GREYWATER POLLUTANT ATTENUATION IN A BASALTIC SOIL

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Abstract

This paper describes a soil column study investigating the pollutant removal performance of a basaltic Chocolate Soil in the Lismore area of NSW. A $2 \times 2 \times n$ factorial design experiment with three replicates (control vs treatment soils, 400mm vs 700mm column lengths, in up to seven effective sampling periods) was set up. Soil columns of 100mm diameter with basaltic Chocolate Soil enclosed in PVC piping were arranged to receive daily hydraulic loading of 45mm areal volume of greywater influent for 31 days. The leachate was sampled bi-weekly and analysed for faecal coliforms, total nitrogen, ammonia-N, NOx-N, total phosphorus, orthophosphate and pH. An additional sub-experiment was performed to ascertain hydraulic residence time. Reductions in faecal coliforms of 4 logs, total nitrogen of 95.5% and total phosphorus of 97.9% were achieved, within a hydraulic residence time of 4.5 and 8.5 days for the 400mm and 700mm soil columns respectively. These results show that basaltic Chocolate Soil has excellent treatment capabilities. The possibility of using soil in contained secondary treatment units is also raised.

Keywords

basaltic soil, faecal coliforms, greywater, hydraulic residence time, nitrogen, phosphorus, soil columns

1 Introduction

Well designed and correctly sized primary and secondary treatment devices in on-site wastewater management systems may provide a level of on-site treatment which takes pressure off the last stage, land application. Yet under the right conditions the unsaturated zone of soil can provide excellent treatment performance in its own right (Siegrist, 1987), taking pressure off the contained treatment stages. Inadequate knowledge of a particular soil may lead to faulty assessments of its likely pollutant attenuation capabilities.

It is necessary to contrast less weathered Chocolate Soils with the more widely recognized and more highly weathered Krasnozem, or red basaltic soils. The literature available on Krasnozems (Black & Waring, 1976; Moody, 1994) cannot be mistakenly applied to Chocolate Soils or other basaltic soils in the Lismore area. *Krasnozem* and *Chocolate Soil* are Great Soil Group categories (Stace *et al.* 1968). In the most recent of Australian soil identification systems *The Australian Soil Classification (ASC)* (Isbell, 1996), Krasnozems are usually reclassified as Ferrosols, whilst Chocolate and Prairie Soils are generally Dermosols (Morand, *pers. comm.*, 2002). The *Georgica* soil unit on which the study site stands (Morand, 1994) is most likely a Dermosol (Morand, *pers. comm.*, 2002). Ferrosols are usually dominated by kaolin which is conducive to anion adsorption (e.g. nitrate adsorption) due to high anion exchange capacity (AEC). Dermosols, on the other hand, are dominated by montmorillonite clay, having a much higher cation exchange capacity (CEC) and lower AEC

(Isbell, 1996; Morand, *pers. comm.,* 2002), and are therefore less likely to adsorb nitrate, an important factor in on-site wastewater management.

This study, described in more detail in McCardell (2002), discusses a 2 x 2 x n factorial soil column experiment (2 sites – treatments and controls, 2 depths of soil column – 400mm and 700mm and several time periods – usually 7). It investigates the pollutant removal capacity of a dark basaltic soil from the *Georgica* soil unit about 20 km north of Lismore, loaded with primary treated domestic greywater, and addresses the question "could differences in pollutant attenuation in the soil columns be related to previous land application use, soil depth and duration of treatment?"

2 Methods

Twelve loosely packed soil columns of 400 and 700mm length held in 100mm diameter PVC tubes by stretched geotextile fabric were set up in two matching rows, the controls and treatments (Figure 1). The soil for the treatments came from a land application area which had been regularly dosed with primary-treated greywater for two years. The controls were taken from untreated soil adjacent to the land application area.

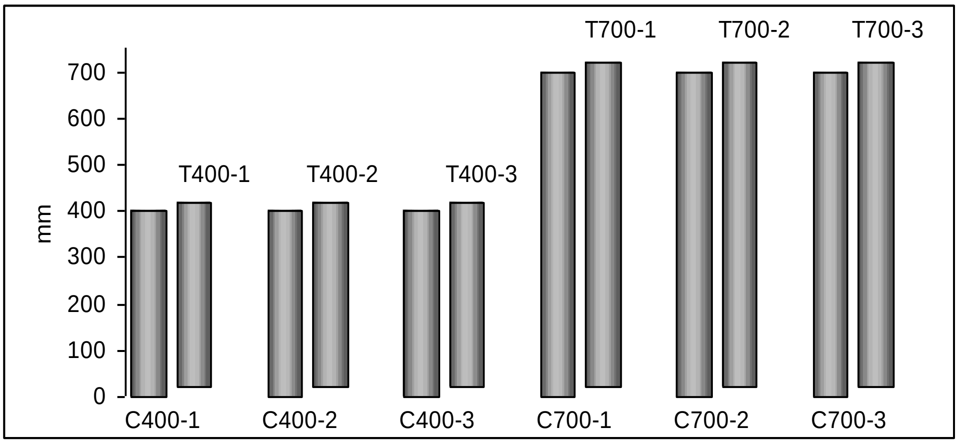


Figure 1. Rows of control and treatment soil columns (three replicates)

Each column was supported to allow free drainage of leachate. Greywater from the collection tank was applied to the soil columns. For the purposes of the experiment this liquid is named the *influent*. Before sampling commenced, a start-up dose of influent was applied in order to bring the soil columns to field capacity. The soil columns were then dosed daily for 31 days with an average 352mL of influent (45mm areal dosing). Twice weekly the leachate was sampled and analysed at the Environmental Analysis Laboratory (EAL) at Southern Cross University (SCU).

The samples were analysed for faecal coliforms (FC), Total Nitrogen (TN), ammonium N, combined nitrate and nitrite (NOx-N), Total Phosphorus (TP), orthophosphate (PO_4) and pH. The retention and drainage from four of the soil columns was also measured in a sub-experiment over several hours to determine the average time a dose of effluent remained within the soil columns ("Hydraulic Retention Time" or HRT). The results were extrapolated from these observations using first order decay principles.

Only mean data will be cited here, the results of the ANOVAs only being quoted where necessary. All ANOVA analyses used $\alpha = 0.05$.

3 Results and Discussion

The concept of "leachate-to-influent concentration ratio" (LICR) is used as the main index of attenuation of a nutrient pollutant. This is the ratio of the concentration of a nutrient form (such as NOx-N or TP etc), measured in the leachate collected from the soil columns, to the concentration of that nutrient measured in the influent applied. It is expressed as a percentage. Thus TN LICR of 5%, for instance, represents a 95% TN reduction.

According to mass balance principles, ratios between mass loads are equivalent to ratios between concentrations when volume remains constant. Assuming the volume of applied influent is roughly equal to the volume of leachate recovered, the LICR values quoted in the Results and Discussion sections also broadly represent mass balance ratios.

3.1 Hydraulic retention time (HRT)

The HRT, obtained in the sub-experiment, was about 4.5 and 8.5 days respectively for the 400mm and 700mm soil columns.

3.2 Faecal coliforms (FC)

The experiment demonstrated excellent FC removal - a mean 4.06-log reduction. ANOVA showed that FC attenuation was not significantly different between treatments and controls, nor between 400mm and 700mm soil columns. The lack of further FC attenuation beyond 400mm in the 700mm columns shows that the reduction occurred within 400mm from the soil surface (Figure 2). There were no definitive trends over time.

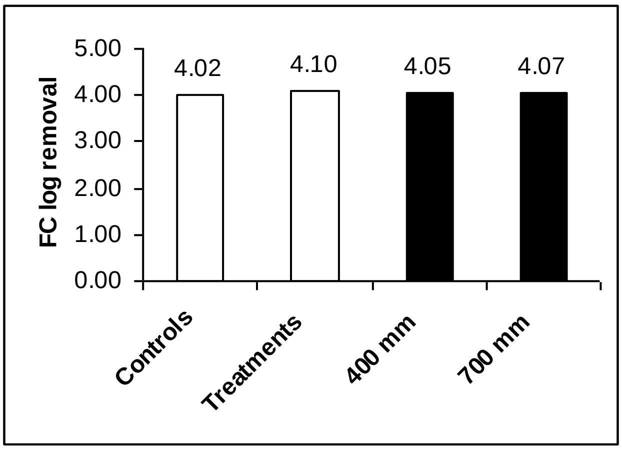


Figure 2. Mean faecal coliform removal (logs cfu/100 mL) grouped according to the factors of Site (treatments vs controls) and Length (400mm vs 700mm).

Other studies also indicate the shallow soil zone as being the main locus of pathogen attenuation (Abu-Ashour *et al.*, 1998; van Cuyk *et al.*, 2001; Weaver *et al.*, 1978).

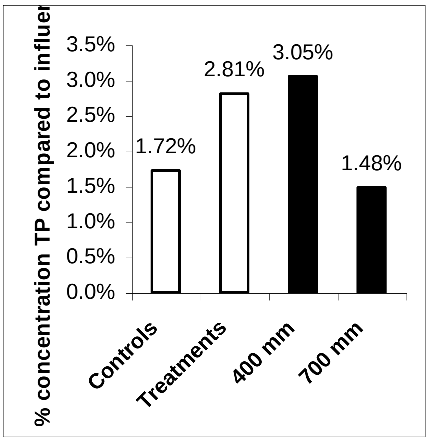
3.3 Phosphorus

The mean concentrations of phosphorus species in the influent and leachate, over all periods, is displayed in Table 1. (PO_4-P refers to PO_4^{3-} and it protonated forms, synonymous with ortho-P).

Table 1. Mean concentrations of P species

Mean conc. (all periods)	Influent (mg/L)	Leachate (mg/L)
Org/poly-P	1.55	0.053
PO_4-P	1.40	0.008
TP	2.95	0.062

The overall TP reduction of 97.9% (Figure 3b) is a reflection of very strong phosphate fixation in the soil. ANOVA indicated that the 700mm columns removed only slightly more P than the 400mm columns, indicating that most attenuation occurred within the first 400mm. However ANOVA was inconclusive as to whether controls removed any more P than the treatments (white columns in Figure 3a).



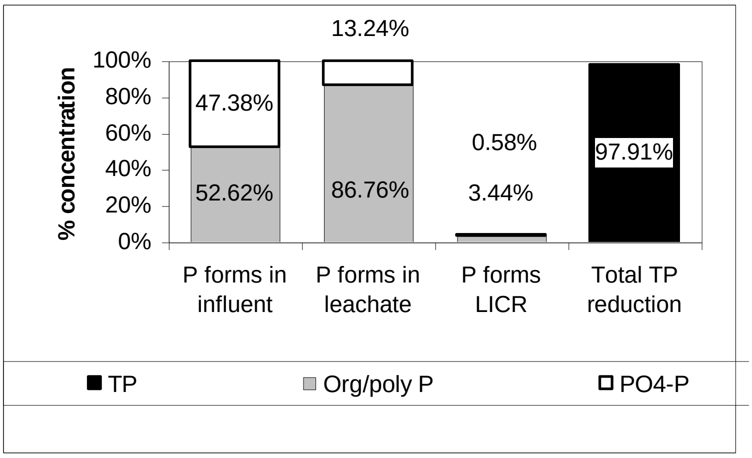


Figure 3. a) Mean TP LICR
b) Mean composition influent & leachate, LICR and mean TP reduction

No conclusive trends where observed over time. Figure 3b shows that PO_4-P was a major component of TP (about half) only in the influent data. In the leachate data organic/polyphosphate-P predominated, indicating preferential removal of PO_4-P in the soil.

Ortho-P in the leachate has two possible origins - pre-existing orthophosphate and the hydrolised product of organic P and polyphosphate. The readiness with which soil takes up orthophosphate contrasts with slowness of the hydrolisis of organic/poly-P (Brady, 1990; Evangelou, 1998). Therefore the PO_4-P LICR (0.58%, Figure 3b) is a good indication that nearly all the PO_4-P was adsorbed within the soil, whilst more organic/polyphosphate-P remained untransformed (LICR 3.44%).

3.4 Nitrogen

The mean concentrations of nitrogen species in the influent and leachate, over all periods, are shown in Table 2.

Table 2. Mean concentrations of N species

Mean conc. (all periods)	Influent (mg/L)	Leachate (mg/L)
Org-N	11.8	0.28
NH_4-N	13.7	0.042
NOx-N	0.006	0.83
TN	25.5	1.2

The removal of TN was 95.5%. However, unlike the results for faecal coliforms and P, the data for N showed some striking trends over time. There was a rise in TN concentrations in the leachate in what appeared to be a two-step process (Figure 3a). In the first phase (September 23, 25 and 30), the TN LICR was small. In the second phase (October 8, 10 and 15) the TN LICR was higher. October 3 was a transition between the two phases.

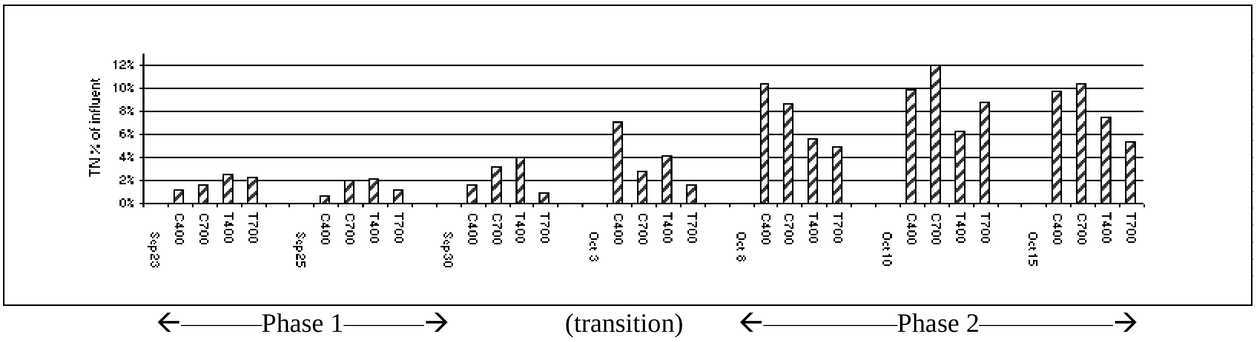


Figure 3(a): Mean TN LICR (ratio of conc. of TN in leachate to influent)

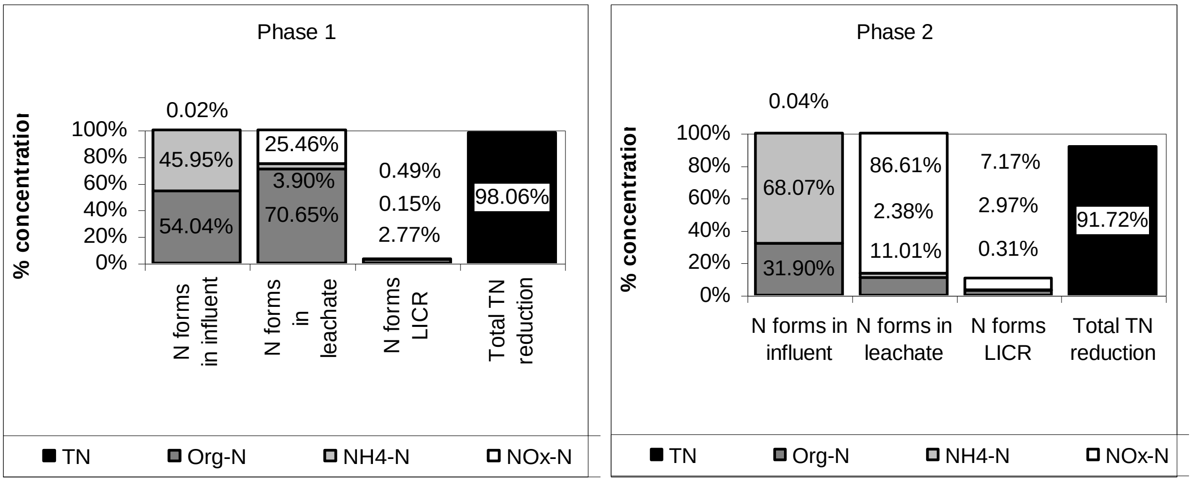


Figure 3(b): Mean composition of influent & leachate, LICR and mean TN reduction in the two phases (transition period not shown)

Figure 3b shows that organic-N and NH_4-N completely dominated the influent in both phases, whilst NO_x-N became the dominant form in the leachate during Phase 2.

No conclusive evidence of differences between the TN removal capacities of the treatments vs the controls was found.

A small but persistent concentration of organic N was observed in the leachate after passage through the soil. The mean organic N LICR over all phases was 2.4%. In contrast the NH_4-N LICR was only 0.3% . This implies that, almost as fast as organic-N was being mineralised, its product, NH_4-N, was being either nitrified, recycled or retained within the soil columns.

The acidity of the leachate was remarkably constant across factors, with a mean pH of 6.15. In considering the 95.5% TN reduction between influent and leachate, there are several possible pathways for such a reduction to take place in an acid environment: assimilation by microorganisms, ammonium cation fixation, nitrate anion adsorption and exchange, and denitrification - the process by which N is returned to the atmosphere (Brady, 1990; Evangelou, 1998). Assuming a microorganism community where death and lysis roughly balance reproduction and growth it can be assumed that assimilation is not a significant sink.

Ammonium *cation* fixation is a process very likely to occur in the Chocolate Soil under study, because the clay is likely to contain significant montmorillinite which tightly binds NH_4^+ ions (Brady,1990). On the other hand nitrate *anion* adsorption in a Chocolate Soil is likely to be limited as these soils have a low AEC (Brady,1990; Evangelou, 1998).

Denitrification proceeds well at pH around neutral, but requires anaerobic conditions (Evangelou, 1998). The loading phase could provide such conditions (Patterson, 1994). However in the HRT sub-experiment, it was observed that the soil columns drained nearly to field capacity within a few hours. In other words the proportion of time spent in the loading phase (suggesting anaerobic conditions) would likely be relatively short compared to that spent in the resting phase (suggesting aerobic conditions). However, a long aerobic phase seems inconsistent with the large TN reduction (95.5%) observed. Therefore it is suggested that the denitrification necessary to achieve this reduction was promoted by other factors such as anoxic microenvironments within the filter media (Gold *et al.*, 1992) and anaerobic conditions perhaps favoured by confined PVC tubes. In short it appears that both nitrification and denitrification processes were at work in the soil columns.

The important component in the leachate that remained in an un-oxidised state was the organic N. Its significant presence in the leachate may have been due in part to macropore preferential flow (Nieber, 2001), consistent with the highly unconsolidated nature of the soil used in the columns. This would account for the rapid drainage observed after applying influent.

Many intermittent sand filter studies cite nitrification rates based on the ratios of ammonium-N and NOx-N in the influent and effluent. The influent is usually from a septic tank where ammonium N typically makes up about 75% of the TN concentration and organic-N makes up 25% (Osesek *et al.*, 1994). In contrast, the ammonium-N content of the greywater used in this study comprised only 54% of TN concentration. Nitrification of ammonia-rich septic tank effluent in sand filters is often around 98% (Davison *et al.*, 2002; Sievers, 1998 and many others). Sand filters achieve only limited, if any, denitrification due to the lack of anoxic microsites in the filter medium (Gold *et al.*, 1992). By contrast the soil columns in this study not only nitrified most of the TN but in addition removed 95.47% of TN overall. The sand filter studies assume that the nitrification rate of sand filters directly relates to the ratio of Total Kjeldahl Nitrogen (TKN) removed (Davison *et al.*, 2002) and the concentration of nitrate in the leachate (Sievers, 1998 and others). When soil columns are studied, however, the fate of nitrate-N and ammonium-N is much more complex due to the additional pathways of denitrification and anion adsorption (in the case of nitrate) and cation fixation (in the case of ammonium). The relative dominance of each of these processes depends on time, as retention and fixation capacity is limited by available microsites on soil particles (Brady, 1990).

The experimental results suggest that, from the beginning, the soil columns were able to absorb quantities of ammonium-N by microbial assimilation and population growth (since a stable population had not yet been reached), and by ammonium ion fixation (since the soil was rich in montmorillinite). The influent was rich in ammonium-N and enhanced by the ammonification of organic-N. But ammonium-N was also increasingly nitrified, as evidenced by the increasing concentration of nitrate in the leachate and the correspondingly small quantity of ammonium-N. As fast as organic-N was mineralised, ammonium-N was being nitrified, assimilated and/or fixed. The nitrate was also adsorbed by the soil, to some extent. As the microbial population stabilised and less ammonium-N cation fixation sites and nitrate anion microsites were available, the nitrate concentration rose. It could be expected to rise until few available microsites remain and a balance is reached between nitrification and denitrification.

The comparison with sand filters, discussed earlier, raises the possibility of using soil in contained packed bed aerobic treatment units. However, as this work was of the nature of a pilot study, long term predictions of nitrification/denitrification rates remain hypothetical. It is intended that a longer experiment of a similar nature be carried out to investigate this further.

4 Conclusion

The pollutant attenuation through the soil columns was high, with overall reductions in faecal coliforms - 4 logs, total nitrogen - 95.5% and total phosphorus - 97.9%, from a hydraulic loading rate of 45 mm/day within a hydraulic retention time of between 4.5 and 8.5 days for the 400mm and 700mm soil columns respectively. These results demonstrate the excellent treatment capabilities of the basaltic Chocolate Soil studied, and point to the possible use of soil in aerobic secondary treatment units.

References

Abu-Ashour, J., Joy, D.M., Lee, H., Whiteley, H.R. and Zelin, S. 1998. Movement of bacteria in unsaturated soil columns with macropores. *Transactions of the ASAE* **41**(4): 1043-1050.

Baird, C. 1999. *Environmental Chemistry*. W.H. Freeman and Company, New York.

Black, A.S. and Waring, S.A. 1976. Nitrate leaching and adsorption in a krasnozem from Redland Bay, Qld. III Effect of nitrate concentration on adsorption and movement in soil columns. *Aust. J. Soil. Res.* **14**: 189-195.

Brady, N.C. 1990. *The Nature and Properties of Soils, Tenth Edition*. Macmillan Publishing Company, New York.

Davison, L., Bayley, M., Kohlenberg, T. and Craven, J. 2002. *Performance of Reed Beds and Single Pass Sand Filters with Characterisation of Domestic Effluent: NSW North Coast*. NSW Department of Local Government's *Septic Safe* Scheme, Lismore City Council, Lismore Water, Lismore NSW.

Evangelou, V.P. 1998. *Environmental Soil and Water Chemistry: Principles and Applications*. Wiley-Interscience Publ., New York.

Gold, A.J., Lamb, B.E., Loomis, G.W., Boyd, J.R., Cabelli, V.J. and McKiel, C.G. 1992. Wastewater renovation in buried and recirculating sand filters. *J. Environ. Qual.* **21**: 720-725

Isbell, R.F. 1996. *The Australian Soil Classification*. CSIRO Publishing, Collingwood VIC.

McCardell, A. 2002. *Greywater Pollutant Attenuation in a Basaltic Soil: A soil column experiment*, Integrated Project as partial fulfillment of the requirements of the Bachelor of Applied Science, School of Resource Science and Management, Southern Cross University, Lismore NSW.

Moody, P.W. 1994. Chemical fertility of krasnozems: a review. *Aust. J. Soil. Res.* **32**: 1015-1041.

Morand, D.T. 1994. *Soil Landscapes of the Lismore-Ballina 1:100,000 Sheet*. Department of Conservation and Land Management, Sydney.

Nieber, J. L. 2001. The relation of preferential flow to water quality, and its theoretical and experimental quantification. In *Preferential Flow, Water Movement and Chemical Transport in the Environment - Proceedings 2nd International Symposium, Honolulu*, Pub. no. 701P0006, American Society of Agricultural Engineers, St. Joseph, MI USA.

Osesek, S., Shaw, B. and Graham, J. 1994. Design and optimization of two recirculating sand filter systems for nitrogen removal. In *Proceedings of the Seventh International Symposium on Individual and Small Community Sewage Systems, Atlanta, Georgia*. American Society of Agricultural Engineers, St. Joseph, MI USA.

Patterson, R. 1994. *On Site Treatment and Disposal of Septic Tank Effluent*, PhD thesis, University of New England, Armidale NSW.

Siegrist, R.L. 1987. Soil clogging during subsurface wastewater infiltration as affected by effluent composition and loading rate. *J. Environmental Quality* **16**(2): 181-187.

Sievers, D.M. 1998. Pressurized intermittent sand filter with shallow disposal field for a single residence in Boone County, Missouri. In *Proceedings of the Eighth National Symposium on Individual and Small Community Sewage Systems, Orlando, Florida*. American Society of Agricultural Engineers, St. Joseph, MI USA.

Stace, H. C. T., Hubble, G. D., Brewer, R., Northcote, K. H., Sleeman, J. R., Mulcahy, M. J. and Hallsworth, E. G. 1968. *A Handbook of Australian Soils*, Rellim Tech. Pubs., Glenside, SA.

van Cuyk, S., Siegrist, R. and Logan, A. 2001. Evaluation of virus and microbial purification in wastewater soil adsorption systems using multicomponent surrogate and tracer addition. In *Proceedings of the Ninth National Symposium on Individual and Small Community Sewage Systems, Fort Worth, Texas*. American Society of Agricultural Engineers, St. Joseph, MI USA.

Weaver, R.W., Dronen, N.O., Foster, B.G., Heck, F.C. and Fehrmann, R.C. 1978. Sewage Disposal on Agricultural Soils: Chemical and Microbiological Implications. Vol II: Microbiological Implications. Ada, Okla.: US EPA