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Intrusion of Soil Water through Pipe Cracks

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Intrusion of Soil Water through Pipe Cracks

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Disclaimer

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Abstract

This report describes a series of experiments conducted at U.S. EPA's Test and Evaluation Facility in 2013-2014 to study the intrusion of contaminated soil water into a pipe crack during simulated backflow events. A test rig was used consisting of a 3' x 3' x 3'[1] acrylic soil box with a one-inch diameter pipe running along 2 inches[1] above the bottom of the soil box. The pipe had a 1/16-inch[1] hole at its top, positioned in the center of the box. Each experiment consisted of filling the box with soil media, saturating the media with a solution containing both a microbial and chemical tracer, running tap water through the pipe at a specific pressure to represent normal conditions where clean water leaks out into the soil, and then turning off the pipe flow and sampling the water drawn back into the pipe through the crack either by gravity or forced pumping. Ten experimental runs were performed under various conditions – backflow method (gravity drainage or forced pumping); type of soil media (sand or gravel); microbial tracer (*B. globigii* or *E. coli*), and leak pressures (20, 40 and 55 psi[1]). All of the tests indicated that significant levels of microbial tracer re-entered the pipe during the first five minutes of backflow while the chemical tracer remained essentially at background. This behavior can be explained by the displacement of soil water around the hole with clean water during normal operation which removes the dissolved chemical tracer, but allows some microbial particles to remain due to filtration through the soil media. The sand media provided higher filter efficiency than the gravel media resulting in lower numbers of microorganisms entering the pipe during backflow. Lower backflow rates produced lower average concentration of microorganisms in the intruded soil water. As the gravity backflow period extended beyond 5 minutes, microbial levels tended to level out or be reduced while the chemical tracer concentrations began to increase.

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[1] Note the (') = foot = 0.3048 meter; 1 inch = 2.54 cm; 14.5 psi = 760 mm Hg

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Abbreviations

AL	after leak
B. globigii	*Bacillus globigii*
BL	before leak
CFU	colony forming units
DRN	drain
E. coli	*Escherichia coli – K12 strain*
EPA	Environmental Protection Agency
gpm	gallons per minute
HASP	Health and Safety Plan
L	liter
min	minute
mg/L	milligram per liter
mL	milliliter
mL/min	milligram per minute
NA	not available
OVF	overflow
ppm	parts per million
PSI	pounds per square inch
PVC	polyvinyl chloride
QAPP	Quality Assurance Project Plan
rpm	revolutions per minute
SMP, SMPL	sample
SOP	Standard Operating Procedure
T&E	EPA Test & Evaluation Facility
TMTC	too many to count

[1] Note the (‘) = foot = 0.3048 meter;   1 inch = 2.54 cm;   14.5 psi = 760 mm Hg

Executive Summary

Does water leaking out of the pipe during normal pressure operation create a "soil washing" effect that protects against contaminant intrusion during low pressure events? Or do contaminants backflow from the surrounding media into a hole in a pipe when water is no longer flowing from the pipe out into the surrounding media? A series of experiments were designed to answer these questions.

An apparatus was constructed at EPA's Technology and Evaluation Center in 2013.

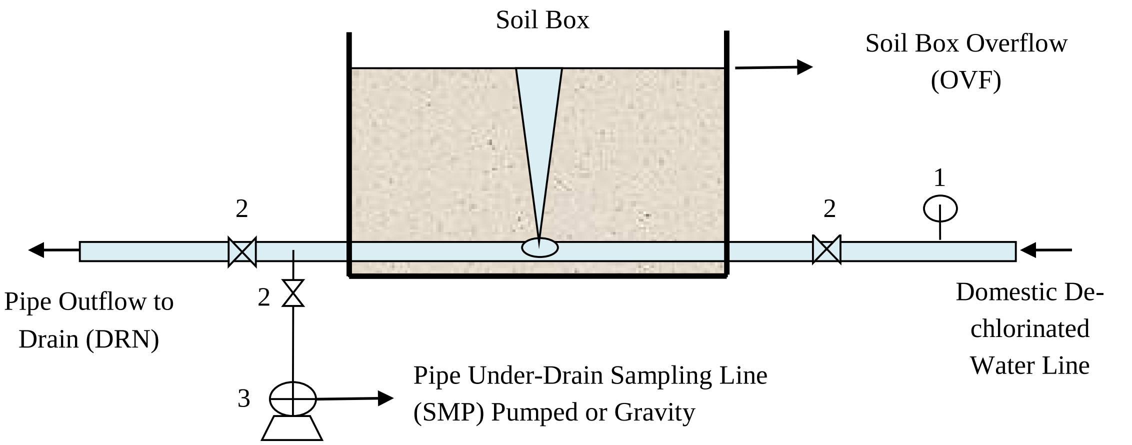

Figure 1-1 Schematic Diagram of Experimental Setup (1 - pressure sensor; 2 - shutoff valves; 3 – peristaltic pump)

The details for this apparatus are presented in Section 2.0. The soil box was filled with sand or gravel media saturated with microbial and bromide tracers. The under-drain valve was closed and Greater Cincinnati MSD water flowed through the pipe for one hour. The pipe's inlet and outlet valves were closed and the under-drain valve was opened and pump operated if needed. The water in the pipe was sampled at 30 second intervals for five minutes, then five minutes, and then every ten minutes until one hour after the under-drain valve was opened. Based on the results of the experiments reported here, the following conclusions can be drawn for short term backflow events (less than 5 minutes):

1. There will be no intrusion of chemical tracer into the pipe because of tracer washout in the vicinity of the crack during normal operation of the leaking pipe.
2. There will however, be intrusion of microbial tracer since only partial washout occurs because of filtering by the soil media
3. Sand media provides higher filter efficiency than does gravel media in the direction of backflow resulting in lower numbers of microorganisms entering the pipe during backflow.

4. The lower the backflow flow rate the lower the average concentration of microorganisms in the back-flowed soil water.
5. Higher leak pressures result in lower microbial concentrations in backflow from sand media. The same could not be shown for gravel.

As the backflow period was extended up to 60 minutes, the microbial tracer level tended to decrease for sand and level out for gravel. The chemical tracer continued to stay at background level for sand but started to rise for gravel.

1.0 Introduction

1.1 Background

The U. S. Environmental Protection Agency (EPA) has identified the possible intrusion of pathogenic organisms from surrounding soil into pipeline cracks during low pressure events as being a potentially serious source of drinking water contamination (EPA 2006). During normal periods of operation, water flowing under pressure in a pipe would leak out of any cracks and present a hydraulic barrier against the entry of any contaminants from the soil surrounding the pipe. However, short-term transient pressure drops can occur when pumps and valves are closed during the course of normal system operations. In certain cases, these pressure drops can be large enough to create a negative pressure inside the pipe that would allow outside water to be drawn into the pipe through a crack. These transients normally last only for a few seconds. A similar condition could occur after a pipe break where cracks downstream of the break could allow contaminated soil and water to enter during the period of time that water continues to flow in a de-pressurized state. Although these kinds of hydraulic conditions have been known to occur (AWWARF 2004), it has not been established whether any water drawn back into the pipe through the crack would be contaminated or not, since the soil in the vicinity of the crack is being washed with clean water for the majority of the time. EPA sponsored an experimental test program to address this issue.

1.2 Experimental Overview

The experimental test runs documented in this report were designed to simulate the conditions described in Section 1.1. Specifically, the objective was to determine the extent of contamination due to soil water entering a pipe crack after a low pressure condition is induced. In a series of test runs, a leaking pipe was placed in a soil box whose media was saturated with "contaminated" tracer solution, and clean water was subsequently allowed to leak into the surrounding soil over a period of time. Then the clean water pipe flow was shut off, allowing soil water to flow back through the leak opening into the pipe main. Water samples were then drawn through a drain port/line connected to the main pipe, either by gravity or by applying suction (using a peristaltic pump). Tracer concentrations of the backflow samples collected through the drain line were monitored over time. The tracer solution contained both an inert non-reactive inorganic salt (sodium bromide) and non-pathogenic microbiological contaminants [either *Bacillus globigii (B. globigii) or Escherichia coli (E. coli) – K12 strain*]. A detailed protocol is provided in Section 2.0 of the document. A project specific Quality Assurance Project Plan (QAPP) was developed by CB&I Federal Services LLC, formerly Shaw Environmental & Infrastructure, Inc. (CB&I 2014), for conducting these tests. Both of these documents were approved by EPA, prior to conducting the experimental test runs.

2.0 Experimental Setup and Test Protocol

2.1 Experimental Design

Figure 2-1 shows the schematic of the experimental setup at the EPA Test & Evaluation (T&E) Facility. It consists of an open 3'x3'x3' acrylic box with sections of a 1" diameter clear Polyvinyl Chloride (PVC) pipe running through it. During the tests, the section of pipe within the box was replaced with one that had a crack of desired size and shape drilled into it. One corner of the box was sectioned off with pluggable holes at different vertical depths to provide an outlet to capture any overflow when the box was operated with the pipe leaking water into it. Preliminary tests indicated that it was best to plug all of the holes except at the top of the soil level to allow for water to build up and overflow.

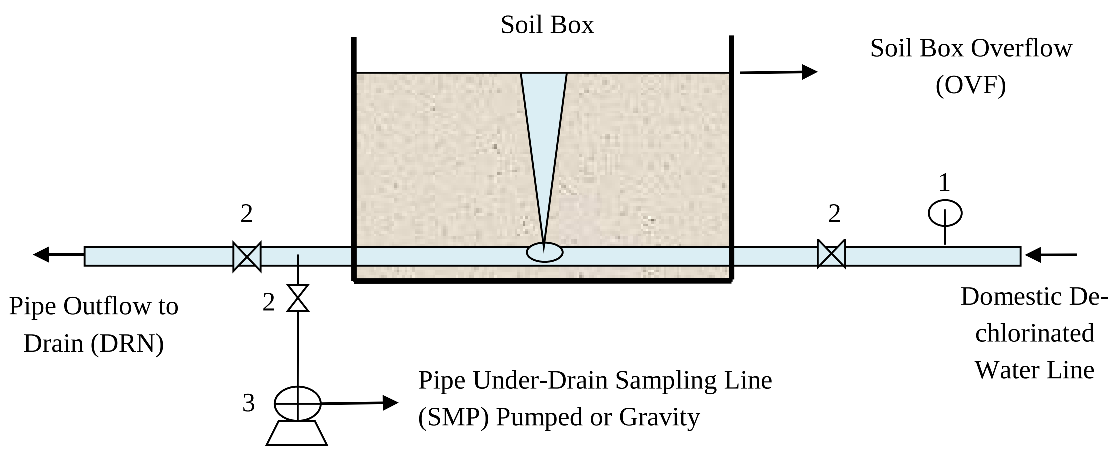

Figure 2-1 Schematic Diagram of Experimental Setup (1 - pressure sensor; 2 - shutoff valves; 3 – peristaltic pump)

Table 2-1 presents the experimental conditions for a series of ten experimental runs that were performed using the soil box for this study. Commercially available all-purpose sand or pea sized gravel (gravel size ranging between 0.5 to 1.5 centimeters) purchased from a local retailer (Home Depot) was used as the media in the soil box. The pipe leak opening was simulated as a 0.0625 inch (1.59 mm) diameter round hole. Once flow through the pipe was stopped, samples were withdrawn from the pipe either under gravity flow or by induced suction (i.e., pumped) flow. The pumped-flow was performed using a peristaltic pump (GeoPump Series II, Geotech Environmental Equipment, Inc., Denver, Colorado). The pumped flow simulates a worst-case scenario of potential intrusion of contaminants occurring due to transient negative-pressure conditions (created by pressure surges and water hammer) in a typical water supply system. The GeoPump Series II model pump is designed to deliver water at a rate of 1.67 milliliters (mL) per revolution with operating speeds ranging between 60 to 600 revolutions per minute (rpm), effectively delivering water at a rate between 100 and 1,000 mL per minute (mL/min). Whenever utilized for testing, the pump was operated at the maximum allowable speed.

Table 2-1 Experimental Test Conditions

Experimental Test Run No.	Leak Pressure	Soil Medium	Contaminant Tracer in Soil-Box Media	Sample Withdrawal Method
1	40 psi	Sand	Bromide and *B. globigii*	Gravity
2	40 psi	Sand	Bromide and *B. globigii*	Pumped
3	40 psi	Gravel	Bromide and *B. globigii*	Gravity
4	40 psi	Gravel	Bromide and *B. globigii*	Pumped
5	40 psi	Sand	Clean Water (Control)	Gravity
6	40 psi	Gravel	Bromide and *E. coli*	Pumped
7	55 psi	Gravel	Bromide and *E. coli*	Pumped
8	55 psi	Sand	Bromide and *B. globigii*	Gravity
9	20 psi	Sand	Bromide and *B. globigii*	Gravity
10	20 psi	Gravel	Bromide and *E. coli*	Pumped

The soil medium used in each experiment was initially saturated with a tracer solution of de-chlorinated water containing approximately 10^6 and 10^8 *B. globigii* spores or *E. coli*, respectively reported as Colony Forming Units per 100 mL (CFU/100 mL) and 30 mg/L of bromide ion. The water flowing through the leaky pipe originated from a de-chlorinated city water line at various target pressures between 20 and 55 pounds per square inch (psi) and a pipe main flow rate between 7 and 18 gallons per minute (gpm). During the testing, the measured pressure was the key criterion and the main pipe flow rate was simply monitored at the stable condition that was achieved during the individual test run. Tests under the same pressure criteria were run with similar main flow rates.

2.2 Experimental Test Run Protocol

Overall, each test run comprised of the following three categorical steps: 1) Preparing/sampling the stock solutions and applying it to the selected soil medium, 2) Establishing initial pressurized pipe condition with clean tap water leaking out into the soil-box for an hour and collecting specified timed-samples (from pipe outflow and soil-box overflow), 3) Inducing backflow by shutting off the clean water supply and collecting specified timed samples from the sampling line (pipe under drain). Appendix A of the QAPP contains the datasheet that describes the sample times and sample locations. The general procedure used for conducting the intrusion tests are outlined below:

Preparing/sampling the stock solutions and applying it to the selected soil medium.

1. The stock tracer solutions were prepared for each test run and analyzed for bromide and *B. globigii* (or *E. coli*). The prepared stock was mixed with bromide and de-chlorinated water in a 55-gallon drum immediately before application to soil (Sample IDs T-XX-Stock 1 and T-XX-Stock 2).
2. Starting with an empty soil box with all drain valves closed, six inches of dry media were filled and saturated with tracer solution (the media was raked as needed to achieve a relatively even distribution of soil and tracer solution).
3. Step 2 was repeated for two more six-inch layers of media for a total of 18 inches of media.
4. Another six inches of selected media were added without any tracer solution for a total of 24 inches of media.
5. The under-drain valve was opened and allowed to flow for a few minutes before taking a sample (Sample IDs T-XX-SMPL-BL [before the main pipe line was pressurized and a leak was induced]). This sample was considered to be representative of the contaminated water that could potentially infiltrate into the main pipe during a back-siphoning event.

Establishing initial pressurized pipe-condition with de-chlorinated tap-water leaking out into the soil-box for an hour and collecting specified timed-samples (from pipe outflow to drain and soil-box overflow shown in Figure 3-1).

6. The under-drain valve was closed and the main pipe shut-off valves were opened to allow de-chlorinated city water to run through the pipe at the selected pressure rate. The pressure rate was adjusted by restricting the shut-off valves until the desired pressure was reached (which took about a minute).
7. At fifteen minute intervals, samples were collected from the main pipe outflow drain line (Sample IDs T-XX-DRN 15 through T-XX-DRN 60) and soil box overflow lines (Sample IDs T-XX-OVF 15 through T-XX-OVF 60). Flow rates and main line pressure were recorded to ensure the desired pressure was maintained.
8. After 55 minutes, with water still running through the main pipe, the under-drain line was opened to allow the water to flow freely for 1-2 minutes to remove air bubbles and any contamination in the line from Step 5.

Inducing backflow by shutting off the clean water supply and collecting specified timed samples from sampling line (pipe under drain shown in Figure 2-1).

9. At 60 minutes, sample was taken from the under-drain line (Sample IDs T-XX-SMPL-AL [after the main pipe line is pressurized and leak was induced]) and then the valves were closed on both ends of the pipe to stop all flow through it.
10. Immediately a sample was taken from the under-drain line (Sample ID T-XX-SMPL 0.1) and subsequently at 30-second intervals (Sample IDs T-XX-SMPL 0.5 through T-XX-SMPL 5.0) until five minutes elapsed since flow to the pipe was stopped. During gravity

discharge sampling, the flow rate was slow and did not allow for sampling at the 30-second rate. Therefore, samples were collected at the maximum rate possible during this initial post-leak 5-minute period.

11. After the initial 5-minute high-rate sampling activities were completed, the flow from the under-drain sample line (SMPL) was directed into a graduated cylinder or a pre-weighed container and recorded the water level or weight for one-minute to compute sample flow rates was recorded.
12. At 10-minutes post-leak time, another sample was collected (Sample ID T-XX-SMPL 10) and sample flow rate was recorded using the methodology described in Step 11.
13. Step 12 was repeated at ten minute intervals until 60 minutes post-leak time had elapsed.
14. At this point, the test was considered complete and water was drained from the soil box. Collected samples were transferred for analysis.

After completion of each test, the soil box media was decontaminated and disposed in accordance to the EPA approved HASP procedures.

2.3 Contaminant Tracer Stock Preparation and Analysis

The stock of *B. globigii* spores or *E. coli* with approximate concentration of 10^9/mL were grown at the EPA T&E Facility BSL-2 laboratory following CB&I T&E SOP 309 and T&E SOP 310 for *B. globigii* and *E. coli*., respectively. The stock *B. globigii* with the target concentrations were prepared by mixing a culture of vegetative cells/stock with generic sporulation media and incubating by gentle shaking (~150 rpm) at 35ºC for five days. The presence of spores was confirmed using phase-contrast microscopy (<0.1% vegetative cells). Stock *E. coli* was prepared by sub-culturing a pre-existing flask in nutrient broth. Cultures of *E. coli* were incubated at 37°C with gentle shaking (~150 rpm) for twenty-four hours. The injection suspension was prepared by mixing an appropriate amount of the *B. globigii* or *E. coli* stock in 1 L of 0.01% Tween 20 (a dispersing agent). The amount of the stock was estimated based on the target influent concentration (~ 10^6/100 mL) and the pore volume of the media placed in the soil box.

All samples collected from the stock tracer solution, the pipe outflow drain line, the soil box overflow line, and the soil box under-drain line were analyzed for bromide ion using CB&I SOP 405 Ion Chromotography (CB&I 2014 Appendix C) and *B. globigii* (CB&I 2014 Appendix B SOP 309) *(or E. coli)* (CB&I 2014 Appendix D SOP310). Additional sampling plan detail is included in the project QAPP (CB&I 2014).

3.0 Experimental Results

3.1 Test Run 1

The test run conditions for this test were as follows: leak pressure - 40 psi; soil media – sand; selected contaminant tracer in soil-box media – bromide and *B. globigii*; and backflow sample withdrawal method – gravity. Table 3-1 summarizes the results from Test Run 1.

Table 3-1 Test Run 1 Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-01-Stock-01	3.50E+07	7.54	29.73
T-01-Stock-02	2.90E+07	7.46	29.67
T-01-SMPL-BL	2.80E+05	5.45	27.76
T-01 SMPL-AL	5	0.70	0.04
T-01-SMPL-0.1	50	1.70	0.08
T-01-SMPL-1.20	38	1.58	0.03
T-01-SMPL-2.20	663	2.82	0.03
T-01-SMPL-3.30	2550	3.41	0.03
T-01-SMPL-4.40	2450	3.39	0.03
T-01-SMPL-10	260	2.41	0.04
T-01-SMPL-20	225	2.35	0.05
T-01-SMPL-30	350	2.54	0.06
T-01-SMPL-40	ND	ND	0.07
T-01-SMPL-50	ND	ND	0.08
T-01-SMPL-60	10	1.00	0.09
T-01-OVF-15	TMTC*	NA**	15.45
T-01-OVF-30	1.90E+04	4.28	8.39
T-01-OVF-45	4.00E+03	3.60	6.54
T-01-OVF-60	1.30E+03	3.11	4.94
T-01-DRN-15	ND	ND	0.04
T-01-DRN-30	5	0.70	0.03
T-01-DRN-45	ND	ND	0.03
T-01-DRN-60	ND0	ND	0.03

*TMTC - too many to count, **NA – not available, ND-not detected.

As mentioned previously (in Section 2.2, Step 10), the gravity-based sample flow rate encountered during the test run was too slow to allow for sampling every 30 seconds (first 5-minutes post-leak sampling requirement). Field measurements indicated that the gravity-based sample flow rates ranged from 215 ml/min (at five minutes) to 160 ml/min (towards the end of the 60-minute sampling period). Therefore, samples were collected as often as the flow rate allowed and the time stamps were noted in the Sample IDs. For example, in Table 3-1, the Sample ID T-01-SMPL-1.20

represents a sample collected at the 1.2 minute interval post leak. In general, for all test runs, if the *B. globigii* values in the first pass were below detection (i.e., lower than 3 orders of magnitude based on expected value from preliminary and/or previous test runs), the samples were reanalyzed if sufficient sample volume was available. In this test, the sample ID T-01-OVF-15 yielded counts at a much higher than expected three orders of magnitude range. Prior to analysis, each *B. globigii* sample was diluted and analyzed to fit within an expected 3 orders of magnitude range. However, this was the first test and there was no clear expected range, and a reanalysis for this sample was not possible because the sample volume was spent during the initial analysis.

3.2 Test Run 2

The test run conditions for this test were as follows: leak pressure - 40 psi; soil media – sand; selected contaminant tracer in soil-box media – bromide and *B. globigii*; and backflow sample withdrawal method – pumped. Table 3-2 summarizes the results from Test Run 2.

Table 3-2 Test Run 2 Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-02-Stock-01	3.65E+07	7.56	30.08
T-02-Stock-02	6.60E+07	7.82	29.96
T-02-SMPL-BL	1.50E+06	6.18	30.28
T-02-SMPL-AL	*		0.02
T-02-SMPL-0.1	5.20E+04	4.72	0.02
T-02-SMPL-0.5	*		0.02
T-02-SMPL-1.0	2.05E+04	4.31	0.02
T-02-SMPL-1.5	6.07E+04	4.78	0.02
T-02-SMPL-2.0	8.00E+03	3.90	0.02
T-02-SMPL-2.5	7.37E+03	3.87	0.03
T-02-SMPL-3.0	5.80E+03	3.76	0.02
T-02-SMPL-3.5	5.65E+03	3.75	0.02
T-02-SMPL-4.0	2.95E+03	3.47	0.03
T-02-SMPL-4.5	2.10E+03	3.32	0.03
T-02-SMPL-5.0	1.90E+03	3.28	0.03
T-02-SMPL-10	2.70E+03	3.43	0.03
T-02-SMPL-20	9.50E+02	2.98	0.04
T-02-SMPL-30	1.00E+02	2.00	0.05
T-02-SMPL-40	1.05E+02	2.02	0.06
T-02-SMPL-50	1.05E+02	2.02	0.06
T-02-SMPL-60	4.50E+01	1.65	0.07

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-02-OVF-15	2.50E+04	4.40	9.026
T-02-OVF-30	8.00E+02	2.90	19.85
T-02-OVF-45	5.00E+02	2.70	12.50
T-02-OVF-60	7.38E+02	2.87	8.05
T-02-DRN-15	ND	ND	0.05
T-02-DRN-30	ND	ND	0.03
T-02-DRN-45	ND	ND	0.02
T-02-DRN-60	40	1.60	0.02

*Samples lost during heat-shock treatment (lids popped), ND-not detected.

Field measurements indicated that the pumped sample flow rate was approximately 740 ml/min and relatively constant over time.

3.3 Test Run 3

The test run conditions for this test were as follows: leak pressure - 40 psi; soil media – gravel; selected contaminant tracer in soil-box media – bromide and *B. globigii*; and backflow sample withdrawal method – gravity. Table 3-3 summarizes the results from Test Run 3.

Table 3-3 Test Run 3 Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-03-Stock-01	8.40E+07	7.92	30.53
T-03-Stock-02	7.43E+07	7.87	30.18
T-03-SMPL-BL	2.60E+05	5.41	26.48
T-03-SMPL-AL	5.00E+00	0.70	0.02
T-03-SMPL-0.1	ND	ND	0.02
T-03-SMPL-0.5	7.50E+03	3.88	0.02
T-03-SMPL-1.0	1.75E+04	4.24	0.02
T-03-SMPL-1.5	2.60E+04	4.41	0.03
T-03-SMPL-2.0	6.00E+03	3.78	0.04
T-03-SMPL-2.5	1.05E+04	4.02	0.04
T-03-SMPL-3.0	1.68E+04	4.23	0.04
T-03-SMPL-3.5	7.10E+03	3.85	0.05
T-03-SMPL-4.0	9.23E+03	3.97	0.05
T-03-SMPL-4.5	8.50E+03	3.93	0.06
T-03-SMPL-5.0	5.00E+03	3.70	0.06
T-03-SMPL-10	1.24E+03	3.09	0.12
T-03-SMPL-20	1.43E+03	3.15	0.47
T-03-SMPL-30	2.20E+03	3.34	0.75

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-03-SMPL-40	1.80E+03	3.26	0.87
T-03-SMPL-50	1.80E+03	3.26	1.02
T-03-SMPL-60	1.70E+03	3.23	0.94
T-03-OVF-15	8.55E+05	5.93	25.32
T-03-OVF-30	5.75E+05	5.76	24.58
T-03-OVF-45	1.80E+05	5.26	22.11
T-03-OVF-60	8.95E+04	4.95	13.59
T-03-DRN-15	5	0.70	0.03
T-03-DRN-30	ND	ND	0.03
T-03-DRN-45	ND	ND	0.02
T-03-DRN-60	ND	ND	0.02

ND-not detected

Field measurements indicated that the gravity sample flow rate ranged from 646 ml/min (at five minutes) to 583 ml/min (towards the end of the 60-minute sampling period).

3.4 Test Run 4

The test run conditions for this test were as follows: leak pressure - 40 psi; soil media – gravel; selected contaminant tracer in soil-box media – bromide and *B. globigii*; and backflow sample withdrawal method – pumped. Table 3-4 summarizes the results from Test Run 4.

Table 3-4 Test Run 4 Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-04-Stock-01	7.37E+07	7.87	30.04
T-04-Stock-02	8.03E+07	7.90	29.96
T-04-SMPL-BL	5.20E+06	6.72	27.65
T-04-SMPL-AL	1.00E+01	1.00	0.06
T-04-SMPL-0.1	TMTC*	NA**	0.02
T-04-SMPL-0.5	2.23E+04	4.35	0.03
T-04-SMPL-1.0	4.60E+04	4.66	0.03
T-04-SMPL-1.5	3.95E+04	4.60	0.03
T-04-SMPL-2.0	4.05E+04	4.61	0.03
T-04-SMPL-2.5	4.35E+04	4.64	0.04
T-04-SMPL-3.0	2.03E+04	4.31	0.04
T-04-SMPL-3.5	2.47E+04	4.39	0.04
T-04-SMPL-4.0	1.53E+04	4.19	0.05
T-04-SMPL-4.5	1.35E+04	4.13	0.05
T-04-SMPL-5.0	1.15E+04	4.06	0.05
T-04-SMPL-10	8.05E+03	3.91	0.11

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-04-SMPL-20	3.10E+04	4.49	0.40
T-04-SMPL-30	3.90E+04	4.59	0.64
T-04-SMPL-40	3.20E+04	4.51	0.75
T-04-SMPL-50	3.70E+04	4.57	0.84
T-04-SMPL-60	4.40E+04	4.64	0.98
T-04-OVF-15	3.10E+06	6.49	24.66
T-04-OVF-30	3.00E+06	6.48	24.68
T-04-OVF-45	1.30E+06	6.11	18.97
T-04-OVF-60	4.35E+05	5.64	9.39
T-04-DRN-15	5	0.70	0.03
T-04-DRN-30	ND	ND	0.03
T-04-DRN-45	5	0.70	0.02
T-04-DRN-60	ND	ND	0.02

*TMTC - too many to count, values outside of expected range. **NA – not available, ND-not detected

Field measurements indicated that the pumped sample flow rate ranged from 800 ml/min (at five minutes) to 735 ml/min (towards the end of the 60-minute sampling period).

3.5 Test Run 5 – Control Run

The test run conditions for this test were as follows: leak pressure - 40 psi; soil media – sand; selected contaminant tracer in soil-box media – de-chlorinated water (control run); and backflow sample withdrawal method – gravity. Table 3-5 summarizes the results from Test Run 5.

Table 3-5 Test Run 5 (Control) Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-05-Stock-01	NA	NA	NA
T-05-Stock-02	NA	NA	NA
T-05-SMPL-BL	ND	ND	0.66
T-05-SMPL-AL	ND	ND	0.01
T-05-SMPL-0.1	ND	ND	0.014
T-05-SMPL-0.5	ND	ND	0.02
T-05-SMPL-1.5	ND	ND	0.02
T-05-SMPL-2.5	ND	ND	0.02
T-05-SMPL-3.5	ND	ND	0.02
T-05-SMPL-4.5	ND	ND	0.02
T-05-SMPL-5.0	ND	ND	0.02
T-05-SMPL-10	ND	ND	0.02

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-05-SMPL-20	ND	ND	0.03
T-05-SMPL-30	ND	ND	0.03
T-05-SMPL-40	ND	ND	0.03
T-05-SMPL-50	ND	ND	0.04
T-05-SMPL-60	ND	ND	0.03
T-05-OVF-15	ND	ND	1.16
T-05-OVF-30	ND	ND	0.71
T-05-OVF-45	ND	ND	0.32
T-05-OVF-60	ND	ND	NA
T-05-DRN-15	ND	ND	0.03
T-05-DRN-30	ND	ND	0.02
T-05-DRN-45	ND	ND	0.01
T-05-DRN-60	ND	ND	0.02

ND-not detected

As mentioned previously, the gravity-based sample flow rate encountered during the test run was too slow to allow for sampling every 30 seconds (first 5-minutes post-leak sampling requirement). Therefore, samples were collected as often as the flow rate allowed and the time stamps were noted in the Sample IDs. For example, in Table 3-5, the Sample ID T-05-SMPL-1.5 represents a sample collected at the 1.5 minute interval post leak. Field measurements indicated that the gravity sample flow rate ranged from 215 ml/min (at five minutes) to 160 ml/min (towards the end of the 60-minute sampling period).

3.6 Test Run 6

The test run conditions for this test were as follows: leak pressure - 40 psi; soil media – gravel; selected contaminant tracer in soil-box media – bromide and *E. coli*; and backflow sample withdrawal method – pumped. Table 3-6 summarizes the results from Test Run 6.

Table 3-6 Test Run 6 Results

Sample ID	*E. coli* (CFU/100 mL)	*E. coli* (log values)	Bromide (mg/L)
T-06-Stock-01	4.10E+05	5.61	30.22
T-06-Stock-02	5.20E+05	5.72	30.31
T-06-SMPL-BL	3.50E+05	5.54	26.29
T-06-SMPL-AL	ND	ND	0.03
T-06-SMPL-0.1	1.00E+02	2.00	0.03
T-06-SMPL-0.5	9.70E+01	1.99	0.03
T-06-SMPL-1.0	1.48E+02	2.17	0.03

Sample ID	*E. coli* (CFU/100 mL)	*E. coli* (log values)	Bromide (mg/L)
T-06-SMPL-1.5	2.41E+02	2.38	0.04
T-06-SMPL-2.0	1.75E+02	2.24	0.04
T-06-SMPL-2.5	2.18E+02	2.34	0.06
T-06-SMPL-3.0	7.17E+02	2.86	0.13
T-06-SMPL-3.5	1.45E+03	3.16	0.30
T-06-SMPL-4.0	4.35E+03	3.64	0.54
T-06-SMPL-4.5	6.13E+03	3.79	0.86
T-06-SMPL-5.0	8.16E+03	3.91	1.21
T-06-SMPL-10	3.00E+04	4.48	4.65
T-06-SMPL-20	6.20E+04	4.79	8.49
T-06-SMPL-30	5.00E+04	4.70	11.29
T-06-SMPL-40	2.42E+03	3.38	13.17
T-06-SMPL-50	2.42E+03	3.38	14.20
T-06-SMPL-60	2.42E+03	3.38	14.84
T-06-OVF-15	2.00E+05	5.30	26.97
T-06-OVF-30	2.00E+05	5.30	24.39
T-06-OVF-45	1.10E+05	5.04	21.67
T-06-OVF-60	1.60E+05	5.20	19.30
T-06-DRN-15	ND	ND	0.05
T-06-DRN-30	ND	ND	0.04
T-06-DRN-45	ND	ND	0.03
T-06-DRN-60	ND	ND	0.03

ND-not detected

Field measurements indicated that the pumped sample flow rate ranged from 725 ml/min (at five minutes) to 670 ml/min (towards the end of the 60-minute sampling period).

3.7 Test Run 7

The test run conditions for this test were as follows: leak pressure - 55 psi; soil media – gravel; selected contaminant tracer in soil-box media – bromide and *E. coli*; and backflow sample withdrawal method – pumped. Table 3-7 summarizes the results from Test Run 7.

Table 3-7 Test Run 7 Results

Sample ID	*E. coli* (CFU/100 mL)	*E. coli* (log values)	Bromide (mg/L)
T-07-Stock-01	6.10E+06	6.79	29.94
T-07-Stock-02	5.30E+06	6.72	29.83
T-07-SMPL-BL	ND	ND	25.06
T-07-SMPL-AL	ND	ND	0.039

Sample ID	*E. coli* (CFU/100 mL)	*E. coli* (log values)	Bromide (mg/L)
T-07-SMPL-0.1	ND	ND	0.038
T-07-SMPL-0.5	1.00E+03	3.00	0.040
T-07-SMPL-1.0	1.70E+03	3.23	0.043
T-07-SMPL-1.5	2.00E+03	3.30	0.042
T-07-SMPL-2.0	3.10E+03	3.49	0.047
T-07-SMPL-2.5	2.00E+03	3.30	0.047
T-07-SMPL-3.0	2.00E+03	3.30	0.049
T-07-SMPL-3.5	1.00E+03	3.00	0.052
T-07-SMPL-4.0	1.10E+03	3.04	0.054
T-07-SMPL-4.5	3.10E+03	3.49	0.058
T-07-SMPL-5.0	3.10E+03	3.49	0.059
T-07-SMPL-10	1.20E+03	3.08	0.089
T-07-SMPL-20	2.70E+03	3.43	0.171
T-07-SMPL-30	1.00E+04	4.00	0.238
T-07-SMPL-40	3.70E+03	3.57	0.296
T-07-SMPL-50	4.30E+03	3.63	0.356
T-07-SMPL-60	3.60E+03	3.56	0.421
T-07-OVF-15	6.40E+05	5.81	27.41
T-07-OVF-30	6.20E+05	5.79	22.23
T-07-OVF-45	1.60E+05	5.20	15.42
T-07-OVF-60	1.90E+05	5.28	9.209
T-07-DRN-15	ND	ND	0.074
T-07-DRN-30	ND	ND	0.058
T-07-DRN-45	ND	ND	0.046
T-07-DRN-60	ND	ND	0.040

ND-not detected

Field measurements indicated that the pumped sample flow rate ranged from 840 mL/min (at five minutes) to 790 mL/min (towards the end of the 60-minute sampling period). It should be noted that the *E. coli* concentration in sample T-07-SMPL-BL was not detected, but bromide was recovered as expected. In this case, a non-detect value simply indicates that *E. coli* was either below the detection limit or the sample was potentially over diluted based on expected value and did not fit in the expected 3 orders of magnitude values. Also, the *E coli* test kit covers only 3 orders of magnitude during analysis and with a 24-hour hold time, there is only one pass at the laboratory analysis and re-analysis was not possible.

3.8 Test Run 8

The test run conditions for this test were as follows: leak pressure - 55 psi; soil media – sand; selected contaminant tracer in soil-box media – bromide and *B. globigii*; and backflow sample withdrawal method – gravity. Table 3-8 summarizes the results from Test Run 8.

Field measurements indicated that the gravity sample flow rate ranged from 130 mL/min (at five minutes) to 91 mL/min (towards the end of the 60-minute sampling period). It is interesting to note that the *B. globigii* concentration in timed samples T-08-SMPL-40 through T-08-SMPL-60 was found to be non-detect.

Table 3-8 Test Run 8 Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-08-Stock-01	3.27E+08	8.51	29.97
T-08-Stock-02	7.23E+07	7.86	29.80
T-08-SMPL-BL	ND	ND	5.05
T-08-SMPL-AL	ND	ND	0.04
T-08-SMPL-0.1	ND	ND	0.04
T-08-SMPL-1.0	ND	ND	0.04
T-08-SMPL-2.0	5.00E+02	2.70	0.04
T-08-SMPL-3.0	1.00E+03	3.00	0.04
T-08-SMPL-4.0	3.00E+03	3.48	0.05
T-08-SMPL-5.0	3.25E+03	3.51	0.05
T-08-SMPL-10	5.00E+02	2.70	0.05
T-08-SMPL-20	1.00E+02	2.00	0.06
T-08-SMPL-30	1.00E+02	2.00	0.04
T-08-SMPL-40	ND	ND	0.04
T-08-SMPL-50	ND	ND	0.04
T-08-SMPL-60	ND	ND	0.05
T-08-OVF-15	ND	ND	29.83
T-08-OVF-30	ND	ND	16.57
T-08-OVF-45	ND	ND	8.87
T-08-OVF-60	ND	ND	5.18
T-08-DRN-15	ND	ND	0.07
T-08-DRN-30	ND	ND	0.06
T-08-DRN-45	ND	ND	0.05
T-08-DRN-60	ND	ND	0.04

ND-not detected

Although bromide was recovered in the overflow samples as expected, no *B. globigii* were detected in these samples (T-08-OVF-15 through T-08-OVF-60). A post-test of water-rise from the gravel pack on the overflow drain side (which is decontaminated with bleach and rinsed thoroughly with de-chlorinated water after each test) indicated ~300 ppm of residual chlorine. This indicates chlorine build-up over time on that line at a high level, which resulted in these anomalies. However, these values do not impact the main intrusion results or focus of the testing. No further corrective action was considered necessary or implemented as the testing was considered to be complete after the 10th test run.

3.9 Test Run 9

The test run conditions for this test were as follows: leak pressure - 20 psi; soil media – sand; selected contaminant tracer in soil-box media – bromide and *B. globigii*; and backflow sample withdrawal method – gravity. Table 3-9 summarizes the results from Test Run 9.

Table 3-9 Test Run 9 Results

Sample ID	*B. globigii* (CFU/100 mL)	*B. globigii* (log values)	Bromide (mg/L)
T-09-Stock-01	6.27E+07	7.80	29.91
T-09-Stock-02	5.33E+07	7.73	29.77
T-09-SMPL-BL	ND	ND	1.03
T-09-SMPL-AL	ND	ND	0.04
T-09-SMPL-0.1	ND	ND	0.04
T-09-SMPL-0.5	3.05E+03	3.48	0.04
T-09-SMPL-1.5	1.07E+04	4.03	0.04
T-09-SMPL-2.0	7.50E+03	3.88	0.04
T-09-SMPL-3.0	6.87E+03	3.84	0.04
T-09-SMPL-4.0	2.50E+03	3.40	0.04
T-09-SMPL-5.0	1.33E+03	3.12	0.04
T-09-SMPL-10	1.70E+02	2.23	0.05
T-09-SMPL-20	55	1.74	0.06
T-09-SMPL-30	15	1.18	0.07
T-09-SMPL-40	40	1.60	0.08
T-09-SMPL-50	20	1.30	0.08
T-09-SMPL-60	10	1.00	0.09
T-09-OVF-15	5.00E+03	3.70	8.56
T-09-OVF-30	ND	ND	27.96
T-09-OVF-45	ND	ND	18.76
T-09-OVF-60	ND	ND	10.82
T-09-DRN-15	ND	ND	0.06
T-09-DRN-30	ND	ND	0.05
T-09-DRN-45	ND	ND	0.04
T-09-DRN-60	ND	ND	0.04

ND-not detected

Field measurements indicated that the gravity sample flow rate ranged from 188 mL/min (at five minutes) to 146 mL/min (towards the end of the 60-minute sampling period). Similar to Test Run 8, although bromide was recovered in the overflow samples as expected, the non-detectable concentrations for *B. globigii* (T-08-OVF-30 through T-08-OVF-60) were once again likely due to chlorine build-up on the gravel-packed line (as reported under Test Run 8).

3.10 Test Run 10

The test run conditions for this test were as follows: leak pressure - 20 psi; soil media – gravel; selected contaminant tracer in soil-box media – bromide and *E. coli*; and backflow sample withdrawal method – pumped. Table 3-10 summarizes the results from Test Run 10.

Table 3-10 Test Run 10 Results

Sample ID	*E. coli* (CFU/100 mL)	*E. coli* (log values)	Bromide (mg/L)
T-10-Stock-01	1.80E+06	6.26	29.78
T-10-Stock-02	2.40E+06	6.38	29.79
T-10-SMPL-BL	6.50E+05	5.81	27.51
T-10-SMPL-AL	1	0.00	0.04
T-10-SMPL-0.1	ND	ND	0.04
T-10-SMPL-0.5	1.80E+02	2.26	0.04
T-10-SMPL-1.0	41	1.61	0.04
T-10-SMPL-1.5	86	1.93	0.04
T-10-SMPL-2.0	1.10E+02	2.04	0.04
T-10-SMPL-2.5	84	1.92	0.05
T-10-SMPL-3.0	74	1.87	0.05
T-10-SMPL-3.5	61	1.79	0.05
T-10-SMPL-4.0	41	1.61	0.06
T-10-SMPL-4.5	85	1.93	0.06
T-10-SMPL-5.0	63	1.80	0.06
T-10-SMPL-10	5.20E+02	2.72	0.13
T-10-SMPL-20	1.00E+04	4.00	0.79
T-10-SMPL-30	2.90E+04	4.46	1.85
T-10-SMPL-40	4.60E+02	2.66	3.10
T-10-SMPL-50	7.70E+04	4.89	4.62
T-10-SMPL-60	8.10E+04	4.91	0.04
T-10-OVF-15	ND	ND	23.65
T-10-OVF-30	ND	ND	21.64
T-10-OVF-45	ND	ND	13.11
T-10-OVF-60	ND	ND	13.46
T-10-DRN-15	ND	ND	0.04
T-10-DRN-30	ND	ND	0.04
T-10-DRN-45	ND	ND	0.04
T-10-DRN-60	ND	ND	0.04

ND-not detected

Field measurements indicated that the pumped sample flow rate ranged from 822 mL/min (at five minutes) to 795 mL/min (towards the end of the 60-minute sampling period). Similar to Test Runs 8 and 9, although bromide was recovered in the overflow samples as expected, the non-detectable concentrations for *E. coli* (T-10-OVF-15 through T-08-OVF-60) were once again likely due to chlorine build-up on the gravel-packed line (as reported under Test Runs 8 and 9).

4.0 Analysis of Results

4.1 Intrusion Flow Rates and Pressures

Table 4-1 summarizes the flow rates obtained through both the sand and gravel media over the first 5 minutes of backflow under both gravity and pumping. The test results indicate that the median pumped flow rate was 3.6 times higher than the gravity rate for sand but only 1.2 times higher for gravel.

Table 4-1 Observed 5-Minute Backflow Rates

Media	Backflow Method	Min. Flow Rate (ml/min)	Max. Flow Rate (ml/min)	Median Flow Rate (ml/min)
Sand	Gravity	130	215	202
Sand	Pumped	740	740	740
Gravel	Gravity	646	646	646
Gravel	Pumped	725	840	811

Under gravity backflow, the external head applied to the soil water equals the depth of the saturated soil above the hole which was 24 inches (2 feet) (see footnote, page 2) in all experiments. Under pumped flow, the additional suction pressure produced by the pump can be estimated by assuming that the flow rate is limited by the orifice formed by the pipe crack. Thus, knowing the flow rates for both gravity and pumped intrusion flow, and the external head for both conditions (2 feet), the suction pressure produced under pumped flow P_p can be expressed as follows:

$$P_p = 0.433\left\{4\left(Q_p/Q_g\right)^2 - 2\right\}$$

where Q_p is the flow rate under pumping and Q_g is the flow rate under gravity. Using this equation and the 5-minute flow rates from Table 4-1, the estimated median intrusion pressure for the experiments using sand was 20 psi while for gravel it ranged from 1.3 to 2.1 psi.

The 20 psi suction pressure for the pumped sand experiment (there was only such experiment, Run 2) would never be observed in a real distribution system. In retrospect, it would have been better to have adjusted the pump speed to draw around 1.3 times the gravity flow rate (about 260 ml/min) to keep the suction pressure at a more reasonable 2 psi.

4.2 Short Term Intrusion Behavior

Even though backflow sample through the pipe crack was collected and analyzed over a period of 60 minutes, only the first 5 minutes of data are presented here since low pressure transients rarely (if ever) last beyond a few minutes (AWWARF 2004). Figure 4.1 presents results for sand media while Figure 4.2 illustrates the same for the gravel media for the *B. globigii* runs at 40 psi leak pressure (Runs 1– 4).

The spike concentration of *B. globigii* in both sand and gravel runs varied from 10^5 to 10^6 CFU/100 ml and bromide concentrations were between 27 and 30 mg/L. Also, because there are some concerns about the reliability of the first microbial samples taken at 0.1 minutes for the gravel experiments (Runs 3 and 4), they are not presented in Figure 4-2.

The data clearly show that the microbial and chemical tracers behave significantly different under backflow conditions. While *B. globigii* enters the pipe in significant numbers, the bromide tracer remains at essentially background level over the entire short-term duration of backflow. This behavior is repeated in all of the other test runs, including those using *E. coli*, as well. One possible explanation for this behavior is presented below.

During the leaking phase of the experiment, “clean” water enters the soil through the pipe crack and completely displaces contaminated water within the cone of the vertical jet that forms above the crack. In addition, there is likely to be some expansion of the media in this zone as it partially fluidizes, which would apply more to the smaller sand particles than to the larger gravel. A dissolved contaminant like bromide would be completely washed away as the original contaminated pore water is replaced with clean water. However, for the suspended microbial organisms, the sand or gravel acts as a filter media that prevents some fraction of the organisms from being carried away from the soil above the pipe crack, most likely by interception. It is this fraction that provides a reservoir of microbial particles in the vicinity above the crack that can then be transported into the pipe during the backflow event. In addition, additional filtering can occur in the opposite direction as backflow carries soil water back into the pipe.

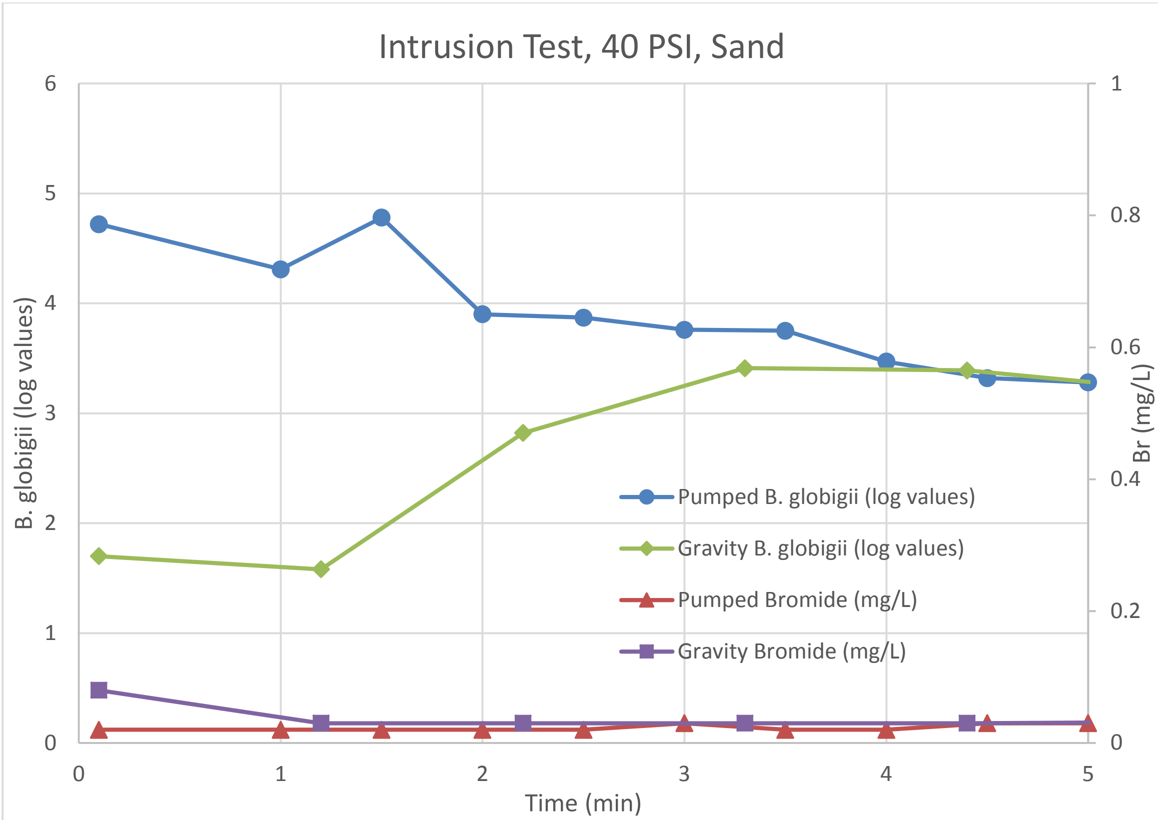

Figure 4-1 Intrusion of Tracer into Pipe for Sand Media

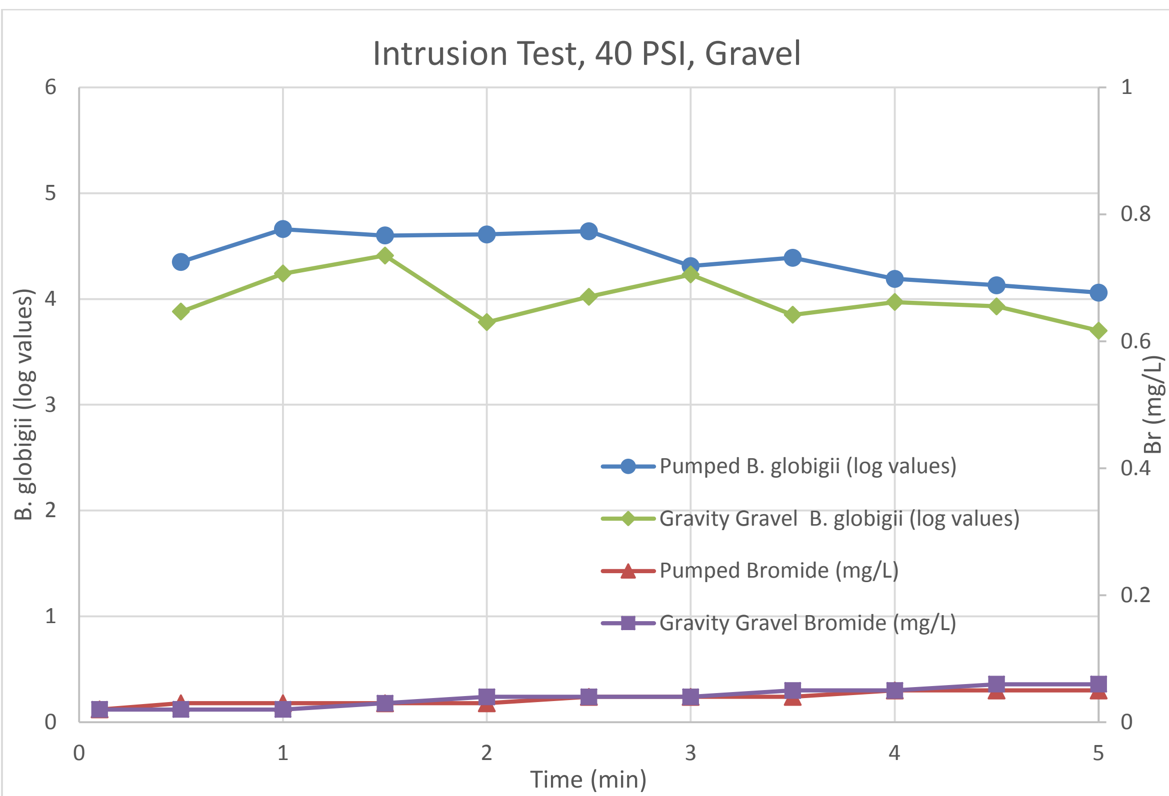

Figure 4-2 Intrusion of Tracer into Pipe for Gravel Media

4.3 Effect of Media and Backflow Method

Table 4-2 compares the log reduction in B. globigii from the concentration in the stock solution to the average backflow concentration over the first five minutes for the 40 psi runs 1-4.

Table 4-2 Log Reductions of B. globigii

Media	Backflow Method	Initial Tracer Concen. Log (CFU/100 ml)	Avg. Backflow Concen. Log(CFU/100 ml)	Avg. Log Reduction
Sand	Gravity	7.50	2.76	4.74
Sand	Pumped	7.69	3.92	3.77
Gravel	Gravity	7.90	4.00	3.89
Gravel	Pumped	7.89	4.39	3.49

These results show that fewer organisms (i.e. higher log reductions) relative to the initial level of soil contamination enter the pipe for sand than for gravel, and that the same is true for gravity as compared to pumped backflow. This behavior is consistent with the higher filtration efficiency of sand versus gravel and the lower pore water velocity experienced under gravity flow as compared to pumped flow.

One can also examine the contribution that the leak period makes in dispersing and diluting organisms in the vicinity of the pipe crack resulting in lower microbial concentrations in this zone as compared to the initial tracer concentration. The "BL" sample is taken in the same manner as the gravity backflow samples are, except before the pipe is operated in leak mode. For the sand media of Run 1, the initial tracer concentration was 7.5 logs while the BL sample was only 5.54 logs. This 2.8 log reduction of organisms was due just to the adherence of organisms on the sand particles plus any filtering provided by the sand in the vicinity of the pipe crack opening. When this process was repeated after an hour of allowing 40 psi clean water to leak out into the sand, the total reduction in organism concentrations entering the pipe rose to 4.74. Thus an additional 2 logs reduction can be attributed to the dispersal/dilution effect of pressurized water leaking out of the pipe. The gravel media used in Run 3 saw an initial log removal of 1.4 before the leak was started and an additional 2.5 log reduction resulting from the leak phase of the experiment.

4.4 B. globigii versus E. coli

Figure 4-3 compares the intrusion behavior of the two different microbial contaminants used in this study, *B. globigii and E. coli*, under similar experimental conditions of gravel media, 40 psi leak pressure, and pumped backflow (Runs 4 and 6). Because the stock solutions used to initially saturate the gravel contained different concentrations of B. globigii (7.7e+07 CFU/100 ml) and *E. coli* (4.7e+05 CFU/100 ml), the data plotted in the figure are the ratios of the backflow sample concentration to the stock solution concentration expressed as a log reduction. When plotted in this fashion the behavior of the two microbial tracers appears to be quite similar through the first 3 minutes of backflow. The average log reduction over the full 5 minute period was 3.5 for the *B. globigii* and 3.2 for *E. coli*. Claghorn and Lange (2000) had previously reported that the two organisms yielded statistically similar tracer curves when injected into porous media.

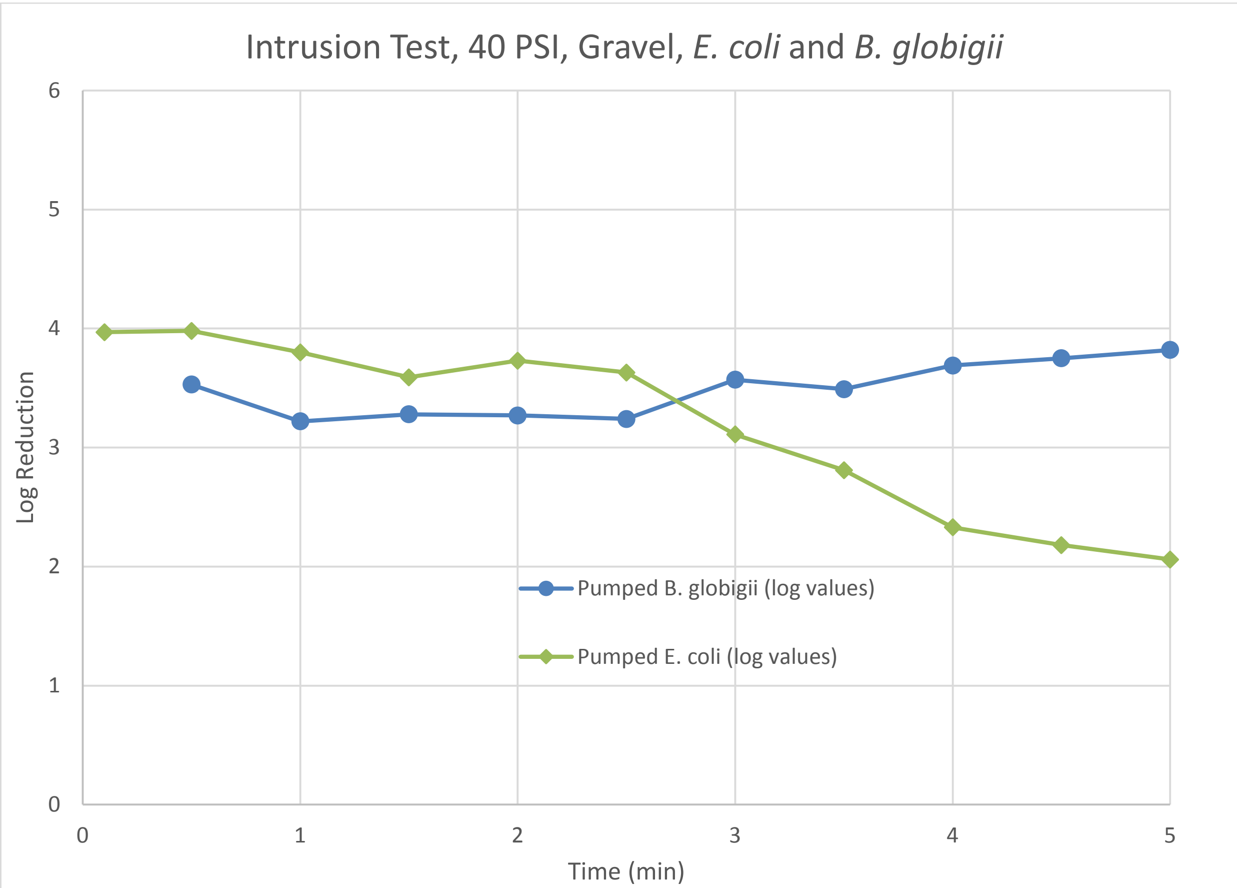

Figure 4-3 Comparison of Microbial Tracers

4.5 Effect of Leak Pressure

Figure 4-4 plots the average log reduction of the microbial concentration (relative to the stock solution) over the initial five minutes of backflow against the line pressure maintained during the leak phase of the experiment for two sets of runs. One set consists of runs made with sand media, gravity backflow and *B. globigii* (Runs 1, 8, and 9) and the second is with gravel using pumped backflow and *E. coli* (Runs 6, 7, and 10). The results for sand show a clear and expected trend of higher reductions (lower relative concentrations) of organisms with higher leak pressures due to greater leakage volumes and expansion of the sand around the pipe crack. The results for gravel do not follow this trend. The effect of pumping may have obscured any differences caused by pressure-related leak flow rates in the dispersal of *E. coli* during the leak phase of the experiment.

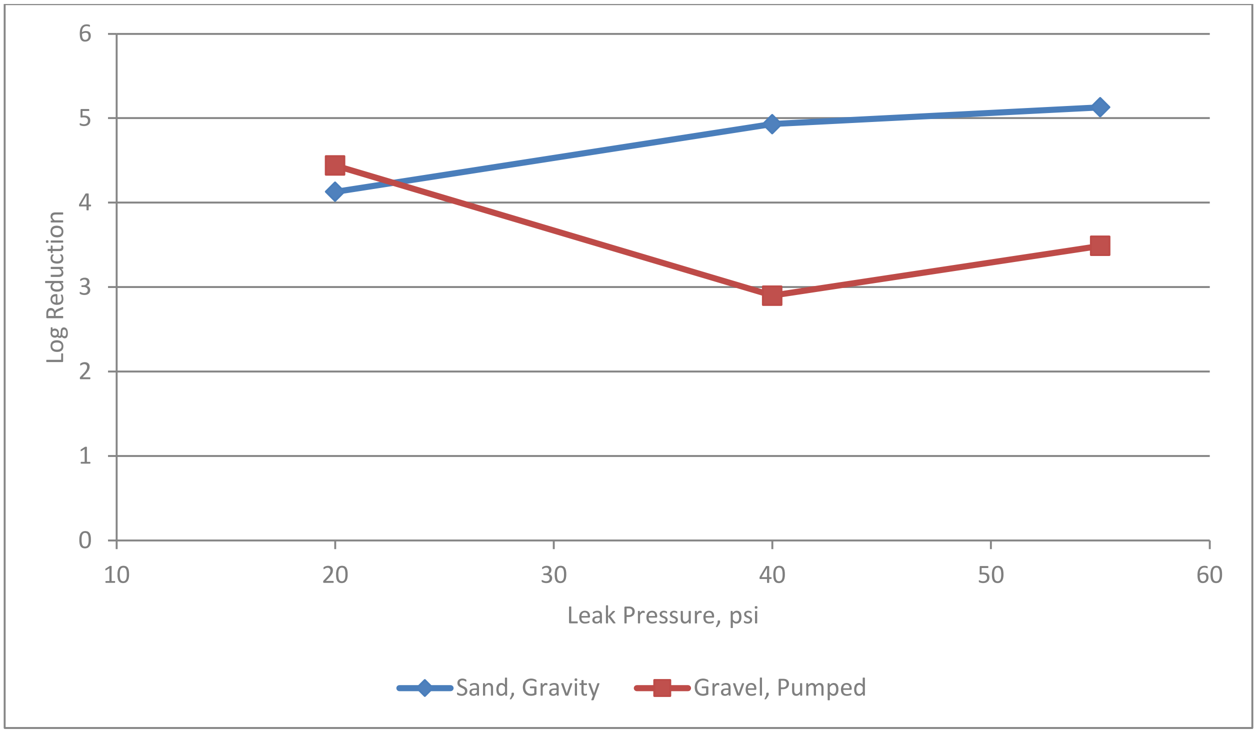

Figure 4-4 Effect of Leak Pressure on Intrusion of Microbial Tracer

4.6 Longer Term Intrusion Behavior

Low pressure intrusion conditions are usually caused by short term events such as pump shut downs, valve closures, or temporary power outages. Longer periods of low pressure might occur in systems that operate intermittently or when pipes are taken off-line to repair leaks. Figure 4-5 shows the intrusion of soil tracer over the full 60-minute sampling period for Runs 1 and 3. Run 1 was for sand and Run 3 for gravel, with both runs using a leak pressure of 40 psi, gravity backflow, and *B. globigii* as the microbial tracer. The tracer stock solution had similar levels of both *B. globigii* and bromide. The backflow rates ranged from 215 to 160 ml/min for the sand run and from 646 to 583 ml/min for the gravel run.

As expected, the looser gravel media with the higher flow rate provided less filtration efficiency allowing higher numbers of organisms to enter the pipe over time. The filtration efficiency of the sand media appears to improve over time, as the flow rate decreases due to less available head, reaching a point where only small numbers of organisms break through into the pipe. For the dissolved bromide tracer, at some point in time the higher backflow rate and intrusion volume for gravel begins to draw water from beyond the immediate area of the crack that had tracer completely displaced with clean water during the leak phase, resulting in increasing bromide concentrations over time (but still well below the initial 30 mg/L in the tracer solution). This behavior is not evident for the sand media, since at the smaller back flow rate it continues to draw from the clean leaked water over the duration of the run.

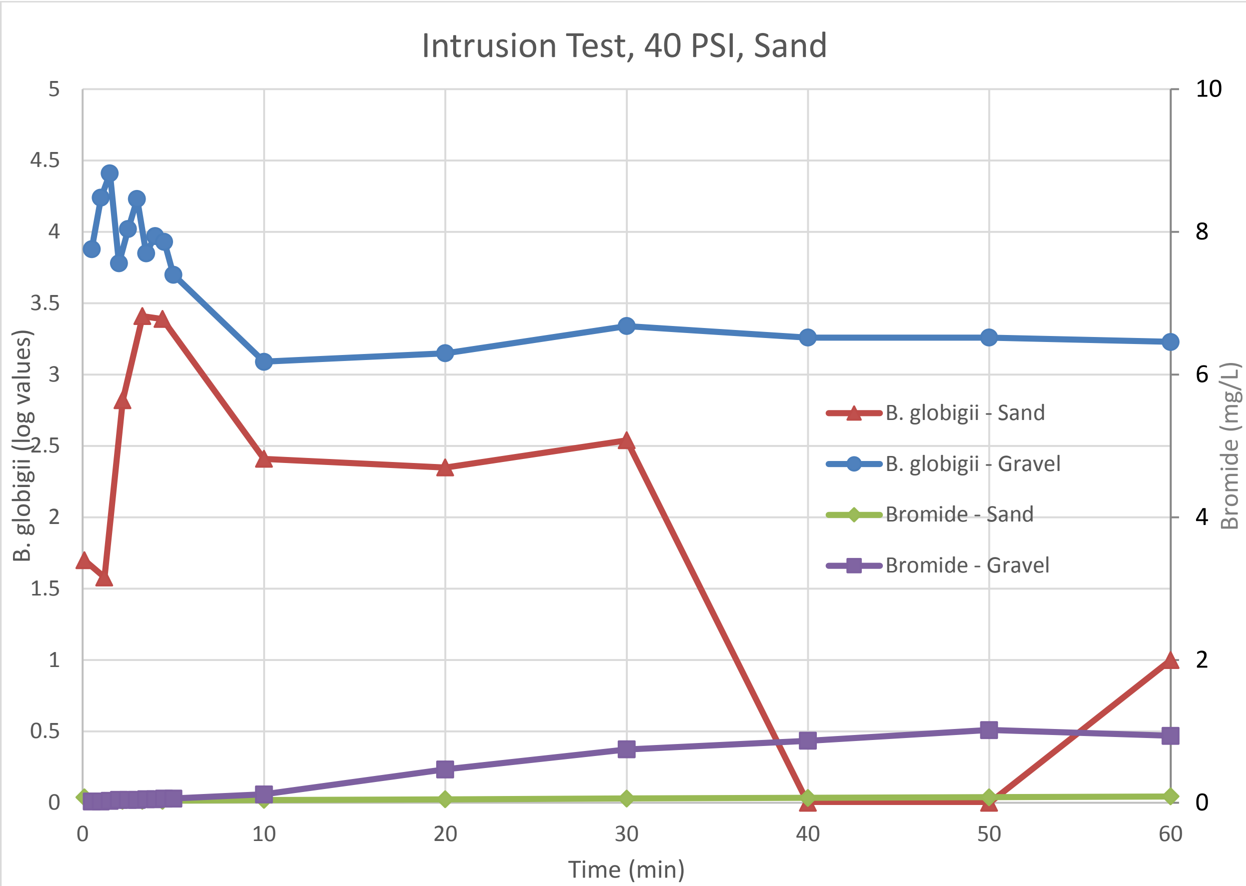

Figure 4-5 Longer Term Intrusion under Gravity Backflow

5.0 Conclusions and Recommendations

This project measured the concentrations of a biological tracer (*B. globigii* and *E. coli*) and an inert chemical tracer (bromide) added to soil media placed above a pipe with a small opening in it under a period of pressurized flow through the pipe followed by induced backflow from the soil into the pipe. Various experimental conditions were tested – sand versus gravel media; pumped versus gravity backflow; *E. coli* versus *B. globigii* microorganisms; and several different leak pressures. These conditions represent a worst case scenario since the experiments begin with fully contaminated soil media right next to the pipe crack, only allow leakage with de-chlorinated water for a period of one hour, and, since pipe flow is shut off during backflow, ignore any dilution of the intruded soil water with clean water flowing through the pipe. Nevertheless, they help reveal the potential behavior of how pipe leaks influence possible contamination during an intrusion event.

Based on the results of the experiments reported here, the following conclusions can be drawn for short term backflow events (less than 5 minutes):

6. There will be no intrusion of chemical tracer into the pipe because of tracer washout in the vicinity of the crack during normal operation of the leaking pipe.
7. There will however, be intrusion of microbial tracer since only partial washout occurs because of filtering by the soil media
8. Sand media provides higher filter efficiency than does gravel media in the direction of backflow resulting in lower numbers of microorganisms entering the pipe during backflow.
9. The lower the backflow flow rate the lower the average concentration of microorganisms in the back flowed soil water.
10. Higher leak pressures result in lower microbial concentrations in backflow from sand media. The same could not be shown for gravel.

As the backflow period was extended up to 60 minutes, the microbial tracer level tended to decrease for sand and level out for gravel. The chemical tracer continued to stay at background level for sand but started to rise for gravel.

The following recommendations are made for future intrusion studies:

1. Ways should be found to make the experiments easier to set up and be more reproducible, perhaps by using a smaller soil box.
2. Experiments should be performed using chlorinated tap water during the leak phase to see the effect that disinfection would have on microbial concentrations in the backflow into the pipe.
3. Experiments should be run under several leak/backflow cycles to be more representative of actual field conditions.

4. The backflow pumping rate for sand media should be adjusted so that more realistic suction pressures are obtained.

6.0 References

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