WASHINGTON STATE DEPARTMENT OF HEALTH

Rule Development Committee Issue Research Report - Draft

Special Features and Applications of Drainfield Products

For information or additional copies of this report contact:
Wastewater Management Program

Physical address: 101 Israel Road SE, Tumwater, WA 98501
Mailing Address: PO Box 47824, Olympia, Washington 98504-7824

Phone: (360) 236-3330
Webpage: www.doh.wa.gov/wastewater
Email: wastewatermgmt@doh.wa.gov

DOH 337-096 April 2025
To request this document in another format, call 1-800-525-0127. Deaf or hard of hearing customers, please call 711 (Washington Relay) or email doh.information@doh.wa.gov.

DOH Staff Researcher(s):	**Selden Hall**		
Date Assigned:	**December 17, 2001**		
Date Completed:	**April 17, 2002**		
Research Requested by:	☐ RDC	☒ TRC	☐ Other:
Issue Subject:	Technical ☒	Issue ID: T4P2	
	Administrative ☐		
	Regulatory ☐		
	Definitions ☐		
Specific WAC Section Reference, if WAC related:	**Section WAC 246-272-11501(2)(k)(l)**		

Topic & Issues:

DISPOSAL COMPONENT REDUCTIONS – PATHWAY NUMBER 2

(SPECIAL FEATURES AND APPLICATIONS OF DRAINFIELD PRODUCTS)

- Address how size reductions are applied. The limitations to these sizing reductions should apply to all technologies for which an absorption area is proposed.
- When allowing reductions in installed drainfields, should 100% available primary and reserve area set aside be required in rule?
- There is an allowance for 50% reductions in installed drainfield size when using enhanced treatment. Should there be an allowance for additional reductions due to disposal component reduction allowance?

In order to provide a logical framework for this report, the following set of questions have been developed to address the issues stated above. The Rule Development Committee (RDC) and DOH would like the TRC to answer questions 4-6.

1. Where are we now with disposal component reductions based on special features and applications of drainfield products?
2. Why are special (alternative, proprietary) drainfield products used?
3. What does the scientific literature say about the hydraulic and treatment performance, and longevity of alternative drainfield products?
4. Based on the literature review, should reductions for special features and application of drainfield products be allowed?
5. If reductions are allowed:
    a. What should the reduction allowances be?
    b. Should 100% primary and reserve absorption areas be required?
    c. Should O&M be required?

6. When reductions are allowed for pathway 1, should additional reductions due to pathway 2 be allowed (increasing the loading rate even further)?

Summary:

Of the two pathways currently available for applying reductions in absorption area ([1] highly pretreated effluent and [2] special features and application of alternative drainfield products), this literature review is focused on the second pathway. The first pathway, reductions for highly treated effluent, is the subject of a separate literature review.

Of the 36 documents included in the review, 12 are journal articles, 15 are conference proceedings papers, 3 are government reports, 3 are reports to a manufacturer, 1 is an ASTM Paper, 1 a master's thesis, and 1 an unpublished paper.

All drainfields have certain required features and functions in common. Alternative drainfields have other attributes and characteristics that promote their use. Washington state currently allows for drainfield size reductions up to 40% for two classes of alternative drainfield products. Despite considerable attention in the scientific and related literature, there is no conclusive resolution to the issue of hydraulic performance related to reductions based on special features of the products. Several recent publications report on laboratory work that measured higher infiltrative rates for sand surfaces that are free of gravel as compared to sand surfaces with gravel. Other reports on field scale studies (units installed for experimental study) were unable to find statistically valid differences in the infiltration rates of gravel-free and gravel laden surfaces. Reports from a number of field monitoring studies (information gathered from systems that are in use) of installed systems conclude that gravel-free systems sized at 50%-60% the size of gravel systems perform hydraulically as well as the standard gravel systems. However, most of these studies are weakened by serious shortcomings in the scientific method. Based on the laboratory studies, some reduction may be justified as long as conditions are present for the formation of a clogging zone. Long-term hydraulic performance is not addressed in the literature. Thus questions of long-term public health and environmental protection remain.

Laboratory and scientific field studies comparing the treatment performance of gravel-free and gravel-laden systems are reported in the literature. The findings support the conclusion that there is no statistical difference in the treatment performance related to the surface character (gravel-free and gravel-laden), despite gravel-free systems being loaded at higher rates. Good removals of BOD, TSS, fecal coliforms and viral surrogates at 30 and 60 cm beneath the infiltrative surface indicate that reduced size (up to 60%) gravel-free infiltrative surfaces are unlikely to present treatment problems any greater than a gravel-laden system under the same conditions.

When the information on hydraulic and treatment performance is viewed together, increased loading of septic tank effluent to gravel-free infiltrative surfaces does not appear to compromise the ability of the system to remove the BOD, TSS, and pathogen indicators, as these removals are largely accomplished in the clogging zone. While there is accumulating evidence of increased ability of the infiltrative surface to transmit effluent into the soil when gravel is not present during the early part of a system's life, the long-term capacity is not revealed in the scientific literature. If reductions for special features and applications of drainfield products are allowed, additional measures to assure public health protection over the long-term are prudent.

KEYWORDS: Chambers, chamber system, drainfield, gravelless, infiltration, infiltrative surface, leachfield, on-site alternative, seepage field, soil absorption, soil compaction, subsurface disposal

Introduction:

In Washington state, loading rates to the soil absorption system, and therefore the size of the absorption system, are determined by soil texture (WAC 246-272-11501). These loading rates assume a well-developed clogging mat, which greatly retards the infiltration rate into the native soil. There are two pathways to absorption area reductions, one based on highly pretreated effluent that eliminates or greatly retards the development of a clogging zone, and the other based on special features and application of alternative drainfield products. This literature review will address the second pathway: reductions for alternative drainfield products. The first pathway, use of highly pretreated effluent, is the subject of a separate literature review.

Currently, any drainfield products approved for sizing reductions are in the category of products covered by the DOH Recommended Standards and Guidance for Gravelless Drainfields (RS&G). Based on requests from manufacturers of alternative drainfield products and on recommendations from the TRC, two types of products are allowed sizing reductions, chambers and gravel substitute products. The amount and limitations of these reductions are currently contained in the above noted Standards and Guidance and in a memo (dated 9/5/2001) to Environmental Health Directors and Sewage Program Coordinators. The sizing modifications have an upper limit of 40% and are based on the recommendations of the manufacturers. To provide assurance of public health protection and long-term function, the drainfield reductions carry with them additional requirements. One of these requirements is the dedication of additional area to expand the installed system to full size (based on design flow and loading rate for the soil) and a similar full sized replacement area.

The purpose of this review is to synthesize the literature available on the topic of drainfield size reductions based on special features and application of alternative products. The findings will assist the TRC in making appropriate recommendations to the Rule Development Committee about absorption area requirements for these proprietary products. Thirty-six publications were collected and reviewed. These publications included peer-reviewed journal articles, other journal articles, conference proceedings, engineering reports, and some miscellaneous sources. Even though the conference proceedings, which are not typically peer-reviewed, comprised the largest group of publications, they provide useful information and many of the authors are recognized scientific experts in the on-site sewage field. Many of the other sources of the information on this topic are likewise not peer-reviewed, and combined with other shortcomings in scientific methods, may not represent the best available science.

This literature review will describe why gravelless drainfield products are used, including common characteristics of drainfields, additional characteristics that are common to gravelless drainfield products and a description of the classes of gravelless drainfield products approved in Washington. The review will then describe what is known from the literature about the hydraulic and treatment performance of gravel free systems. In the conclusion section, a series of questions are posed for decision by the TRC, based on the information provided.

Body:

Why are gravelless drainfields used?

Gravel and gravelless drainfield products in Washington state are expected to have the following characteristics and functions: (1) Non-deteriorating, (2) Provide void space for passage and temporary storage of the effluent it receives, (3) Present an interface with the infiltrative surface for absorption of the wastewater, (4) Maintain the integrity of the excavation against the soil forces in the sidewalls and soil backfill. These attributes of drainfield products are consistent with descriptions in the literature (Amerson et al., 1991; Tyler, Milner, Converse, 1991, 1992; Keys, 1996).

Gravelless drainfield products have some attributes that are in addition to those shared by gravel-based systems. They are generally light weight, are free of associated fine soil particles and do not compact the infiltrative surface as falling gravel may. Most gravelless and gravel substitute products approved in Washington state incorporate plastic and/or geocomposite materials to reduce the weight and meet the common characteristics of the drainfield. They do not require the use of heavy machinery to place them in the trench and can be moved and installed with hand labor. In addition, they are excellent choices where suitable gravel is not available.

Chambers are domed structures with an infiltrative surface that is open and available for observation, monitoring the liquid level, raking, and easy exposure for repairs. They are quite amenable for pressure distribution, have an impervious top, and require the trampling of disturbed soil around the sides to hold them in place. In the case of large diameter, geotextile-wrapped pipe the clogging mat forms on the surface of the geotextile. In the case of geocomposites and gravel substitute products, the top is open for air and water movement, and there are large voids between the bundles that are not effective in holding the shape of the trench.

These systems are usually more costly than gravel drainfields on a per foot comparison. The two classes of gravelless products allowed a sizing reduction are chambers and gravel substitute products. Gravelless products are selected in on-site system designs for one or more of these attributes described above or because of the allowed sizing reduction.

What does the scientific literature reveal about the hydraulic performance when gravelless systems are used at increased loading rates?

As mentioned in the introduction, loading rates to the soil absorption system and therefore, the size of the infiltrative area, assume a well-developed clogging mat. The infiltration rate through the clogged zone is usually a fraction of the saturated conductivity of the soil. Some researchers have reasoned that the presence of gravel in a drainfield reduces the clogged infiltration rate per unit area of infiltrative surface because the gravel particles take up some of that area (Magdoff and Bouma 1975; Siegrist 1987; Amerson, et al. 1991). The size of the area taken up by gravel has been variously estimated at up to 60% of the total area (Magdoff and Bouma 1975). Other effects of dropping gravel into an on-site system have been considered, such as compaction of the infiltrative surface and introducing entrained fine soil particles and dust (Amerson et al., 1991; Van Cuyk et al., 2001). While concern for the deleterious effects of fine particles associated with gravel is commonly expressed, gravel masking and compaction of the infiltrative surface by falling gravel are not universally accepted.

LABORATORY STUDIES

There are several laboratory scale studies of the difference in the infiltrative rate for surfaces with gravel and without gravel. Amerson et al., 1991 used a device and methods to measure the unclogged infiltration rate for two soils. This study compared the infiltration rates of surfaces without gravel to those with fines, compacted by the dropping of gravel, gravel interlaced with fines washed from the gravel and a combination of compaction, gravel and fines. The study concluded that the fines are potentially more of a problem in new systems than either the compaction by falling gravel or by contact area effect of the gravel pieces.

Using sand columns, Keys 1994, found a strong significant difference up to 10.4% in saturated conductivities between open sand surfaces and gravel/sand surfaces that were unclogged and dosed with water. The findings of these studies were not correlated to the conditions of clogged infiltrative surfaces.

Other studies (Siegrist 1999, Van Cuyk et al., 2001) used laboratory sand lysimeters to compare the hydraulic and purification performance of aggregate free and aggregate laden surfaces dosed with septic tank effluent at 8.4 cm/day (2.05 gpd/ft^2) and 5.0 cm/day (1.22 gpd/ft^2), respectively. After 45 weeks of operation the hydraulic performance of each surface was indirectly determined by timing the appearance of bromide tracer in the percolate at 10% and 50% of the initial concentration. The authors concluded that the hydraulic performance was the same despite the 67% higher loading rate to the aggregate free surface.

In an unpublished paper Lowe and Siegrist (2001) used packed sand columns to study the effects of accelerated loading of septic tank effluent and infiltrative surface character (gravel-free vs. gravel-laden) on hydraulic performance and on the development of soil clogging at the infiltrative surface. After 119 days the throughput volume for most of the columns leveled off at a small fraction of the initial volumes. Using measurements of the throughput volumes for days 119 to 131 for all column types (combination of various loading regimes and gravel-free or gravel-laden), the authors calculated the gravel-free mean throughput was 8.5 cm/d (2.08 gpd/ft^2) and the gravel-laden was 3.5 cm/d (0.86 gpd/ft^2). The authors further report that a statistical evaluation of the data indicates that the columns approached pseudo-equilibrium conditions representative of, but not equal to, the long-term infiltration rates. They also do not attempt to extrapolate to other soil types.

FIELD SCALE RESEARCH STUDIES

Several field scale research studies (where systems are constructed to allow experimental testing) in the literature report some comparison of the hydraulic performance of infiltrative systems using gravel with systems having open bottoms. In side by side tests of chamber systems and gravel systems receiving septic tank effluent Tyler, Milner and Converse (1991, 1992) were unable to provide conclusive data due to excessive loading rates in the case of sand, too great a variability in the infiltration rates in silt loam soil, and to mechanical problems. Similar experiments by Keys (1996) on the same two soils did not show a statistically significant difference in infiltration rates between chambers and gravel systems.

Louden, Salthouse and Mokma, (1998) reported on a project to use an automated control system to dose and monitor ponding levels in a variety of trench designs. The test included three replicates of each trench type, and was intended to collect data on long-term infiltration rates of gravel and open bottom trench systems receiving septic tank effluent. Any differences in the measured infiltration rates were not statistically significant due to the high variability of the infiltration rates within each trench type.

An engineering report (Nodarse & Associates, 1997) commissioned by a chamber manufacturer concluded from a side by side test site, that hydraulic infiltration rates for chambers were higher than for gravel trenches. However, this study was hampered by serious mechanical defects, lack of a reliable source of wastewater, no statistical analysis of the data to show significance, and no peer review or publication.

FIELD MONITORING STUDIES

Field monitoring studies (where information is gathered on existing systems that are in use) have been used to demonstrate the lack of problems with a technology, to compare the performance of a technology with gravel systems and to demonstrate the appropriateness of sizing reductions. Such comparisons and demonstrations are used to support regulatory approval requests. Baranco and Sherman (1991) report on a test protocol for experimental systems in Florida and a case study of a specific brand of chambers tested against the protocol. The protocol called for review of the hydraulic performance of 50 randomly selected chamber systems sized at 60% of conventional size after a minimum of one year of operation. The success rate did not meet that called for in the protocol, but the protocol could not distinguish between size reduction and numerous other factors in the installations. The report concludes that the protocol failed to test the sizing reduction, that assurance was not provided for long-term hydraulic performance of reduced size systems, and that a side-by-side protocol was needed.

A report by Dix and May (1997) presents observations and conclusions from several field studies including three that are referenced separately: Hoxie and Frick (1984), Hoxie, Frick and Hardcastle (1990), and Ricklefs (1992). The report concludes that these field studies provide substantial evidence that sizing chamber systems at 50-60% of conventional gravel systems will provide equally effective soil absorption. This report is weak in terms of best available science for several reasons: the authors have an economic interest in the product, the evidence for equivalence is based on observations over the early part of the systems' life, and most of the studies and reports have one or more deficiencies that prevent numerical comparison with conventional gravel systems. Nevertheless conclusions are made about the comparable hydraulic performance. Examples of deficiencies in these studies follow. The Hoxie et al. studies have assumptions about the ratio of system type (gravel to chamber) taken in one time frame and applied in an earlier time frame. The Texas study (Ricklefs, 1992) provides data for one year with a letter after five years saying that the data are the same as for the first year. Because failures were not observed in the chamber systems (installed at 60% sizing of conventional gravel systems) during the first year these systems were approved for use at the reduced sizing. The Washington study assumed that the observed systems are typical household systems. The authors of the study acknowledge that employees of and a contractor for the manufacturer conducted the study. They also do not explain how the seasonal nature of many of the homes would affect the results.

England and Dix (1999) use health department records to do a data capture and statistical analysis of their brand of chambers that were installed in Hamilton County, Kentucky. Analysis included quantity and the year installed, quantity and age of reported failures. They conclude that the study provides significant evidence that 50-70% sizing provides equally effective leaching systems. The authors draw comparisons with gravel systems without providing any data for gravel systems. The authors do not analyze how reliance on reported failures affects the strength of the evidence for hydraulic performance. Similar low reporting rates might occur with failures of gravel systems. The systems in the study were all less than 8 years old.

Several field studies of installed fabric-wrapped large diameter pipe are reported in the literature. Carlisle and Osborne (1982) evaluated and inspected 92 of these systems and 12 conventional gravel systems in Texas coastal plain soils. These soils often have high water tables and other restrictive conditions. The authors found a lower percentage of problems with the large diameter pipe systems than with the gravel systems. However they suggest that the low number of gravel systems may influence this difference. In addition, the authors offer possible advantages of the gravelless system such as reduction in the use of heavy equipment on the site and increased solids retention in the pipe. The study did not include the ages of the systems examined. Another study (Anderson et al., 1985) made observations on 8 sites in Minnesota with existing systems that used this drainfield technology. The drainfields were in a variety of soils, were arranged in serial distribution and one was a newly constructed site with monitoring instrumentation. This study measured the long-term acceptance rates (LTARs) per lineal foot for these gravelless systems and compares the results with the predicted LTARs for 2 and 3-foot wide gravel trenches per lineal foot. Based on the measured LTARs, the authors conclude that the manufacturer's sizing recommendations are realistic (10 inch diameter tubing system is equivalent to 3 foot wide gravel trench).

An experimental field study comparing the hydraulic performance of fabric-wrapped pipes to gravel systems is reported by Effert and Cashell (1987). Side by side systems were installed in an area historically unsuited for on-site sewage systems due to low permeability of the soils and a high water table for a large part of the year. An automated system was used for dosing septic tank effluent to the cells, recording the amount dosed, and maintaining a constant head between 7 and 9 inches. For the two-year study period, the authors report that under the conditions of the study, there was no statistically significant difference in the absorption rates of the conventional 2-foot wide gravel-filled trenches and the 10-inch diameter gravelless pipe trenches. The authors do not speculate how the disturbed silt loam backfill around the fabric-wrapped pipe affects the absorption rate into the trenches.

Treatment Performance of Gravelless Drainfield Products

LABORATORY STUDIES

A number of reports from a long-term program of research provide information on the treatment performance of soil absorption systems. The studies have used controlled lab and field scale experiments and field investigations of full-scale systems. In lysimeter studies using a sand medium gravel-laden and gravel-free cells are loaded at 5.0 cm/day (1.22 gpd/ft^2) and 8.3 cm/day (2.03 gpd/ft^2) respectively. After 45 weeks of dosing the cells with septic tank effluent, the BOD and TSS removals and nitrification were high and were similar (95% confidence level) for all lysimeters (Van Cuyk et al., 2001). After week 28, fecal coliforms in the percolates were non-detectible or very low (<6 cfu/100 ml) (Van Cuyk et al., 2001, Van Cuyk, Siegrist and Logan, 2001). Viral surrogates (bacteriophages) were substantially retarded in all lysimeters, irrespective of the infiltrative surface character (Van Cuyk et al. 2001 and Van Cuyk, Siegrist and Logan, 2001). These studies are summarized by Siegrist and Van Cuyk (2001).

FIELD STUDIES

In field investigations associated with this same long-term research program, systems for 16 homes (10 with chambers and 6 with gravel) were studied. Based on the water meter readings and the dimensions recorded in the health department records, the average loading rates for gravel systems was estimated to be 0.74 cm/day (0.18 gpd/ft^2) and for chamber systems 1.31 cm/day (0.32 gpd/ft^2). Monitoring of soil properties and pollutant concentrations with depth beneath the infiltrative surfaces of 14 homes revealed that pollutant concentrations declined with depth and by 60 cm (24 inches), fecal coliform were not detected. The authors report that fecal coliform levels at both the 30 and 60 cm (12 and 24 inches) depths were not significantly different between the chamber and the gravel systems (Siegrist et al., 2000). In a bench-scale analysis completed with mini-columns and two different soil media (clean sand with low total organic carbon and silty sand with higher total organic carbon), the estimated concentrations of fecal coliforms in percolating water can be conservatively estimated based on analysis of bulk soil solids (Siegrist et al., 2000). This experiment was undertaken to help relate the soil sample results under the systems in the field study with the standard of fecal coliforms (cfu) per 100 ml in the soil percolates. The same viral surrogates as in the laboratory lysimeters (MS-2 and PRD-1 bacteriophages)

were added to the septic tank effluent delivered to one chamber system in the field study. Three log reductions of the bacteriophages were achieved at the 30 cm depth, and fecal coliform concentrations measured in soil core samples were directly correlated with the viral concentrations (Siegrist et al., 2000, Van Cuyk, Siegrist and Logan, 2001). These determinations are consistent with the laboratory lysimeters results (Van Cuyk et al., 1999). These studies are summarized by Siegrist and Van Cuyk (2001).
.

Cost Information:

In areas where suitable gravel is available, gravel-based drainfield systems are reported to be the less costly than similarly sized alternative drainfield systems. However, where suitable gravel is not easily available or where other attributes of alternative drainfield products are advantageous for the site and installation conditions, these products may be the less costly option. When sizing reductions are factored into the design and installation costs, systems using alternative drainfield products become competitive in cost with gravel based drainfields.

Conclusions:

Hydraulic Performance

1. Laboratory lysimeters and column studies indicate that gravel-free and gravel-laden infiltrative surfaces have different infiltrative rates. The studies speculate on what caused the difference and one study identified fine particles entrained with gravel as a cause.
2. Field scale studies provide little help in comparing infiltration rates in actual soil conditions. Differences in hydraulic performance were overshadowed by high variability between units with the same surface character.
3. Field evaluation studies of actual installed and in-use systems are a mixed review and provide limited scientifically valid evidence for equivalent hydraulic performance for gravel-free systems sized at 50-60% of gravel systems, and are not able to provide assurance for long-term hydraulic acceptance at the elevated loading rates.

Treatment Performance

4. Laboratory and field studies indicate that despite higher loading rates for gravel-free systems, the removal of BOD, TSS, fecal coliforms and viral surrogates is not significantly different from standard gravel systems.
5. As the clogging zone develops on both gravel-free and gravel-laden infiltrative surfaces, the treatment efficiencies improve with no difference found between the two surface characters.
6. Laboratory systems comparing the two surface characteristics used sand media, and did not test other soil media. The field studies were conducted on systems installed in soils dominated with loam, clay loam, and silty clay and in some cases containing 30-80% large fragments.
7. Any differences in infiltration rate and clogging zone development between gravel-free and gravel-laden systems using pressure distribution are not addressed in the literature.

Recommendations:

1. Size reductions of up to 40% where a clogging zone will develop can be considered, because treatment efficiency is not compromised by a 67% increase in loading rates when a 40% size reduction is applied to a drainfield receiving septic tank effluent.
2. Because long-term hydraulic performance for gravel-free systems cannot yet be established with scientific confidence, full area set aside for the primary and replacement areas is recommended in order to provide long-term assurance of public health protection.
3. Coupling reductions allowed for special features and application of drainfield products with reductions allowed for highly pretreated effluent is not answered in this review, as this review assumes the development of a clogging zone. This question should refer back to Technical Issue 4, Pathway 1.

References:

Amerson, RS, Tyler, EJ, Converse, JC. 1991. Infiltration as Affected by Compaction, Fines and Contact Area of Gravel, in On-Site Wastewater Treatment: Proceedings of 6th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1991, Pp. 243-247.

The purpose of this study was to evaluate the effect of gravel on soil infiltration rates. Specifically, the objectives were to evaluate the effect of 1) soil compaction and smearing by falling gravel, 2) the fine earth material carried by gravel, and 3) the masking of the infiltrative surface caused by the contact area between the gravel and the soil. These experiments indicate that fines carried by gravel are a potentially greater problem in newly constructed on-site wastewater treatment systems than either compaction by falling gravel or the contact area effect.

Anderson, JL, Machmeier, RE, Gaffron, MP. 1985. Evaluation and Performance of Nylon Wrapped Corrugated Tubing In Minnesota, in On-Site Wastewater Treatment: Proceedings of 4th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1985, Pp. 79-86.

This study made observations on 7 sites with existing large diameter, fabric-wrapped corrugated pipe arranged with serial distribution and one site at which used an existing septic tank and pump chamber which was modified to deliver effluent to a newly constructed large diameter pipe system with monitoring instruments. At two of the sites a section of the pipe was excavated to describe the character and penetration of the developed biomat. Acceptance rates for each of the sites studied are calculated and reported. Ages of the systems are not given. The authors conclude:

1. Based on the data from the systems studied, the gravelless trench system appears to establish LTARs on a variety of soils, with the biomat developing at the fabric-soil interface.
2. Variations in the LTARs for the different soils are not unlike the design LTARs for gravel-filled trenches.
3. Manufacturer’s recommendations for 10-inch diameter pipe as equivalent to 3’ wide gravel trench appears to be realistic except for the fine sands.
4. 8 inch diameter pipe should be equivalent to a 2’ wide gravel-filled trench.

Baranco, EJ, Sherman, KM. 1991. Florida’s On-site Sewage Disposal (OSD) Experimental System Protocol in Proceedings of 6th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1991, pp. 266-275.

This paper describes an experimental system protocol developed by the state of Florida, describes a case study of Infiltrator® chambers tested under this protocol, and provides some results of the case study and conclusions about the protocol itself.

The protocol, as applied to the Infiltrator chamber case study was as follows: 1. Temporary permits for 100 systems installed at 60% of Florida’s sizing requirements were granted. 2. Infiltrator would test and monitor for 1 year. 3. Florida would randomly select and review the performance of 50% of these installations. 4 If 95% were found to be performing satisfactorily, then statewide approval would be granted. 6. Failure was defined as one or more of the following: need for additional absorption area (additional chambers) to achieve adequate performance; system replacement due to surfacing sewage or backup into the house; systems ponding above the inlet invert to the chambers (7”); systems described by

homeowners as having a sluggish performance during wet weather or signs of wet spots developing above the drainfield.

The findings from the case study:

- 9 of the 50 systems, at an average age of 16.8 months, met one or more of the failure definitions.
- Resulting success rate was 82%.
- The principle limiting condition for the 9 failures was hypothesized to be the overall undersizing of the systems (beyond the 40% reduction allowed) with respect to the site-specific soils and design loading rates. Specific reported factors included erroneous soil evaluations, miscalculated wet season water tables, poor installation practices and poor workmanship, and extensive irrigation over the drainfield area.

The overall conclusions from Florida's use of the protocol in this case study were:

- Protocol failed to test Infiltrator's case for a 40% reduction.
- The researchers could not state with assurance that when systems are designed at 60% of the conventional size and where flows to the system may be equal to or exceed the maximum design flows, these systems will operate properly over the long term.
- The only effective way to evaluate reduced drainfield sizing claims and requests is to install, monitor and measure the experimental systems side by side with conventional systems so that the measurements can be done on both systems under nearly identical conditions.
- Wastewater flow measurements to the drainfields must be incorporated into the experimental design.

Brown, KW, Wolf, HW, Donnelly, KC, Slowey, JF. 1979. The Movement of Fecal Coliforms and Coliphages Below Septic Lines, J. Environ. Qual. 8(1): 121-125.

This study used lysimeters in 3 undisturbed soils over a two-year period. Leachate samples were collected from a series of porous cups placed 4' below the infiltrative surface and at different horizontal distances from the trench. Soil samples were taken from the field lines on several occasions during the study and from the lysimeters at the end of the study. Fecal coliforms were detected occasionally in the leachate water and rarely after the 1st year. Soil sample data indicated that fecal coliform population decreases greatly with increasing distance from the septic line. In most cross sections, fecal coliforms were not present below 14". Coliphages were also rarely found in the leachates at 4' below the trenches, and only when abnormally high concentrations of the phage were added to the effluent.

Carlisle, BL, Osborne, DJ. 1982. Some Experience with Gravel-less Systems in Texas Coastal Areas in On-Site Wastewater Treatment in Proceedings of 3rd National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1982, Pp. 160-169.

Inspections and evaluations were performed on 100 large diameter pipe gravelless systems in the Texas Coastal Plain. The authors concluded that design criteria for these systems should be based on the same soil and site parameters used for conventional gravel systems. This system may offer some advantages over conventional gravel systems due to the reduction of heavy equipment use that is needed. Other possible advantages may be improved distribution and increased solids retention.

Daniel, TC, Bouma, J. 1974. Column Studies of Soil Clogging in Slowly Permeable soils as a Function of Effluent Quality, J. Env. Quality 3(4):321-327.

Undisturbed 2 ft long soil cores of a very slowly permeable silt loam were subjected to constant ponding for 120 days. Liquid dose to the cores were STE, extended aeration effluent, and distilled water. Although column influents differed markedly, the effluents had consistently low levels of contaminants. The most severe barriers to infiltration were in columns flooded with extended aeration effluent, followed closely by STE. No barriers developed in columns ponded with water. This study points to the significant role of suspended solids in soil clogging.

Dix, S, May, R. 1997. Field Evaluation of the Performance if Chamber Leaching Fields, Site Characterization and Design of On-site Septic Systems, ASTM 1324, MS Bedinger, AI Johnson, JS Fleming, Eds. American Society for Testing and Materials, Conshohocken, PA, Pp. 248-260.

This paper presents observations and conclusions from several field surveys in an attempt to establish failure rates of gravity and gravelless systems.

The authors site 3 studies from North Carolina in which the failure rate for conventional systems less than 6 years old was determined to range from 11% to 34%. (The authors suggest that the 34% figure might be inflated due to using political boundaries for determining study areas.)

A study in a Texas Coastal Plain soil is cited in which 100% of the systems were found in failure or marginal condition. Two studies from Maine, which has allowed chambers to be installed at 50% sizing compared to gravel systems since 1974, are cited and include 1,995 replacement systems in one study and 6,288 systems in the other. In both studies, the researchers conclude "…that chambers do not have a higher rate of failure than bed systems [with gravel], although chamber area designs are 50% smaller than bed systems for a given soil type."

Another survey study is cited from Amarillo Texas in which 42 chamber systems were observed beginning at one year of age. These systems were installed at 60% of the size of a gravel system for the soil type. A minimum of 10 observations were made on each system over a 5-year period. During the evaluation period, no systems failed and none had persistent ponding. Based on the performance of these 42 systems, the Amarillo Health Department has allowed the continued use of a 60% sizing criterion for chamber systems.

A survey of systems in Georgia is cited, in which a reported 232 systems were observed. The systems ranged in age from 1 to 7 years. The surveyors found the failure rates of the standard gravel systems and the 50% sized chambers systems to be within 1% of each other.

A field survey in Washington state by a proprietary chamber manufacturer is cited. Twenty-eight systems were observed over a 5-month period with a minimum of 2 visits and maximum of 7. Varying and fluctuating levels of ponding were noted in some systems and none in others. The authors conclude that the data indicate that the 60% sized chamber systems evaluated in the survey were all functioning well. The authors do not address the effect on the study by the intermittent occupancy of many of the homes.

Of 19 experimental chamber systems installed in Illinois, 10 were selected for field visits. Six were investigated, including excavation, after 3 years of service and the remaining 4 were evaluated after 3.4 years of service. The report summary concludes that all systems were operating in a satisfactory manner.

This paper also cites experimental results that are relevant to the issue of sizing of chambers. Essentially, they point out the difficulty in drawing conclusions based on the experimental data regarding the relative performance of gravel and gravelless systems. The authors imply that the field studies should be given attention and credence in the light of equivocal experimental data.

Effert, D, Cashell, M. 1987. A Comparative Study of Three Soil Absorption Trench Designs Installed in an Illinoian Till Soil, in On-Site Wastewater Treatment: Proceedings of 5th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1987, Pp. 346-355.

These researchers compare the performance of 10" diameter corrugated, fabric-wrapped gravelless pipe trenches with conventional gravel trenches over a two-year period. The soil had a high water table for much of the year and a silt loam texture. They concluded that when soil conditions were not saturated, the 10" gravelless pipe systems had an absorption rate of a 24" wide gravel trench.

Emerick, RW, Test, RM, Tchobanoglous, G, Darby, G. 1997. Shallow Intermittent Sand Filtration: Microorganism Removal, Small Flows 3(1): 2-22.

Twelve lab scale sand filters (0.38 meters deep, 1.2 meters in diameter) were loaded with septic tank effluent to evaluate the effects of hydraulic loading rate, dosing frequency and sand medium characteristics on the removal of indigenous coliphages, total coliforms and other constituents of sewage. Removal of microorganisms was found to be affected by the combination of hydraulic loading rate and dosing frequency, with a decrease of microbe removal as the hydraulic loading rate was increased (dosing frequency kept constant).

England, A, Dix, S. 1999. Performance of the Infiltrator Chamber System in Hamilton County, Tennessee, in Proceedings of 8th Annual Conference, National On-site Wastewater Recycling Association, Laural, MD, Pp. 99-106.

A representative of Infiltrator Systems, Inc. reviewed all subsurface wastewater disposal permits and drawings in Hamilton County to determine the quantity and performance of their brand of chamber systems installed in the county. The study evaluates the sizing of chamber systems, soil conditions within Hamilton county, quantity and classification of the installations, and a description of causes of problem systems identified during the study. The authors provide a summary of their findings, as well as conclusions and recommendations.

Hoxie, DC, Frick, A, Hardcastle, J. 1990. Subsurface Wastewater Disposal Systems Designed in Maine by the Site Evaluation Method: System Design, Land Use Trends and Failure Rates. Maine Department of Human Services, Division of Health Engineering.

This report is an extension of the study reported in Hoxie and Frick (1984). In this report, the study period is from May 1983 to July 1986. Calculated failure rates for 1, 5 and 10 years are reported the same as in 1984: 0.12%, 1.0% and 5.0% respectively. The study period included a larger sample base (23,031 systems installed during this time) but the ratio of new to replacement systems is the same as in the earlier report: 69% and 27% respectively.

The authors report the "…ratio of beds to chambers failure rate is 5:1 and the ratio of beds to chambers installed is 2:1." From this observation, they suggest that chambers do not have a higher incidence of failure than bed systems, although chamber systems have a 50% smaller absorption area for a given soil type.

Other conclusions in the report are:

- Approximately 9.3% of the new systems required a variance to Maine's on-site rules, whereas, 62.7% of the replacement systems required a variance.
- Of the total number of systems installed during the study period (23,031), 64% were gravel beds and 34% were chambers.

Hoxie, DC, Frick, A. 1984. Subsurface Wastewater Disposal Systems Designed in Maine by the Site Evaluation Method: Life Expectancy, System Design and Land Use Trends, in On-Site Wastewater Treatment: Proceedings of 4th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1984, Pp. 362-371.

This study examines the effectiveness of Maine's site evaluation program (as opposed to percolation tests) and Subsurface Wastewater Disposal Rules after 10 years of implementation and refinement. The investigation included the types of absorption systems installed, soil types utilized and a failure rate by system type. Information was gleaned from permits obtained prior to installation. Records from May 1983 to July 1984 were used to determine the soil types utilized for on-site system absorption areas and the ratio of new systems VS repair systems being permitted. Repair records from May 1983 to July 1984 were also used to identify systems installed since 1974 (site evaluation and state on-site rules went into effect in 1974) that failed. These repair permits were then matched with the original permits to determine the age and type of original system. Using these data the authors calculated a failure ratio for the two system types. The study also recorded the age of the failing system and developed a table to correlate the age of the systems and number of failures, from which projected failure rates were calculated for systems for a given age.

The authors report that chambers do not have a higher incidence of failure than gravel beds, despite a 50% smaller absorption area. This conclusion is based on a calculated failure rate ratio of 10:1 while the ratio of installed beds to chamber is 8:1.

The authors arrived at the following conclusions:

- New and replacement systems were 69% and 27% of the total (7,677) systems sampled, respectively.
- Approximately 3% of the new systems required a variance to Maine's Subsurface Wastewater Disposal Rules, whereas 60% of the replacement systems required a variance (where the systems being replaced were installed prior to the land use and more stringent current regulations).
- Of the total absorption areas installed, 84% were gravel beds, 10% were chambers, and the remainder trenches or unknown.
- Although the majority of soils in Maine are poorly suited for on-site sewage systems, the land use laws and sewage rules direct systems onto the better soils, because 81% of the total systems are on well-drained or moderately well-drained soils and address site limitations.
- Chamber systems do not have a higher incidence of failure than bed systems, based on limited data, although the chamber systems are 50% smaller than beds for the same soil type.
- The projected failure rates in Maine, based on a review of 1,995 replacement systems, are 0.12, 1.0 and 5.0 percent within 1, 5, and 10 years, respectively.

Huysman, F, Verstraete, W. 1993. Water Facilitated Transport of Bacteria in Unsaturated Soil Columns: Influence of Inoculation and Irrigation Methods, Journal of Soil Biology and Biochemistry 25(1):91-97.

In this paper, the authors report on the transport of bacteria in soil columns and bacterial accumulations in the top few centimeters. Several variables were investigated: (1) delay in irrigation after depositing bacteria on soil surface, (2) mixing bacterial suspension with clay loam soil or montmorillonite or kaolinite before irrigating the soil with the suspension, and (3) the rate of irrigation. The transport of bacteria was compared to what would be predicted by a mathematical formula they call "the colloidal filtration model".

The authors conclude that water facilitated migration of bacteria is influenced by the hydrophobicity of the bacteria and also greatly influenced by the inoculation and irrigation method. They found that translocation of the cells into the subsoil can be greatly reduced by exposure of the bacterial suspension to clay, by applying irrigation water at a low rate, and by leaving an interval of 10 minutes or more between the addition of bacteria and the start of the irrigation. The translocation can be increased by applying water at a high rate immediately after inoculation of the bacteria.

Jenssen, PD, Siegrist, RL. 1990. Technology Assessment of Wastewater Treatment by Soil Infiltration Systems, Water Science Technology 22(3/4):83-92.

This is a review paper, and reports the following conclusions, especially as applied to large systems:
1. Present design criteria for large subsurface wastewater treatment systems are approximate and not always well founded.
2. Poor siting is a main cause of early failure. For large subsurface systems, large-scale infiltration tests and tracer studies should be considered in siting procedures.
3. The hydraulic loading rate should be based on soil type and wastewater quality. Better pretreatment yields larger allowable loading rates.
4. In general, trench designs are preferred over beds.
5. A stepwise extension of the system is recommended, as the need arises. This approach will optimize the size and increase the overall cost-effectiveness.
6. Purification performance of subsurface wastewater infiltration systems is generally good. Estimates of purification on the basis of grain size, loading rate and soil depth can be given.

Keys, JR. 1996. Septic Tank Effluent Infiltration and Loading Rates for Gravel and Chamber Absorption Systems. MS Thesis. University of Wisconsin-Madison, 109 pages.

Triple replicates of chamber and gravel soil absorption systems on both silt loam and sand soils were studied to compare the infiltration rates of each system on each soil. As ponding has not occurred after 8 years, no comparisons can be made for the silt loam soils. For systems in sand soil, a loading rate of 1 gpd/ft^2 was too high and both gravel and chamber systems failed within 5 years. At lower infiltration rates (0.66 gpd/ ft^2 for chambers, 0.4 gpd/ ft^2 for gravel), 2 of 3 chambers failed and none of the gravel systems failed.

Kristiansen, R. 1981. Sand Filter Trenches for Purification of Septic Tank Effluent: I. The Clogging Mechanism and Soil Physical Environment, J. Environmental Quality, 10(3): 353-357.

Three sand filters received septic tank effluent at different loading rates using gravity feed. Rate and degree of ponding were observed. Aerobic conditions beneath the clogged zone are measured. Also, crust resistances, C/N ratios, and percentage of soil pore volume occupied by bacterial cells are reported.

Louden, TL, Salthouse, GS, Mokma, DL. 1998. Wastewater Quality and Trench System Design Effects on Soil Acceptance Rates, in On-Site Wastewater Treatment: Proceedings of 8th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, March 1998, Pp. 186-194.

Various trench designs are compared for their ability to accept either septic tank effluent or highly treated sand filter effluent in a slowly permeable clay loam soil. Trench designs compared include conventional stone trenches and three gravelless trench types with trench bottoms placed at three different depths. There is significant variability between trenches within a trench type. Due to this variability it is not possible to conclude that any of the trenches receiving septic tank effluent are different [in acceptance rate] than the others. Soil acceptance rates through the bottoms of trenches are 7-12 times greater for those receiving sand filter effluent than for those receiving septic tank effluent.

Lowe, KS, Siegrist, RL. 2001. Evaluation of Soil Infiltration Rates For Septic Tank Effluent as Affected by Aggregate-Free versus Aggregate-Laden Infiltrative Surfaces, Unpublished (contact principle author at Environmental Science and Engineering, Colorado School of Mines, Golden, Colorado, 80401-1887), 7 pages.

This study is a statistical analysis of the infiltration rates of sand columns after clogging development with accelerated effluent loading. The work compares the infiltration rates of clogged aggregate-free columns and aggregate-laden columns. The results of the study showed that the difference in infiltration rates was due to the difference in the character of the infiltrative surface and that the rate for aggregate-free columns was 2.08 gpd/ft^2 and for aggregate-laden columns was 0.86 gpd/ft^2.

All columns were open to the atmosphere. The aggregate-laden columns were prepared by removing 1 cm of sand from the top, scarifying the surface, adding a layer of washed gravel, adding dry sand to fill the voids between the gravel pieces, and adding more gravel to a height of 10 cm above the soil surface.

Lowe, KS, Van Cuyk, S, Dodson, E, Siegrist, RL. 2001. Letter Report Summarizing the Field Evaluation of Virus Treatment Efficiency by Wastewater soil Absorption systems with Aggregate-Free and Aggregate-Laden Infiltrative Surfaces, Report for Infiltrator Systems, Inc, Old Saybrook, CN.

This report describes the results of a study in which the septic tank effluent of 4 systems (1 aggregate-laden and 3 aggregate-free) received additions of bromide tracer and two different bacteriophages. The objective of the study was to test these systems' ability to remove the viral contaminants. The authors conclude that 3-log reductions in the applied viral surrogate concentrations were achieved at 30 cm below the infiltrative surface. They also conclude that under the conditions of the study, the performance and viral treatment efficiency measurements made for the chamber systems were comparable to those determined for the gravel systems, even though the chambers were loaded at twice the rate as the gravel systems. The findings indicate that aggregate-free chamber systems and aggregate-laden gravel systems provided equivalent environmental protection.

Magdoff, FR, Bouma, J. 1975. The Development of soil Clogging in Sands Leached with Septic Tank Effluent, in Proceedings of National Home Sewage Disposal Symposium, American Society of Agricultural Engineers, St. Joseph, MI, 1974, Pp. 37-47.

The purpose of this paper is to describe crust [soil clogging] genesis in sand columns being dosed with septic tank effluent, using tensiometry and a physical flow model. It also compares some measurements on the columns, constructed to mimic sand-fill mounds, with the same measurements on 4 field installations. The approximate agreement in results from lab columns and <u>in situ</u> field installations indicates that the general conclusions of the column study as related to soil clogging apply to field conditions. The observations and conclusions of the study are:

- Moisture tensiometer readings in unclogged soil demonstrate rapid wetting and drying in the upper portions of the sand fill after an 8cm addition of liquid and decreasing tension fluctuations with depth. As clogging develops, the tensiometer fluctuations throughout the column decrease until a near steady state condition develops. Gas studies on O_2 and CO_2 indicate a similar trend..
- Microscopic analysis of freeze-dried sand, sampled 3 cm below the infiltrative surface at the end of the experiments, revealed the accumulation of isotropic organic compounds and opaque organic fragments in the soil pores that did not occur in the unclogged sand.
- In the early stages of clogging, the crustal resistance determined experimentally agreed with the calculated values from the physical flow model. However, in later stages of clogging, the experimental values were lower than those calculated with the model. The researchers

assume, and include in their calculations, that the clogged layer does not form under the gravel pieces, and this interface was visually estimated to be 60%.

May, R. 1996. Problems Associated with the Use of Gravel in Septic Tank – Leachfield Systems. J. Environmental Health 59(2): 6-11.

This paper is an essay describing the negative aspects in using gravel in subsurface soil absorption systems, which affect the long-term acceptance rate of natural soil. Negative effects are listed: soil pore blockage, layer of fines from gravel deposited on infiltrative surface decreases transmissivity, blocked contact area (masking), and combined effect of all the factors. States that gravel-free surfaces are more transmissive.

Nodarse & Associates. 1997. Final Report-Infiltrator Florida Side-By-Side Test Site, Killarney Elementary School, Winter Park, Florida. JW Casper, PE, Manager, Geotechnical Services, (Report is property of Infiltrator Systems, Inc. Old Saybrook, CN).

This report is of a study sponsored and paid for by Infiltrator Systems, Inc. to generate data from side-by-side of Infiltrator chambers and gravel-filled trenches. The report refers to a test protocol reportedly developed in concert by Infiltrator Systems, Inc. and Florida Department of Health and Rehabilitative Services. This protocol included a procedure for accelerated loading with characteristic wastewater on 2 soil types. This project was to determine the relative performance of Infiltrator chambers and aggregate filled trenches in terms of hydraulic capacity. The evaluation would challenge the systems hydraulically (4 times the design load for the specific soil) until overflow.

Several problems are noted after the start of the test, which required the experimenters to change methods and alter materials:

- Securing adequate flows of representative strength, especially during summer months.
- Methods of measuring equal flow to each type of system
- Results from which conclusions were drawn, not based on original experimental design.

Ricklefs, SA. 1992. Evaluating Innovative Systems: A Field Study Utilizing Leaching Chamber Design, Proceedings, Texas On-site Wastewater Treatment and Research Conference, Austin, TX. 1992, 7 pages.

In response to a request for approval for chambers installed with a 40% reduction in absorption area (as compared to gravel-based systems), the Amarillo Bi-City-County Health Department undertook a project to allow the installation of 42 chamber systems at randomly selected sites where the owners would allow access for observations and monitoring. 36 of the 42 systems were monitored. Monitoring frequency was monthly for six months and then quarterly thereafter. Systems were monitored for ponding level and overt failure (to the surface of the ground). The purposed of the study was to determine the effluent acceptance capabilities of chamber systems.

On completion of 1 year of monitoring, the Amarillo Health Department concluded that "…none of the systems appeared to be anywhere near reaching the failure status." The department plans to continue monitoring for a total of 5 years.

Ricklefs, SA. 1995. Letter Report to the Texas Natural Resources Conservation Commission, On-site Wastewater Team, Austin, Texas, 2 pages.

Siegrist, RL. 1987. Soil Clogging During Subsurface Wastewater Infiltration as Affected by Effluent Composition and Loading Rate, J. Environmental Quality, 16(2):181-187. April-June 1987.

This study used pilot-scale infiltration cells installed in structured silty clay loam. These cells were loaded over a 70-month period with domestic septic tank effluent, graywater septic tank effluent or tap water. The liquids were applied in an average of 5.2 doses per day to yield daily loading rates of 0.32, 0.63 and 1.27 gpd. The researcher made the following observations:
1. Soil clogging was negligible in all tap water treatments and in the graywater units receiving 0.32 and 0.63 gpd.
2. In Graywater units receiving 1.27 gpd and all domestic septic tank effluent units severe soil clogging led to continuous ponding of the soil infiltrative surface.
3. Soil clogging development is highly correlated with the cumulative mass density loadings of total biochemical oxygen demand and suspended solids.
4. Clogged infiltrative surface zones exhibited significant accumulations of organic materials at the infiltrative surface and within the first few millimeters of the soil matrix.
5. Higher quality wastewater effluents can be discharged to subsurface infiltration systems at hydraulic loading rates in excess of those utilized for domestic septic tank effluent without stimulating soil clogging development.

Siegrist, RL, Boyle, WC. 1987. Wastewater Induced Soil Clogging Development, J. Environmental Engineering, ASCE 113(3):550-566.

Soil clogging development in intermittently loaded subsurface wastewater infiltration systems is a long-term process.
1. Soil clogging development is highly correlated with the cumulative mass density loadings of total BOD and TSS.
2. Proper design of these systems should include consideration of wastewater effluent composition as well as hydraulic loading rate.
3. Soil clogging can be delayed or altogether mitigated by reducing the applied mass loading rates of BOD and TSS either through lower hydraulic loading rates or by reduced effluent concentrations.
4. Reduced concentration of BOD and TSS can facilitate the use of higher hydraulic loading rates without accelerating soil clogging.

Siegrist, RL, Van Cuyk, S. 2001. Wastewater Soil Absorption Systems: The Performance Effects of Process and Environmental Conditions, in On-Site Wastewater Treatment: Proceedings of 9th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, March 2001. Pp 41-51.

Wastewater soil absorption systems (WSAS's) have the potential to achieve high treatment efficiencies, yet the understanding and predictability of performance as well as the risk of inadequate function has not been fully quantified. This has been due to the complex and dynamic relationships between hydraulic and purification processes and the factors that control their behaviors. This paper provides an overview of WSAS process principles and performance, and then describes initial experimental research completed as part of a long-term program to elucidate the fundamental relationships between performance and WSAS process design and environmental conditions. Laboratory research has employed 3-D physical models of full-scale WSAS's to explore the effects of infiltrative surface character (e.g., soil clogging development; aggregate-laden vs. aggregate-free) and vadose zone soil depth (e.g., 60 vs. 90 cm). Factorial design experiments have included monitoring of flow and transport behavior and treatment efficiency for nearly one year, periodic multicomponent surrogate and tracer tests using chemical and microbial agents, and soil core sampling and biogeochemical analyses. Field investigations have been completed at 16 WSAS's located in Colorado including those of aggregate-free or aggregate-laden designs. At each site, wastewater characteristics were monitored and soil cores were collected to a depth of 60 to 75 cm with analyses made for chemical and microbial properties. At one site, a multicomponent surrogate and tracer test was completed to assess virus treatment. The observations made to date have demonstrated the advanced treatment potential of WSAS's due to dynamic and interactive hydraulic and purification processes as affected by system design and environmental conditions.

Siegrist, RL, Van Cuyk, S, Logan, A, Masson, S, Fischer, E. 1999, Hydraulic and Purification Behavior in Wastewater Soil Treatment Systems as Affected by Infiltrative Surface Character and Vadose Zone Soil Depth, in Proceedings of 8th Annual Conference, National On-site Wastewater Recycling Association, ., Laural, MD, Pp. 181-189.

Siegrist, RL, Van Cuyk, S, Masson, S, Fischer, E. 2000. Field Evaluation of Wastewater Soil Absorption Systems with Aggregate-Free and Aggregate-Laden Infiltrative Surfaces, Final Report for Infiltrator Systems, Inc, Old Saybrook CN.

This report discusses a field study of 10 aggregate-free and 6 aggregate laden systems ranging in age from 1 to 11 years. It reports on hydraulic performance, pollutant concentrations at 30 and 60 cm depths beneath the infiltrative surface, and concentrations of viral surrogates and bromide tracers added to the septic tank effluent. It also discusses the results of a laboratory experiment aimed at correlating fecal coliform sampling of percolating soil water and bulk soil sample.

The report concludes that the composition of the septic tank effluent at the homes in the study was typical of residential STE found in other studies. The estimated hydraulic loading rate for chamber systems was 0.32 gpd/ft^2 and for gravels systems was 0.18 gpd/ft^2 while about half of the systems of each type exhibited some degree of ponding. The pollutant concentrations declined with depth and by 60 cm depth, fecal coliforms were not detected. Statistical comparisons between the chamber and gravel systems showed that there was no difference in terms of fecal coliform levels. When viral surrogates were introduced, there was a strong correlation between fecal coliform and virus concentrations.

Under the conditions of the study, the authors conclude that the performance measurements made on the chamber systems were comparable to those made on the gravel systems, even though the chamber systems were estimated to be loaded at 78% higher rates.

The laboratory study on correlating fecal coliform concentrations in percolated soil water versus bulk soil samples showed that fecal coliforms in bulk soil are as high or higher than in percolating soil water. The authors state that further testing under a wider range of conditions is warranted.

Smith, MS, Thomas, GW, White, RE, Ritonga, D. 1985. Transport of Escherichia coli Through Intact and Disturbed Soil Columns, J. Environmental Quality 14(1): 87-91.

This study evaluated the transport of E. coli through several soils, both disturbed and undisturbed. The bacteria were cultured and added to the liquid at 10^7 cfu/ml densities. Liquid was applied to the soil columns at 5-40 mm/hr for 8 to 12 hours (1 gal/ft^2 to 11.7 gal/ft^2). Filtrate was collected and analyzed. Moderate to high rates of water suspended bacteria can move rapidly through the well-structured soil, suggesting transport is through the macropores. The degree of macropore movement of water influences the rate of movement of water, but determines the extent of E. coli transport. Very different conclusions are reached with disturbed soils. In repacked columns, there is a high capacity for adsorption of bacterial cells. Because of the extreme differences between intact and disturbed soil cores, the authors question the relevance to many field situations of bacterial and virus transport studies in sieved, packed soil columns.

Stevik, TK, Ausland, TA, Jenssen, PD, Siegrist, RL. 1999. Purification of E. coli Bacteria During Intermittent Filtration of Wastewater Effluent as Affected by Dosing Rate and Media Type, Water Research Journal 33(9): 2088-2098.

This study used columns packed with 3 different granular media and tested their hydraulic behavior, rate of removal of E. coli, and where the removal occurred. The removal of E. coli was decreased as a result of increasing the dosing rate for all 3 media. For all 3 media, the highest removal was observed in the upper part of the columns. Hydraulic measurements showed that each effluent dose rapidly penetrates through the upper part of the filters, until a steady state, unsaturated flow was established in the lower sections. Different flow patterns were observed for the two dosing rates. For 50 mm/day (applied in 8 doses with 3 hours between doses) the flow was penetrating faster and to a deeper level before going to an unsaturated flow. These studies show that most of the water movement occurs right after dose application. This indicates that dose size may be just as important for bacterial removal as the daily dosing rate.

Tyler, EJ, Converse, JC. 1994. Soil Acceptance of On-site Wastewater as Affected by Soil Morphology and Wastewater Quality, in On-Site Wastewater Treatment: Proceedings of 7th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1994, Pp. 185-194.

Maintaining the wastewater infiltrative surface in the soil is dependent on never exceeding the design hydraulic of BOD and SS loading rate. Design and maintenance procedures must assure that only the highly pretreated wastewaters reach the soil. Conclusions of the authors:
1. Reducing organic materials with wastewater pretreatment systems reduces soil pore plugging and has the potential for higher long-term infiltration or loading rates.
2. Loading rates of pretreated wastewater in sands can be increased more than in clayey soil.
3. Rates for highly pretreated wastewaters might be 2-16 times greater than rates recommended for septic tank effluent.
4. The higher the loading rate the more attention needs to be paid to construction practices and materials, and the addition of hydrolysable cations.
5. Higher loading rates reduce the wastewater retention time and thus the wastewater treatment in the soil.
6. In the event of a pretreatment system failure to deliver highly pretreated effluent to the soil, it is likely that a rapid hydraulic failure of the soil system will occur.
7. A table is presented with a set of possible loading rates to consider for highly pretreated wastewaters. The greatest reduction in infiltration area for using highly pretreated effluent is for the coarser sands and the least is for the more slowly permeable soils.

Tyler, EJ, Milner, M, Converse, JC. 1991. Wastewater Infiltration from Chamber and Gravel Systems in On-Site Wastewater Treatment: Proceedings of 6th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, December 1991. pp.214- 222.

This paper reports the results of measuring wastewater depths and infiltration rates for drainfield cells using chambers and cells using gravel. Cells of each type were placed in triplicate in sand and in a silt loam. Loading rates for the sand are 1.0 gpd/ft^2 and the silt loam 0.6 gpd/ft^2. After 3 years of operation and measurements, the silt loam cells remain unponded and the sand cells are ponded. The infiltration rates for the silt loam cells are too variable to distinguish a difference between cell types. The ponding depths in the sand cells fluctuate seasonally, and are greater for the gravel cells than for the chamber cells.

Tyler, EJ, Milner, M, Converse, JC. 1992. Soil Acceptance of Wastewater from Chamber and Gravel Infiltration Systems, in Proceedings of 7th Northwest On-site Wastewater Treatment Short Course and Equipment Exhibition, University of Washington, Seattle, WA., September 1992, Pp. 93-104.

> Ponding depths and infiltration rates of septic tank effluent for chamber and gravel systems (3 replications for each system in each soil type) were determined for more than 4 years. Systems were installed in sand and silt loam soils. Loading rates were 1.0 and 0.6 gpd/ft^2 respectively for the sand and silt loam soils. After 4 years there is no ponding in either the gravel or chamber systems, and infiltration rates are much higher than the long-term acceptance rate for the silt loam. Rates vary greatly among the several replicates for each system type. In the sand systems, after 1 year all chamber and gravel systems were ponded, with the level of ponding fluctuating seasonally. After 4 years, two chamber and two gravel systems have reached the failure limit. Authors conclude that 1.0 gpd/ft^2 is too high for sand, regardless of system type. They also found in impossible to form conclusions concerning long-term acceptance rates in the silt loam systems, because of the variability within the same system type.

Van Cuyk, S, Siegrist, R, Logan, A, Masson, S, Fischer, E, Figueroa, L. 2001. Hydraulic and Purification Behaviors and their Interactions During Wastewater Treatment in Soil Infiltration Systems, Water Research Journal 35(4): 953-964.

> This study reveals a dynamic, interactive behavior for hydraulic and purification processes that are similar for systems using gravel and gravelless infiltrative surfaces and 2 feet or 3 feet of unsaturated flow. Under the conditions studied, infiltration surface character (aggregate laden and aggregate free) did not exert a measurable effect on hydraulic and purification performance.

Van Cuyk, S, Siegrist, RL. 2001. Pathogen Fate in Wastewater Soil Absorption Systems as Affected by Effluent Quality and Soil Clogging Genesis, in On-Site Wastewater Treatment: Proceedings of 9th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, March 2001. pp 125-136.

> Over 25% of the US population and 37% of all new development is served by onsite and small scale wastewater systems, the majority of which rely on percolation of primary treated effluent through soil to achieve purification prior to recharge to the ground water. Attempts to exploit the benefits of decentralized system approaches have resulted in innovations in design approaches and technologies that are emerging at a growing rate. In some cases, modifications to historical practice are warranted and supported by a sound scientific and engineering foundation. In others, design practice has evolved ahead of the knowledge needed to support such change. One such situation concerns the trend where wastewater soil absorption systems (WSAS) are being designed utilizing a higher level of pretreatment than provided by the common septic tank (e.g., sand filter or constructed wetland) to enable elevated hydraulic loading rates and smaller soil treatment systems (either in infiltration area or depth of vadose zone soil). These practices may be sound based on hydraulics, but purification of contaminants of concern, especially pathogenic bacteria and virus has not been proven. This paper discusses the need for a more fundamental understanding of the fate and transport of pathogens in WSASs. The relationship between hydraulic loading rate and quality of applied effluent and their effect on pathogen purification performance is required to utilize soil-aquifer systems effectively while preventing drinking water contamination.

Van Cuyk, S, Siegrist, RL, Logan, AJ. 2001. Evaluation Of Virus And Microbial Purification In Wastewater Soil Absorption Systems Using Multicomponent Surrogate And Tracer Addition, in On-Site Wastewater Treatment: Proceedings of 9th National Symposium On Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI, March 2001. pp 30-40.

Wastewater soil absorption systems (WSAS) have the potential to achieve high treatment efficiencies, yet the understanding and predictability of performance with respect to removal of virus and other pathogens remains limited. As part of a long-term program of research to elucidate the fundamental relationships between performance and WSAS process design and environmental conditions, research has been completed to evaluate virus and microbial purification using multicomponent surrogate and tracer addition. The primary goal of this research was to quantify the removal of virus and bacteria through the use of microbial surrogates and conservative tracers during controlled experiments with 3-D lysimeters in the laboratory and testing of mature WSAS under field conditions. The surrogates and tracers employed to date have included two viruses (MS-2 and PRD-1 bacteriophages), one bacterium (ice-nucleating active (INA) Pseudomonas), and one conservative tracer (bromide ion). In addition, efforts have been made to determine the relationship between virus and fecal coliforms in soil samples below a WSAS, and the correlation between E. coli. concentrations measured in percolating soil solution as compared to those estimated from analyses of soil solids samples. The results of the research completed to date have revealed that episodic breakthrough of virus and bacteria does occur in WSAS, particularly during early operation, but that a 3-log removal of virus and near complete removal of fecal bacteria can reasonably be expected in WSAS with 60 to 90 cm of sandy medium. Additionally, results from the research indicate that fecal coliforms may be indicative of virus in soil media directly beneath WSAS receiving STE and the concentrations of fecal coliforms in percolating soil solution may be conservatively estimated from analysis of soil solids. Further laboratory and field research is continuing.