ELSEVIER

Ecological Engineering 5 (1995) 37–50

ECOLOGICAL
ENGINEERING

Flow characteristics of rock-reed filters for treatment of landfill leachate [☆]

William E. Sanford [a,b,*], Tammo S. Steenhuis [c], Jan M. Surface [d], John H. Peverly [e]

[a] *Environmental Sciences Division, Oak Ridge National Laboratory [1], P.O. Box 2008, MS-6352 Bldg. 1503, Oak Ridge, TN 37831-6352, USA*
[b] *Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN, USA*
[c] *Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY, USA*
[d] *Water Resources Division, U.S. Geological Survey, Ithaca, NY, USA*
[e] *Department of Soil, Crops and Atmospheric Sciences, Cornell University, Ithaca, NY, USA*

Abstract

To characterize the flow patterns of wastewater through subsurface-flow rock-reed filters, a combination of tracer studies and specific conductance measurements were used. Neither the tracer study nor the specific conductance measurements alone provided the necessary information to understand the flow of wastewater through the system. However, the data taken together indicate that preferential flow occurred due to density effects and surface flow. In gravel substrates, dense wastewater flowed beneath the less dense rainwater and influent, resulting in a decrease in the residence time. Sand-and-gravel substrates, which experienced a great deal of surface flow as a result of clogging, were shown to have very little, if any, flow through the subsurface. The results of this study indicate that both preferential and overland flow should be taken into account for the proper design of rock-reed filters.

Keywords: Constructed wetlands; Preferential flow; Hydrology; Wastewater treatment; Tracers

---

[☆] Paper presented at the IV International INTECOL Wetlands Conference, Columbus, Ohio, USA, 13–18 September, 1992.

[*] Corresponding author.

[1] Managed by Martin Marietta Energy Systems, Inc. under contract DE-AC05-84OR21400 with the U.S. Department of Energy.

SSDI 0925-8574(95)00012-7

1. Introduction

With the ever increasing costs of treatment of wastewaters, alternative methods of treatment, such as constructed wetlands, having nearly the same efficiency yet substantially lower costs than conventional methods, are being examined. One type of constructed wetland that generally is used to treat domestic wastewater is the subsurface-flow reed-bed system. Other wastes treated by these systems include chemical wastes and landfill leachate. For landfill leachate the system is moderately successful (Staubitz et al., 1989; Sanford et al., 1990; Surface et al., 1993). One major problem with reed-beds is the clogging of the substrate, especially if the substrate is a soil or sand, resulting in overland flow and bypassing of the treatment zone within the matrix and rhizosphere of the reeds (Brix, 1987; Cooper et al., 1990; Schierup et al., 1990; Conley et al., 1991; Sanford, 1992). In addition, the production of odors can become a problem.

One of the important design parameters for reed beds is residence time. The "design" residence time is defined as the average time that the water remains in the bed and is equal to the time needed for the incoming waste water to be treated. This calculation assumes, in general, that the added water flows through all the pore spaces and that the whole bed participates in the treatment process. When there is preferential flow, short circuiting occurs and portions of the bed are bypassed and the residence time becomes less than the design residence time.

Although in many studies the concentrations of the in- and out-flowing water from the reed-bed have been measured (e.g., see examples in Hammer, 1989), little is known about the flow characteristics and the resulting residence time within the reed-bed systems. In one experiment using LiCl as a tracer, highest concentrations of Li^+ were found in the effluent 1–2 days after being introduced for two beds with design retention times of 5 and 8 days (Schierup et al., 1990).

In this paper, the results of a tracer experiment performed on four 3-year-old rock-reed filters (a type of reed-bed) are presented, together with specific conductance measurements made at several locations and depths within each bed to illustrate how the wastewater flows through the substrate. The data indicate that there was density stratification of the wastewater within the coarser substrates during normal operation and that preferential flow occurred due to both the density stratification and clogging of the finer substrates, which resulted in overland flow.

2. Material and methods

2.1. General

The rock-reed filters discussed in this paper are of an experimental nature and are being investigated as a possible treatment alternative for landfill leachate. The four beds, located near a municipal solid waste landfill in upstate New York, USA, are lined with 60 mil high density polyethylene to form a barrier between the treatment beds and the surrounding environment (Fig. 1a). The dimensions are 33 m × 3 m × 0.6 m with a bottom slope of 0.5%. There are 1.5 m long segments of coarse gravel at both the feed end and drain end of each bed to provide even distribution of leachate to the substrate and to facilitate drainage of the beds if need arises. At the head of the beds there is a 7.6 m^3 tank from which leachate is fed by gravity to each bed (Fig. 1b). Leachate is added to the beds at a design rate of 1.4 m^3/day, which yields a nominal design residence time of 15 days. As part of the overall research on treatment efficiency, three substrate types were used in the four beds: a coarse gravel (3-cm diameter stone), a pea gravel (0.5-cm diameter stone) and a sand-and-gravel mixture. One bed of each substrate type was planted with reeds (*Phragmites australis*) while a second bed with the sand-and-gravel substrate was left unplanted as a control. The four beds will be referred to as: PCG (planted coarse gravel), USG (unplanted sand-and-gravel), PSG (planted sand-and-gravel), and PPG (planted pea gravel) (Fig. 1b).

Five slotted teflon wells were installed along the longitudinal axis of each bed at approximately 5-m intervals to collect pore water samples, with the end wells located 5 m from the inflow and outflow ends. These wells also provided locations at which to measure the height of the water table and to measure the specific conductance of the wastewater within the substrate. Precipitation was measured at the site with a tipping bucket raingauge and recorded at 30-min intervals by a data logger. More detailed descriptions of the physical layout and operation of the experiment and treatment efficiencies are given in Sanford et al. (1990) and Surface et al. (1993).

2.2. Tracer experiment

Saturated hydraulic conductivity measurements during the 26 months prior to the tracer experiment (Sanford, 1992) found that the sand-and-gravel beds were largely clogged. The planted pea gravel experienced a decrease in hydraulic conductivity but the lowest value of 0.7 cm/s was adequate to maintain subsurface flow. No changes in hydraulic conductivity in the planted coarse gravel substrate have been measured (Sanford, 1992). With the reductions in hydraulic conductivity measured, questions arose as to how the lowered permeability affects the residence time and if the water flows preferentially through the substrate.

To examine if preferential flow was occurring, a tracer experiment was performed. A tracer (described below) was added in the inflow water and its concentration was measured in the effluent. By fitting the outflow concentration against the convective-dispersive equation, an average "tracer" residence time was calculated. If the "tracer" residence time was less than the "design" residence time, preferential flow occurred.

The major problem encountered in designing the tracer experiment was in selecting what tracer would be the best to use in conjunction with the chemicals present in the leachate. The leachate in the bed had a very high chloride concentration (around 1000 mg/l) which precluded the use of a non-adsorbed anion (Cl^- or Br^-) as the tracer. Because of this problem, we chose clean water as

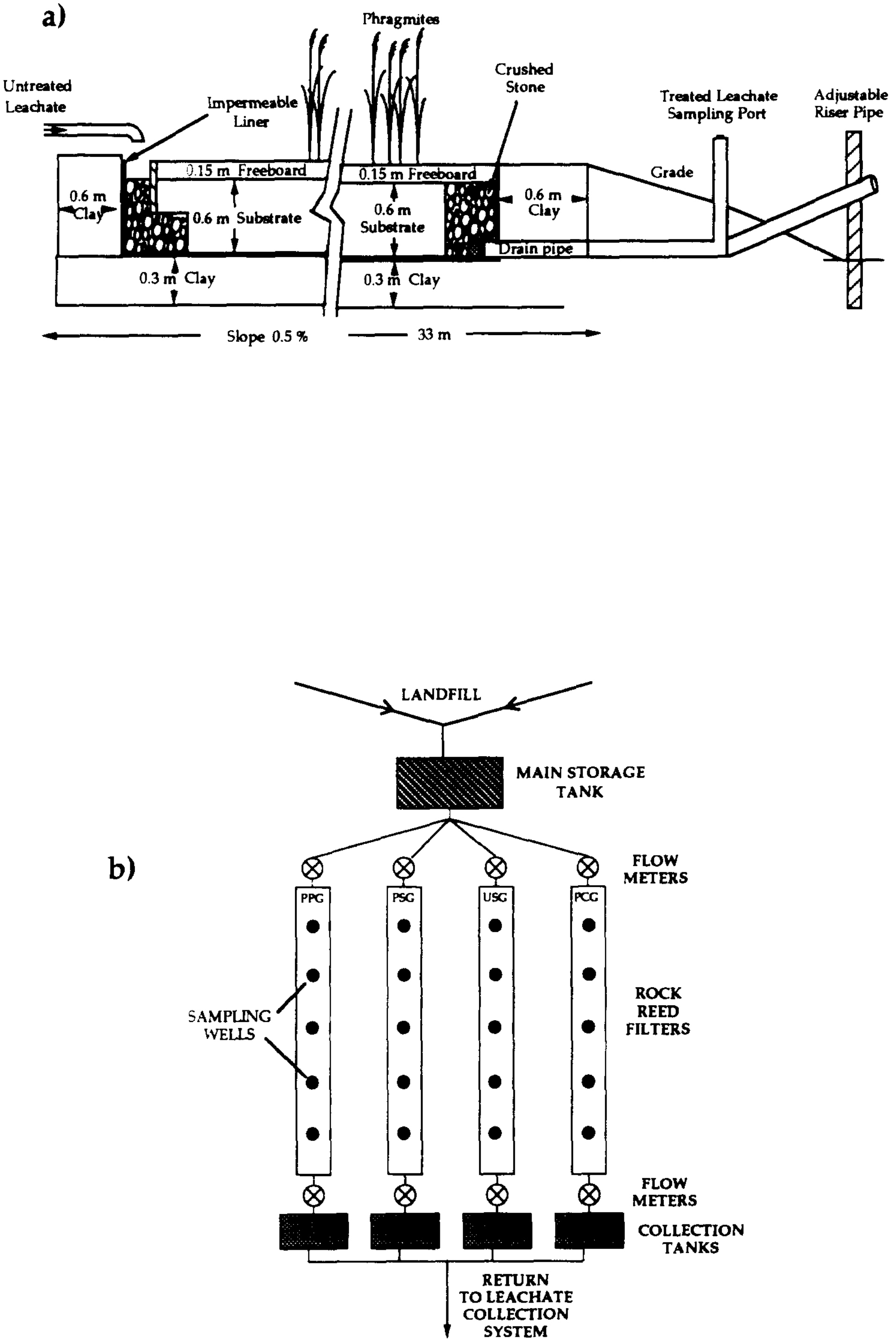
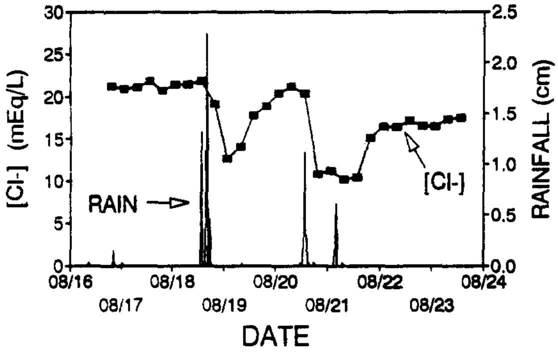
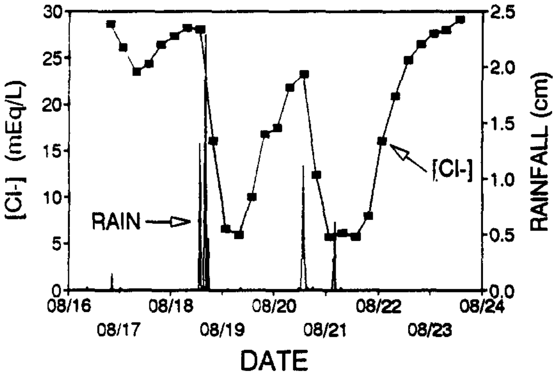


Fig. 1. (a) Schematic cross-sectional view of a rock-reed filter. (b) Plan view of the field layout. PCG = planted coarse gravel; USG = unplanted sand and gravel; PSG = planted sand and gravel; PPG = planted pea gravel.

PCG
PRE-DILUTION



PSG
PRE-DILUTION



PPG
PRE-DILUTION

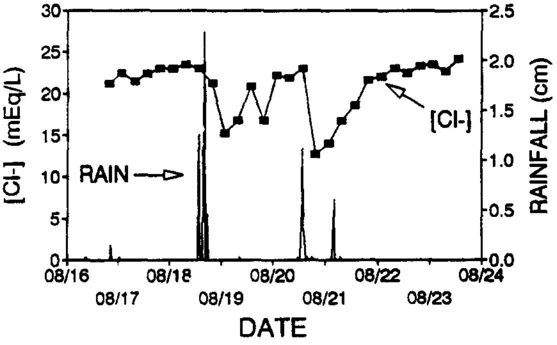


Fig. 2. Chloride concentrations in the effluent for 1 week prior to the dilution experiment and the rainfall during that period. PCG = planted coarse gravel; PSG = planted sand and gravel; PPG = planted pea gravel.

a tracer. The fresh water was added by filling the feed tank using a fire tanker once a day for 2 weeks. During the time of the dilution experiment, influent and effluent samples were collected and analyzed for Cl^- and the inflow and outflow volumes were recorded. Effluent was collected using an automatic sampler. Each sample consisted of a composite of 4 sub-samples collected at 1.5 h intervals. Prior to the beginning of the dilution experiment, outflow samples were collected at the same frequency for one week during normal operations. These samples were used to determine the background concentrations of chloride in the effluent.

To provide further information on how the wastewater flowed through the substrate, the specific conductance of the leachate in the subsurface was measured at 7.6 cm depth intervals beneath the water surface in each of the five inplot wells. Specific conductance measurements were also taken prior to the dilution experiment to determine if there was any stratification of the wastewater within the substrate during normal operations.

3. Results

3.1. Pre-dilution chloride data

The chloride concentrations in the outflow water together with rainfall are presented for the PCG, PSG, and PPG beds in Fig. 2 for the week before the tracer experiment (see Table 1 for substrates used in each bed). No data was collected for the USG bed due to an electrical malfunction of the sampler. Chloride concentration in the influent leachate was measured on August 7 and August 16 and was found to be 26.1 and 23.5 mEq/l, respectively. Immediately after the large rainfall on August 18 and August 20, the concentration of chloride in the effluent dropped sharply. The concentration decreased most in the PSG bed (sand-and-gravel mixture with the lowest hydraulic conductivity) followed by the PCG bed (coarse gravel with the highest hydraulic conductivity) and then the PPG bed. Even the small rain on August 16 lowered the chloride concentration in the effluent from the PSG bed while it had no effect on the effluent from the PCG and

Table 1
Bed composition and results of modeling using the statistical model CXTFIT

Substrate material	Planted coarse gravel (PCG)	Unplanted sand and gravel (USG)	Planted sand and gravel (PSG)	Planted pea gravel (PPG)
Initial [Cl^-] (mEq/l)	20.5	28	34	22.5
Time period used in CXTFIT (days)	0–7	0–2.5	0–2.5	0–14
Fraction of bed used in flow	0.78	0.22	0.49	0.79
Dispersion coefficient (m^2/day)	24	150	130	60

PPG beds (Fig. 2). For all beds, the chloride concentration increased to nearly its original level within 24 h after the rain stopped (Fig. 2).

3.2. Pre-dilution specific conductance

Measurements of specific conductance of the wastewater in each inplot well (presented in Fig. 3) during normal operations were taken on August 20 before the

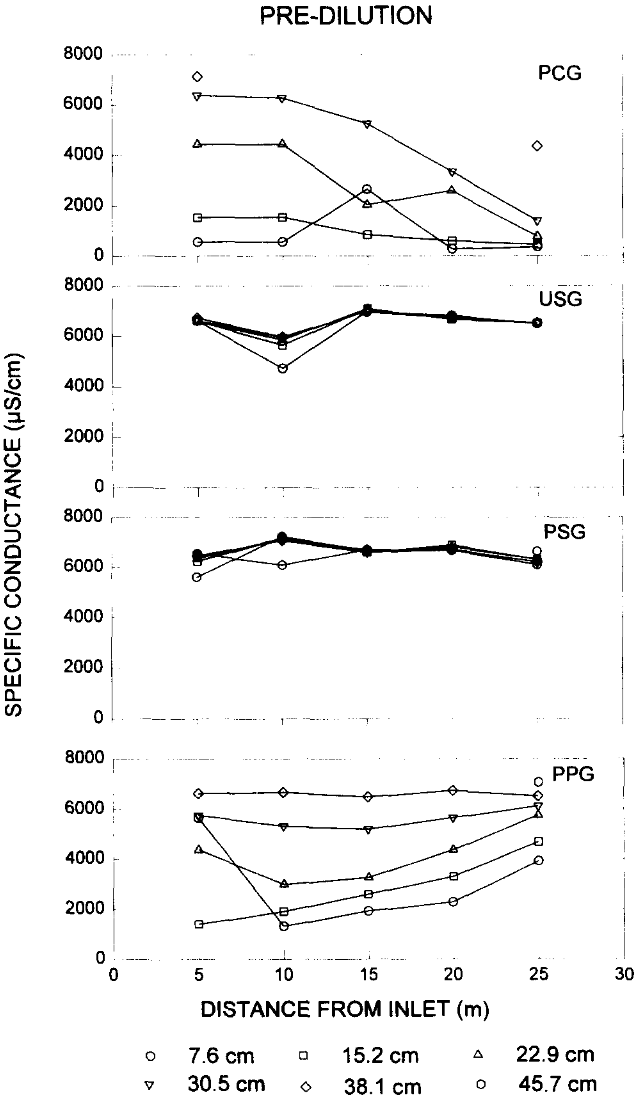


Fig. 3. Specific conductance measurements taken in each bed prior to the dilution experiment. Measurements made on August 20. PCG = planted coarse gravel; USG = unplanted sand and gravel; PSG = planted sand and gravel; PPG = planted pea gravel.

rainfall that occurred on that day and 2 days after a major rainfall on August 18. The specific conductance pattern was distinctly different between the two sand-and-gravel and the two gravel beds. The PSG and USG beds, with low hydraulic conductivity, had uniformly high specific conductance values of 6000–7000 μS/cm, while the high hydraulic conductivity PCG and PPG beds exhibit a pronounced vertical stratification of specific conductance throughout the length of the bed (Fig. 3), with the greatest values of 6000–7000 μS/cm occurring near the bottom of the substrate and the lowest values (~ 1000 μS/cm) occurring just below the surface. The average specific conductance of the influent leachate during the summer was 7390 μS/cm.

The pre-dilution chloride outflow and specific conductance data suggest that there were two methods of short circuiting (preferential flow) within the rock-reed filters. One type occurred in the two sand-and-gravel beds. Due to the low hydraulic conductivity there was very little infiltration of rain water in the substrate, as shown by the uniformly high specific conductance, and all water flowed directly overland to the outlet, reducing the concentration immediately (Fig. 2, Fig. 3). The other type of short circuiting was caused by density differences within the bed. In the PCG and PPG beds, the rain water was "floating" on top of the denser leachate. The specific conductance profile of the PCG bed (Fig. 3) indicates that the rain flowed over the denser leachate towards the tile drain at the end of the plot causing a moderate lowering of the concentration (Fig. 2). The pea gravel behaved almost completely as an "ideal" plug flow system and consequently most rain was retained in the bed with a minimum of preferential flow on August 20. The tracer dilution experiment described below confirms these findings.

3.3. Dilution experiment -Effluent chloride concentrations

Plots of the chloride concentration and outflow rate versus time since the start of fresh water addition are presented in Fig. 4 for all four beds. The inflow to all beds during the dilution experiment was characterized by a steady state inflow rate on which short periods of increased inflow rates were superimposed. The outflow rates shown in Fig. 4 reflected this pattern. For the two sand-and-gravel plots (PSG and USG), an increase in the outflow rate was accompanied by a decrease in the effluent chloride concentration. The small increase in outflow rate from the USG bed around Day 7 halved the effluent concentration. Once the flow rate slowed the concentration rebounded to higher levels. This concentration pattern is typical for soils in which short circuiting or preferential transport occurs (e.g., Steenhuis et al., 1992; Wilson et al., 1993). At low flow rates the outflow concentration equaled matrix water concentration near the outlet and at high flow rates the outflow concentration reflected, to a degree, the input concentration of the water (which was < 1 mEq/l for the experiment). For the PPG bed, the effluent concentration was not as strongly influenced by the fluctuations in flow rate, which is typical for systems with little or no preferential flow. In the PCG bed, there was only a minor effect of flow rate on concentration outflow patterns.

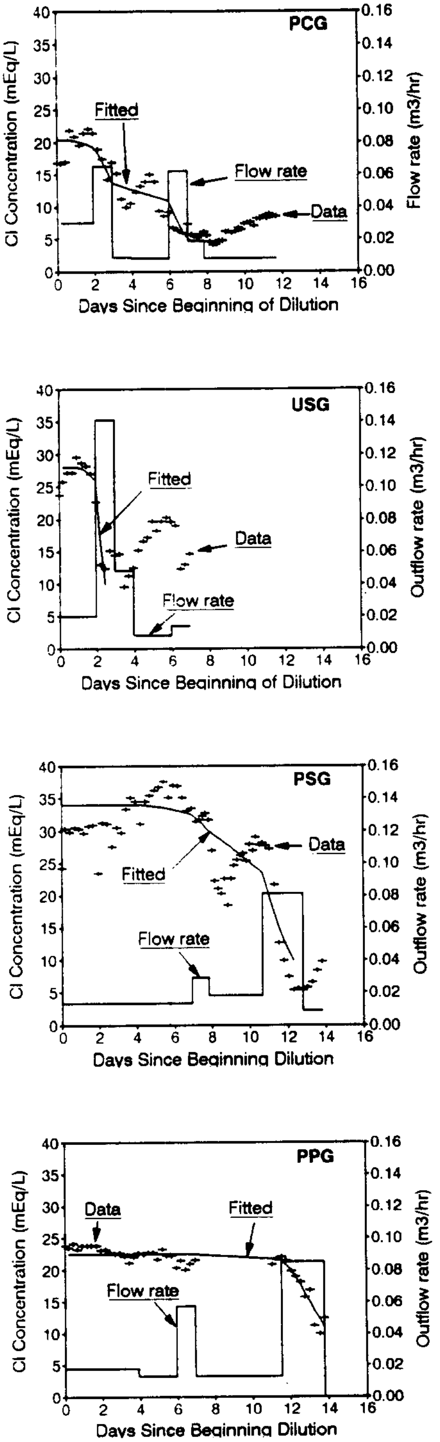


Fig. 4. Chloride concentrations measured in the effluent during the dilution experiment. Also plotted are the flow rates and the curve which was fitted to the data by the statistical model CXTFIT.

3.4. Dilution experiment –Quantitative estimates

To obtain quantitative estimates of the transport parameters and to compute the residence time in each of the four reed-beds, the nonlinear least-squares inversion method of Parker and van Genuchten (1984) (CXTFIT) was used. The model chosen was the one-dimensional convection-dispersion equation with the assumptions of steady state flow, no retardation, no adsorption, and no sinks or sources of chloride present. Outflow volumes were converted to fractions of total water in the bed (i.e. pore volumes). For the PCG bed, inflow rather than outflow was used as a result of a faulty flow meter on the outflow end. The fraction of the bed that participated in the flow process and the dispersion coefficient (D; units of length^2/time) were determined by a least-squares fit to the breakthrough curves (BTCs) from each bed. Due to the preferential flow in the PSG and USG beds, only portions of each BTC were used. The resulting fitted curves are shown in Fig. 4.

The input data and fitted values from CXTFIT are given in Table 1. The same pattern emerges as for the pre-dilution experiments. In the gravel beds (PCG and PPG) there was very little preferential flow (nearly 80% of the substrates participated in flow) and for the sand-and-gravel beds (PSG and USG) the convective-dispersive equation did not, as expected, fit the data very well. For the portions of the BTCs used there was significant short circuiting with only 22% of the USG bed and 49% of the PSG bed participating in flow. The resulting dispersion values were within the ranges of typical values reported in the literature (e.g., Gelhar et al., 1992).

3.5. Dilution experiment –Specific conductance

Specific conductance measurements of the leachate within the four beds were taken 11 days after the beginning of the dilution experiment (Fig. 5). Additional measurements were taken on Day 13 in the PSG and PPG beds because the last two deliveries of water (beginning on Day 11) were run through these two beds only (Fig. 6). The pronounced stratification that was evident in the pre-dilution measurements was not observed because the condition of a less dense fluid displacing a denser fluid is a stable configuration.

On Day 11, the specific conductance in the PCG bed was around 1000 μS/cm for all locations. This indicates that most of the initial leachate present in the bed had been flushed out, confirming that plug flow occurred before that date.

The inflow rate to the PPG bed was much slower than to the PCG bed and therefore, unlike the planted coarse gravel, on Days 11 and 13 there was still leachate in the bed. The specific conductance measurements from the PPG bed (Fig. 5, Fig. 6) indicate that dilution was occurring from the inlet to the outlet (exemplifying the plug flow concept) and show much less stratification than was present before the dilution experiment (Fig. 3).

The specific conductance measurements from the USG bed (Fig. 5) on Day 11 show that there was still no vertical stratification but that the leachate within the

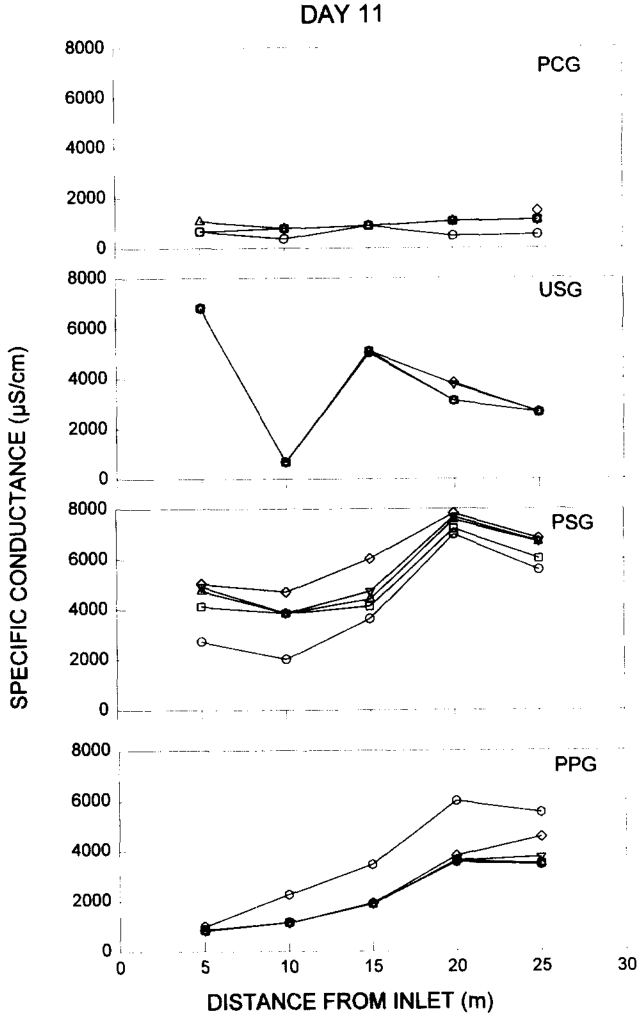


Fig. 5. Specific conductance measured in all four beds on Day 11 of the dilution experiment.

bed was more dilute towards the outflow end. The low readings from the inplot well at 10 m were due to ponding of water around the well allowing contamination by surface water. The closest well to the inlet (5 m) showed no evidence of any dilution throughout its entire depth. The well closest to the outlet exhibited the greatest amount of dilution (excluding the well at 10 m). Water thus flowed overland to the outlet end where it infiltrated and flowed to the drain at the bottom of the bed.

In the PSG bed, in contrast to the USG bed, the specific conductance measurements from Days 11 and 13 (Fig. 5 and 6) show that dilution was occurring at both the inlet and outlet ends of the bed. This is especially evident from the data

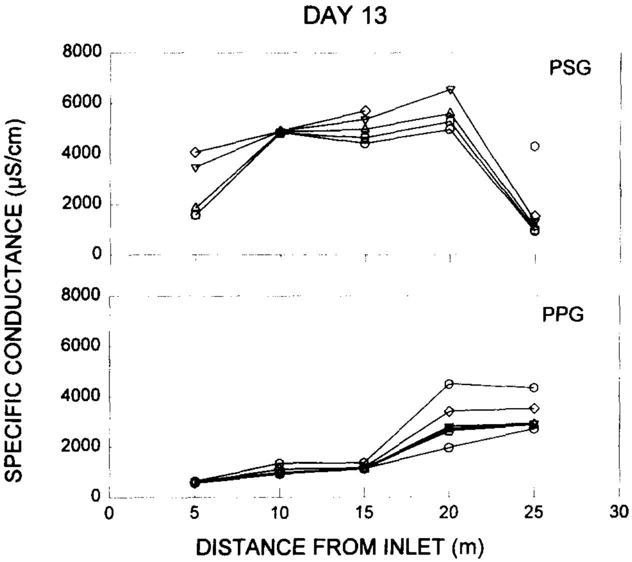


Fig. 6. Specific conductance measured in the PSG (plated sand and gravel) and PPG (planted pea gravel) beds on Day 13 of the dilution experiment.

collected on Day 13. The pattern indicates that there was substantial overland flow of water to the outlet which resulted in the lowering of the specific conductance from 6000 μS/cm to 1000 μS/cm in the well closest to the outlet. The decrease in specific conductance occurring from the inlet end towards the outlet end seen in the wells at 5 and 10 m from the inlet indicates that there was a minor amount of subsurface flow of the influent.

4. Discussion

There were two types of preferential flow observed in the rock-reed filters of this study. One was the result of density differences that can occur due to the addition of rainwater or a more concentrated influent and the other was the result of clogging of the pore space within the substrate. The density stratification was most important within the gravel substrates (the PCG and PPG beds) which have high hydraulic conductivities so that there is little resistance to flow at the flow rates present in the system.

There are several ramifications of density stratification. A major concern is the reduction of the contact time that the wastewater has with the substrate. For example, if the denser leachate is flowing through only the bottom half of the substrate, beneath the less dense fluid, then the residence time is one half the designed value, greatly decreasing treatment efficiency. Another problem is associated with the analyses made on the concentration of chemical constituents in the effluent. If the sample is collected soon after a rainstorm, the concentration in the effluent would be much less than the concentration of the same constituent in the substrate, thereby suggesting a much greater treatment efficiency than what is actually occurring. One method to use which avoids this problem is to measure treatment efficiency based on loading rates of the constituent in question (Surface et al., 1993). A related problem arises in the sampling of pore water for analysis. Integrated samples collected from an inplot well will consist of a mixture of fluid from all depths. Analyses will find the concentration of a chemical lower than it actually is in the flowing segment of the wastewater since the concentrated part of the sample (from the denser fluid flowing beneath the less dense fluid) has been diluted by the less dense fluid above. This was seen in the PCG bed just prior to the dilution experiment where the chloride concentration of the influent was 23.5 mEq/l and of the effluent was 16.8 mEq/l, while pore water concentrations from the five inplot wells ranged from 2.1 to 10.9 mEq/l.

The problems of preferential flow caused by clogged substrates are similar to some of the problems associated with density stratification. One similar problem is in the rapid decrease in concentration in the effluent following a rainstorm due to the overland flow of the rainwater. An extreme example is seen in the chloride concentrations measured in effluent samples collected during normal operations from the PSG bed (Fig. 2). Another associated problem is the lowering of treatment efficiency due to in the reduced residence time of the wastewater in the system as a result of preferential and overland flow which cause the wastewater to bypass the treatment zone within the substrate.

An important finding of this study is that the tracer experiment itself would not have yielded sufficient information to interpret the effects that density stratification and clogging have on the flow characteristics of the wastewater through the beds. The specific conductance measurements were vital in determining that preferential flow occurs within the gravel beds due to density differences. The specific conductance data were also instrumental in determining that in the sand-and-gravel beds, overland flow dominated the system and that there was little or no flow through the substrate.

The results suggest that the best substrate for use in a rock-reed filter from a flow characteristic point-of-view is gravel. Gravel substrates have sufficiently high hydraulic conductivity to prevent overland flow (Sanford, 1992) and, although density stratification was observed, the specific conductance measurements suggest that the flow through the substrate is a combination of density effects and plug flow displacement. The significant displacement flow will offset some of the problems associated with the density flow. From a treatment efficiency point-of-view, the pea-gravel substrate has an advantage over the coarse gravel because of the increased surface area for treatment (Surface et al., 1993).

Acknowledgements

Partial funding for this project was provided by the New York State Energy Research and Development Authority and the United States Geological Survey.

Additional support was provided to W.E.S. by an appointment to the Oak Ridge National Laboratory Postdoctoral Research Program administered by the Oak Ridge Institute for Science and Education.

References

Brix, H., 1987. Treatment of wastewater in the rhizosphere of wetland plants –The root-zone method. Water Sci. Technol., 19: 107–118.

Conley, L.M., R.I. Dick and L.W. Lion, 1991. An assessment of the root zone method of wastewater treatment. Res. J. Water Pollut. Control Fed., 63: 239–247.

Cooper, P.F., J.A. Hobson and C. Findlater, 1990. The use of reed bed treatment systems in the UK. Water Sci. Technol., 22: 57–64.

Gelhar, L.W., C. Welty and K.R. Rehfeldt, 1992. A critical review of data on field-scale dispersion in aquifers. Water Resources Res., 28: 1955–1974.

Hammer, D.A. (Editor), 1989. Constructed wetlands for wastewater treatment: Municipal, industrial and agricultural. Lewis Publishers, Inc., Chelsea, MI. 831 pp.

Parker, J.C. and M.Th. van Genuchten, 1984. Determining transport parameters from laboratory and field tracer experiments. Virginia Agric. Exp. Station Bull., 84-3.

Sanford, W.E., T.S. Steenhuis, R.J. Kopka, J.H. Peverly, J.M. Surface, J. Campbell and M.J. Lavine, 1990. Rock-reed filters for treating landfill leachate. Am. Soc. Agric. Eng., Paper No. 90-2537, 15 pp.

Sanford, W.E., 1992. Hillslope drainage: Theory and application to laboratory experiments and rock-reed filters. Ph.D. Dissertation, Cornell University, Ithaca, NY, 173 pp.

Schierup, H.-H., H. Brix and B. Lorenzen, 1990. Wastewater treatment in constructed reed beds in Denmark –State of the art. In: Cooper, P.F. and B.C. Findlater (Eds.), Constructed Wetlands in Water Pollution Control: Advances in Water Pollution Control. Pergamon Press, Oxford, pp. 498–499.

Staubitz, W.W., J.M. Surface, T.S. Steenhuis, J.H. Peverly, M.J. Lavine, N.C. Weeks, W.E. Sanford and R.J. Kopka, 1989. Potential use of constructed wetlands to treat landfill leachate. In: Hammer, D.A. (Ed.), Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural. Lewis Publishers, Chelsea, MI, pp. 735–742.

Steenhuis, T.S., B.M. Nijssen, F. Stagnitti and J.-Y. Parlange, 1992. Preferential solute movement in structured soils: Theory and application. In: Challenges for Sustainable Development. Proceedings of International Hydrology and Water Resources Symposium. Perth, Australia, October 2–4, 1991. pp. 925–930.

Surface, J.M., J.H. Peverly, T.S. Steenhuis and W.E. Sanford, 1993. Constructed wetlands for landfill leachate treatment. In: Moshiri, G.A. (Ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publishers, Chelsea, MI, pp. 461–472.

Wilson, G.V., P.M. Jardine, J.D. O'Dell and M. Collineau, 1993. Field-scale transport from a buried line source in variably saturated soil. J. Hydrol., 145: 83–109.