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Fecal Bacteria: Removal From Sewage By Soils

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1975

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PAPER NO. 75-2579

FECAL BACTERIA: REMOVAL FROM SEWAGE BY SOILS

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For presentation at the 1975 Winter Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Palmer House
Chicago, Illinois
December 15-18, 1975

SUMMARY:

Septic tank effluent purification and flow regime in soil columns (60 cm deep) were assessed by analyses for bacteria and chlorides. In sand, purification was greatest at 5 (compared to 10) cm/day loading or under clogged conditions (with or without ponding). Short-circuiting thru natural soil voids occurred at 1 cm/day loading in intact cores of silt loam soil.

American Society of Agricultural Engineers
St. Joseph, Michigan 49085

INTRODUCTION

Soil disposal of septic tank effluent is the common means of on-site disposal of domestic liquid waste in unsewered areas. An estimated 49 million people are served by 15 million such disposal systems in the United States (U.S. Public Health Service 1967). The bacteria of public health concern in sewage are the intestinal (fecal) bacteria, some of which are disease-producing (pathogenic) to man. To avoid contamination of groundwater, fecal bacteria, including the pathogens, must be removed in the soil during percolation of the liquid. Removal mechanisms are directly related to the physical flow processes which can be controlled by the amount and frequency of effluent applications. High loading rates, which may occur locally in the seepage area if effluent is poorly distributed during application, result in high flow rates in the soil as liquid moves through the larger soil pores (Bouma et al. 1974 [a]). Associated short retention times often do not allow adequate interaction between the soil and the percolating effluent, and pathogens may penetrate more deeply into the soil and may pollute groundwaters. Conversely, lower loading rates result in lower flow rates in the soil as liquid moves through the finer pores, with associated longer retention times for removal of fecal bacteria within a short vertical distance of travel (Bouma et al. 1972; Converse et al. 1974). Innovative pressure distribution systems were developed to achieve equal distribution of effluent over a seepage area during intermittent applications (dosing regimes) of effluent (Otis et al. 1974; Converse et al. 1974). One of the major justifications for developing these systems was their assumed capacity to induce relatively low flow rates in the soil, thereby improving potential soil purification (Bouma 1975). A series of innovative soil disposal systems for septic tank effluent, designed on the basis of this principle, have been constructed and monitored. Favorable potential for the removal of fecal indicators from septic tank effluent was shown (Bouma et al. 1974 [c]; Converse et al. 1974). However these earlier data reflected the accumulative effect of many factors and did not allow conclusions as to relative importance of specific factors such as loading rate, temperature, soil type and degree of soil clogging. This paper will discuss the results of a series of column experiments in which removal of fecal bacteria, including pathogens, was studied as a function of these specific factors. Studies were made on 60 cm sand columns, similar in depth to the fill in the mound systems (Bouma et al. 1974 [a], 1974 [b]) and on 50 cm columns of undisturbed Almena silt loam, a slowly permeable clayey soil often presenting problems for on-site disposal of septic tank effluent. These two types of soil represent a broad range of soil conditions encountered in the field.

MATERIALS AND METHODS

Eight columns, of 10 cm (4") diameter (four with sand and four with Almena silt loam) were subjected to different dosing regimes at different temperatures as shown in Table 1. Soil and bacteriological aspects of the experimental procedures used will now be discussed separately.

Table 1. Experimental design for column studies investigating removal of pathogens by soil.

Column	1	2	3	4	5	6	7	8
SOIL	sand	sand	sand	sand	silt loam	silt loam	silt loam	silt loam
TEMPERATURE (C)	25	25	5	5	25	25	25	25
LOADING (cm/day)	10	5	10	5	cont. ponding	cont. ponding	1	1

Soil Aspects

The four sand columns were filled with a sand from the C horizon of the Plainfield loamy sand. The four silt loam columns contained undisturbed cores of the A2 and B21 horizons of the Almena silt loam; these cores had been coated in the field with paraffin to facilitate handling as transferred to set up the columns (Daniel and Bouma, 1974). The particle size distribution of these soils and other relevant physical characteristics are presented in Table 2. The sand had a single grain structure and the Almena silt loam had a prismatic structure: 2-5 cm wide and 5-10 cm high, relatively compact natural soil aggregates ("peds") separated by planar voids. Horizontal sections through both soils are shown in Figure 1. The sand columns had one tensiometer at a depth of 5 cm (2") below the sand surface. Six air exchange tubes were placed at various levels in the column walls to ensure aerobic conditions in the sand (Magdoff et al., 1974). The silt loam columns had four tensiometers at depths of 5, 10, 20 and 30 cm below the surface (Daniel and Bouma, 1974). All columns were covered with vented plexiglass caps to restrict drying. The sand columns received daily dosages of 5 and 10 cm of effluent (Table 1). These loadings were chosen on the basis of field monitoring studies. The infiltration rate through the clogged layer in sands is approximately 5 cm (1.2 gals/sq ft)/day (Bouma et al., 1972). This loading rate is therefore applicable to soil disposal systems, including mound systems, in the field to allow continued functioning even when clogged (Bouma et al., 1974 [b]; Bouma, 1975). However, irregularities in liquid distribution may result in local overloading and the higher loading rate was therefore also included in the experimental plan to investigate its effect on purification.

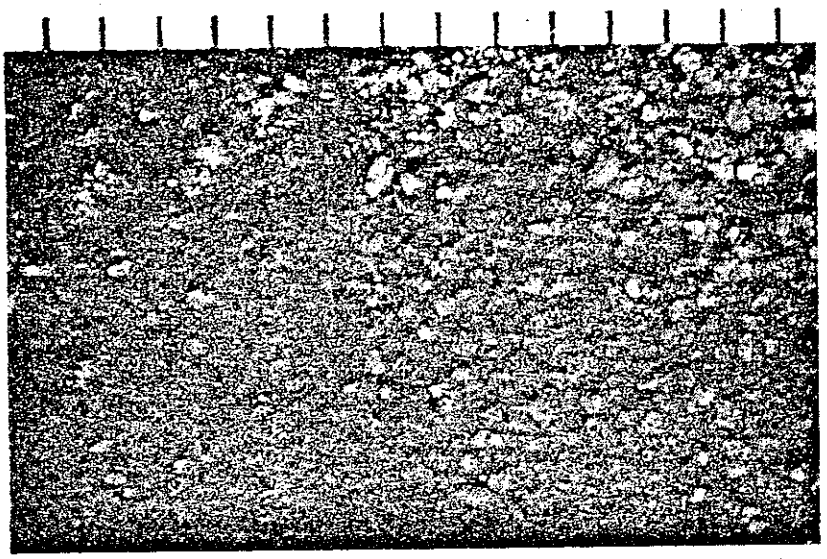
Soil disposal systems have to function during the entire year, under quite varying temperature conditions. *In situ* measurements of soil temperatures in mound systems were found to range approximately 5°C to 25°C, suggesting the temperatures to be used in these experiments (Bouma et al., 1974 [c]; Bouma, 1975).

The type of silt loam tested has a low hydraulic conductivity at saturation, generally not exceeding 4 cm/day and sometimes even lower (Daniel and Bouma, 1974). A dosing rate of 1 cm/day (0.24 gal/sq ft/day) applied to this soil permits infiltration within a day, thereby allowing some period of drainage after which the infiltrative surface is exposed to the air, so that aerobic decomposition of clogging compounds can occur. The ponded columns simulate conditions where the loading rate exceeds the capacity of the soil to conduct the liquid downward. The silt loam columns were therefore dosed at 1 cm/day or continuously ponded.

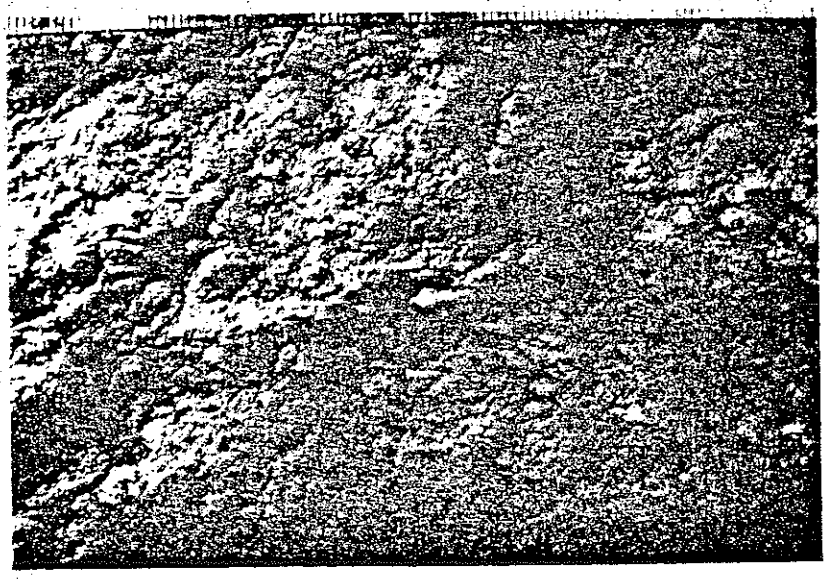
Travel times of liquid were determined in the columns with a 300 ppm KCl solution as a tracer, used as described by Converse et al, 1974. Times were recorded when the first trace, then 150 ppm and 300 ppm chlorides appeared in column effluents. Retention times in the clogged and ponded sand columns were not determined with tracer studies but were estimated as follows:

Table 2. Physical characteristics of sand from the C horizon of the Plainfield loamy sand and of the A2 and B21 horizons of the Almena silt loam.

	Particle size distribution (%)									Texture	Particle density (gr/cm^3)	Bulk density (gr/cm^3)
	Clay	Silt			Sand							
		fine	medium	coarse	very fine	fine	medium	coarse	very coarse			
C horizon Plainfield	--	--	--	1.00	0.11	0.63	6.68	86.0	6.2	coarse sand	2.63	1.67
A2 horizon Almena	21	11.6	30	25	10.5	1.2	0.6	0.1	--	silt loam	2.26	1.45
B21 horizon Almena	27	6.1	18	36	12.7	0.1	0.1	--	--	silt loam	2.22	1.60



PLAINFIELD LOAMY SAND (non-aggregated)



ALMENA SILT LOAM (aggregated)

Figure 1. Horizontal sections through the sand and silt loam soils showing the natural non-aggregated and aggregated structures.

in sterile polypropylene bottles attached to screw cap lids with tubes leading to the base of the column.

The numbers of bacteria in the fortified septic tank effluent and in column effluents were monitored regularly over a period of 200 days. Soil moisture tensions and column effluent volumes were recorded prior to each dosing. Occasionally soil moisture tensions were recorded periodically throughout a day to establish column performance and to relate changes in recovery pattern in terms of moisture conditions within the column as the experiment progressed. For example, these data were helpful in judging whether clogging was developing.

RESULTS AND DISCUSSION

Sand Columns

For purposes of discussion columns 1 and 2, then columns 3 and 4 will be considered as pairs, although within each pair one is at the low loading of 5 cm/day and the other at the higher loading of 10 cm/day.

Liquid retention data:

The results of the flow experiments, based upon chloride tracer data, are reported in Table 3. It is apparent that all sand columns drained in a matter of hours. Physical flow conditions can be pictured as follows: liquid applied to the top of a sand column at equilibrium will leave the column only *after* it displaces the liquid that was present. In fact, the applied liquid will have to "push" out liquid present in the column, before it can flow out (see Otis et al., 1974). This rule of thumb allows a general estimate of travel time. For example, the 5 cm daily loading is 385 cc of liquid for a column of 10 cm diameter, which is well below the initial volume of liquid *in* the column, i.e., 720 cc, the volume of water filled pores at equilibrium. Outflow of this applied liquid within a day after application is therefore not expected and in fact 26 hours were required for the first trace of Cl^- to appear. The 10 cm loading, on the other hand, represents 770 cc of liquid, which is above the 720 cc water-filled pore volume of the column and outflow would begin within a day (the first trace of Cl^- was detected at 1.5 hrs).

Bacterial removal and physical data:

Figures 2 and 3 give results from paired columns 1 and 2: both at 25°C with column 1 receiving 10 cm and column 2 receiving 5 cm of sewage per day. Both columns effectively removed bacteria at first but after the first 5-10 days began to release FC in their effluents. During the first 100 days of the experiment, the number of effluent FC reached a relative plateau of approximately 3×10^5 FC/100 mls from

Table 3. Results of chloride tracer studies for determining travel times of liquid at different dosing regimes in sand.

Loading rate (cm/day)	K_{sat} (cm/day)	First chloride appearance		Appearance of 150 ppm chlorides		Appearance of 300 ppm chlorides		Volume of water filled pores at equilibrium (cm^3)
		Time (hrs)	Cumulative outflow (cm^3)	Time (hrs)	Cumulative outflow (cm^3)	Time (hrs)	Cumulative outflow (cm^3)	
10	500	1.5	618	23	800	25	1018	720
5	500	26	675	47	780	50	1025	720

$$T = \frac{L \cdot \Theta_v}{v}$$

where T = retention time (days), L = length of column (cm), Θ_v = moisture content at tensiometer level (cm^3/cm^3) and v = steady flow rate (cm/day) of liquid leaving the column (Bouma et al., 1972).

Bacteriological Aspects

Bacteria used to evaluate degree of purification included: the indicator types, fecal coliforms and fecal streptococci; and the pathogens, Staphylococcus aureus, and Pseudomonas aeruginosa. Fecal coliform (FC) and fecal streptococcal (FS) bacteria are commonly used as indicators of recent fecal pollution and the possible presence of pathogenic organisms because these indicators are a natural part of the human intestinal flora, being shed daily with feces in great numbers. Pseudomonas aeruginosa and Staphylococcus aureus are of great health concern at the present time because of their natural resistance to antibiotics. They often cause massive bacterial infections, especially in persons receiving antibiotic therapy for prior infections, as in cases of pneumonia, chronic bronchitis, cystic fibrosis, wounds, severe burns, etc. For these reasons, Ps. a. and S. a. are considered opportunistic pathogens (Prier and Friedman, 1974). In addition, these bacteria can cause other types of disease as severe ear and sinus infections by Ps. a. and food poisoning by S. a. toxin.

These pathogens are present in sewage in sufficient numbers to be of significance numerically, i.e., are shed by many apparently healthy persons in high enough numbers to offer statistically valid recovery data (Hoadley, 1966; Elek, 1959).

The methods for counting fecal coliform and fecal streptococcal organisms were based on Standard Methods (1971) with m-FC Broth and m-Enterococcus Agar and membrane filtration or pour plates.

The number of S. aureus were determined by membrane filter concentration with the membranes placed on pads with modified m-Staphylococcus Broth (Standard Methods, 1971) in 15 x 60 mm Petri dishes. The addition of 48.8 mg/ℓ sodium azide eliminated interference by spreading bacilli (Smuckler and Appleman, 1964). Incubation was at 37°C for 48 hr followed by room temperature incubation for 24 hr to enhance yellow-orange pigmentation. S. aureus colonies were confirmed by the test for coagulas (Standard Methods, 1971).

Most probable number (MPN) series were used to enumerate Ps. aeruginosa. Five tubes of modified Acetamide Broth* (Standard Methods, 1971) were inoculated with appropriate sample volumes or dilutions and incubated at 40°C for 4 days. Confirmation was obtained by streaking from positive fluorescent and/or turbid tubes on King's A Agar** (King et al., 1954) with incubation at 42°C for 24 hours and observing blue-green pigmentation. Septic tank effluent was obtained weekly from a residence at the U.W. Experimental Farm, Arlington, Wis. and stored at 4°C until used. This effluent contained relatively low numbers of 1.7×10^5 fecal coliforms (FC)/100 mls and 3.8×10^4 fecal streptococci (FS)/100 mls (Magdoff et al., 1974). For this reason an isolate of each indicator organism was obtained from the sewage and grown for 20-24 hours in shake flasks with Nutrient Broth (Standard Methods, 1971), and added to the septic tank effluent to obtain average concentrations of 5.1×10^6 FC/100 mls and 7.3×10^6 FS/100 mls. Sewage, thus fortified, was prepared every two days and stored at 4°C, with insignificant die-off occurring in this period.

Staphylococcus aureus (S.a.) generally was not present in the septic tank effluent from Arlington. An isolate of this organism (S.a. FDA 209) was also grown in nutrient broth and added to obtain initial concentrations of 10^4/100 mls of septic tank effluent; this number is similar to those found in some septic tank effluents (Ziebell et al., 1974). However, rapid die-off of this organism occurred, dropping the counts by approximately 2 logs in the 2 day storage. Nevertheless, the numbers of S.a. applied to the columns were still in a realistic range for S.a. in sewage, i.e., 10^2-10^4/100 mls.

Pseudomonas aeruginosa was present and survived in the Arlington septic tank effluent; no attempt was made to alter its numbers. The average concentration was 1400/100 mls.

Before the start of experiments, tap water was applied to wet all columns at the respective loading volumes for three days prior to initial septic tank effluent application. The prepared fortified septic tank effluent was then used at one dose per day to all columns except #5 and #6 which were kept ponded with Mariotte bottles filled with fortified septic tank effluent every two days. Samples were collected

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*Modified Acetamide Broth: acetamide, 10.0 g; NaCl, 5.0 g; K_2HPO_4 1.4 g; KH_2PO_4, 0.7 g; $MgSO_4$, 0.5 g; KNO_3, 0.5 g; sodium citrate, 0.2 g; proteose peptone #3, 0.2 g; distilled water 1000 mls.

**King's A Agar: peptone, 20.0 g; glycerol, 10.0 g; K_2SO_4, 10.0 g; $MgCl_2$, 1.4 g; agar, 23.0 g; distilled water, 1000 mls.

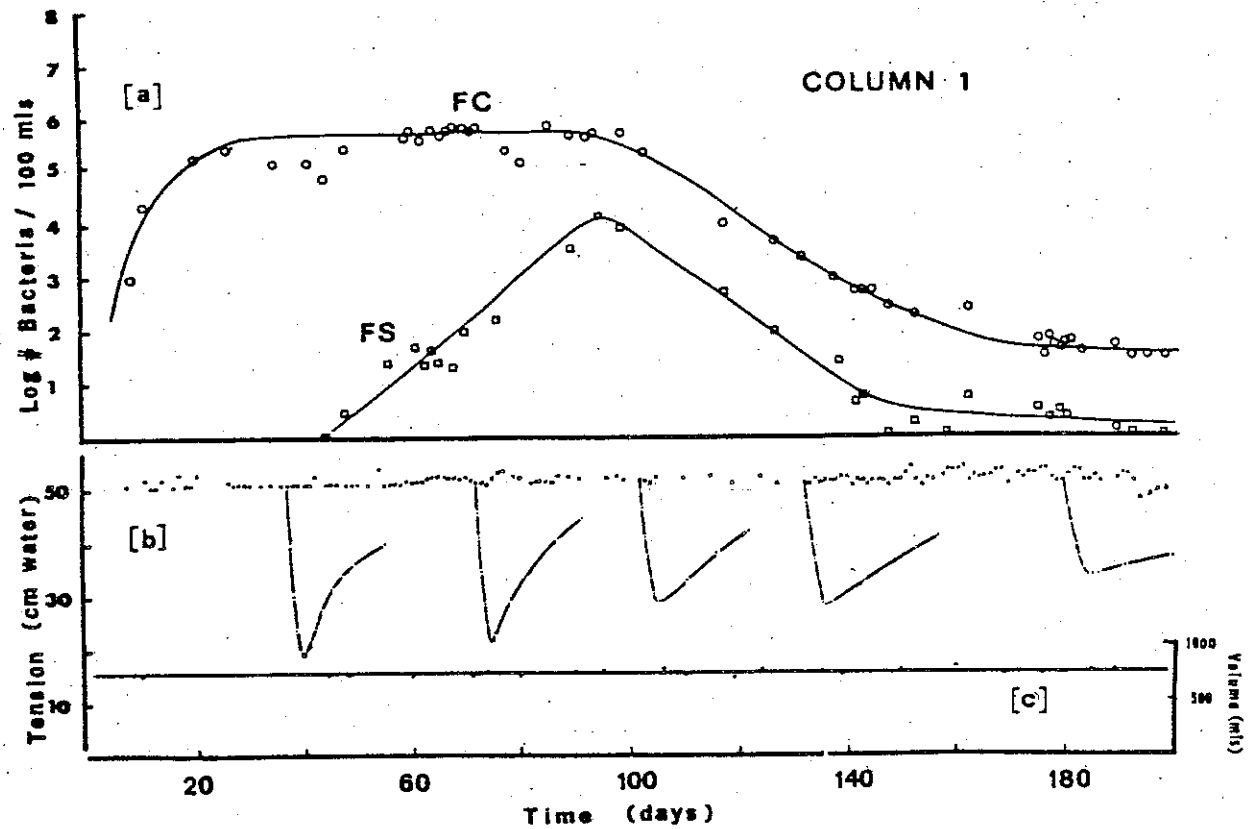

Figure 2. Bacterial and physical data from column 1 (sand, 25 C, 10 cm/day loading): [a] bacteria in column effluent; FC = fecal coliforms; FS = fecal streptococci. [b] X's represent soil moisture tensions 5 cm below sand surface before daily dosing, drainage curves given have the same linear time scales, each curve giving tensions for approximately 150 minutes after dosing on the day indicated. [c] daily volume of effluent leaving the column. The numbers [a], [b] and [c] have an identical meaning in Figs. 3, 4, 5, 7 and 8.

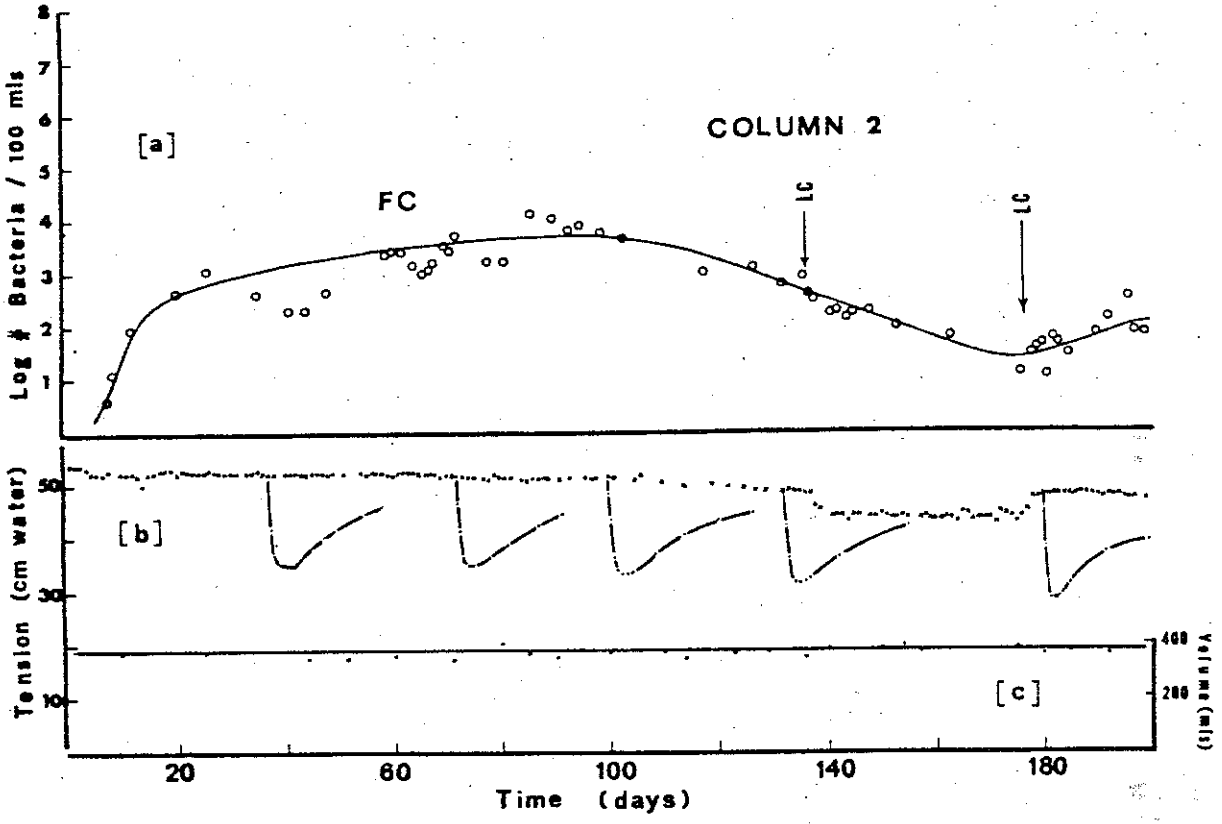

Figure 3. Bacterial and physical data from column 2 (sand, 25 C, 5 cm/day loading): LC = loading change, i.e., first change from one 5 cm/day dose to three applications per day of 1.7 cm each, and the second change restoring the 5 cm/day dosage regime.

column 1 and 10^3/100 mls from column 2; from the initial 5.1 x 10^6 FC/100 mls of sewage. While these numbers are unacceptably high for a finish treatment effluent, they are still very good in percentage removal, i.e., 94.1 and 99.98%, respectively. Fecal streptococci appeared in effluent from column 1 (high loading) on day 48 and reached a peak of 13000/100 mls on day 95. Fecal streptococci, however, were never detected in the effluent of column 2 (low loading, although 100-350 mls/sample were analyzed). Thus, the efficiency of the columns is shown, especially that of the lower loaded column 2. At approximately 100 days and thereafter, the effluent FC counts of both columns 1 and 2 and the FS of column 1 began to decline still further and so continued to the end of the 200 day experiment. These columns can be said to have reached an equilibrium at a state of excellent removal of the fecal indicator bacteria. As to the performance in terms of removal of pathogens, efficiency is again shown, but with borderline failures in the over-loaded column 1. Pseudomonas aeruginosa was detected in three effluent samples out of 19 tested; 23/100 mls on day 91, 3/100 mls on day 96, and 3/100 mls on day 128. Staphylococcus aureus was not found in any of the 15 column samples tested, although 200-600 mls per sample were analyzed. These pathogens were *never* detected in the outflow from column 2, although sample volumes of 30-50 mls for Ps.a. and of 100-350 mls for S.a. were tested.

The performance of these columns can also be judged by outflow and moisture tension characteristics. The hydraulic data for these columns show sustained equilibrium and adequate passing of the daily loading in terms of volume of effluent. Column 1, however, after 100 days showed some lag in recovery of tension after each application, thus suggesting flow impediment or early stages of clogging (Figure 2[b]; see also Magdoff and Bouma, 1974). Column 2 tensiometer data, relating to the 5 cm/day loading rate which is the one used in field design did *not* show evidence of this condition (Figure 3 [b]).

Toward the end of the experiment a change in dosage regime was made for column 2 in order to test multiple instead of single dose application. On day 137, the same daily quantity of 5 cm was applied but it was divided into three 1.67 cm (126 mls) doses, the first being applied in the morning and the remaining two at approximately 4 hr intervals. There was only a slight effect (Figure 3) and on day 176 the original once-a-day rate of 5 cm/day was restored.

Columns 3 and 4, which were run at 5°C, present a somewhat different pattern, but a very interesting one including a drastic change when a malfunction of the refrigeration occurred (see Figures 4 and 5). Thus, the data should be looked at mainly in terms of temperature effect, remembering that at 5°C bacterial growth and metabolism are very slow.

In the first days of operation both columns 3 and 4 removed at least 4 log numbers of the FC before allowing a peak of about 10^3 FC/100 mls to pass. The peak period of release was short, about 10-20 days, followed by rapid decline, which *coincided with ponding* in both columns.

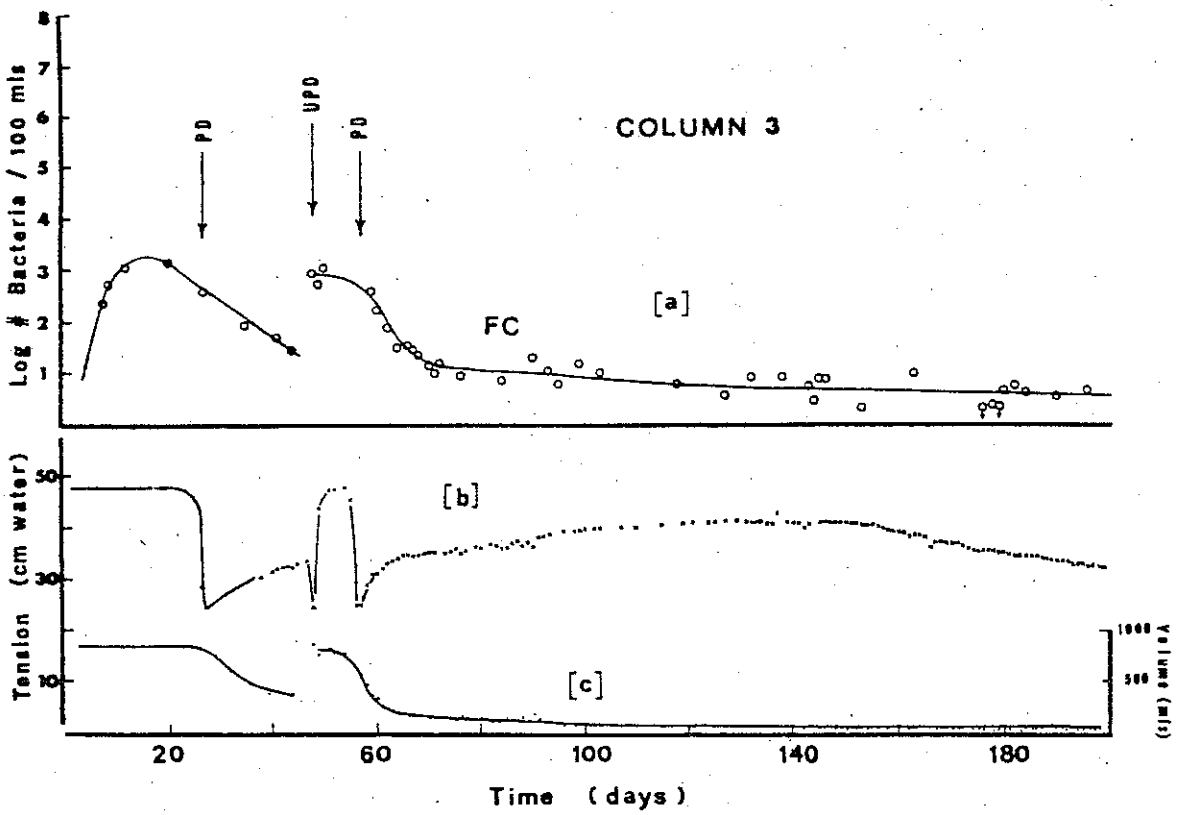

Figure 4. Bacterial and physical data from column 3 (sand, 5 C, 10 cm/day loading): PD = continuous ponding after the indicated time, UPD = unponded conditions after the indicated time.

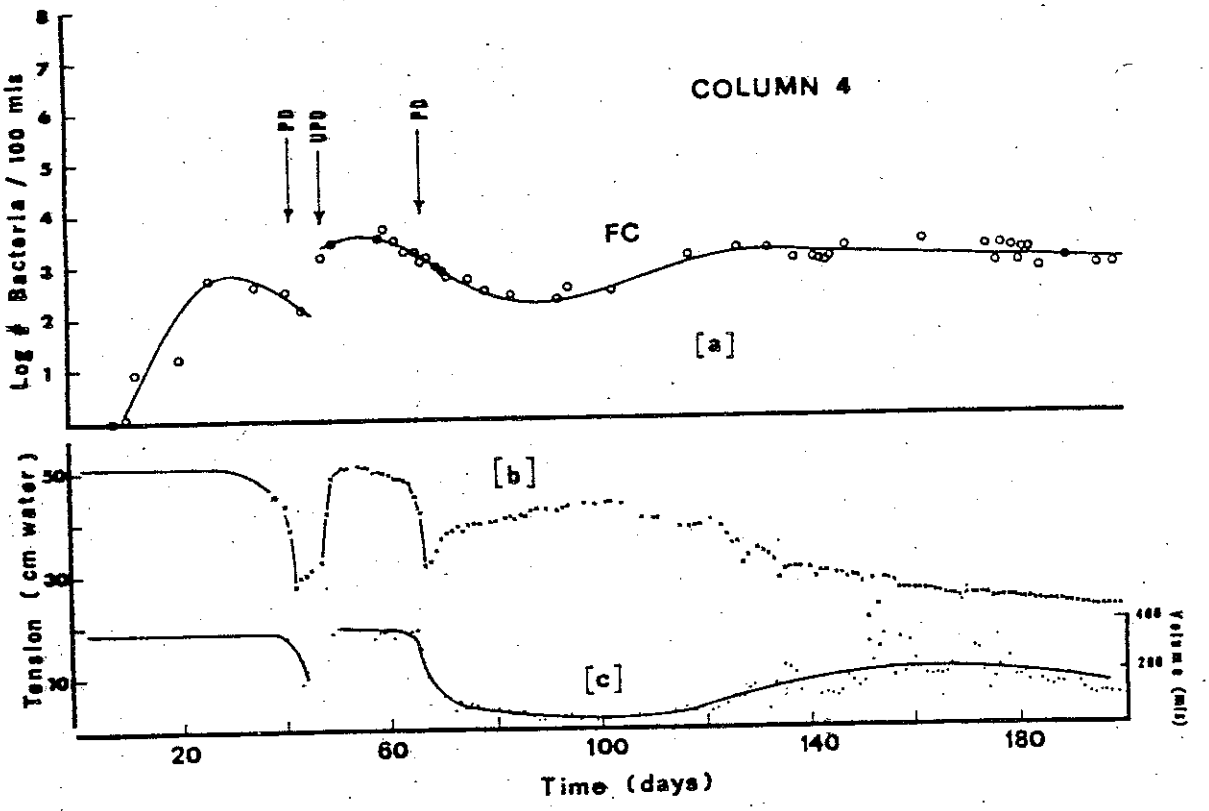

Figure 5. Bacterial and physical data from column 4 (sand, 5 C, 5 cm/day loading): PD = continuous ponding after the indicated time, UPD = unponded conditions after the indicated time.

It is reasonable to assume that this ponding resulted from accumulation of organic clogging compounds, not decomposed due to the low temperature. During this ponded period, tensions (in both columns) stabilized at approximately 30 cm and likewise the volumes of effluent dropped to 400 and 200 mls for columns 3 and 4, respectively. The refrigeration failure at day 48 resulted in unponding with consequent rise in bacterial numbers in the effluents, high tensions after daily drainage, and larger daily volumes of effluent, corresponding with the total daily applied volumes (see days 50-55 for column 3 and day 50-60 for column 4). The latter was the lower dosage column and could therefore probably remain unponded for a longer time. Both columns, when restored to 5°C, returned to the ponded state and so remained for the duration, during which column 3 passed very little liquid (about 40 mls/day) or bacteria (approximately 5 FC/100 mls) whereas column 4 (originally the lightly loaded one) functioned better in terms of liquid outflow but still poorly in terms of bacterial removal. About 10^3 FC/100 mls were released and liquid volumes were erratic but about 125 mls, about 1/3 of the initial dosage at the last, i.e., 200 days. The higher FC counts in column 4 effluent (as compared to column 3) are reflected by liquid retention times. Effluent volumes from column 4 of 100-200 mls/day can be associated with approximate retention of 3-4 days, while liquid entering column 3 would require approximately 12 days (at a flow rate of 40 mls/day) before leaving the column. Associated with these outflows, moisture tensions for column 3 remained between 35 and 41 cm, while tensions in column 4 reached 43 cm, then dropped (with the erratic outflow volumes and FC remaining at the high 10^3/100 ml) to 22 cm. Gas bubbles were observed between the sand grains in the clogged zone of column 4 and disruptions resulting from their release were believed to cause these irregularities. Similar observations have been made elsewhere (Kropf et al., 1973).

Although FC were present in the effluents of columns 3 and 4, these columns functioned very efficiently in removal of FS and the pathogens, Ps. a. and S. a. Fecal streptococci were found in only 2 of 21 samples of column 3 (3/100 mls on day 9, and 58/100 mls on day 50) and in only 1 of 32 samples from column 4 (1/100 mls on day 62). Pseudomonas aeruginosa was present in 2 of 18 samples from column 3 (3/100 mls on days 42 and 45); only 1 of 20 samples from column 4 contained 3 Ps. a./100 mls (on day 94). Staphylococcus aureus was not detected in column 3 or 4 effluent; 14 and 16 samples being analyzed, respectively.

In summary, data for the sand columns indicate that only 60 cm of sand can remove large numbers of fecal indicators and pathogens. Flow regime and soil temperature clearly affect the removal process, in part indirectly, by inducing early soil clogging at low temperatures. Removal below normal detection levels was generally not achieved, especially during the early weeks of operation of the columns (the first 100 days here). The retentive power of the columns improves as bacterial films build up on the sand surfaces. However, such columns can allow escape of FC, FS and the pathogens and thus, for safety, more than 60 cm of sand is required. Additional soil in the mound system or soil absorption field would serve that purpose (Bouma et al., 1974 [c]; Bouma, 1975).

Low dosing rates significantly enhanced removal of fecal indicators and pathogens indicating field system overloading (as represented by the 10 cm/day dosed columns) should be avoided.

Silt Loam Columns

Liquid retention data:

Results of the chloride tracer study with silt loam columns are reported in Table 4 and show a significant difference between the ponded columns 5 and 6, and the columns which received daily dosages of only 1 cm, i.e., columns 7 and 8. Five and 15 days were required for displacement of liquid present in columns 5 and 6, respectively, as evidenced by the first appearance of chlorides (Table 4). The longer retention time for column 6 was due to its low hydraulic conductivity at saturation. The latter value is controlled by the size and continuity of few but relatively large planar and tubular voids in the soil (Figure 1). These are the only pores conducting significant quantities of liquid, since water moves very slowly through the soil aggregates (Bouma and Anderson, 1973). Columns 7 and 8 received a daily volume of liquid smaller than the conductivity at saturation (Table 4). Therefore, these columns drained successfully in one day, as evidenced by unponding several hours before the next liquid addition. Drainage in this period resulted in moisture tensions in the columns, decreasing with depth as shown in Figures 6, 7 [b], and 8 [b]. Theoretical tensions after free drainage would be 50 cm at 50 cm from the bottom, 40 cm at 40 cm from the bottom, etc. The total volume of water filled pores after drainage, i.e., at equilibrium, was 1455 and 1575 cm^3, for columns 7 and 8, respectively. Chlorides appeared in the column effluent after passage of only 700 and 640 cm^3 of liquid, about half the volume of liquid present at equilibrium. This can be interpreted by considering the special nature of flow processes in aggregated soils. Immediately after dosing, the large air-filled pores fill with liquid and allow this liquid to move for considerable distances, depending on pore-continuity, bypassing liquid which is present inside the aggregates. If such short-circuiting extended deep enough it could have implications on sewage purification. The retention data reported for columns 7a and 8 in Table 4 were determined at the start of the experiment, indicating relatively long retention times of 10 days. However, changes occurred in the pore structure of column 7. Interconnection of larger pores, perhaps caused by faunal activity in these undisturbed cores, resulted in significant short-circuiting, as illustrated by tensiometric data presented in Figure 6. Penetration of liquid into a relatively homogeneous core at equilibrium implies that the top tensiometer will react first by dropping, followed by the second tensiometer, etc. as shown by Figure 6, curves [a], determined during the chloride studies which were the first to be made. Short-circuiting of liquid along larger voids would result in a strong reaction of a tensiometer in the lower portion of the column when this tensiometer is in contact with such a larger void, while the reaction of a tensiometer, in contact with soil inside a ped, in the upper portion of the column

Table 4. Results of chloride tracer studies for determining travel times of liquid at different loading regimes in silt loam.

Column no.	K_{sat} (cm/day)	First chloride appearance		Appearance of 150 ppm chlorides		Appearance of 300 ppm chlorides		Total initial volume of water filled pores (cm^3)
		Time	Cumulative outflow (cm^3)	Time	Cumulative outflow (cm^3)	Time	Cumulative outflow (cm^3)	
5	5.2	5 days	1600	8.7 hrs	2782	13 days	4160	1700
6	1.0	15 "	1545	24 days	2472	33 "	3400	1600
7a	7.9	10 "	700	19 "	1330	33 "	2310	1455
7b		5 hrs	70	8 "	560	18 "	1260	1455
8	2.4	10 days	640	21 "	1344	35 "	2240	1575

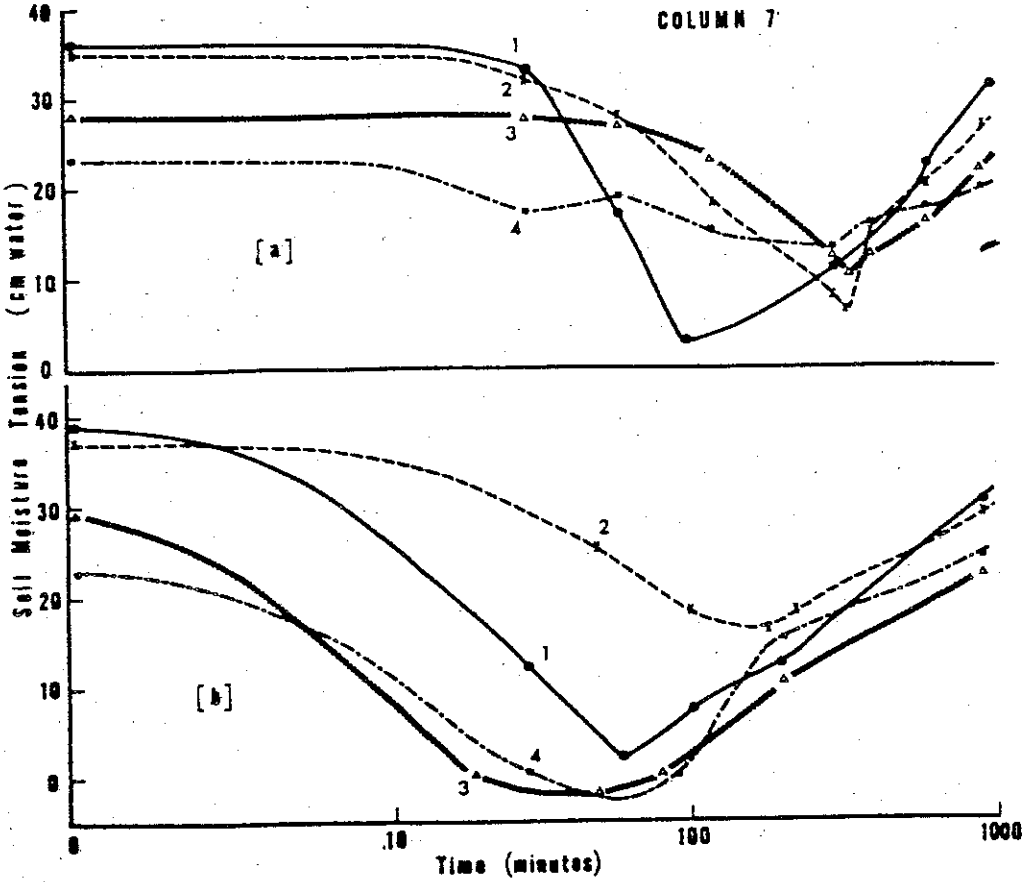

Figure 6. Moisture tensions in column 7 before (curves [a]) and during (curves [b]) the bacteriological experiments, illustrating the development of continuous large pores in the core. Curve 1 represents conditions at 5 cm, curve 2 at 10 cm, curve 3 at 20 cm, and curve 4 at 30 cm below the soil surface.

would be less abrupt and delayed. This phenomenon was observed during the bacteriological studies made in column 7 as shown in Figure 6, curves [b]. After the bacteriological experiments were completed, chloride tracer studies were again conducted on column 7. Results presented in Table 4 (column no. 7b) show that chlorides appeared in the effluent within 3 hours, after only 70 cc of liquid had moved through. Field measurements have been reported indicating similar phenomena in undisturbed soils below seepage systems (Bouma et al., 1974 [b]; Bouma, 1975).

Bacterial removal and physical data:

Bacteriological analyses of effluents from column 5 and 6 indicate excellent removal of fecal indicator bacteria from sewage during saturated flow. Two of 22 effluent samples from column 5 contained 10 to 13 FC/100 mls and 1 of 13 contained 2 FS/100 mls. Pseudomonas aeruginosa was found in 4 of 13 samples with highest numbers occurring after day 100 (23, 180, $\geq$ 240, and $\geq$ 24,000 Ps. a./100 mls on days 100, 104, 143 and 148, respectively). These data indicate conditions, within this column, favorable for survival and possible growth of this bacterium. Staphyloccus aureus was not detected in 14 samples analyzed.

Even better results were found for column 6. An average of 15 samples were tested for each organism (FC, FS, Ps. a. and S. a.), none of which contained any of these bacteria.

Fecal coliforms, FS, and Ps. a. were found in the effluent of column 7 as indicated in Figure 7 [a]. The concentration of these bacteria reached 83,000 FC, 10,000 FS and greater than 2 x 10^6 Ps. a./100 mls of column effluent on day 91. The numbers of Ps. a. were often greater than those of the influent sewage, indicating, as in column 5, conditions favorable for survival and potential growth. The large number of fecal bacteria in the effluent implied short-circuiting between soil aggregates or through channels formed by roots or worms as discussed earlier. On day 93, the loading was changed to 3 mm/day to test a physical hypothesis, i.e., a reduction of the loading rate would reduce the amount of liquid available for vertical flow along cracks and channels, thereby allowing lateral capillary forces to pull the liquid into the aggregates. Movement of sewage through the aggregrates should result in longer retention (because of lower flow rates), more contact of sewage bacteria with soil particles, and better purification. The results confirmed this hypothesis. After the loading change, fecal indicator bacteria were removed and undetected in the effluent within 30 days and, similarly, Ps. a. within 90 days (Figure 7 [a]). Staphyloccus aureus, unlike Ps. a., was never found in column 7 effluent.

Fecal coliforms and FS were also found in effluent of column 8 (see Figure 8 [a]) during the first 40 days when unsaturated flow conditions existed. However, the flow rate through this column gradually decreased below 1 cm (77 mls)/day and ponding with saturated flow, as indicated by tensiometer data, resulted (see Figure 8 [b] and [c]).

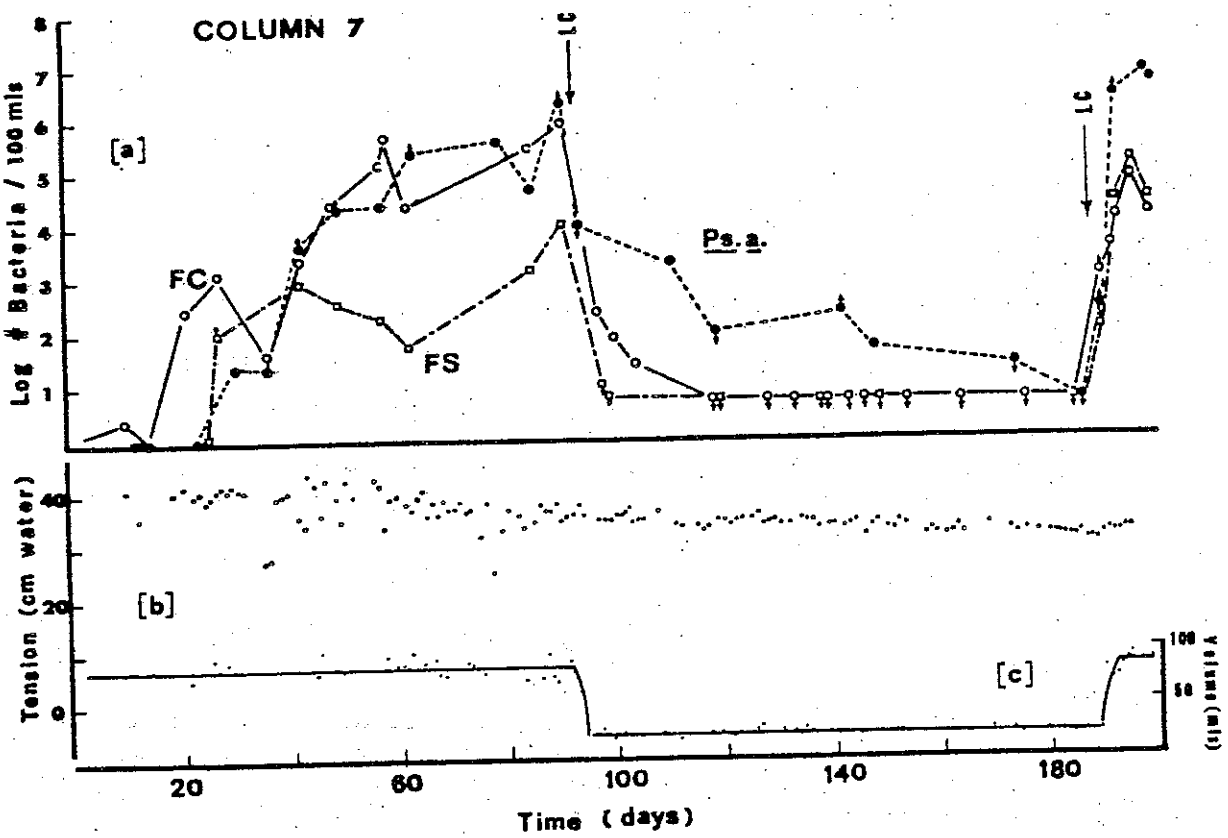

Figure 7. Bacterial and physical data from column 7 (silt loam, 25 C, 1 cm/day loading): *Ps. a.* = *Pseudomonas aeruginosa*. LC = loading change, i.e., first change from 1 cm/day to 3 mm/day and second change restoring 1 cm/day. Moisture tensions [b], 5 cm below the soil surface, are prior to daily dosing.

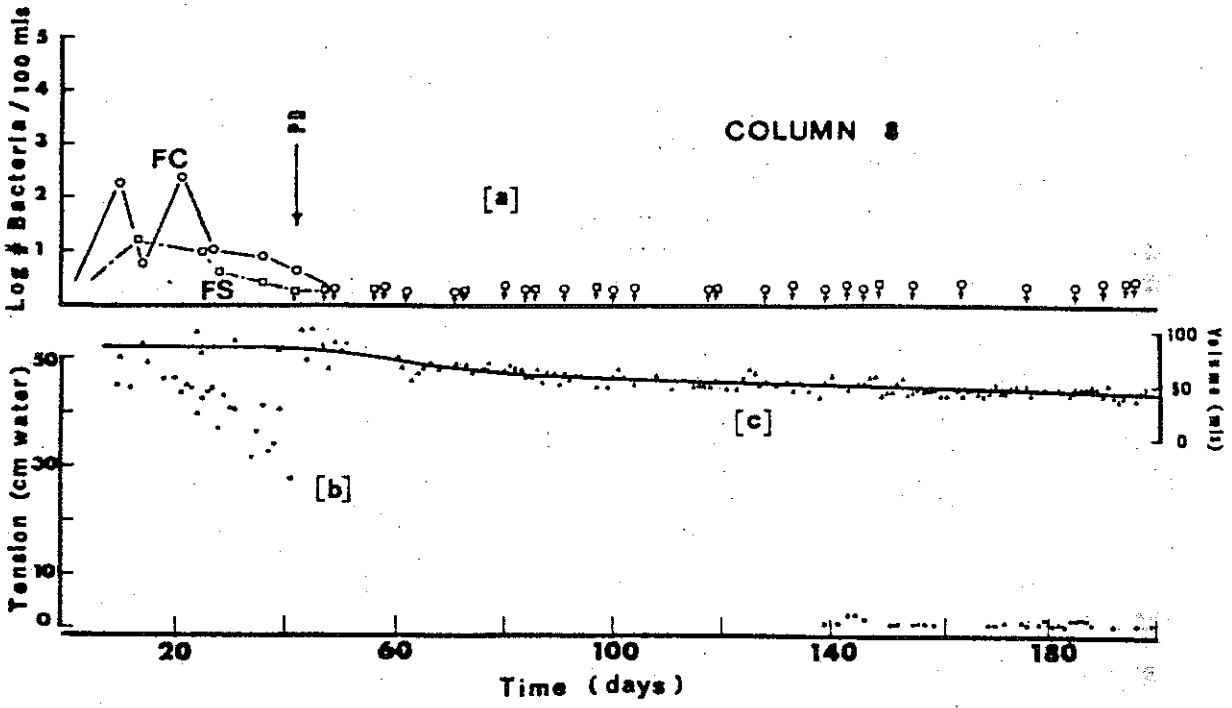

Figure 8. Bacterial and physical data from column 8 (silt loam, 25 C, 1 cm/day loading): Moisture tensions [b], 5 cm below soil surface, are prior to daily dosing.

At this point, column 8 was operating under conditions similar to columns 5 and 6. Indicator organisms were no longer detected in the effluent. Pseudomonas aeruginosa and S. a. were never found in 12 and 14 respective samples from this column.

In summary, data derived from the silt loam columns indicate that 50 cm of a slowly permeable silt loam soil can remove fecal bacteria very effectively under certain flow regimes. The heterogeneous pore structure of these aggregated clayey soils affects removal in that during unsaturated flow, as created by dosing, removal may be less effective than during saturated flow. Short-circuiting of effluent through large air-filled pores resulted in movement of fecal indicators for considerable distance, as demonstrated in columns 7 and 8. These observations have practical implications for construction of on-site disposal systems in slowly permeable soils having seasonally high groundwater tables. Bacterial contamination of groundwater from septic tank-absorption fields under such conditions in similar soil has been shown by others (Viraraghaven and Warnock, 1973). The theoretical pore continuity patterns in clayey soils indicate that the large pores, through which short-circuiting occurred in this study, would not extend indefinitely into the soil and problems of groundwater contamination are unlikely in slowly permeable soils having deep groundwater tables (Bouma and Anderson, 1973).

Removal of high groundwater tables by curtain drains or underdrains, with surface discharge of the drainage water, is being used as a procedure to improve on-site conditions for disposal of septic tank effluent (Bouma, 1975). However, short-circuiting of effluent could lead to pollution of the water in these drains and to surface water contamination following discharge. One such field system has been investigated and liquid in the curtain drain had a high content of fecal indicator bacteria (Ziebell et al., 1973). This problem is particularly relevant because drains in slowly permeable soils have to be deep and within a few feet of seepage trenches to function properly from a hydraulic standpoint (Childs, 1973).

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