Bull. Environ. Contam. Toxicol. (1989) 42:518–525

Bulletin of Environmental Contamination and Toxicology

Treatment of Landfill Leachate by Spray Irrigation— An Overview of Research Results from Ontario, Canada. II. Soil Quality for Leachate Disposal

R. A. McBride,[1] A. M. Gordon,[2] and P. H. Groenevelt[1]

[1]Department of Land Resource Science, and [2]Department of Environmental Biology, University of Geulph, Guelph, Ontario, Canada N1G 2W1

Slow rate infiltration wastewater treatment systems, as applied to landfill leachate disposal on land, are designed to introduce leachate into the soil-vegetation ecosystem in such a way that the maximum degree of renovation and attenuation of contaminants is effected before the leachate re-enters the hydrologic cycle as deep drainage within the land disposal area. Through the processes of soil infiltration and interflow in the unsaturated zone, the applied leachate will be physically dispersed and diluted to varying degrees. Furthermore, inorganic compounds will be chemically precipitated or adsorbed on soil colloid exchange sites and many of the organic contaminants will either be volatilized or will be decomposed or transformed to more innocuous compounds by the soil microbial population. Both of these chemical processes will contribute macro- and micronutrients to the soil root zone as well as other substances available for plant uptake and bioaccumulation. An additional design criterion is that, before the leachate reaches the groundwater table and flow systems, evapotranspiration be maximized and overland leachate flow (surface runoff) be strictly controlled or avoided. Thus, both biological and physico-chemical forms of treatment are required to encompass the broad range of leachate constituents. This is particularly true of medium-aged, decommissioned landfills like the Muskoka Lakes site since the dominant renovation process required shifts from biological to physico-chemical with time reflecting the temporal variability of leachate constituents and concentrations.

The present spray area of 4.3 ha is made up of two distinctly different landscape units. Spray areas 1 and 2 (preceding paper, Figure 1) consist of a shallow veneer (less than 2 m deep) of rapidly permeable fine and medium sands with occasional silty or gravelly substrata. Spray area 3 is comprised of deeper and more homogeneous fine and medium sands (generally greater than 3 m deep) with few textural discontinuities. The design application rates recommended by the consulting engineers of 2.3×10^4 ℓ ha^{-1} d^{-1} (April, May, September, October) and 3.4×10^4 ℓ ha^{-1} d^{-1} (June-August) have been based on a very simplistic water balance

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Send reprint requests to R.A. McBride at the above address.

with little regard for soil infiltration rates, water storage capacities, attenuation capacities, depth to bedrock, or the composition of the leachate itself. This segment of the study involved the characterization of the local soils and their water regimes both in situ and in the laboratory in order to refine these application rate recommendations.

RESULTS AND DISCUSSION

The extent of volatile organic contaminant loss from the point that the leachate leaves the vicinity of the landfill in the groundwater flow system (i.e. culvert well sample) to the point where it is ejected from the spray nozzle is appreciable (Table 1, preceding paper). Precipitation of metallic inorganics such as iron in the settling lagoons gives rise to lower concentrations in samples taken from the lagoon surface (11 mg Fe ℓ^{-1}) relative to the culvert well samples (49 mg Fe ℓ^{-1}) (Table 2, preceding paper).

Of equal importance to contaminant concentration changes along the collection-disposal network is the distribution of spray around the nozzles and with distance from the pumping station. The overhead spray nozzle type used in this system results by design in an exponential decline in irrigation water depth with distance from the nozzle. This, when combined with the appreciable line pressure drop with distance from the pumping station as well as the frequent malfunctioning of individual nozzles and pump breakdowns observed in 1986, gave rise to highly inequitable leachate distribution patterns over the three spray areas.

Soil characterization in the field included a number of detailed soil pit descriptions which revealed the presence of fully developed or developing iron-indurated B horizons ("ortsteins"). Most soils examined belong to the Humo-Ferric Podzol Great Group (Canadian Soil Survey Committee 1978) and are in various stages of the "podzolization" soil-forming process. Large loadings of iron-laden leachate appear to accelerate this process leading to major soil morphological changes over relatively short periods of time which can radically alter soil water and nutrient regimes.

The soil water regimes of both irrigated and non-irrigated soils were characterized using a network of tensiometers installed from 15 to 120 cm below the surface, a neutron thermalization soil moisture depth gauge, and groundwater table observation wells. Figure 1 shows the extent to which heavy irrigation can cause chronically low aeration conditions in the soil root zone which in turn gives rise to root dysfunction and changes in the soil microbial population and activity.

Field saturated hydraulic conductivity (K_{fs}) was further measured using the Guelph Permeameter method (Reynolds et al. 1983). A mean K_{fs} of 7.5×10^{-3} cm sec^{-1} was obtained in the deep, non-irrigated sands near spray area 3 which corresponds to the highest

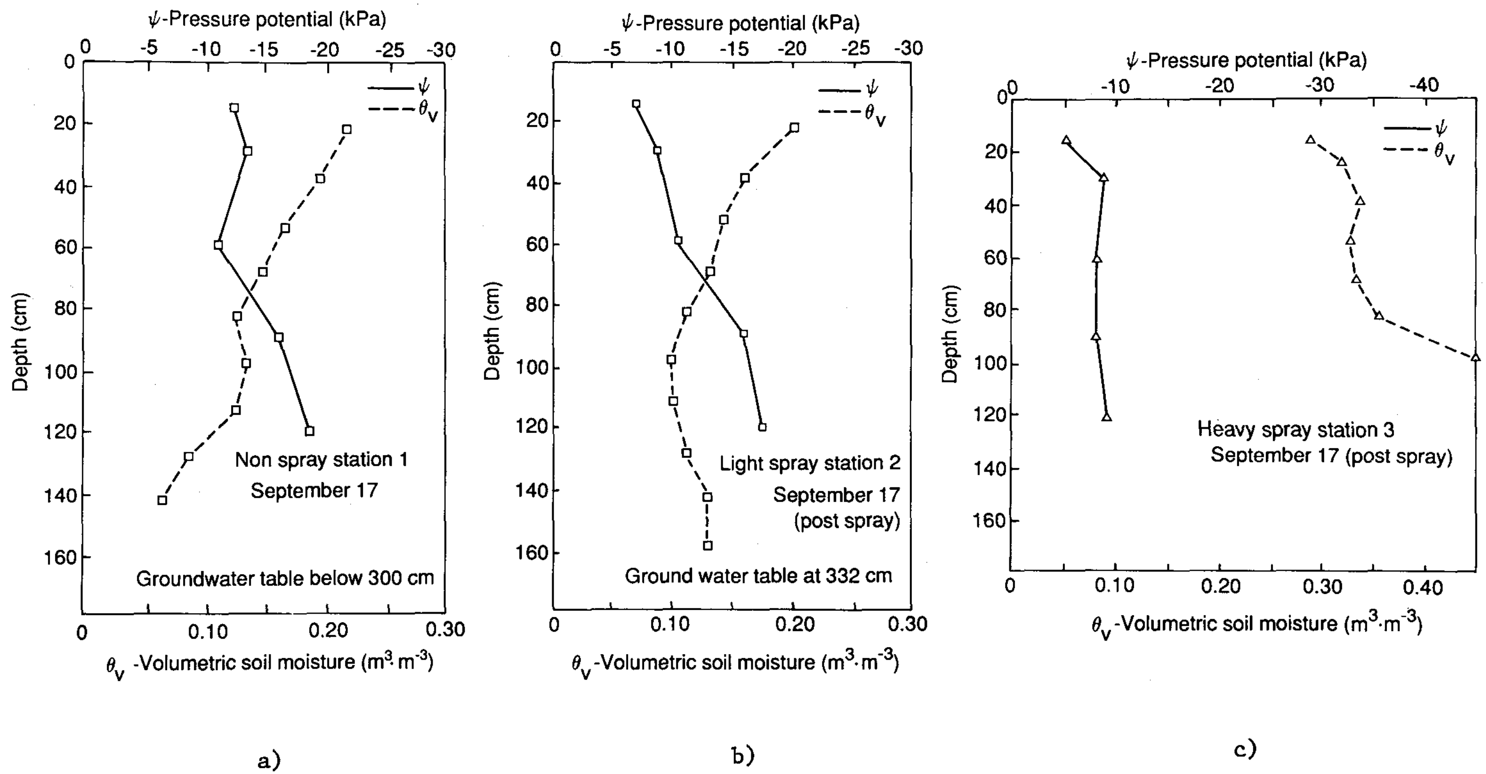


Figure 1. Soil moisture regimes under a) non-spray, b) light spray and c) heavy spray irrigation conditions on September 17, 1986.

conductivity (H1) category of the Agriculture Canada macrostructural description scheme (McKeague et al. 1982). A methylene blue dye infiltration experiment carried out on the forest floor, however, indicated that significant quantities of surface applied leachate could potentially move to depths beyond the root zone by even more rapid preferential flow along old root channels.

Soil attenuation capacities were evaluated in a leaching column experiment. Thirty intact soil columns (4.5 cm diameter x 75 cm long) were extracted in clear acrylic tubes from both previously irrigated and non-irrigated locations. These columns were subjected to surface applications of raw leachate at rates of 3.5, 7 and 14 mm d^{-1}. Application of rainwater collected on site was included as the control treatment. The effluent which percolated through each soil column was collected weekly and analysed for NO_3^-, NH_4^+, P, K, Ca, Mg, Mn, Fe, and pH. Data from the highest loading rate columns (14.0 mm d^{-1}) are given in Table 1.

Table 1. Relative concentration and attenuation/elution patterns of leachate constituents from intact leaching columns subjected to the high application rate (14.0 mm d^{-1}).

	Previously non-irrigated columns		Previous irrigated (1980-86) columns	
Constituent	Leachate	Rainwater (Control)	Leachate	Rainwater (Control)
$N\text{-}NH_4^+$	0.0-0.16 A	n.c.	0.0 A	n.c.
$N\text{-}NO_3^-$	0.9-7.5 E→A	1.0-21.0 E	1.4-33.0 E	1.3-75.0 E
P	n.c.	n.c.	n.c.	n.c.
K	0.03-0.06 A	0.08-0.2 A	0.4-0.97 A	3.4-12.3 E
Ca	0.04-0.2 A	0.07-9.2 E→A	0.2-0.6 A	0.09-26.8 E→A
Mg	0.06-0.1 A	0.08-6.9 E→A	0.4-2.7 E→A	0.27-45.8 E→A
Mn	0.01-0.08 A	0.002-2.5 E→A	0.03-0.25 A	0.0-8.0 E→A
Fe	0.0-0.1 A	0.0 A	0.0-0.02 A	0.0 A

n.c. - relative concentration not calculated since influent concentration below detectable limits
A - attenuation
E - elution
E→A - initial elution, subsequent attenuation

In order to compare the leachate and water irrigated treatments, the relative concentration (R.C.) of each constituent was calculated as the ratio of the column effluent concentration divided by the influent concentration. An R.C. >1.0 thus indicates elution or displacement of a chemical constituent from the soil exchange sites whereas an R.C. <1.0 indicates that attenuation or adsorption is occurring within the soil profile. Table 2 lists the mean pH and influent concentration of constituents delivered to the soil columns.

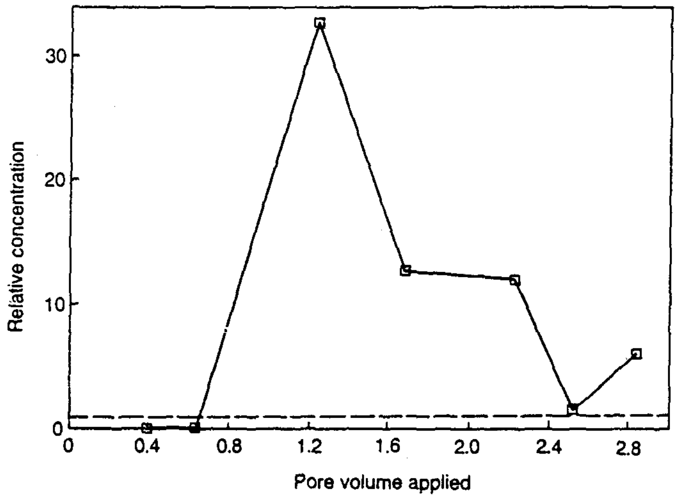
Table 2. Mean influent pH and concentration of leachate constituents delivered to soil columns.

Treatment	NO_3^-	NH_4^+	P	K	Ca	Mg	Mn	Fe	pH
	mg ℓ^{-1}								
Rainwater	7.4	<0.1	<0.1	3.5	2.0	16.5	0.1	1.3	6.30
Untreated leachate	5.6	28.7	<0.1	37.6	93.1	18.5	2.8	10.7	6.30

As anticipated, NO_3^- formed by the nitrification of mineralized soil N showed strong elution patterns while cations were attenuated to varying degrees. Certain cations,however, showed some elution before the R.C. fell below 1.0 (Figure 2). The elution of Mg in particular is caused by its displacement on soil exchange sites by cations with greater exchange site affinity. Only Fe and Mn were strongly attenuated, with the basic cations (Ca, Mg, K) exhibiting relative concentrations close to 1.0 even after 2.5 pore volumes had been applied. Peaks in the R.C. for most leachate constituents tended to occur after about 1.0 pore volume had been applied, but the precise maxima are somewhat obscured by the weekly periodicity of effluent sampling. These data also indicate that the attenuation-elution patterns of the Muskoka Lakes soils stabilize much more rapidly than with clay soils (Griffin et al. 1976).

Prolonged spraying has also dramatically lowered the attenuation capacity of the Muskoka Lakes soil for K, as it has for most other cations. Only Fe attenuation appears to be essentially unaltered by past leachate applications (Table 1). No visible evidence of the formation of a Fe placic layer was apparent over the duration of the experiment in any of the leaching columns containing previously unsprayed soil.

By using a modified energy budget approach, the mean daily Ep rates estimated for the months of May through October in 1986 were 3.31 mm, 3.29 mm, 3.58 mm, 3.34 mm, 1.66 mm and 1.20 mm, respectively. Both monthly and daily soil moisture budgets utilizing precipitation, Ep estimates and the soil storage capacity of the local soils have shown that the 1986 spray season a)



b)

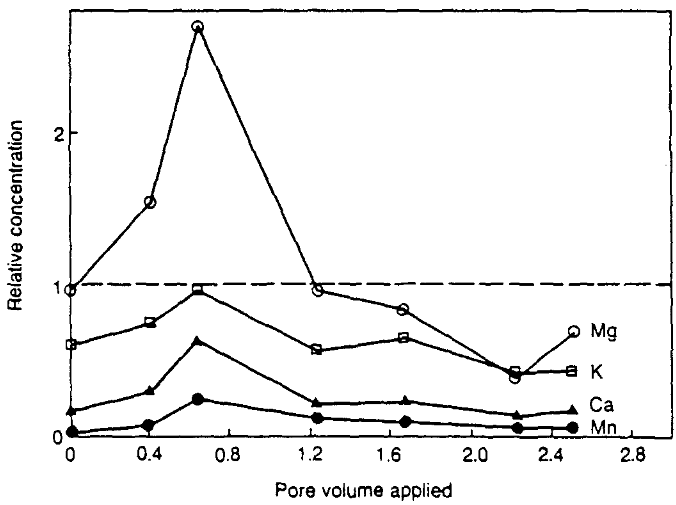


Figure 2. Measured a) elution(NO_3^-) and b) attenuation (K,Ca,Mn) and elution-attenuation (Mg) patterns for leachate application rate of 14 mm d^{-1} on previously sprayed soil.

was abnormally wet with few dry spells of any duration. Superimposing an irrigation schedule under these types of conditions while attempting to avert serious soil waterlogging is very difficult. The reality is that a large volume of leachate must be handled during a limited spray season, and it is this more than any other factor which determines the spray application rates. A standard rain gauge placed 5 m from a spray nozzle position in 1986 frequently recorded daily application rates in excess of the recommended rates by many fold. With revised leachate generation rates of about 5.3×10^4 ℓ d^{-1} during the 1986 spray season, a mean daily irrigation rate of 1.23 mm d^{-1} over the 4.3 ha spray area would have to be maintained to handle the daily accumulation, with no consideration given to rainfall amounts or the leachate generated during the winter season. Mean daily rainfall amounts of 3.32 mm, 4.24 mm, 3.35 mm, 3.10 mm, 5.82 mm and 3.34 mm from May to October, respectively, in 1986 easily balance the mean daily Ep values cited above, leaving even an irrigation rate of 1.23 mm d^{-1} clearly in excess of atmospheric demand. These excesses will be extreme in particular locations within the spray area due to the approximate observation that greater than 80% of the leachate is applied to less than 20% of the 4.3 ha spray area with the current system (i.e. < 1 ha). Weather conditions in 1986 would certainly not have allowed for the effective implementation of a spray scheduling program more attuned to daily evapotranspirative conditions in the forest ecosystem. This will only be feasible during abnormally dry or more normal precipitation years.

Given the nature of the local soils, the forest floor litter layer is key to increasing the residence time of the wastewater in the unsaturated zone and effecting a suitable level of renovation before the effluent reaches the groundwater table. High water table levels and shallow bedrock over much of spray areas 1 and 2 greatly reduce this residence time and cause the formation of leachate breakouts in depressional areas. The wastewater distribution system is currently less than satisfactory which gives rise to localized application rates far in excess of evapotranspirational demand and soil attenuation capacity. Pretreatment of leachate for Fe removal is necessary to avert major soil morphological changes with long-term spray irrigation.

Major transformations in the soil water regime due to heavy leachate loadings and soil morphological changes are responsible for adverse impacts on forest microbial populations and possibly on forest understory communities and tree vigour. More specifically, spray irrigation of leachate has induced a relatively rapid forest decline caused by a sequence of factors as outlined in Table 3.

Table 3. Factors responsible for forest decline at the Muskoka Lakes landfill site [adapted from Manion (1981)].

Predisposing Factors	Inciting Factors	Contributing Factors
- coarse soils shallow to bedrock (deficient water and nutrient availability, inadequate root support) - acid precipitation	- micronutrient (Fe, Mn) imbalance - low soil oxygen caused by waterlogging and high COD leachate - formation of indurated Fe horizon of low permeability in soil - reduced photosynthesis and transpiration caused by excess soil water and foliar staining in understory	- insect, disease and microbial infestations (e.g. bark beetles, needle fungi viruses, root-decay fungi)

Acknowledgments. The authors gratefully acknowledge the financial support of the Ontario Ministry of the Environment (Project No. 244-RR).

REFERENCES

Canadian Soil Survey Committee (1978) The Canadian System of Soil Classification. Agriculture Canada Publication 1646. Supply and Services Canada, Ottawa, Ont. 164 pp

Griffin RA, Cartwright K, Shimp NF, Steele JD, Ruch RR, White WA, Hughes GM, Gilkeson RH (1976) Attenuation of pollutants in municipal landfill leachate by clay minerals: Column leaching and field verification. Env. Geology Notes, No. 78. Illinois State Geological Survey, Urbana IL 34 pp

Manion PD (1981) Tree Disease Concepts. Prentice-Hall, Englewood Cliffs, NJ 399 pp

McKeague JA, Wang C, Topp GC (1982) Estimating saturated hydraulic conductivity from soil morphology. Soil Sci Soc Am J 46:1239-1244

Reynolds WD, Elrick DE, Topp GC (1983) A re-examination of the constant head well permeameter method for measuring saturated hydraulic conductivity above the water table. Soil Sci 136:250-268

Received June 24, 1988; Accepted August 1, 1988