RISK-BASED APPROACH TO ON-SITE WASTEWATER TREATMENT

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Abstract

On-site wastewater treatment system siting and design has commonly been based on site specific conditions with little regard to the surrounding environment or the cumulative effect resulting from clusters of systems. The numerous cases of poor treatment performance of on-site systems reported over the years highlight the need for a risk-based approach underpinned by strong scientific knowledge for the management of on-site wastewater treatment systems.

A study is being conducted in the Gold Coast City region in collaboration with the Gold Coast City Council for the development of an integrated risk based approach for the siting, design and management of on-site wastewater treatment systems. The inclusion of relevant stakeholders through a series of workshops during various phases of project development has been crucial for the development of the risk assessment process. An initial risk zoning of the region was developed based on the integration of scientific and qualitative data relating to the themes; soil suitability for effluent disposal, planning criteria and environmental sensitivity. This entailed the development of an appropriate framework for the integration of these diverse qualitative and quantitative data. The use of multivariate statistical techniques such as Principal Component Analysis and multicriteria decision making aids such as PROMETHEE and GAIA enabled the finding of significant correlations and patterns between selected soil physical and chemical data. The initial risk zones thus developed have subsequently undergone a series of refinements based on the outcomes of comprehensive soil analysis. The availability of risk zoning in terms of on-site wastewater treatment would assist the Gold Coast City Council in land development planning and the development of appropriate strategies to ensure improved management of on-site wastewater treatment. Investigations into nutrient and microbiological contamination of ground and surface waters are currently being conducted to develop risk assessment frameworks for environmental and public health factors. Subsequently, the developed soil suitability framework will be combined with the environmental and public health assessment frameworks to develop an integrated risk assessment process for on-site wastewater treatment systems.

Keywords

Risk, on-site wastewater treatment, effluent renovation, soil suitability

Introduction

Over the last few years there has been increasing recognition that on-site wastewater treatment systems (OWTS) are in fact treatment systems, providing a means of dispersing treated wastewater back to the environment or recycling it in a manner that protects both public health and the environment. However, there is concern that these systems are not providing the necessary treatment expected of them. Numerous cases of poor performance of on-site systems have been reported in recent years which can be primarily attributed to unsatisfactory soil and siting conditions (Goonetilleke *et al.* 2002, Siegrist *et al* 2000). Traditionally on-site wastewater treatment system siting, design and management have been based on site specific conditions with little regard to the surrounding environment or the cumulative effect of clusters of systems. The primary intent of the AS/NZS 1547:2000, which is a performance based approach to system design, is being undermined by the continuation of prescriptive practices.

The move towards risk-based assessment should be the next logical step for the siting, design and management of OWTS. This will enable the application of a scientifically based framework for the assessment of environmental and public health risks, as well as a means of assessing the treatment performance of OWTS. The process requires an assessment at the site-specific (individual OWTS assessment) and generic (assessment of multiple OWTS) risk assessment levels in order to identify and characterise the inherent hazards and formulate management strategies to mitigate the possible consequences (Siegrist *et al.* 2000). The hazards resulting from poor OWTS treatment performance, such as contamination of the receiving environment and potential disease outbreaks are of importance, and an appropriate means of assessing the risks imposed by these hazards is vital.

The integrated risk assessment process to be developed will incorporate all OWTS types, both primary and secondary. However, the focus of this paper only considers the more common septic tank-soil absorption systems. The soil plays a crucial role in the treatment of discharged effluent, and the current regulatory procedures to evaluate land capability can be inadequate (Siegrist *et al.* 2000). The development of a soil suitability framework for effluent renovation based on multivariate data analysis is outlined in the paper. Investigations into nutrient and microbiological contamination of ground and surface waters are currently being conducted to develop risk assessment frameworks for environmental and public health factors. The development of a risk assessment framework for the siting and design of OWTS which encompasses soil suitability, environmental and public health risks is currently on-going, and subsequently these will be integrated into a single framework.

Project Area

The project area consists of the area under Gold Coast City Council (GCCC) jurisdiction, situated in Southeast Queensland, Australia, covering approximately 1500 km^2. The region has approximately 14500 OWTS with a majority of these systems being common septic tank-soil absorption systems. Large clusters of OWTS exist in various locations throughout the area, and the cumulative effect as a result of these large clusters has become a major concern. Being a major tourist location and with numerous environmentally sensitive areas situated throughout the region, the issues and consequences resulting from the poor performance of OWTS has led to the need for developing a more robust approach to siting, design and management. The inclusion of relevant stakeholders through a series of workshops during various phases of project development, particularly in identifying areas of high concern relating to OWTS, has been crucial for the development of the risk assessment process.

Risk Zoning

A preliminary risk zoning of the GCCC region was initially undertaken to identify areas of possible high risk as a result of poor system performance. These risk zones were established based on three main criteria identified through the Council and relevant stakeholders viz [1] Soil Suitability for effluent renovation, [2] Planning, and [3] Environmental Sensitivity. Table

1 outlines the specific criteria established for the development of the initial risk zones. The criteria adopted a qualitative approach to develop the risk zones. Initially, soil suitability was evaluated based on the drainage characteristics of the various soil types in the Gold Coast region as outlined in the Australian Soil Classification (Isbell 1998; Isbell *et al.* 1997; McDonald *et al.* 1998). Planning criteria was based on the allowable lot size as specified in the Town Plan. Environmental sensitivity was based on the current regulatory setback distances outlined in AS1547:2000 and the *'Onsite Sewerage Code'* (DNR 2002). However, these distances were increased to allow for high densities of systems. The criteria were ranked using a simple linear ranking method and an initial risk zoning scheme was identified. These zones have subsequently been refined as more data and analytical results become available.

Table 1: Initial criteria developed for risk zones

Soil Criteria		
Risk	Criteria	Implication
High	• Soils that have imperfect or poor drainage ability • Hydrosol Soils; soils that are seasonally or permanently saturated	• Soils that have poor drainage inhibit the disposal of effluent through the soil, which reduces the soils renovation ability. • Hydrosol soils, although generally well drained sandy soils, are saturated, making drainage poor.
Medium	• Soils that are moderately well drained • Anthroposols (man-made soils) and soils which have been altered	• Moderately well drained soils allow slow drainage, which can affect the soils renovation ability
Low	• Soils that are well drained	• Soils that have good drainage, increase its ability to renovate effluent

Planning Criteria		
Risk	Criteria	Implication
High	• Less than 0.4 Ha • Urban residential areas developed for high-density housing which are provided with reticulated water, but utilise on-site wastewater systems	• Minimum lot size for developments in these residential areas must not be less than: 1. Residential -400m^2 2. Detached dwellings-600- 2000m^2 3. Village -600m^2 4. Hinterland subdivision -4000m^2
Medium	• 0.4 to 4 Ha • Park Living residential areas developed for low-density housing with reticulated water and utilise on-site wastewater treatment	• Lot sizes must not be less than 4000m^2 minimum and no larger than 4 Ha
Low	• Greater than 4 Ha • Rural residential areas utilising both on-site wastewater treatment and water supplies	• Rural residential areas with lot sizes greater than 4 Ha, with maximum lot sizes up to 20 Ha
Sewered	• Urban residential areas with high density housing with both reticulated water and sewerage	• Research not required in this area.

Environmental Sensitivity Criteria		
Risk	Criteria	Implication
High	• Less than 100m from nearest water source	• Greater risk of contamination of surface water resources from both surface and subsurface flow.
Medium	• Between 100 and 500m from nearest water source	• May impose some risk of contamination from surface and subsurface flow, more likely surface flow.
Low	• Greater than 500m from nearest water source	• Minimum risk of contamination of water resources.

Soil Sampling and Testing

Detailed scientific investigations were conducted to evaluate soil suitability for effluent renovation. Soil information was collected from 28 sampling sites within the GCCC region and supplemented with soil data collected during previous studies conducted by Queensland University of Technology (QUT). The sampling sites were selected based on areas that were rated poorly (high risk) in relation to the criteria, as well as to obtain adequate soil data for various common soil types identified in the study area. Soil samples were collected from the

B horizon to a depth of 1200mm which would be representative of the '*zone of influence*' of a typical subsurface treatment field. As subsurface disposal trenches are typically at a depth of approximately 450mm, the soil most predominant in renovating effluent is the B horizon. Samples were extracted by hand auger, and approximately one kilogram of the representative B horizon soil was collected and sealed in marked plastic bags for transport back to the laboratory. Samples were tested for pH, electrical conductivity (EC), chloride (Cl^-), cation exchange capacity (CEC), organic content (%OC), and particle size distribution (for %sand and %clay). Additionally, the CEC/Clay ratio (CCR) (Shaw *et al.* 1998) was calculated from the derived parameters. These parameters have generally been identified as the most indicative of a soil's suitability for effluent renovation.

All soil samples were air dried, ground and sieved to <2mm. pH and EC were measured using a 1:5 soil:water suspension solution with a combined pH/Conductivity meter. Chlorides were analysed by the ferric thiocyanate method using automated colourmetry in a 1:5 soil:water suspension (Rayment and Higginson 1992). CEC was determined saturating all available exchange sites in the sample with ammonia and analysed using the ammonia selective electrode method as described by Borden and Giese (2001). %OC was analysed by oxidising the soil organic matter using 50% hydrogen peroxide, followed by combustion of samples at 1300˚C. Particle size distribution (for %sand and %clay) was determined using a 'Malvern Mastersizer S' particle size analyser following dispersion of the soil with sodium hexametaphosphate and sodium carbonate. CCR was calculated by dividing the CEC value by the %clay (Shaw *et al* 1998). As adequate soil permeability data were not available for most of the soil types, permeability values (k) were assessed based on the formula developed by Krumbien and Monk (1943). This method calculates k from values determined during the soil particle size distribution analysis. The calculated k values were then assessed with the permeability classifications described by McDonald *et al.* (1998) The drainage ability of the soil was established using the drainage classifications developed by McDonald *et al.* (1998) and available soil textural and particle size distribution information.

Data Analysis

Multivariate statistical analysis was undertaken in order to estimate correlations between various soil types and relevant soil physical and chemical data derived from the soil sampling and testing. This approach underpins one of the most important issues that need to be taken into consideration in the context of siting and design assessment techniques for OWTS. A single soil parameter, such as soil permeability cannot provide an accurate depiction of soil suitability. However, a range of soil parameters when considered together such as in multivariate analysis can provide a more accurate representation of soil suitability (Diack and Stott 2001). The collected soil information was assessed employing multivariate statistical techniques including Principal Component Analysis (PCA) and multi-criteria decision-making aids, PROMETHEE and GAIA. The results of this analysis was integrated with existing permeability and drainage characteristics classifications as outlined in the Australian Soil Classification (Isbell 1998; McDonald *et al.* 1998)

A PCA was conducted on the soil data to determine which soil types were highly correlated with each other and the selected variables. PCA is a multivariate statistical data analysis technique which reduces a set of raw data into a number of principal components which retain the most variance within the original data in order to identify possible patterns or clusters between objects and variables. Detailed descriptions of PCA can be found elsewhere (Massart *et al.*, 1988, Adams 1995, Kokot *et a.,l* 1998), and therefore will not be discussed in detail. All raw data used in the PCA analysis underwent specific pre-treatment to eliminate spurious sources of variation or *'noise'* from the data which may interfere in the analysis (Adams 1995). Raw data was log transformed to reduce data heterogeneity, column-centred (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 of soil types contained in the soil data, and relevant correlations between specific soil types and the analysed variables.

The results from the PCA were subsequently used to structure the preference functions and threshold information for use with the multi-criteria decision making methods of PROMETHEE and GAIA, analysed with Decision Lab 2000 v1.01 software (Visual Decision Inc. 1999). 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 *et al.* 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 selected preference functions, thresholds and weights adopted by the decision maker (Decision Lab Inc, 2002). For this analysis, all variables were equally weighted to remove any bias from the overall ranking. The resulting PROMETHEE analysis is further defined via GAIA, which provides a diagrammatic representation of the ranking methods of PROMETHEE, utilising a PCA technique.

Results

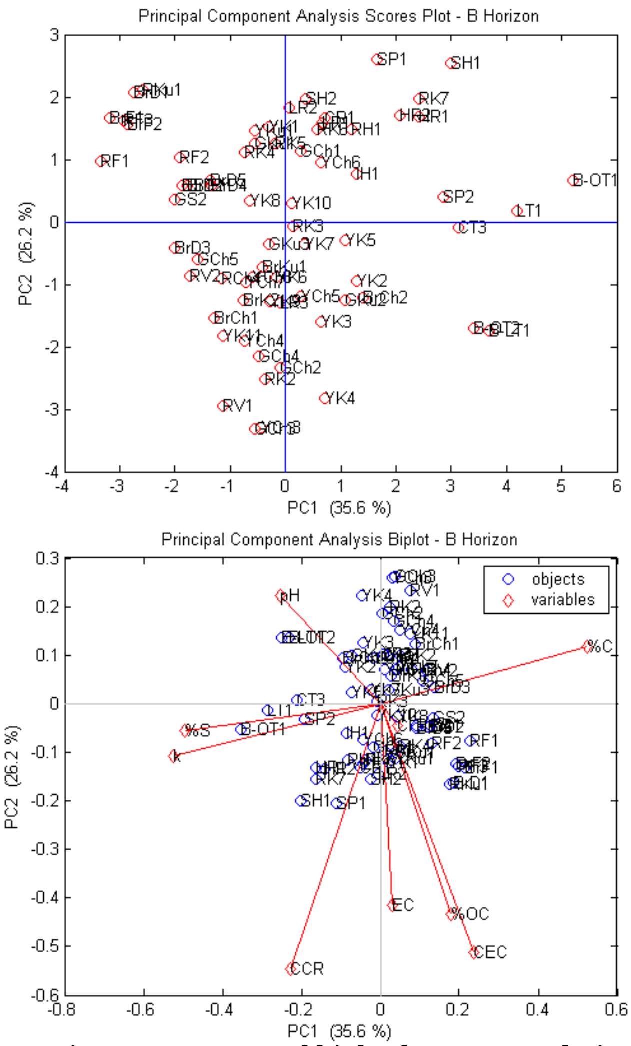

Figure 2: Scores and biplot for PCA Analysis

The PCA of the physico-chemical soil data resulted in 61.8% of the data variance being contained in the first two principal components. Therefore, the first two principal components (PC) were retained for the analysis. Figure 2 provides a scores and biplot of the soil data analysis. The scores and biplot provide a graphical representation of clusters of soils which retain similar physico-chemical properties, represented by the vectors.

From these plots, obvious relationships can be identified between the soils investigated. Soils with higher clay percentages retained positive scores on PC1, with sandier soils falling directly opposite, while soils that retained a high CEC value fell positively on PC2. The loadings of the analysed soils, represented by the eigenvectors, provide an indication of the correlations between the different variables, as depicted in Figure 2. Vectors situated closely together represent variables that are highly correlated while orthogonal vectors represent variables that are uncorrelated. A simple example is where permeability k, is shown to be closely correlated with the %sand, while negatively correlated with %clay. CEC is also highly correlated with EC, Cl^- and OC%. This correlation is driven mostly due to the soils that have significant salts (in this case chlorides) and high CEC levels, such as the Hydrosols. With high levels of Cl^- in the soil, it is obvious that the electrical conductivity will also increase.

The biplot also provides an indication of the relationship between particular soil types and the different variables analysed. As shown in the biplot, %sand and k are highly correlated with the Tenosol soils, as they possess the highest percentage of sand. Likewise, percentage clay is correlated with Ferrosol, Dermosol, Vertosol and Sodosol soils. 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 relatively large CCR values. As CCR is correlated with the clay type, it is possible that the small percentage of clay contained in the Podosol and Hydrosol soils are smectite type clays which have a higher adsorption ability and will therefore produce a higher CEC value. However, as the %clay for these soil types is quite small, <10%, it was decided to disregard the CCR value for these soils, as it is assumed that the small amount of clay will have little impact in the overall soil structure. The scores plot also indicates major clusters of soil that retain similar physico-chemical properties. 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.

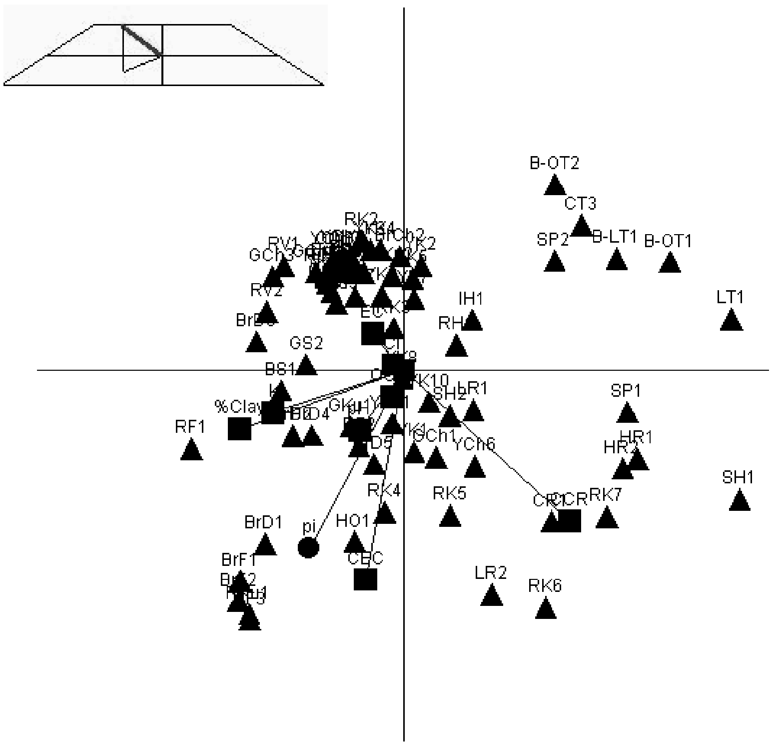

Figure 3: GAIA plot of PROMETHEE analysis of the soil samples

From the PROMETHEE analysis, similar patterns to those identified through the PCA analysis were found. However, some minor variations in these patterns were found and these are related to the various preference functions and threshold values adopted for the analysis. For example, permeability is highly correlated with %clay. Permeability was minimised to account for the fact that low permeable soils are considered to provide higher renovation ability than highly permeable soils (Hartmann *et al.* 1998). Therefore, from the PROMETHEE rankings of the soil data, which was based on the analysis of physical and chemical parameters, specific soil types were shown to be more efficient in terms of effluent renovation than others. The soil clusters developed from the analysis in terms of their ability 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. The GAIA plot shown in Figure 3 provides a graphical representation of the PROMETHEE analysis, which highlights the correlations between analysed variables and also depicts the identified soil clusters. The *Pi* axis shown in the GAIA plot represents the direction of the more highly ranked soils, such as the Ferrosol and Dermosol soils, which highlight soils with a relatively greater ability for effluent renovation.

Development of Soil Suitability Framework and Refined Risk Zones

The developed soil suitability rankings produced from the multivariate analysis and the permeability and drainage characteristics established for the soil classifications were incorporated into a soil suitability framework. The framework provides a means of assessing the soil suitability of a site using a simple standard scoring function (SSF) consisting of either a *less is better* (value is divided by the highest possible value as to receive a maximum score) or *optimum* (mid-point values receives maximum) model (Andrews 2002). This is a semi-quantitative method for establishing a rank for each soil type. Subsequently, the associated rank for the soil's ability for effluent renovation together with permeability and drainage characteristics were merged on an equal weight basis to obtain a soil suitability score.

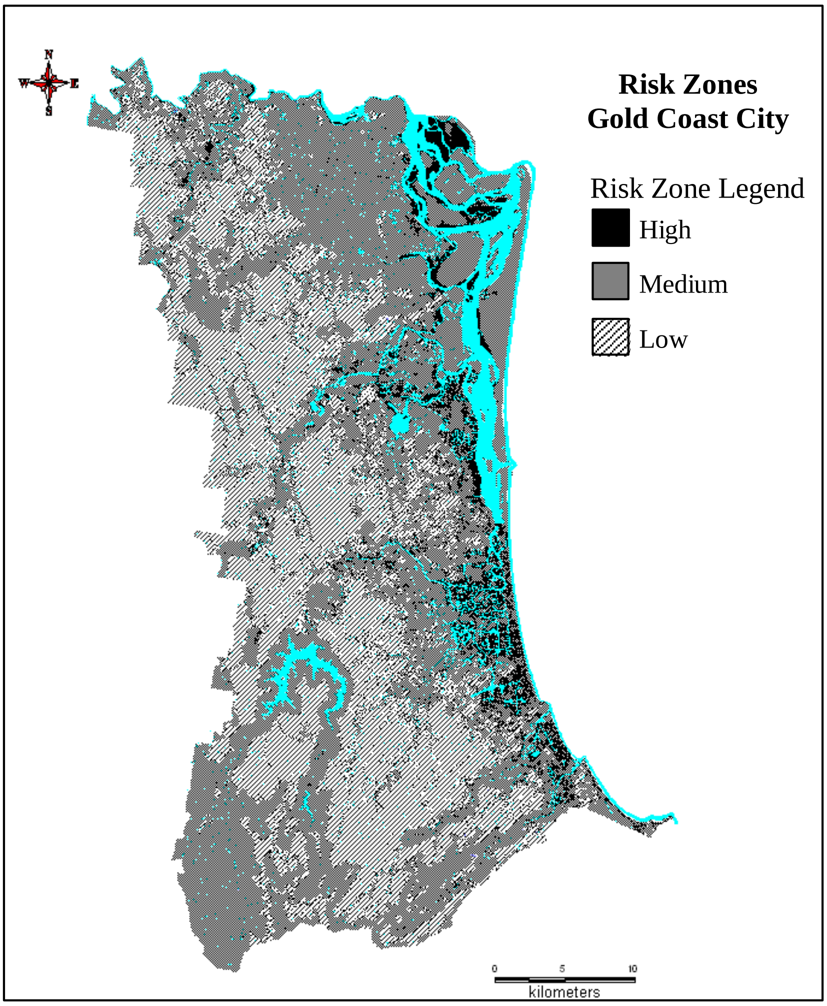

Figure 4: Current risk zone map for Gold Coast

Using the developed framework for the Gold Coast region, the soil types in order of preference for effluent renovation are; [1] Chromosols, Ferrosols and Dermosols, [2] Kandosols, Kurosols and Rudosols, [3] Podosols and Tenosols, [4] Sodosols, [5] Organosols, [6] Hydrosols.

The development of the soil suitability framework then led to the refinement of the soil suitability map, which currently considers three soil functions; renovation ability, permeability and drainage characteristics.

This has also enabled a refined risk zone map to be established. Figure 4 shows the current risk zone map for the Gold Coast region.

Conclusions

The numerous reports of inadequate treatment performance of on-site wastewater treatment systems have led to the need to establish a more robust method for identifying and mitigating the resulting potential hazards. The evolving risk-based approach to on-site wastewater treatment system siting, design and management can be considered as the next improvement to the current standards and codes. The framework developed for the assessment of soil suitability for effluent renovation highlights the importance of identifying and assessing multivariate factors for the siting and design of OWTS. On-going investigations into ground and surface water contamination as a result of poor system performance, combined with the developed soil suitability framework will enable a more generic risk assessment to be undertaken for OWTS. The use of risk zoning in relation to OWTS will enable the Gold Coast City Council to better manage siting and design implications for on-site systems, and to mitigate potential hazards resulting from poor treatment performance.

References

Adams, M. J, (1995) Chemometrics in analytical spectroscopy, Royal Society of Chemistry, Springer Verlag, New York.

Andrews SS, Karlen DL and Mitchell JP, (2002) A Comparison of Soil Quality Indexing Methods for Vegetable Production Systems in North California, *Agriculture Ecosystems & Environment, Vol. 90, No., pp. 25-45.*

Borden, D. and Giese, R. F., (2001) Baseline Studies of the Clay Minerals Society Source Clays: Cation Exchange Capacity Measurements by the Ammonia-Electrode Method, *Clays and Clay Minerals, Vol. 49, No. 5, pp. 444-45.*

Diack, M. and Stott, D. E., (2001) Development of a Soil Quality Index for the Chalmers Silty Clay Loam from Midwest USA, *10th International Soil Conservation Organisation Meeting, Purdue University and USDA-ARS National Soil Erosion Research Laboratory, pp. 550-55.*

DNR, (2002) On-Site Sewerage Code, Department of Natural Resources and Mines, Brisbane.

Goonetilleke, A., Dawes, L. and Biddel, D. (2002) Performance Evaluation of Septic Tanks in the Gold Coast Region, Physical Infrastructure Centre, Queensland University of Technology, Brisbane.

Hartmann, A. Gräsle, W. and Horn, R. (1998) Cation Exchange Processes in Structured Soils at Various Hydraulic Properties, *Soil & Tillage Research, Vol. 47, No., pp. 67-72.*

Hoxley, G. and Dudding, M., (1994) Groundwater Contamination By Septic Tank Effluent: Two Case Studies in Victoria, Australia, *Proceedings of the Conference: Water Down Under '94, Adelaide, Australia, pp. 145-52.*

Isbell, R. F., (1998) The Australian Soil Classification, CSIRO Publishing, Collingwood, Victoria, Australia.

McDonald RC, Isbell RF, Speight JG, Walker J and Hopkins MS. (1998) Australian Soil and Land Survey - Field Handbook, Second Edition, Australian Collaborative Land Evaluation Program, Canberra, Australia.

Keller, H.R., Massart, D.L and Brands, J.P. (1991) Mulitcriteria Decision Making: A Case Study, *Chemometrics and Intelligent Laboratory Systems, Vol. 11, pp. 175-189*

Krumbein, W. C., and Monk, G. D., (1943) Permeability as a function of the size parameters of unconsolidated sand, *Transaction of the American Institute of Mining, Metallurgical and Petroleum Engineers, 151:153-163.*

Massart, D. L, Vandeginste, B.G.M, Deming, S.M., Michotte, Y. and Kaufman, L. (1988) Chemometrics – A Text Book, Elsevier, Amstadam.

Rayment, G. E. and Higginson, F. R., (1992) Australian Laboratory Handbook of Soil and Water Chemical Methods, Australian Soil and Land Survey Handbook Inkata Press, Sydney.

Shaw, R. J. Coughlan, K. J. and Bell, L. C. (1998) Root Zone Sodicity. *In* "Sodic Soils: Distribution, Properties, Management and Environment Consequences" (Summer, M. E. and Naidu, R., Eds.), pp. 95-106. Oxford University Press, New York.

Siegrist, R. L., Tyler, E. J. and Jenssen, P. D. (2000) Design and Performance of Onsite Wastewater Treatment Soil Adsorption Systems, *Proceedings of the National Research Needs Conference: Risk-Based Decision Making for On-Site Wastewater Treatment, Palo Alto, CA, pp.*

Standards Australia, (2000) AS/NZS 1547: Onsite domestic-wastewater management, Standards Australia/New Zealand, Strathfield

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