

# Hydraulic and Purification Behavior in Wastewater Soil Treatment Systems as Affected by Infiltrative Surface Character and Vadose Zone Soil Depth

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## SUMMARY

Intermediate-scale 3-dimensional lysimeters were used to study the hydraulic and purification behavior of soil infiltration systems used for wastewater treatment. Four lysimeters that each represented a quarter-segment of a subsurface infiltration trench installed in sandy soil were established in a pilot laboratory at the Colorado School of Mines (CSM). Each lysimeter contained the same medium sand but had an aggregate-laden or aggregate-free infiltration surface and either a 60- or 90-cm vadose zone depth to ground water. After pre-operational media and lysimeter characterization, each lysimeter was dosed 4 times per day with septic tank effluent (STE) yielding daily loading rates of 5 cm/d in the aggregate-laden or 8.4 cm/d in the aggregate-free systems. The STE contained appreciable concentrations of solids (avg. TSS = 69 mg/L), biodegradable organics (avg. BOD<sub>5</sub> = 227 mg/L), nutrients (avg. of 57 mg-N/L and 4.6 mg-P/L) and bacteria (avg. fecal coliforms =  $5.4 \times 10^5$  cfu/100 mL). During 48 weeks of operation, the volume and composition of percolate from each of 6 compartments at the bottom of each lysimeter were measured weekly and the soil moisture tensions at 19 locations within the sand profile were determined. At weeks 8 and 45 of operation, bromide salt, ice nucleating active *Pseudomonas syringae*, and MS-2 and PRD-1 bacteriophages were added in the STE dosed to each lysimeter for 3 consecutive days and the percolate was monitored continuously for the next 21 days. After 48 weeks of operation, soil cores were collected at 11 locations within each lysimeter and analyses were made for chemical and microbial properties. The results of this investigation revealed that media utilization and hydraulic retention times increased with continued STE application, with marked changes in hydraulic behavior observed during first two months of operation. Purification processes appeared to be more gradually established over four months or longer. Treatment efficiencies continued to improve with time and eventually reached high efficiencies for most chemical and microbial constituents in all four lysimeters. Greater than 96% of the influent COD and more than 82% of the influent BOD<sub>5</sub> were removed in each of the four lysimeters. Nitrification was initially negligible but gradually increased reaching 100% by week 15 and total N removal amounted to 9 to 12% of that applied. Phosphorus breakthrough occurred earlier than predicted based on adsorption isotherm values and continued throughout the duration of the experiment. Fecal coliform bacteria were initially present in the percolate at and above 200 org./100 mL until week 15 when they were consistently below 100 org./100 mL. During weeks 44 and 45 of operation, the STE was analyzed for enterococci, *Clostridium perfringens*, *Pseudomonas aeruginosa*, fecal streptococci as well as fecal coliforms revealing densities in the range of  $10^3$  to  $10^5$  org./100 mL. However, none of these organisms were detected in any of the percolate samples at these time points. Soil core analyses revealed that concentrations of fecal coliforms decreased with depth and none were found at 30 cm or deeper. The performance observed was consistent with expectations and there were no statistically significant differences attributable to infiltrative surface character or soil depth. This paper provides a synopsis of this laboratory lysimeter work while additional details may be found in Fisher (1999), Masson (1999), Van Cuyk et al. (1999a,b) and in forthcoming publications. Related research is ongoing or planned including sampling and analysis of mature onsite wastewater systems, performance evaluation studies using multicomponent surrogate/tracer mixtures, and process modeling combined with risk assessment methodologies.

## INTRODUCTION

Wastewater treatment for onsite and small community applications commonly relies on infiltration and percolation through unsaturated porous media for purification prior to recharge to ground water or release to a surface water (U.S. EPA, 1978; 1980; 1997; Jenssen and Siegrist, 1990; Crites and Tchobanoglous, 1998). There are numerous system designs that utilize natural soils (e.g., subsurface trenches or beds to shallow drip irrigation systems) as well as engineered media (e.g., intermittent filters of granular sand media or textile or foam materials). Most commonly, system designs include intermittent delivery (by gravity or pressurized dosing) of primary treated wastewater into a subsurface layer of gravel laid on natural soil from which wastewater infiltrates and percolates through a depth of soil media into underlying ground water (Fig. 1). In these systems, effective purification requires adequate hydraulic retention time (HRT) and suitable conditions (e.g., adequate biomass and bioactivity, favorable pH and temperature) for treatment processes to occur including removal (e.g., sorption) and transformation (e.g., biodegradation) of wastewater constituents of concern (Fig. 2).

For purification of primary treated wastewater in natural soils, unsaturated flow in the porous media is critical since this enables extensive contact between wastewater constituents and the soil particles and associated biofilms, over an adequate period for treatment processes to occur (Fig. 2). Unsaturated flow conditions can be achieved by intermittent dosing (e.g., 4 to 24 times/d) of limited daily loadings (e.g., 1 to 5 cm/d) which are usually a small fraction of the media's hydraulic conductivity, and by uniform application to avoid localized overloading. In addition, soil clogging evolves at the infiltrative surface due to filtration of suspended solids and accumulation of biomass, which leads to reduced permeability and more uniform temporal and spatial infiltration with a concomitant unsaturated flow regardless of wastewater loading. Wastewater-induced soil clogging can be extremely beneficial to purification since it yields a biogeochemically active zone that is 1 to 10 cm thick and enables high purification efficiencies. However, if soil clogging yields too great a reduction in permeability of the porous media, it can be detrimental by causing hydraulic dysfunction and anaerobic conditions with reduced purification. Alternatively, if soil clogging does not develop, for example due to application of highly treated effluent, purification of pathogens and other constituents of concern may be less than predicted and desired.

Performance data related to the rate and extent of soil clogging in systems with gravel on the infiltrative surface (aggregate-laden) led to infiltration system designs that have an open surface (aggregate-free), the most common of which is a chamber system (Keys, 1996; May, 1996; Tyler et al., 1991). Gravel on an infiltrative surface can reduce infiltration zone permeability (or infiltrability) by (1) blocking pore entries, (2) becoming embedded in the soil matrix, (3) yielding fines that are deposited in pore entries, or (4) by focusing wastewater constituents as a result of the reduced permeability due to the effects of 1-3 (Amerson, et al., 1991; Jenssen and Siegrist, 1990; Siegrist, 1987; Siegrist and Boyle, 1987; Siegrist et al., 1991; Tyler and Converse, 1994). Based on an equivalency concept with respect to infiltrability, aggregate-free systems are being utilized with design infiltration areas on the order of 40% less than required with aggregate-laden systems, which effectively increases the relative hydraulic loading rate by 67%. While previous experience with aggregate-free systems has revealed satisfactory hydraulic performance, comparatively less experimental data exists regarding purification performance (Keys, 1996; May, 1996; Tyler et al., 1991).

Research was initiated in the Environmental Science & Engineering Division at the Colorado School of Mines (CSM) in 1997 to study the performance of wastewater infiltration systems as affected by infiltrative surface character and vadose zone soil depth. Hydraulic performance was evaluated in terms of the relative rate and extent of loss of initial infiltration rate (cm/day) and the changes in media utilization. Purification performance was evaluated in terms of the relative concentration reduction and total mass removal of nitrogen, phosphorus and coliform bacteria. Solute tracers and bacterial and viral surrogates were also utilized for evaluation purposes. The project was initiated in June 1997 and is comprised of controlled lab experimentation, field monitoring of mature soil infiltration systems, and transport/fate and process modeling. This paper provides an overview of the laboratory lysimeter research. Additional details regarding the lysimeter work may be found in Fisher (1999), Masson (1999), Van Cuyk et al. (1999a,b), and in forthcoming publications.

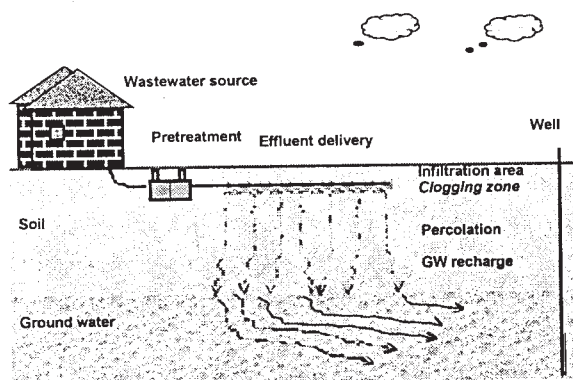


Fig.1. Illustration of an onsite wastewater system typical of the 22 million systems in operation in the U.S. today.

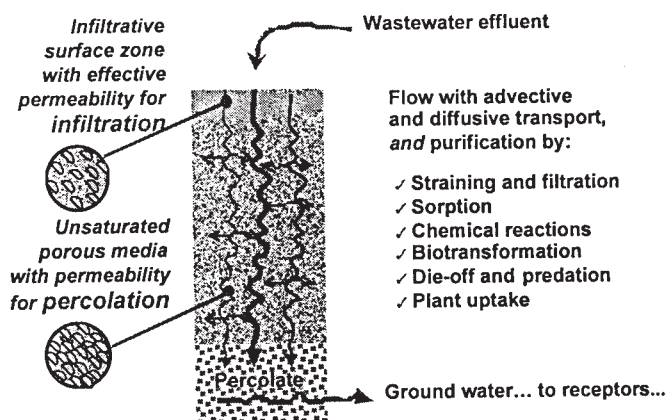


Fig.2. Illustration of hydraulic and purification processes operative during wastewater treatment in soil-aquifer systems.

## EXPERIMENTAL METHODS OVERVIEW

Sand-filled lysimeters were used to physically simulate a portion of a field-scale infiltration system (trench or filter) in a controlled laboratory setting (Fig. 3). This experimental approach was chosen since it allowed for an in-depth investigation of the processes involved by using 3-D intermediate-scale lysimeters but with control of system features (soil heterogeneity, temperature, seasonal effects), wastewater loading (composition, daily rate), and other complexities inherent in field-scale investigations. The lysimeter apparatus used in this study also allowed for visual inspection of the infiltrative surface and clogging layer and collection of percolate samples and soil core samples. The laboratory setting also enabled the controlled release of bacteriophages and other microbial surrogates. Finally, the time frame of this investigation was nearly a year which allowed for detailed study of the purification and hydraulic behavior of these systems during startup and the early development of a clogging layer (Fig. 1-2).

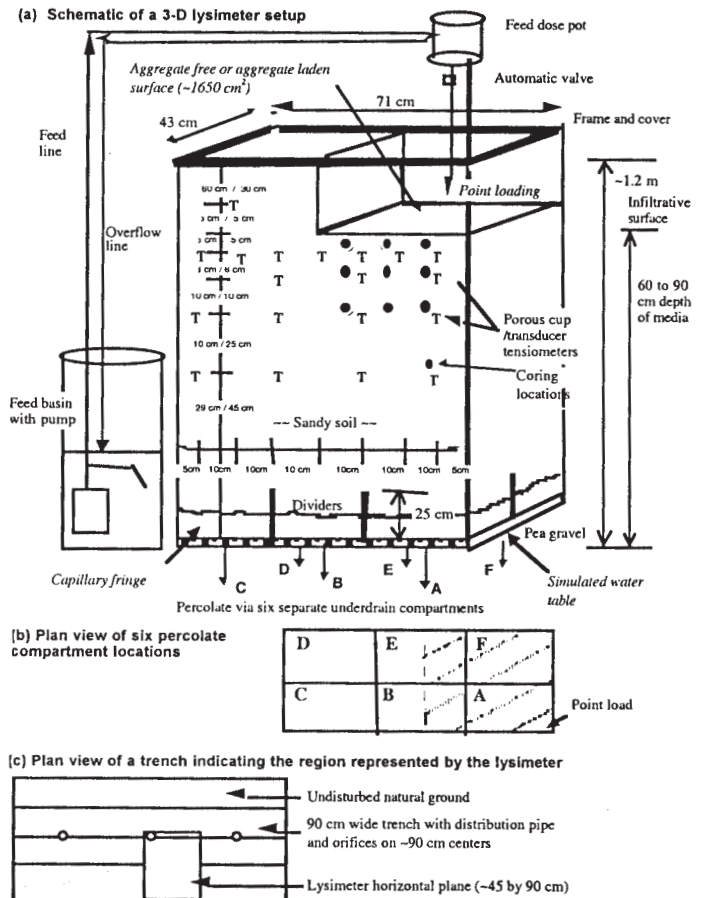
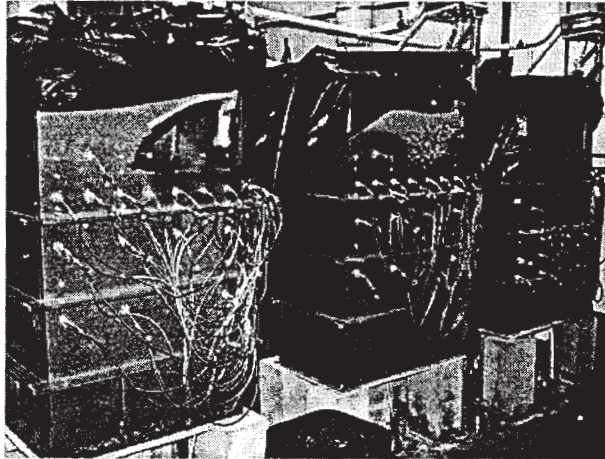


Fig. 3. Photograph (above) and schematic of instrumented 3-D lysimeter facilities in the pilot laboratory at CSM. (only lysimeters L2, L3, and L4 are shown in the photograph).

Laboratory lysimeter experimentation was initiated by designing and fabricating a prototype lysimeter. This lysimeter (L1) was similar to that shown in Fig. 3 and was packed with 90 cm of medium sand (same characteristics as given below) and instrumented with soil moisture tensiometers (SMT). Lysimeter L1 was used for cleanwater hydraulic studies of the main effects and interactions of effluent application rate (6 vs. 12 cm/d), uniformity of distribution (point vs. distributed), and infiltrative surface character (aggregate vs. no aggregate), on water infiltration and percolation in a soil infiltration system with no clogging zone development. Based on bromide tracer tests, the average hydraulic retention time varied from ~9 to 27 hr with the application loading rate having the greatest effect on hydraulic retention time with lesser effects associated with application uniformity and infiltrative surface character. Visible dye tracer tests were also conducted to enable visual observation of water infiltration and redistribution. Details regarding the methods and results of the work with lysimeter L1 at CSM and related research completed in collaboration with the Agricultural University of Norway may be found elsewhere (Ausland, 1998; Ausland et al., 1999; Logan et al., 1999; Stevik et al., 1999).

Following the initial cleanwater studies noted above, wastewater effluent studies were initiated at CSM. A 2<sup>2</sup> factorial design was employed to examine the main effects and interactions of the infiltrative surface character (aggregate-free vs. aggregate-laden) and the depth of sand to a simulated ground water table (60 or 90 cm), on purification and hydraulic performance (Table 1). Four intermediate-scale lysimeters (L2-L5) were established as shown in Fig. 3 to enable evaluation in a 3-D system simulating a quarter segment of a full-scale subsurface infiltration trench. The same sand media was used in all four lysimeters ( $d_{10}=0.22$  mm,  $d_{60}=0.60$  mm; sand pH = 6.8, sand TOC = 0.017 dry wt.%). Vertical dividers that were 25 cm in height divided the bottom of each lysimeter into six compartments (A to F). These dividers allowed two-dimensional characterization of the percolate outflow volume and composition. The lysimeters were cloaked to prevent algal growth and operated at a temperature of 18 to 22°C. Each lysimeter was dosed four times daily (8, 12, 16, 20 hr) with the same medium-strength STE. The STE, collected weekly from a condominium complex and characterized for chemical and biological properties, contained appreciable concentrations of solids (suspended solids = 69 mg/L), biodegradable organics ( $BOD_5 = 227$  mg/L), nutrients (Total N = 57 mg-N/L and total P = 4.6 mg-P/L) and bacteria (fecal coliforms =  $5.4 \times 10^5$  cfu/100 mL). The lysimeters were point loaded with STE by application at one corner of the infiltrative surface, at either 1.25 cm/dose (aggregate-laden) or 2.1 cm/dose (aggregate-free), from an orifice at a rate of 2 Lpm.

Table 1. Experimental conditions evaluated during 3-D lysimeter studies.

Lysimeter	Lysimeter code	Infiltrative surface character	Depth to ground water	Effluent application rate (cm <sup>3</sup> /d per cm <sup>2</sup> of total area)
L2	AF-90	Aggregate free (open via chamber)	90 cm	8.4
L3	AL-90	Aggregate laden (gravel covered)	90 cm	5.0
L4	AL-60	Aggregate laden (gravel covered)	60 cm	5.0
L5	AF-60	Aggregate free (open via chamber)	60 cm	8.4

During 48 weeks of continuous operation, each lysimeter was rigorously monitored to quantify hydraulic and purification behaviors and their inter-relationships. Hydraulic characterization involved spatial and temporal analyses of percolate outflow volumes and *in situ* SMT, along with completion of three solute tracer tests. Once each week, percolate from each lysimeter compartment (A to F) was collected over a 24-hr period in sterile bottles. In addition to volume distribution as measured via the percolate compartments, SMT data was collected at 19 locations (see Fig. 3) over a 24-hr interval on a biweekly frequency. Bromide tracer experiments were also conducted at three time points: (1) at week 0 with tap water prior to dosing with STE, (2) at week 8 with STE, and (3) again at week 45 with STE. For the tracer tests, the lysimeters were dosed with 100 mg-Br/L (added as KBr) for 3 days (12 doses total). Bromide concentrations were measured in the percolate and breakthrough and elution curves were developed. Purification characterization was accomplished via weekly sampling and analysis of the applied STE and the percolate. Each week, STE and percolate samples were analyzed (individual compartments and lysimeter composites) for alkalinity, pH, solids, COD,  $BOD_5$ , TOC, nutrients and bacteria (APHA, 1992). During weeks 44 and 45 of operation, analyses were also made for enterococci, *Clostridium perfringens*, *Pseudomonas aeruginosa*, fecal streptococci and fecal coliforms. During the bromide tracer tests at weeks 8 and 45, ice nucleating active *Pseudomonas syringae* bacteria (INA) (Strong-Gunderson and Palumbo, 1997) and MS-2 and PRD-1 bacteriophages (Adams, 1959; VanDuin, 1988) were also added in the STE and dosed to each lysimeter for 3 days. The lysimeters were dosed with bromide at 100 mg-Br/L (added as KBr), MS-2 at  $1 \times 10^7$  pfu/mL, PRD-1 at  $1 \times 10^3$  pfu/mL (week 8) or  $1 \times 10^7$  pfu/mL (week 45), and INA bacteria at  $1 \times 10^7$ /mL. The percolate concentrations of each tracer and surrogate were monitored multiple times each day for 21 days. After 48 weeks of operation, soil cores were collected at 11 locations within each lysimeter and analyses were made for soil chemical and microbial properties.

## RESULTS AND DISCUSSION

As observed during the course of the study, the volumetric utilization and hydraulic retention times with each lysimeter increased with continued STE application. The most pronounced changes were exhibited during the initial two months (Figs. 4 and 5). The changes in percolate outflow distribution and bromide breakthrough times (Fig. 5) indicated an expansion of the effective infiltrative surface and increased utilization of the vadose zone in each lysimeter. The changes observed in infiltration and percolation are consistent with the development of a wastewater-induced clogging zone at the infiltrative surface (Siegrist, 1987; Siegrist and Boyle, 1987; Schwagger and Bolle, 1997). Consistent with this, visual observation of the infiltrative surface revealed a darkened zone with accumulated solids in all four lysimeters and a

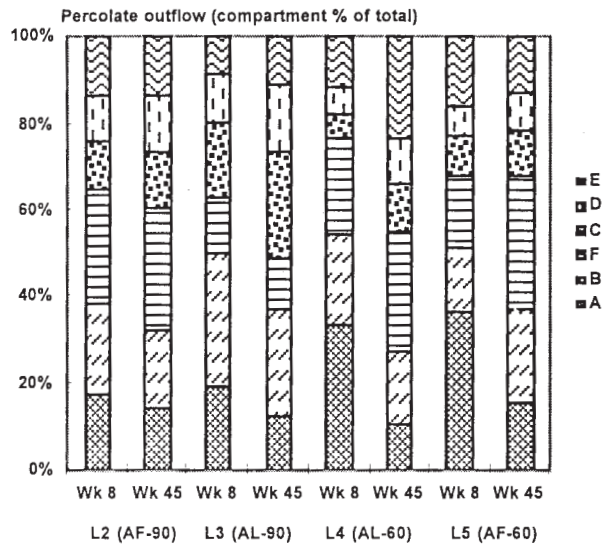


Fig. 4. Percolate outflow volume from each lysimeter compartment (A to F) after 5 weeks and 45 weeks of operation.

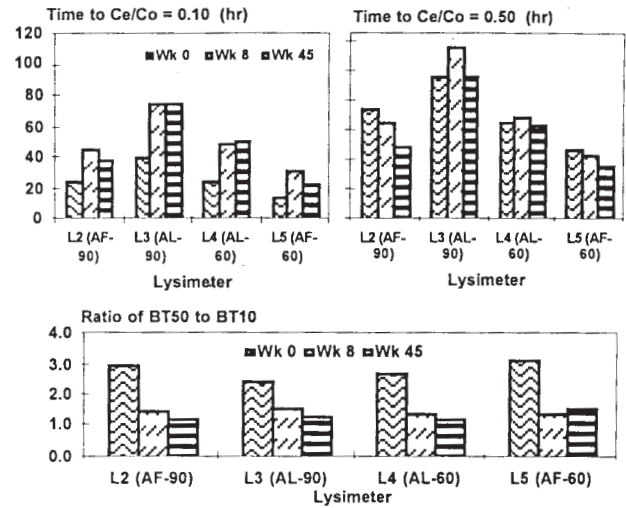


Fig. 5. Bromide breakthrough at 10% and 50% of  $C_0$  before start-up (Wk 0), after 8 weeks (Wk 8) and after 45 weeks (Wk 45) (Van Cuyk et al. 1999).

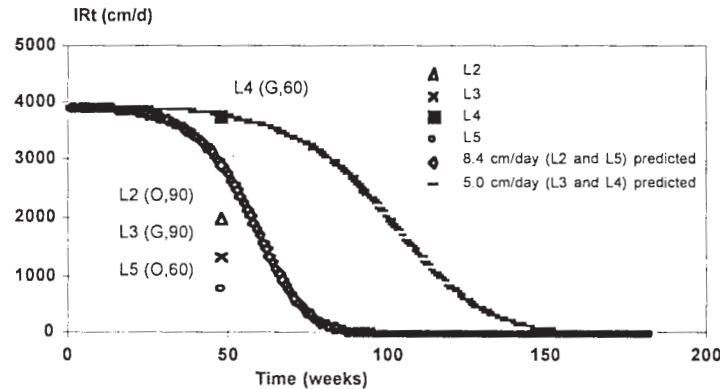
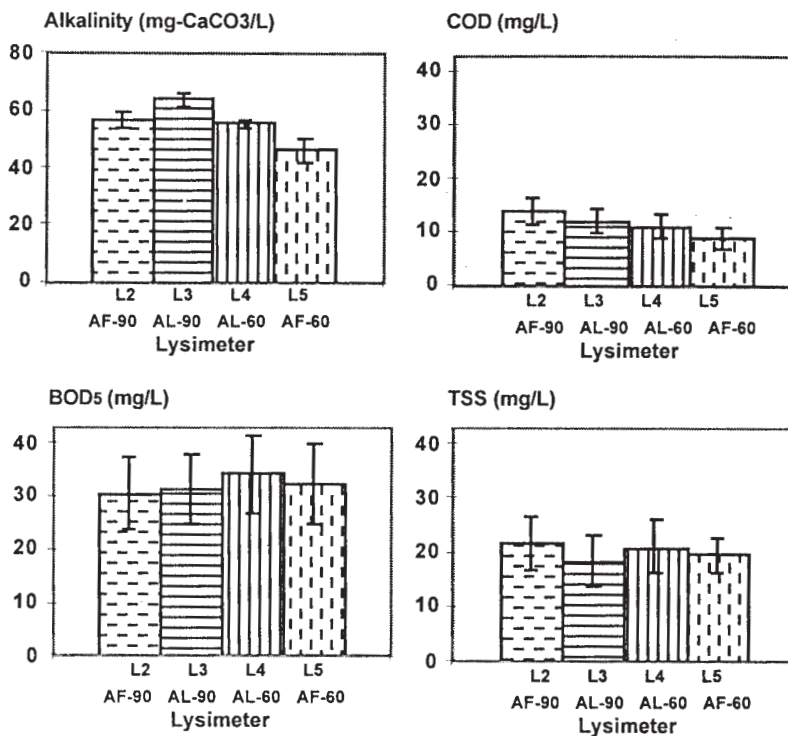


Fig. 6. Predicted infiltration rate loss based on cumulative mass density loadings of biochemically oxidizable substances and suspended particulates (after Siegrist, 1987) versus measured rates at week 48.

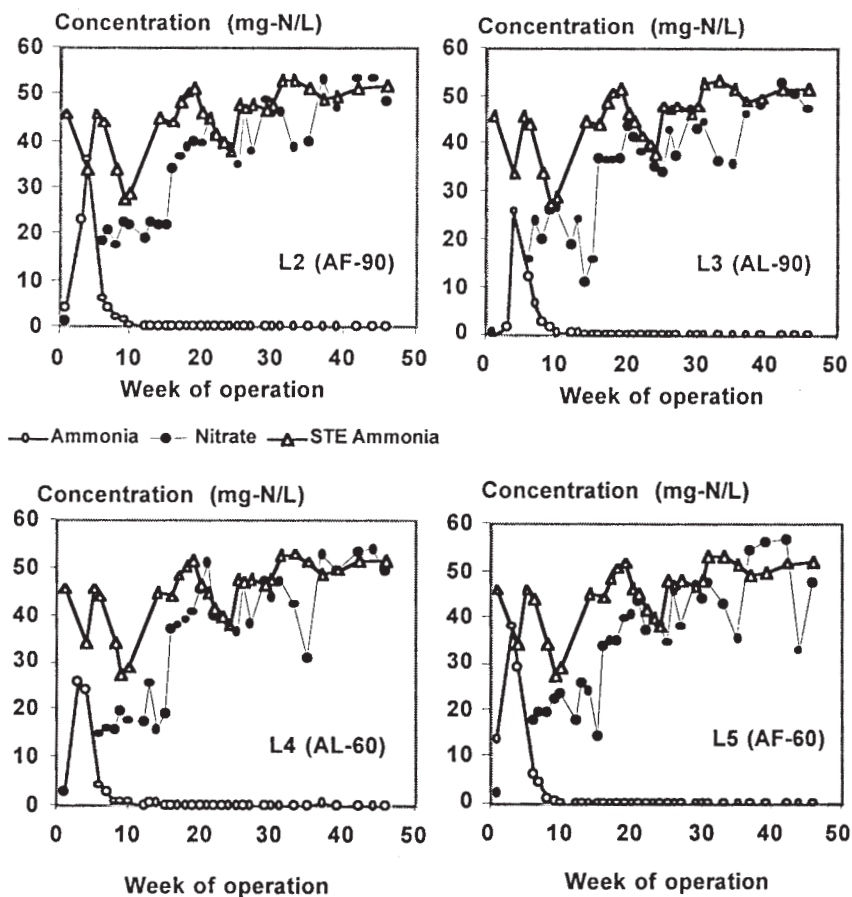
generally declining rate of infiltration immediately following a STE dose. Figure 6 presents the infiltration rate loss predicted for the two STE loading rates (5.0 vs. 8.4 cm/d) based on the model of Siegrist (1987) as well as the infiltration rates measured in a thin-tube infiltrometer within the lysimeter infiltration area at the end of the experiment. Further detailed analysis of the clogging zone genesis is in progress including inverse numerical modeling of the flow data (e.g., SMT and outflow data).

Purification processes were established over time yielding comparatively stable purification efficiencies for key constituents after ~week 20. From that time on, greater than 96% of COD and 82% of BOD<sub>5</sub> were removed in each of the lysimeters (Fig. 7). Two-way analysis of variance (ANOVA) performed on the steady-state percolate data showed no significant differences ( $p=0.05$ ) in BOD<sub>5</sub>, COD and TSS with changes in surface character (aggregate-free versus aggregate laden) or with vadose zone depth to ground water. Nitrification was well established by week 10 in all lysimeters, with complete nitrification achieved by week 15 (Fig. 8). A sharp decrease in the alkalinity of the percolates between weeks 5 and 6 of operation corresponds to the start of active nitrification. Total N breakthrough increased with time stabilizing at a total N removal of 7 to 15% after week 10 (Fischer, 1999). The results of nitrogen analyses in soil core samples, including speciation and nitrification rate tests, revealed that nitrification occurred mainly in the first 8 cm below the point of infiltration. Phosphorus (P) breakthrough occurred during the first week of operation in all four lysimeters. This was much faster than predicted, even though batch experiments demonstrated a low adsorption capacity (10 ug-P/g sand). The early P breakthrough can be potentially explained by channeling of flow that may cause

**Fig. 7.** Percolate composition for alkalinity, COD, BOD<sub>5</sub> and TSS during weeks 20 to 42 of operation (average and standard error).  
 Notes: Average concentrations in the STE were: alkalinity = 322 mg-CaCO<sub>3</sub>/L, COD = 386 mg/L, BOD<sub>5</sub> = 227 mg/L, and TSS = 69 mg/L.



**Fig. 8.** Nitrate and ammonium concentrations in the lysimeter percolates during 48 weeks of operation indicating gradual establishment of nitrification by week 15 to 20. Notes: Lysimeter L2 = Aggregate free and 90 cm soil, L3 = Aggregate laden and 90 cm soil, L4 = Aggregate laden and 60 cm soil, and L5 = Aggregate free and 60 cm soil.



the STE to come in contact with less sand thereby reducing available adsorption sites. However, analyses of available phosphorus in soil core samples collected after 48 weeks of operation revealed 30-100 ug-P/g-sand, suggesting that precipitation of phosphorus may have occurred.

An increase in bacterial removal was observed with continued operation. During early operation there were breakthroughs of coliform bacteria with densities in the percolates exceeding 200 org./100 mL in all lysimeters. From about week 20 on, the lysimeters removed 85 to 99% of the influent total coliform and 96 to 99% of the influent fecal coliform bacteria (Fig. 9). After week 28 of operation, no significant levels of fecal coliforms (> 6 cfu/100 ml) were detected in any of the percolate samples (Fig. 9) (Masson, 1999). STE and lysimeter percolate samples were also analyzed for pathogenic bacteria at weeks 44 and 45. Enterococci, *Clostridium perfringens*, *Pseudomonas aeruginosa*, fecal streptococci and fecal coliform were present at  $2 \times 10^5$ ,  $2 \times 10^4$ ,  $1 \times 10^3$ ,  $1 \times 10^5$  and  $2 \times 10^5$  org./100 mL, respectively in the STE. None of these organisms were detected in any of the percolate samples (L2-L5) at these time points. Results of soil core analyses made at week 48 suggested that with continued development of the clogging zone, no coliform bacteria were reaching depths of 30 cm in either the aggregate-laden or aggregate-free systems. The highest numbers of fecal coliforms were found near the infiltrative surface at 0-8 cm below the point of infiltration. The concentrations of coliform bacteria decreased with increased depth and no coliform bacteria were found in soil cores at depths of 30 cm or deeper.

Bacterial and viral surrogate data revealed complete removal of INA bacteria and >99% removal of MS-2 and >95% removal of the PRD-1 bacteriophages at both weeks 8 and 45 independent of infiltrative surface character and media depth (Fig. 10). Almost all of the INA bacteria were removed within the lysimeters. Removal includes both inactivation and irreversible adsorption. Batch-scale laboratory studies conducted by adding both bacteriophages and INA bacteria to STE showed little degradation of plaque forming activity in the case of virus or ice nucleation in the case of INA bacteria, following a 16-hr period of incubation at both 8°C and 20°C.

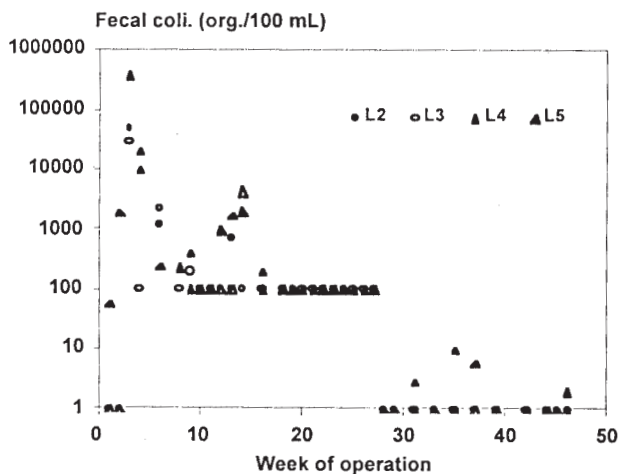


Fig. 9. Fecal coliform bacteria concentrations in the percolate from four soil treatment systems during 46 weeks of operation (Masson 1999). Note that the detection limit was <100/100 mL through week 27 and then reduced to <1/100 mL for weeks 28 to 46. The avg. STE fecal coliform level was 540,000 org./100 mL.

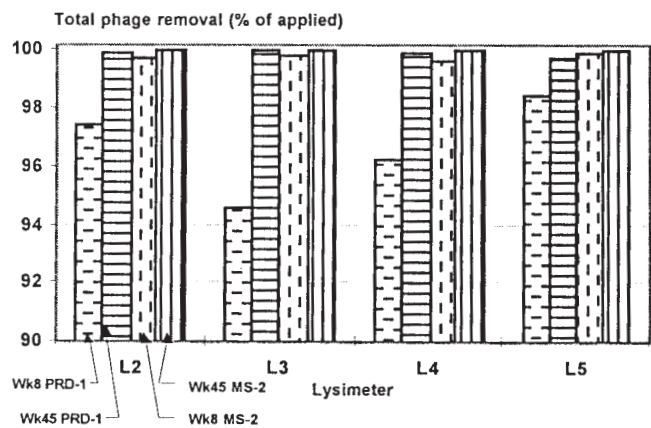


Fig. 10. Percent removal of total applied PRD-1 and MS-2 bacteriophage during a 3-day surrogate loading period after 8 weeks and 45 weeks of operation (Van Cuyk et al. 1999). Notes: L2 = Aggregate free 90 cm sand, L3 = Aggregate laden 90 cm sand, L4 = Aggregate laden 60 cm sand, and L5 = Aggregate free 60 cm sand.

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