhibit some form of soil degradation as a result of continuous sewage effluent irrigation. Thus it is possible to predict which soils are likely to fail hydraulically in terms of clay content, electrical conductivity and exchangeable $Na^+$ content.

**Figure 5 PCI vs PC2 B Horizon soils Sodic soils**

## 5. Conclusions

Principal Component Analysis is a reliable and versatile tool for characterising a soil’s ability to adequately treat of sewage effluent. The PCA and Cluster analysis interpretation based on the physical and chemical properties of soils provides a new insight into the long-term prediction of soil behaviour under effluent disposal. The study enabled the detection of similarities or differences between soils and correlations among properties that were clearly not visible from the examination of the analytical data in the tables where few differences in specific properties were noted. Thus, multivariate statistical methods provide the ability to differentiate the most suitable soils for long-term effluent irrigation and to determine the most influential soil properties in order to characterising them.

The major consequences of wastewater irrigation are that sodium can induce changes in soil properties with the likelihood of soil ESP increase, leading to decreased permeability of water through the soil and subsequent hydraulic failure. The type of clay and clay content along with electrical conductivity and exchangeable sodium content have the potential to be used as possible indicators of soil degradation under effluent irrigation. As the chemical properties can be measured in the field by portable instruments, these properties would be useful in determining the most suitable soils for sustainable effluent irrigation and their long term behaviour. These parameters would also help in predicting gradual adverse changes in other soil properties such as hydraulic conductivity, leaching of nutrients and structural integrity of the soil. By identifying soil properties that are sensitive to minor changes can ensure that continued effluent irrigation is sustainable in the long-term and will not eventually lead to soil degradation.

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