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Hydraulic conductivity of gravel and sand as substrates in rock-reed filters

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Abstract

Long-term use of a constructed wetland to treat landfill leachate requires that the saturated hydraulic conductivity be maintained and clogging avoided to prevent overland flow, which bypasses the treatment process. This paper describes the application of an equation developed for prediction of cumulative drainage volume from hillslopes to measure the saturated hydraulic conductivity (K_s) of substrates used in rock-reed filters. Outflow was measured at five intervals during the first 26 months of operation. The values of K_s obtained by the drainage equation compared favorably with values calculated from a more difficult method based on Darcy's law. Results indicate that the finest substrate (a sand-and-gravel mixture) became almost completely clogged, and that the presence of reeds (*Phragmites australis*) did not maintain or increase the conductivity. Hydraulic conductivity of pea-gravel (0.5-cm diameter) and coarse-gravel (3-cm diameter) substrates with reeds did decrease in the 26-month period.

Keywords: Constructed wetlands; Landfill leachate; Hydraulic conductivity; Subsurface flow

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1. Introduction

Precipitation that falls on municipal solid-waste landfills infiltrates through the waste and forms a leachate that contains a variety of undesirable, and commonly toxic, substances. This leachate then migrates to the underlying aquifer where it causes groundwater pollution. In an attempt to minimize groundwater pollution from landfills, state and federal agencies have closed several landfills and require that most new landfills be built with an impermeable barrier to prevent the leachate from entering the surrounding environment. Nearly all landfills now must have systems to collect as much of the leachate as possible for treatment before disposal.

The most common method of leachate treatment is to haul or pump it to a wastewater-treatment plant, but because many treatment plants are not designed for this purpose, alternative facilities and methods of treatment are needed that (1) can treat a wide range of chemicals, (2) entail low construction and operational costs, and (3) require minimal energy (Staubitz et al., 1989). Rock-reed filters, a type of constructed wetland used for wastewater treatment, show promise as an alternative treatment that meets these criteria (Sanford et al., 1990a,b; Surface et al., 1993).

In 1989, Cornell University, in cooperation with the USGS, began a 3-year study of constructed wetlands near Ithaca, NY to identify (1) treatment efficiency as a function of substrate composition and grain size, degree of plant growth, and seasonal changes in evapotranspiration rates and microbial activity, (2) chemical, biological, and physical processes by which nutrients, metals, and organic compounds are removed from leachate as it flows through the substrate, and (3) effects of leachate and plant growth on the hydraulic characteristics of the substrates. The focus of this paper is the evaluation of the hydraulic performance of four rock-reed filters, each filled with a different type of substrate (3-cm-diameter stone, 0.5-cm-diameter stone, and planted and unplanted sand-and-gravel mixtures). The measurements were repeated five times over a 26-month period to quantify changes in the saturated hydraulic conductivity (K_s) that resulted from plant growth and from clogging associated with leachate treatment. This report (1) describes the equipment and method of data analysis, (2) presents the results as a series of outflow plots, and (3) discusses the degree of clogging in the four substrates.

2. Methods

The study objectives were to develop a relatively simple experimental procedure to measure the effective saturated hydraulic conductivity of each rock-reed filter and to document the changes in the conductivity with time. The typical treatment process at a constructed wetland is as follows: wastewater is added to the upslope end and migrates through the subsurface in contact with the root and rhizome system of the reeds and the zone of anaerobic and aerobic microorganisms that have developed in the substrate. As the wastewater flows toward the outlet, chemical and biochemical reactions remove or transform some of the chemicals. During the treatment, precipitates and biofilms that develop, and suspended solids that are filtered out of the wastewater, contribute to the clogging of the substrate. If clogging is sufficient, the influent will bypass the treatment zone in the substrate by flowing overland, and will exit the system untreated. Therefore, several types of substrates need to be examined to determine which ones best maintain their initial hydraulic conductivity. The treatment efficiency of the four various types of substrates described herein are summarized in Surface et al. (1993).

2.1. Treatment system

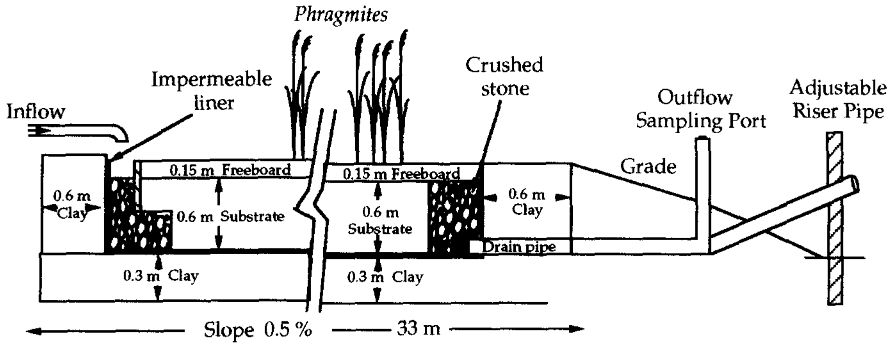
The rock-reed filters consist of four parallel troughs measuring 33 × 3 m by 1 m with a bottom slope (β) of 0.5% and lined with high density polyethylene (Fig. 1). Three types of substrates were added to the beds at a depth of 0.6 m. The first trough (bed 1) contained a coarse gravel (2–4-cm diameter), the fourth (bed 4) contained a pea gravel (0.5-cm diameter), and beds 2 and 3 contained a sand-and-gravel mixture (Fig. 1B). Beds 1, 3, and 4 were planted with *Phragmites australis*, and bed 2 (sand and gravel) was left unplanted as a control. A section 1.4 to 1.5 m long and 0.6 m deep at the inlet and outlet ends of each bed (Fig. 1A) was filled with coarse gravel to provide even distribution and drainage of the wastewater. The leachate was added to each bed by gravity flow from a feed tank at the head of the beds (Fig. 1B).

The residence time of the leachate in the beds was controlled by valves on the inflow pipe. The water level in each was controlled by a riser at the outlet end (Fig. 1A). Volumetric flow meters within the piping at the inflow and outflow ends of each bed recorded the volume of leachate entering and exiting. Rainfall at the site was measured so that the volume of inflow from precipitation could be calculated. Five 5-cm-diameter slotted Teflon [1] wells were installed at roughly 6-m intervals along the length of each bed (Fig. 1B) for collection of pore-water samples and water-level measurement.

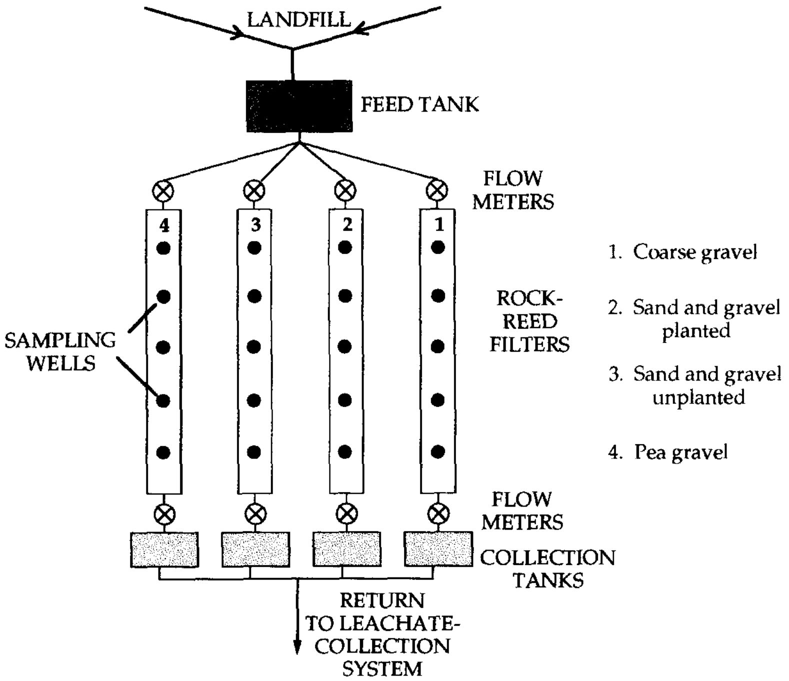
2.2. Experiment design

The experiment entailed allowing each bed to drain while the cumulative outflow volume was recorded and the water level in the five monitoring wells measured. First, the inflow and outflow valves were closed to produce a horizontal water table. Then the riser in the drain system, which is downstream from the outflow valve (Fig. 1A) and controls the depth of the water at the drain, was lowered to below the drain elevation. The initial water-surface elevation in each well was recorded. Then, the outlet valve was opened, and the cumulative discharge volume and water levels were recorded at specified times during the release.

[1] Use of brand names is for identification purposes only and does not imply endorsement.



A Vertical Section



B Plan View

Fig. 1. (A) Longitudinal vertical section of a rock-reed filter. (B) Plan view of the field layout.

The hydraulic conductivity of the bed was calculated by two methods. One consisted of simulating the outflow data by the equation developed by Sanford et al. (1993a) to predict the cumulative drainage volume from aquifers overlying sloping, impermeable layers. The other used Darcy's Law to estimate the hydraulic conductivity of the substrate segments between each monitoring well.

The drainage experiment was performed five times over a 26-month period to measure the changes in substrate conductivity. The first measurement was run in the early summer of 1989, after the reeds had been planted but before they had grown appreciably. The water in the beds at this time was only rainwater or water pumped in from a nearby ditch. The second measurement was 2 months later, at the end of the first growing season, again, with only rainwater or ditch water. The third measurement was run in the spring of 1990, after the reeds had begun new growth, and was the last measurement before the addition of leachate in June 1990. The fourth measurement was run a year later in the spring of 1991, after the first winter of leachate application and soon after the plants had begun their new growth. The final measurement was in the fall of 1991, after nearly a full season of leachate exposure. Just before the final measurement, the four rock-reed filters were flushed with freshwater as part of a different experiment to examine the flow of leachate through the substrate (Sanford et al., 1993b).

2.3. Data analysis

2.3.1. Drainage equation

The equation used to estimate the hydraulic conductivity in each experiment was derived by Sanford et al. (1993a) and is based on the Boussinesq approximation for flow in porous media overlying a sloping, impermeable layer. The resulting equation is

$$V = V^* \left(\frac{1 - \exp\left[-t \dfrac{3h(0,0) K_s \cos\beta}{sL^2} \left(1 - \dfrac{V^*}{V_i} \right) \right]}{1 - \dfrac{V^*}{V_i} \exp\left[-t \dfrac{3h(0,0) K_s \cos\beta}{sL^2} \left(1 - \dfrac{V^*}{V_i} \right) \right]} \right) \tag{1}$$

where

$$V_i = swLh(0,0) \tag{2}$$

$$V^* = swL[h(0,0) - h(0,t)] + \tfrac{1}{2} swL^2 \tan\beta \tag{3}$$

and

V = cumulative drainage volume at any time $[L^3]$
s = drainable porosity $[L^3/L^3]$
x = linear distance from the drain $[L]$
t = time at which drainage volume is calculated $[T]$
β = slope of impermeable layer $[L/L]$

Table 1
Season, initial water depths at drain [$h(0,0)$] in all beds, drainage porosities in all beds, and volume of water in coarse gravel pack

Season	Pea gravel		Coarse gravel		Unplanted sand and gravel			Planted sand and gravel		
	$h(0,0)$	Porosity	$h(0,0)$	Porosity	$h(0,0)$	Porosity	Gravel-pack volume	$h(0,0)$	Porosity	Gravel-pack volume
Summer 1989	0.67	0.33	NA	0.36	0.65	0.14	1.0	0.67	0.12	1.1
Fall 1989	0.67	0.34	NA	0.38	0.63	0.16	1.3	0.68	0.17	0.5
Spring 1990	0.73	0.33	NA	0.36	0.46	0.19	0.6	0.63	0.12	0.8
			Leachate addition started summer 1990							
Spring 1991	0.63	0.37	NA	0.36	0.53	0.10	0.6	0.60	0.09	NA
Fall 1991	0.71	0.27	NA	0.33	0.58	NA	NA	0.66	0.05	0.6

Water depths are in meters. Volumes are in cubic meters. NA = not applicable.

L = length of bed $[L]$
w = width of bed $[L]$
K_s = saturated hydraulic conductivity $[L/T]$
$h(0,0)$ = hydraulic head at $x=0$ and $t=0$ $[L]$
$h(0,t)$ = hydraulic head at $x=0$ and $t>0$ $[L]$.

The only unknown in the above equation when applied to the drainage experiments is hydraulic conductivity, K_s. A range of conductivity values was applied to Eq. (1) until the resulting outflow curve matched the measured outflow. The value of K_s that produced the closest fit is taken as the hydraulic conductivity of the substrate for that particular drainage experiment. Values for initial water level at the drain [$h(0,0)$], drainable porosity (s) and volume of the coarse-gravel pack are given in Table 1.

2.3.2. Darcy's Law

The second method to measure the saturated hydraulic conductivity of the substrate uses the hydraulic head data recorded in each of the five monitoring wells. The volume of substrate that was drained during the time between water-level measurements can be calculated for the four segments between each well and for the entire bed. The volume of water flowing past each well can be estimated as the total volume of drained, upslope substrate multiplied by the drainable porosity. The hydraulic conductivity of the segment between wells can be found through Darcy's Law

$$Q = AK_s i$$

where

Q = volumetric flow rate past a well $[L^3/T]$
A = average cross-sectional area of segment between wells $[L^2]$

i = hydraulic gradient found by dividing water-level differences between wells by distance between wells $[L/L]$.

This technique involves the collection of more data than the previous method as a result of measuring the water-levels in all wells and requires more skill in interpreting the data than the fitting method described above but provides a means of verification for the first method.

2.3.3. Computation procedure

Application of Eq. (1) to calculate the hydraulic conductivity of the four substrates is straightforward. All the geometric variables for each rock-reed filter (length, width, and slope) were known. The drainable porosity of the matrix (s) was calculated as the total amount of water that drained during the experiment, divided by the total volume of substrate that was drained. A slightly different procedure was followed for the two sand-and-gravel beds because the gravel packs at each end of the beds had a much greater drainable porosity and permeability than the sand-and-gravel substrate in which the water levels were measured. Adjustment for this difference required an estimate of the volume of water drained from the coarse-gravel pack at the outlet end of the beds and subtraction of this volume from the cumulative drainage at all points. The first 75 to 90-min segments of the drainage curves were ignored because this was the time in which outflow was mostly drainage from the gravel pack. In addition to the volume correction, the length of the gravel pack was subtracted from the total length of the bed.

Eq. (1) requires the hydraulic head value directly over the drain. The water level at the drain in the pea gravel was assumed to be the same as that in well A (the well nearest the drain, see Fig. 1), and the water level at the drain in the two sand-and-gravel beds was assumed to be zero at all times because the coarse-gravel pack drains much faster than the sand-and-gravel matrix.

Once these corrections were made, the hydraulic conductivity of the substrates were calculated for each experiment as described above.

3. Results

3.1. Calculation of K_s by drainage equation

The following sections present the saturated hydraulic conductivity value calculated for each bed by Eq. (1). For brevity, only the first and last measurements (summer 1989 and fall 1991 for beds 1, 3, and 4, and summer 1989 and spring 1991 for bed 2) for each bed are discussed. Hydraulic conductivity values obtained by the drainage equation and Darcy's Law for all substrates are presented in Table 2; further details are given in Sanford (1992).

Table 2
Hydraulic conductivity values obtained by the drainage equation and average values obtained by Darcy's Law method

Season	Pea gravel		Unplanted sand and gravel		Planted sand and gravel	
	Drainage Eq.	Darcy's Law	Drainage Eq.	Darcy's Law	Drainage Eq.	Darcy's Law
Summer 1989	6.0	7.2 (2.8)	0.22	0.27 (0.17)	0.12	0.15 (0.03)
Fall 1989	6.0	6.2 (2.3)	0.18	0.25 (0.22)	0.17	0.12 (0.07)
Spring 1990	4.7	7.7 (2.8)	0.22	0.20 (0.12)	0.12	0.17 (0.08)
Spring 1991	6.3	5.3 (2.5)	0.03	0.03 (0.02)	–	–
Fall 1991	4.0	5.7 (0.5)	Clogged		0.02	0.03 (0.01)

Values are in centimeters per second. Numbers in parentheses are standard deviation. Dash indicates no measurements made.

3.2. Planted coarse gravel

Outflows measured during the five experiments at the planted coarse-gravel bed are shown in Fig. 2. The data for the summer and fall runs of 1989 and the spring of 1990 and 1991 form nearly straight lines. The initial water level in the fall 1991 experiment was nearly 15 cm lower than the average height in the other four experiments and resulted in outflows that do not parallel the others. During all experiments, the water level was nearly the same at all wells, an indication that the head loss in the bed was small compared to the head loss at the outlet point and that the flow rates were controlled by the drain system rather than by the substrate in the bed.

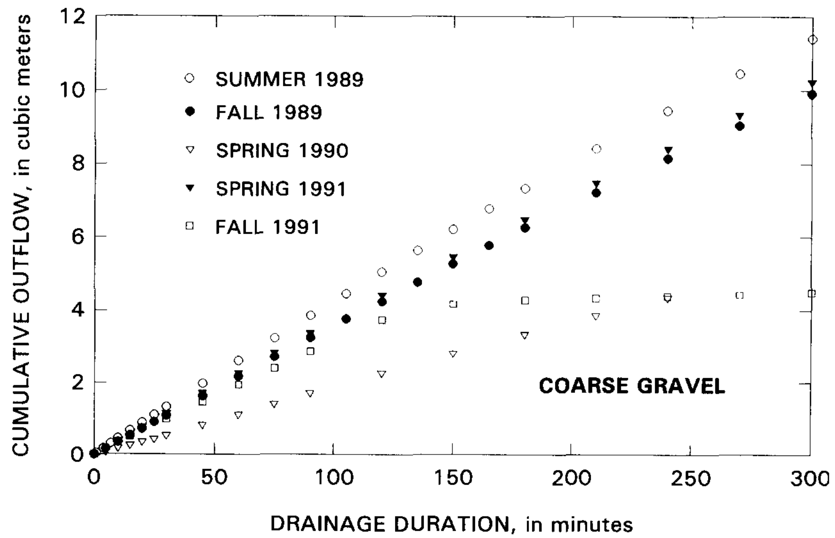


Fig. 2. Measured outflow from planted coarse-gravel bed in all five tests.

The dependency of the flow rate on the outlet point is further illustrated by the outflows from the spring of 1990 (Fig. 2). These values form a line that is straight, but has a considerably lower slope than the others as a result of the clogging of a filter fabric that was wrapped around the drainage pipe during the construction of the beds. The fabric was removed shortly after this experiment, and the values for the spring of 1991 were similar to those for the two experiments in 1989. The only evidence of clogging within the coarse-gravel bed is the decrease in drainable porosity from 0.36 to 0.33 over the 2-year period (Table 1).

3.3. Unplanted sand and gravel

The cumulative outflows measured at the unplanted sand-and-gravel bed (Fig. 3A) indicate less drainage volume for successive measurements – a possible indication of clogging. The data in Fig. 3A are the measured values, not corrected for the coarse-gravel pack at the outflow end of the bed.

The outflows obtained by Eq. (1) for this bed in the summer of 1989 and spring of 1991 are plotted with the measured values in Fig. 3B. These data have been corrected for the volume of water in the coarse-gravel pack and represent a range of values of K_s that illustrate the large change in predicted outflow that results from only a small change in hydraulic conductivity. The intermediate K_s value produces the closest fit to the measured values in both years.

Hydraulic conductivity of the unplanted sand-and-gravel bed changes little during the first three drainage experiments (summer and fall of 1989 and spring of 1990; 0.18 and 0.22 cm/s; Fig. 3B and Table 2). After a year of leachate addition, however, the hydraulic conductivity decreased to 0.03 cm/s (Fig. 3B and Table 2). The measurements of fall 1991 are not plotted because the estimated volume of water in the coarse-gravel pack was roughly the same as the amount that drained from the bed. This, together with the lack of an increase in outflow volume after 3 h of drainage, indicates that the unplanted sand-and-gravel bed had become almost completely clogged.

3.4. Planted sand and gravel

Cumulative outflows for all five tests at the planted sand-and-gravel bed are presented in Fig. 4A. As with the unplanted sand-and-gravel bed (Fig. 4A), the amount of water that could drain from this bed over a given time also decreased greatly over the 2-year study period.

The measured (and corrected) outflows from the summer of 1989 and the fall of 1991 are plotted in Fig. 4B with calculated outflows resulting from three K_s values. As with the unplanted sand-and-gravel bed, the intermediate value of K_s provides the best fit. Hydraulic conductivity of the bed before the addition of leachate ranged from 0.12 to 0.17 cm/s (Fig. 4B and Table 2), but by the fall of 1991, after more than a year of leachate addition and plant growth, it had decreased to 0.023 cm/s (Fig. 4B and Table 2) as a result of clogging. Data from

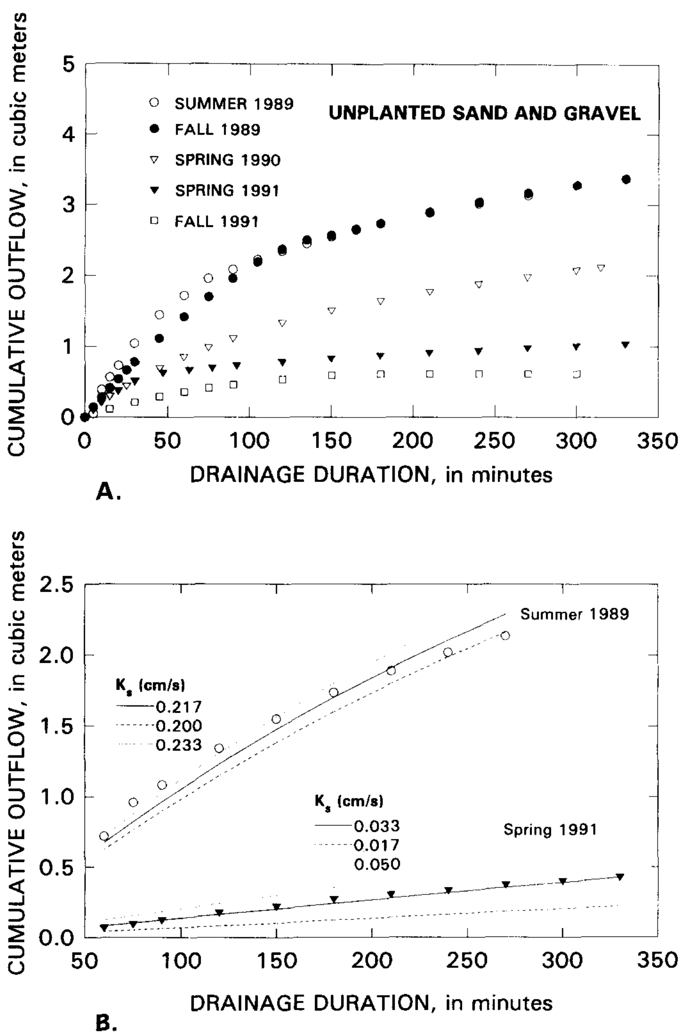


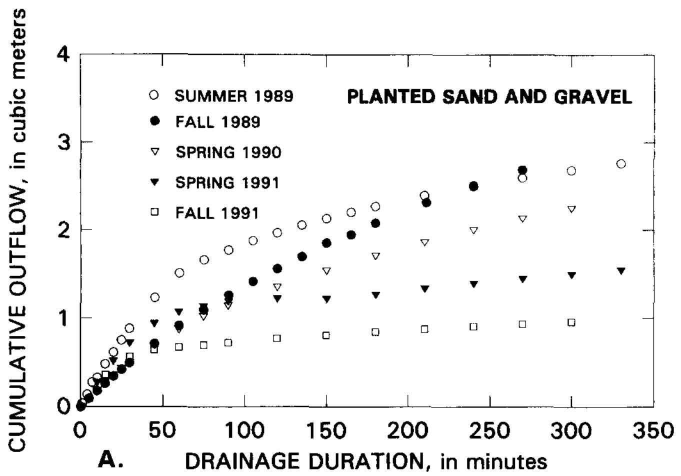
Fig. 3. Outflow curves for unplanted sand-and-gravel bed. (A) Measured outflow in all five tests. (B) Calculated and measured outflow in tests of summer 1989 and spring 1991.

the spring of 1991 are not plotted because during the middle of the experiment, the outflow point had been raised slightly and prevented outflow.

3.5. Pea gravel

Cumulative outflow values for the pea-gravel bed are given in Fig. 5A. The measurements were made for 5 to 6 h.

Outflows obtained by Eq. (1) for summer 1989 and fall 1991 are plotted with the measured values in Fig. 5B; the results indicate a near-perfect fit. K_s values for



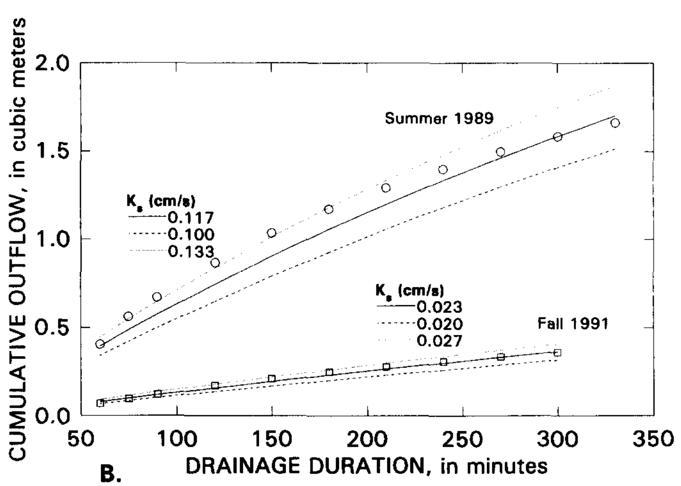


Fig. 4. Outflow curves for planted sand-and-gravel bed. (A) Measured outflow in all five tests. (B) Calculated and measured outflow in tests of summer 1989 and fall 1991.

the summer 1989 (Fig. 5B) and fall 1989 (Table 2) (6.0 cm/s) are within the range expected for this particle size. Conductivity decreased slightly in the spring of 1990 (4.7 cm/s), increased to its original value in the spring of 1991 (6.3 cm/s), and decreased to 4.0 cm/s in the fall of 1991 (Fig. 5B). The second decrease was expected because the bed had been exposed to leachate for a full spring and summer. The increase in the spring of 1990 was unexpected (Table 2) but corresponds to an increase in the measured drainable porosity (Table 1); it could have been the result of (1) winter freeze-thaw action that formed preferential-flow channels, and (2) the seasonal decline in microbial action. The values in Table 2 indicate that the hydraulic conductivity of the pea-gravel bed, in general, de-

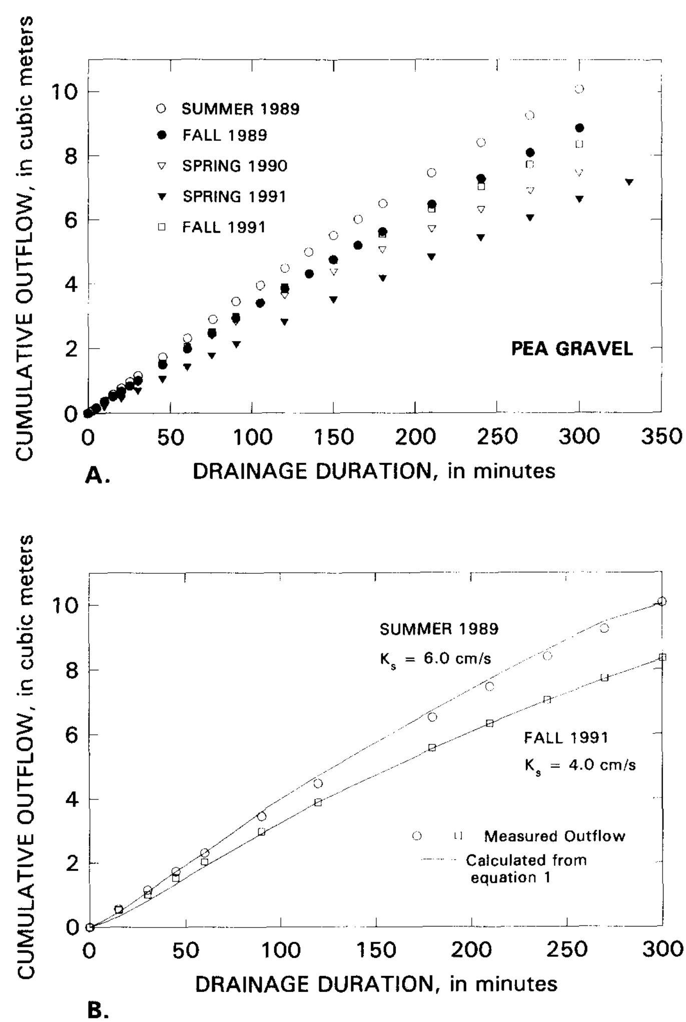


Fig. 5. Outflow curves for planted pea-gravel bed. (A) Measured outflow in all five tests. (B) Calculated and measured outflow in tests of summer 1989 and fall 1991.

creased with time, especially after the addition of leachate, but remained high enough to avoid overland flow throughout the study.

3.6. Calculation of K_s by Darcy's Law

The saturated hydraulic conductivity of the substrate segments between the wells in each rock-reed filter were calculated through Darcy's Law by the procedure discussed earlier. Values for each segment of the planted pea gravel and the unplanted sand-and-gravel beds in the fall of 1989 are given in Table 3. The average value of K_s was calculated for each bed for the five measurements and are given in Table 2 alongside the values obtained by the drainage equation. Values for the coarse-gravel bed are omitted because no significant difference in water level was detected between adjacent wells in any of the drainage experiments. Calculations were not made for the segment between the drain and the well closest to it in any bed because the water level was not measured over the drain, nor were measurements made for the segment between the inlet and the nearest well. To calculate the volume of water drained from this segment, the water level throughout this segment was assumed to be the same as in well E. The first 50 to 90 min of drainage were ignored to eliminate the effects of the coarse-gravel pack at the outlet end of each bed.

The hydraulic conductivity values obtained by Darcy's Law for the pea-gravel and the two sand-and-gravel beds (Table 2) indicate that all three became clogged to some degree, consistent with the results obtained from the drainage equation. The hydraulic conductivity of the substrate segments between wells of the unplanted sand-and-gravel bed for the fall of 1989 are given in Table 3B for selected time intervals. The data indicate that the average K_s calculated for each time interval decreased for later time intervals. The layer of increased conductivity near the top could result from the washout of fine grains from the upper few centimeters of the substrate. The addition of fine grains from the upper layer, suspended

Table 3
Hydraulic conductivity of substrates in fall 1989, by segment, as calculated by Darcy's Law

Measurement interval (minutes since start of flow)	Substrate segments, in meters above outlet				
	5–9.9 m	10–14.9 m	15–19.9 m	20–24.9 m	Average for time interval
(A) Pea gravel (planted)					
75– 90	4.3	6.4	8.4	3.6	5.7
90–120	4.4	6.2	8.6	3.8	5.8
120–150	4.6	6.5	8.5	4.1	4.9
150–180	4.9	6.4	8.6	3.9	6.0
180–210	5.0	6.4	8.6	4.2	6.0
210–240	5.1	6.8	10.1	4.0	6.5
240–270	5.1	6.6	11.5	3.8	6.8
270–300	5.2	7.0	11.6	4.0	7.0
(B) Sand and gravel (unplanted)					
75– 90	0.28	0.25	1.18	0.43	0.53
90–120	0.25	0.20	0.83	0.40	0.42
120–150	0.15	0.12	0.42	0.18	0.22
150–180	0.15	0.10	0.37	0.17	0.20
180–210	0.15	0.10	0.37	0.17	0.20
210–240	0.17	0.10	0.35	0.17	0.20
240–270	0.15	0.08	0.28	0.15	0.17
270–300	0.15	0.08	0.30	0.15	0.17
300–330	0.13	0.08	0.25	0.17	0.17

Values are in centimeters per second.

solids filtered from the leachate, chemical precipitates, and microbial growth could decrease the hydraulic conductivity in the deep part of the substrate.

4. Discussion

4.1. Comparison of the two computation methods

The hydraulic conductivity values obtained for the pea gravel have a larger discrepancy between the two methods for some of the experiments than for the sand-and-gravel beds (Table 2). The high hydraulic conductivity of the pea gravel resulted in only a small difference in water levels between adjacent wells (0.3 to 3.0 cm for the various segments); thus, an error of just a few millimeters in water-level measurement can produce a large difference in the resulting value of K_s for a given substrate segment and time interval. Moreover, because the outflows calculated by the drainage equation fit the actual data well, the best-fit value of K_s is probably a more accurate representation of the effective conductivity of the entire volume of substrate than the values determined by Darcy's Law.

The hydraulic conductivity values obtained for the sand-and-gravel beds by the drainage equation [Eq. (1)] do not differ significantly from the values found by Darcy' Law (Table 2). The main difference between the two methods is that Darcy's Law requires a larger number of measurements and calculations.

The use of the drainage equation has several advantages over other methods of measuring hydraulic conductivity. The main advantage is that the dynamic nature of the drainage process allows the entire volume of the substrate to be sampled and an effective conductivity determined for the system as a whole. This is in contrast to making measurements during steady-state flow conditions in large beds where natural sorting of substrate materials and non-uniform clogging of pores can cause large spatial variations in hydraulic conductivity. For steady-state measurements, it is necessary to assume that the flow between the two measuring points is uniformly distributed; however, in most hydraulic systems this is not the case and the majority of flow may be through a small layer of large conductivity which will bias the measurement of hydraulic conductivity towards the high end. In addition, in long beds (30 m or more in length) evapotranspiration and rainfall vary on a daily basis; therefore, a good deal of the observed hydraulic gradient measured during steady-state may be a result of evapotranspiration and not hydraulic resistance.

4.2. Hydraulic performance

All measurements made on the four rock-reed filters indicate that substrate permeability decreased with time, but the initially high hydraulic conductivity of the coarse-gravel and pea-gravel substrates were sufficient to prevent overland flow. In contrast, the sharp decrease in permeability of the sand-and-gravel beds caused nearly all flow to move across the surface and thereby resulted in a severe decrease in treatment efficiency.

Clogging of the sand-and-gravel substrate is consistent with the results of controlled environment experiments conducted on a laboratory-scale rock-reed filter with a sand-and-gravel substrate (Sanford et al., 1990a,b). The laboratory experiments found that the substrate became clogged after 2 years of leachate addition despite the presence of reeds, and that the thick, extensive root and rhizome system neither increased nor maintained the hydraulic conductivity. McIntyre and Rhia (1991) also observed a decrease in saturated hydraulic conductivity in small laboratory wetlands but the majority of the reduction in conductivity was attributed to compaction of the substrate as a result of draining. The field drainage experiments on the unplanted and planted sand-and-gravel field-scale beds described herein yielded the same conclusion as to the ineffectiveness of reeds in maintaining substrate conductivity.

Other researchers indicate that a wetland treatment system could require several years to develop fully and for the hydraulic conductivity to stabilize (e.g. Kickuth, 1982; Bastian and Hammer, 1993). At the time of this study, the rock-reed filters had been in operation for only 26 months; therefore, the hydraulic conductivity of the planted sand-and-gravel substrate could increase within a few more years, although this is probably unlikely because Brix (1987) and Brix and Schierup (1989) report that overland flow still predominated after more than 4 years of operation of Danish reed beds with local soils as substrate material.

The clogging of gravel substrates with time has been reported by Fisher (1990) and Kadlec and Watson (1993) for portions of systems that are much larger (100 to 330 m in length, respectively) than the ones discussed here. In both studies, the substrates in the one-fifth to one-fourth of the wetlands closest to the inlets had large reductions of hydraulic conductivity relative to the remainder of the bed. These distances are as large as or larger than the entire length of the rock-reed filters of the present study. Both Fisher (1990) and Kadlec and Watson (1993) measured little variations in the measured hydraulic conductivity of the more permeable portions of the gravel beds over a 0.75- to 2-year period.

Recent review articles on the use of reed beds for the treatment of wastewaters have concluded, based on the occurrence of overland flow in most systems which used fine substrates such as soils, that the optimal substrates to use are either coarse sands or gravel in order to provide sufficient hydraulic conductivity from the beginning of operation (Reed et al., 1988; Conley et al., 1991). Based on the results presented above, the optimal substrate from a hydraulic performance point-of-view is a fine gravel since the pea gravel experienced little reduction of permeability while the sand-and-gravel substrates used in the experiments were nearly completely clogged after only one year of leachate addition.

The use of a coarse gravel as a substrate provides an extremely high conductivity but does not provide acceptable treatment of the leachate (Surface et al., 1993). Other data has indicated that there exists significant stratification of the leachate in the substrate due to density differences of the leachate compared to rainwater (Sanford et al., 1993b).

The pea gravel substrate appears to be the better choice of substrate material. The hydraulic conductivity is high enough that clogging will not be a problem for several years.

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