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Assessing changes in soil physical and chemical properties under long term effluent disposal

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ABSTRACT

On-site 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 of physical and chemical soil properties in the treatment performance of subsurface effluent disposal areas. Monitoring changes in these properties will permit improved prediction of the treatment potential of a soil. The changes within soil properties of the disposal area due to effluent application were found to be directly related to the subsurface drainage characteristics including permeability, clay content and clay type. The major controlling soil physical and chemical attributes were found to be moderate drainage, significant soil cation exchange capacity and dominance of exchangeable Ca or exchangeable Mg over exchangeable Na, low exchangeable Na, clay type and a minimum depth of 0.4m of potentially unsaturated soil before encountering a restrictive horizon. An in-depth knowledge of the local soil characteristics and associated soil hydrology is needed for better prediction of long term behaviour of subsurface effluent disposal systems. The study confirmed that both the physical properties and chemistry of the soil can be valuable predictive tools for evaluating the long term operation of sewage effluent disposal systems.

KEYWORDS: effluent disposal, septic tanks, soil chemistry, subsurface drainage

INTRODUCTION

Approximately 15% of the Australian population, or more than two million people, are not serviced by reticulated sewerage facilities (Whitehead and Geary, 2000) 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 on-site wastewater treatment and the associated sub-surface effluent disposal area is a crucial part of the treatment train. The treatment efficiency of this 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). This is especially of concern in areas where there is a high density of such systems.

Despite the seemingly low complexity of septic systems, failure is common. In many cases this can lead to adverse public health and environmental impacts (Whitehead and Geary, 2000). On-site 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 the duration of effluent/soil contact is sufficient. However the ability of the soil to purify effluent is not completely understood. A number of researchers (for example Whitehead and Geary, 2000, Seigrist and Van Cuyk *et al*., 2001) have noted the current lack of in-depth knowledge of the processes taking place within the soil matrix. This paper presents the outcomes of research undertaken to identify the influential soil properties and their use as predictive tools for evaluating the long-term performance of sub-surface sewage effluent disposal systems.

THE RESEARCH PROJECT

The research project was based in the urban fringe of the local government area of Brisbane City Council in the State of Queensland, Australia. This area is currently undergoing significant urbanisation with the development of extensive rural residential allotments which are not serviced by a reticulated sewerage system. A representative sample of sixteen study sites having septic tanks and sub-surface effluent disposal areas was initially selected for detailed investigations. The site selection was based on the proportionate area of urban development in the unsewered region and located within different sub-tropical soil types common to South East Queensland. Five sites were subsequently abandoned due to the inability to obtain sufficient soil water samples and/or lack of reliable historical information.

Sampling and Site Details

Homogeneous paired soil samples were collected from each site. The soil samples were collected from installed 90 mm diameter piezometer locations at 1 m and 3m downstream from the edge of the subsurface disposal area and from control locations that had not received effluent 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. Site and soil classifications derived are given in Table 1. Detailed soil descriptions were used to qualitatively assess the hydrology of the soil profile. 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 dominant soils were Red and Brown Chromosols, which generally exhibit a strong textural contrast between the A and B horizons (Isbell, 1996). The terrain in the effluent disposal fields varied from relatively flat (<5% slope) to significantly sloping (>15% slope).

Table 1. Sewage effluent disposal area site and soil classification

Site No.	System age (yr)	Australian Soil Classification[a]	Soil Texture[b] A – A horizon B – B horizon	Soil Drainage[c]	Slope (deg.)
1	4	Red Chromosol	A – Sandy loam B – Clay loam	Moderately well drained	>15
2[d]	8	Red Chromosol	Sandy clay loam	Moderately well drained	>10
3	5	Brown Chromosol	A - Sandy loam B – Light Clay	Imperfectly drained	<10
4	3	Brown Chromosol	A - Sandy loam B- Clay loam	Imperfectly drained	<5
5[d]	1	Brown Chromosol	Sandy clay loam	Imperfectly drained	<5
6[d]	11	Red Dermosol	Sandy clay	Poorly drained	<5
7	2.5	Red Chromosol	A - Sandy loam B – Sandy clay loam	Moderately well drained	>10
8	4	Red Sodosol	A - Clay loam B – Heavy clay	Poorly drained	<5
9	17	Grey Sodosol	A – Clay loam B – Heavy clay	Poorly drained	<5
10[d]	14	Red Kandosol	Sandy loam	Moderately well drained	>10
11	4.5	Red Kandosol	A - Sandy loam B – Sandy clay loam	Well drained	>15
12	19	Brown Kurosol	A -Loamy sand B – Sandy clay loam	Moderately well drained	>10
13[d]	16	Brown Kurosol	Loamy sand	Imperfectly drained	<10
14	14	Brown Chromosol	A - Loam B – Medium clay	Moderately well drained	>15
15	3	Red Ferrosol	A - Sandy loam B- Light clay	Moderately well drained	>5
16	4	Red Ferrosol	A - Clay loam B- Medium clay	Poorly drained	<5

a Australian Soil Classification after Isbell (1996)
b soil texture based on McDonald *et al.* (1990)
c the classification used complies with AS/NZS 1547:2000 (Standards Australia, 2000), McDonald *et al*. (1990).
d sites abandoned due to insufficient soil water sample and reliable historical site information

The soil sampling strategy was specifically formulated to focus on the ‘zone of influence’ of a sub-surface effluent disposal field. Detailed soil evaluation was undertaken directly downstream of the disposal field. Soil descriptions were used to qualitatively assess the hydrology of the soil profile. Other parameters recorded included the position of perched and true water tables and duration of saturation.

Site conditions such as topography, slope and drainage characteristics were described in detail at the soil sampling points. Drainage information collected includes the presence of preferential flow paths, redoximorphic features, hydraulic conductivity and porosity. Additionally, information on water table depth, presence of effluent flows, depth of soil horizons and depth to the impermeable soil layer were also recorded. This information was utilised in establishing boundary failures based on USEPA Onsite Wastewater Treatment Manual, 2002, Section 5.8.

Analytical Program

The soil samples were air dried within 24 hours of collection. Each sample was then ground to pass a 2mm sieve and sub-sampled for the following tests: (i) electrical conductivity (EC) and pH in a 1:5 soil:water suspension; (ii) Exchangeable cations using displacement with NH_4Cl and analysed by Inductively Coupled Plasma (ICP);and (iii) concentration of chlorides and nitrates in aqueous solution using colorimetry.

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 and between degraded and non-degraded soil conditions. They are being increasingly used in environmental monitoring (Peverill *et al*., 1999).

Parameters such as exchangeable sodium percentage (ESP), Ca:Mg ratio, cation exchange capacity (CEC) or effective cation exchange capacity (ECEC) and Sodium Adsorption Ratio (SAR) were derived from the data obtained. In the case of acidic soils which cover a significant area of South East Queensland, it is ECEC that is relevant where the summation also includes exchangeable acidity (Peverill *et al*., 1999). Particle size analysis was measured by hydrometer analysis including sample pre-treatment for removal of organic matter where necessary. The type of clay was interpreted using published values of CEC and clay activity ratio (CCR) = CEC/clay % (Shaw *et al*., 1997) and randomly selected samples were validated using X-Ray Diffraction. Hydraulic conductivity (constant head method) and porosity were measured using undisturbed cores.

RESULTS AND DISCUSSION

Physical Characteristics

The application of wastewater to soil increases soil water retention, decreases the volume of pores and can also decrease the saturated hydraulic conductivity. Permeable surface layers play an important role in effluent movement through the soil and for successful operation of effluent disposal systems, lateral flow above restrictive layers and macropore flow is essential. As such, an in-depth understanding of the sub-surface drainage characteristics is important in understanding the behaviour of sewage effluent in soils. Drainage characteristics result from a complexity of factors such as layering or stratification of the soil, permeability of soil horizons, presence of restrictive layers, position in the landscape catena and weather conditions (White, 1997). Table 2 presents the drainage characteristics noted in relation to the study sites. It illustrates that lateral seepage of effluent from the disposal field can occur independent of whether the sites are well drained or poorly drained. The data in Table 2 along with laboratory permeability test data in Table 3 confirm the wide variation in infiltration rates for similar soil types. The surface soils can be 1000 times more permeable than the clay enriched ‘B’ horizon. The permeability contrast between the ‘A’ and ‘B’ horizons is primarily associated with soil texture and the migration or illuviation of clay particles by water movement through the soil profile. The clay enrichment deeper in the profile reduces permeability, thereby impeding drainage and can cause waterlogging (White, 1997).

Table 2. Sewage effluent disposal area site and soil classification

Site No.	Soil profile observations at piezometer sites	Drainage Class[a]	Observed Drainage[b]	Depth to water table[c] m
1	Significant lateral seepage at 0.5m. Saturated zone at top of B horizon	Moderately well drained	mainly downward minor ponding observed	NF
3	Significant lateral seepage at 0.5m. Saturated A horizon	Imperfectly drained	lateral minor ponding observed	Perched at 0.5
4	Minor lateral seepage at 0.4m. Saturated profile throughout	Imperfectly drained	mainly downward	NF
7	No lateral seepage observed. Saturated A horizon	Moderately well drained	downward	NF
8	Significant lateral seepage at 0.3m. Saturated A horizon. High water table	Poorly drained	lateral ponding observed	0.3
9	Significant lateral seepage at 0.4m. Saturated profile throughout	Poorly drained	lateral ponding observed	0.8
11	No lateral seepage observed. Uniformly saturated profile	Well drained	downward	NF
12	Minor lateral seepage at 0.4m. Saturated zone at top of B horizon	Moderately well drained	downward	NF
14	Significant lateral seepage at 0.3m. Saturated zone at top of B horizon	Moderately well drained	mainly downward ponding observed	NF
15	No lateral seepage observed. Well drained A horizon	Moderately well drained	mainly downward	NF
16	No lateral seepage observed. Saturated at top of B horizon	Poorly drained	lateral ponding observed	Perched at 0.4

[a] the classification used complies with AS/NZS 1547:2000 (Standards Australia, 2000), McDonald et al., 1990.

[b] derived from soil moisture profiles and soil chloride profiles to determine drainage flow

[c] based on soil profile description and field measurements, NF – Not found

Table 3. Laboratory permeability data

Location	Sample Depth (m)	Horizon	Permeability (mm/day)	Observations
Site 1C	0.2 - 0.35	A	378	Sandy loam
	0.6 – 0.74	B	45	Reactive clay
	1.2 – 1.32	C	1730	Jointed Shale with clay infill
Site 1ED	0.55 - 0.68	B	28	
Site 3C	0.25 – 0.40	A	1258	Sandy loam
	0.55 – 0.67	B	17	Mottling of light to medium clay
	1.1 – 1.2	C	33	Mottling of sandy clay
Site 3ED	0.50 – 0.65	B	2	
Site 4C	0.6 – 0.78	B1	11	Minor mottling of sandy clay
	0.95 – 1.1	B2	22	
Site 8C	0.1 – 0.22	A	1245	Brown sandy loam
	0.3 – 0.44	B1	8	Mottling of loamy clay
	0.60 – 0.72	B2	13	Mottled heavy clay
Site 9C	0.3 – 0.51	B1	12	Red and yellow mottling
	0.90 –1.10	B2	37	
Site 11C	0.7 – 0.85	B1	172	
	1.1 – 1.24	B2	439	Silty loam with some gravel
Site 12C	0.2 – 0.37	A	2540	Brown sand
	0.7 - 0.87	B1	565	Well drained loamy sand
	1.1 - 1.25	B2	280	
Site 15C	0.25 – 0.41	A	881	Sandy loam
	0.7 – 0.85	B1	65	Kaolinite clay
	1.1 -1.25	B2	18	Red and white sandy clay
Site 16C	0.6 – 0.7	B1	5	Red and grey mottling
	1.2 – 1.3	B2	10	Mottled grey red heavy clay

Slowly permeable	less than 10mm/day
Moderately permeable	10mm to 1000mm/day
Highly permeable	more than 1000mm/day

(Adapted from Baker and Eldershaw 1993)

ED - Effluent disposal soil, C - Control soil

Several of the study sites (Sites 3, 8, 9 and 16) had slowly permeable soil at the top of the ‘B’ horizon indicating lateral flow being prevalent. A medium to heavy clay ‘B’ horizon effectively acts as an impermeable barrier to vertical flow through the soil. Therefore as the ‘A’ horizon becomes saturated, lateral flow of effluent is preferred rather than downward movement. This was further confirmed by the fact that the ‘B’ horizon showed signs of redoximorphic features such as free water, presence of mottling and iron accumulation. This indicates a seasonal groundwater table during wet periods. Under these circumstances, flow of effluent into surface water bodies is a distinct possibility. The lateral flow rate is dependent on the slope and hydraulic conductivity of the soil. The soil electrical conductivity profiles shown in Figures 1 and 2 also confirmed the lateral movement of effluent through the more permeable surface layers. Where effluent ponding was observed, salt accumulation in the soil significantly increased, independent of drainage class (Sites 1, 8, 9 and 14 in Figures 1 and 2). This would mean that structural breakdown of the soil has led to restricted water entry and changed the moisture regime of the soil.

Physical soil properties that influence soil structure and stability including soil permeability, clay content and clay type were compared at each site with observed treatment performance. Treatment performance was defined by field observations – whether or not effluent ponding occurs, soil water sampling results – removal of contaminants and detailed site history – trouble free operation obtained from the householder. There is increasing evidence that in land disposal sites (for example Menneer *et al.*, 2001, Halliwell *et al.*, 2001) sodium in wastewater causes soil structural problems and reduced permeability. Site 3 (Tables 3 and 4) display these characteristics. Shaw *et al.*, (1994) found that soils with mixed mineralogies are the most sensitive to sodium and will form the least permeable matrix if the clay content is around 40 to 50%. Sites 3, 8 and 9 exhibited these characteristics as illustrated in Table 4. Subsurface effluent disposal involves a series of wetting and drying cycles which would align the clay and restructure the soil. In soils with minimal shrink swell characteristics (kaolinite and illite clay), a dense soil matrix will form, whereas in soils with appreciable shrink swell properties (smectite clay), some regeneration of soil properties and porosity can be expected. Thus soils with a predominance of smectite clays would have the ability to efficiently renovate effluent even with moderately high exchangeable sodium. Sites 1, 7 and 11 display these characteristics.

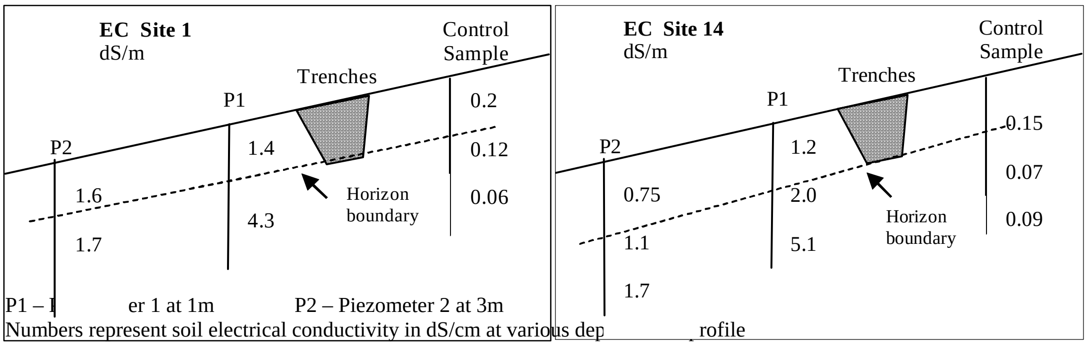
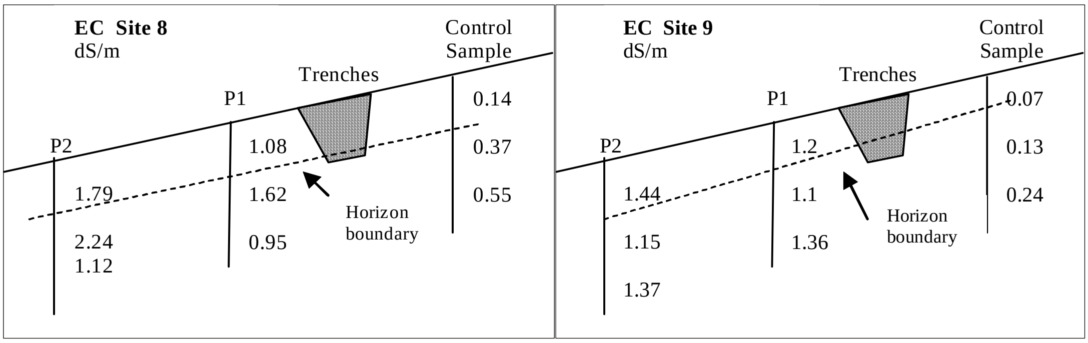


Figure 1 - Soil sampling for electrical conductivity (well drained sites)



P1 – Piezometer 1 at 1m P2 – Piezometer 2 at 3m
Numbers represent soil electrical conductivity in dS/cm at various depths down profile

Figure 2 - Soil sampling for electrical conductivity (imperfectly/poorly drained sites)

A strong correlation between the depth to the restrictive horizon measured at a site and treatment performance was noted from the study results. Treatment performance was defined by field observations, soil water sampling results**,** detailed site history obtained from the householder and surface and sub-surface site conditions noted during the study. In cases where the restrictive horizon was less than 0.4m from the surface, inadequate purification of effluent was the general outcome. The data given in Tables 2 and 4 confirm these conclusions.

Table 4 Soil Properties from Top of B Horizon

Site No.[a]	Treatment Performance[b]	Particle size			Clay type	pH	EC dS/m	Ex Na meq/100g	ESP %	CEC meq/100g	Ca:Mg
		Sand	Silt	Clay							
1C	Satisfactory	41	28	31	S	6.7	0.12	1.55	3	43	0.95
1ED		26	43	34		6.9	1.54	2.40	5	48	0.54
3C	Fail (Hydraulic)	44	21	35	K/I	5.1	0.09	1.95	18	10	1.29
3ED		35	24	41		5.7	0.25	2.01	20	12	0.06
4C	Satisfactory	51	19	30	I	4.2	0.08	0.68	4	9	0.94
4ED		48	18	34		4.5	0.14	0.84	10	14	0.50
7C	Satisfactory	66	14	20	S	7.3	0.17	0.41	2	34	4.00
7ED		62	15	23		7.2	0.24	0.49	2	36	1.72
8C	Fail (Contamination)	13	30	57	K/I	5.7	0.46	4.84	26	7	0.59
8ED		11	25	64		6.3	1.93	5.20	28	11	0.13
9C	Fail (Hydraulic)	8	34	58	K/I	5.5	0.37	0.47	6	8	0.79
9ED		12	21	67		6.4	1.25	1.41	16	11	0.19
11C	Satisfactory	45	35	20	S	5.4	0.11	1.80	4	42	1.05
11ED		40	42	18		6.9	0.17	2.10	8	45	0.84
12C	Satisfactory	49	30	21	K/I	4.7	0.07	0.12	13	10	1.38
12ED		41	33	26		5.2	0.07	0.28	15	12	0.61
14C	Satisfactory	38	30	32	I	4.8	0.07	0.33	5	10	0.47
14ED		32	32	36		6.4	1.10	0.42	6	11	0.38
15C	Satisfactory	33	30	37	K	4.8	0.11	0.09	1	7	1.42
15ED		30	30	40		5.2	0.16	0.15	1	5	2.60
16C	Fail (Hydraulic)	16	25	59	K	4.3	0.10	0.40	6	6	0.38
16ED		20	21	59		5.4	0.19	0.52	7	7	0.09

a missing numbers are sites abandoned due to insufficient soil water sample and unreliable historical site information
b based on field observations, soil water sampling**,** detailed site history and surface and sub-surface site conditions noted during the study
Failure criteria based on USEPA Onsite Wastewater Treatment Manual 2002, Section 5.8
Hydraulic – untreated or partially treated sewage ponding on surface or sewage breakouts on slopes
Contamination – high nitrate levels, microbial contamination
ED - Effluent disposal soil, C - Control soil
S – Smectite, K – Kaolinite, I – Illite, K/I - Mixed mineralogy

Chemical properties

Chemical data such as exchangeable cations, Ca:Mg ratio and ESP were employed as possible indicators to investigate the likely deterioration of the soil structure due to sewage effluent disposal. Influential soil properties were identified and correlations between these parameters and drainage factors were investigated. Parameters including cation exchange capacity (CEC) or Effective Cation Exchange Capacity (ECEC), dominance of exchangeable Ca or exchangeable Mg over exchangeable Na concentration, Ca:Mg ratio and ESP were found to be the dominant soil chemical properties in terms of assessing long term effluent disposal.

Significant changes were noted in exchangeable cations Ca, Mg, Na as well as in parameters such as pH, EC and CEC (or ECEC) due to the sub-surface application of sewage effluent. These changes in chemical characteristics were comparable with other findings relating to New Zealand and Southern Australian soils (Falkiner and Smith, 1997, Speir *et al.*, 1999, Menneer *et al.*, 2001). Exchangeable cations are not typically regarded as contaminants, though large amounts of cations being transported to depth highlight the potential increase in salt load not only in the soil profile but to groundwater and surface water bodies. This is particularly the case where appreciable amounts of lateral water flow occur at the clay interface (Dawes and Goonetilleke, 2003).

So and Aylmore (1993) suggested using exchangeable sodium content (ESC) measured on a dry soil basis, as a means of eliminating the texture factor in defining an index for sodicity. This was supported by Cook and Muller (1997) who concluded that ESC explained soil behaviour better than ESP and hence was a preferable index of sodicity. As shown in Figure 3, comparisons of performance observed at satisfactory and failed sites support this contention. Exchangeable sodium content is highly correlated with ESP in sites where soil degradation and subsequent hydraulic failure occurs. Whereas in sites defined as satisfactory no correlation is observed.

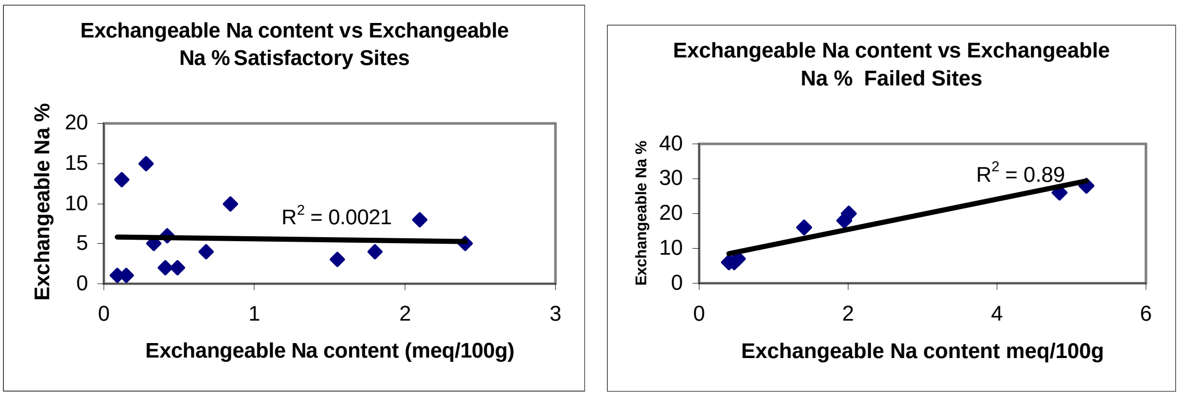


Figure 3 - Regression analysis of exchangeable sodium indices

The Ca:Mg ratio in the soil was employed to understand 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 ratios less than 0.5 are associated with soil dispersion. This is supported by Shaw *et al.*, (1997) who postulated that low Ca:Mg ratios in conjunction with high ESP indicate enhanced dispersion. Soil dispersion will limit effluent treatment capacity of the soil in the long-term. Ca:Mg data shown in Table 4 clearly supports these findings.

CONCLUSIONS

Soils with moderate to high CEC (or ECEC), Ca:Mg >0.5, dominance of exchangeable Ca or exchangeable Mg over exchangeable Na concentration and thus low ESP have the ability to treat effluent without major soil degradation. In some cases such as Sites 1 and 11, moderate to high exchangeable Na concentration was offset by the presence of swelling clays and the co-dominance of exchangeable Ca and exchangeable Mg. These characteristics have the ability to aid the adsorption of cations at depth and confirm that soils with swelling clays can be stable even at high exchangeable sodium levels. These conclusions are supported by Curtin *et al*., (1994) in a study on prairie soils in Saskatchewan, Canada.

The physical properties of a soil which can be used to assess suitability for long term effluent disposal include:

1. Moderate to slow drainage (permeability) to assist the movement of effluent (percolation) through the soil profile and allow adequate time for treatment to occur. With longer percolation times, the opportunities for exchange and transport processes increases;
2. Minimum depth of 0.4m of potentially unsaturated soil before encountering a restrictive horizon to permit adequate purification to take place; and
3. Clay type having appreciable shrink swell properties providing some regeneration of soil properties.

An in-depth knowledge of the local soil characteristics and associated soil hydrology is essential for a better prediction of long-term treatment potential of subsurface effluent disposal systems. Gradual adverse changes in physical soil functions, e.g., hydraulic conductivity, leaching of nutrients and structural integrity, may not be noticed until some time well after soil degradation occurs. Identifying the soil properties that are sensitive to such changes will help predict long-term sustainability of effluent disposal areas.

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