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Topic & Issues:

Hydraulic Loading Rates

- *What are important factors affecting hydraulic loading rates that need to be considered?* Should rates account for factors such as soil structure, bulk density, wastewater strength, oxygen present at the infiltrative surface, wastewater application, and climatic differences?
- *Should the sidewall area be included as an active infiltration surface in sizing the SSAS?* Credit for sidewall vs. bottom area.

Summary:

This report summaries the literature on the topic of hydraulic loading rates of on-site sewage systems. The purpose of the report is to perform a comprehensive review of the literature available on the topic of hydraulic loading rates with focus of several factors affecting these rates.

Hydraulic loading rates or wastewater infiltration define the rate wastewater enters the soil. Correlating design hydraulic loading only to soil texture overlooks several factors such as structure, clay mineralogy, bulk density, effluent quality, soil aeration, and methods of effluent application, which all can greatly affect the hydraulic chacteristics of the soils. When applying septic tank effluent, a clogging layer forms at the infiltrative surface. Clogging layers impede water infiltration and reduce the loading rate applied far below the maximum infiltration rate of unclogged soil. In most subsurface soil absorption systems (SSAS), clogging development must occur to some degree to promote adequate wastewater treatment before ground water recharge, but not to the point where it causes hydraulic problems leading to system failure.

SSAS are being designed to use a higher level of pretreatment than provided by a septic tank (e.g. sand filter) to permit high hydraulic loading rates and smaller on-site sewage systems (either in infiltration area or depth of suitable soil). This modification in practice has evolved based on research and experience that have shown loss in infiltration capacity over time is related to the mass loading of total BOD and suspended solids. These practices may be sound based on hydraulics, but lead to reduced retention time of the wastewater and therefore, reduced treatment of contaminants of concern in soil, particularly pathogens. The reduced retention time may be compensated for by improved wastewater quality achieved from pretreatment systems combined with uniform wastewater application to the soil to ensure that unsaturated flow conditions are maintained.

Even though the majority of states use the soil texture or percolation tests as the only parameter in deciding the hydraulic loading rate, the literature suggests that other soil morphological factors such as structure, bulk density, clay mineralogy be included. Wastewater quality, and treatment requirements should be considered with soil morphology in predicting the hydraulic loading rate and incorporated into a rational design practice for SSAS. Including sidewall area as an active infiltrative surface in SSAS sizing should be avoided. Table 1 presents recommended allowable hydraulic loading rates for septic tank effluent and low organic strength wastewater based on field described soil.

KEYWORDS: *(hydraulic loading rates, infiltration rate, infiltrative surface, hydraulic conductivity, soil clogging)*

Introduction

The hydraulic loading rate is a critical on-site sewage system design parameter, and must integrate system hydraulic and treatment performance as well as service life expectancy to address public health and water quality concerns. Hydraulic loading rates that are required in this state come from those recommended in the 1980 EPA Design Manual and are based on infiltration rates though clogged soil surfaces for domestic septic tank effluent. Current practice has been to simply apply these rates, 0.20 to 1.2 gpd/ft^2, to the infiltrative surface bottom area with the site-specific rate based upon the soil textural properties. This casual design approach, however, overlooks several important factors that affect the hydraulic characteristics of the soils, and may lead to hydraulic failure and improperly treated sewage in many systems.

The purpose of this review is to synthesize the literature available on the topic of hydraulic loading rates of effluent so that the Technical Review Committee can make appropriate recommendations about loading rates, and the factors that need to be considered to accurately predict loading rate requirements to the Rule Development Committee. More than 70 publications, which include peer, reviewed journal articles, conference proceedings and government reports were collected and reviewed. Even through the majority of the publications are conference proceedings, which are typically not peer reviewed, they provide useful information regarding the subject of hydraulic loading rates.

Hydraulic Loading Rate

One of the principal parameters used in wastewater system design is the hydraulic loading rate. Most present criteria for estimation of the loading rate are empirical and either based on a percolation test or textural analysis of the soil (USEPA 1980). Common practice in our state has been to use septic tank effluent and to load the soil infiltrative surface at 0.2 – 1.2 gpd/ft^2 based upon natural soil properties (USEPA 1980). These rates have been developed based on extensive experience with conventional and alternative on-site sewage systems and their long-term performance, and are provided as general guidance by EPA.

A review of current state practices indicates hydraulic loading rates are typically based on soil texture and a crude measure of hydraulic capacity by percolation rate (NSFC, 1996). The percolation test has met with varying success and has been supplemented with soil morphologic descriptions as the basis for establishing loading rates in some states. Some states use soil texture to establish loading rates, while others use soil texture in combination with other soil physical characteristics. Still others use some combination of soil morphology description with an interpretation of soil classification or parent material.

Soil Morphology

Wastewater loading rates are increasingly being based on soil morphology description. Soil morphologic features, particularly structures and texture, have been shown to be better predictors of the soil's hydraulic capacity than percolation tests (Brown et al., 1994; Gross et al., 1998; Simon and Reneau, 1987; Tyler et al. 1991;Tyler and Converse, 1994). Based on the imprecision and error of the percolation test and a lack of any correlation between the test results and a long term soil loading rate (Bouma, 1971; Healy and Laak, 1973), soil morphology evaluation was promoted as a better method to estimate long term infiltrative capacity as well as identify depths to limiting conditions on the soil profile (e.g. high seasonal ground water, and restrictive layers) (Tyler and Converse, 1994).

Important factors in predicting hydraulic conductivity characteristics are the pore geometry or the size, shape, and continuity of the soil pores. These factors are primarily dependent on soil morphological characterics such as texture, structure, bulk density, and clay mineralogy of the soil. Work of Hantzsche et al. (1982), Simon and Reneau, (1987), Tyler et al. (1991), and Brown et al., (1994) demonstrated the use and importance of soil morphological description for estimating hydraulic loading rates. Tyler et al. 1991 developed a method for estimating loading rates for domestic septic tank effluent based on soil morphological descriptions for training of soil and site evaluators.

Texture

The soil texture has a great influence on the size of the pores around the individual particles and is the primary factor in water movement. Soil texture refers to the relative proportions of the various sizes of the soil particles. Specifically, it refers to proportions of sand, silt, and clay smaller than 2 millimeters in diameter that make up the soil.

Aeration and drainage of soil are closely related to texture because of the influence particle size has on pore size and pore continuity. For example, clay soils are quite porous (typically 50-60 %) but they may have low permeability because the orientation of these sub-microscopic particles to one another results in very small pores. Sands, on the other hand, are less porous, (40-45 %) but the large sand grains results in larger pores, which are more conducive to fluid movement.

Because soil clogging affects different soils in dissimilar ways, Bouma (1975) recommended specified loading rates for distinctive soil textural groups, which were placed into the 1980 EPA Design Manual. These recommended rates were based on the interrelationship of each soil's unsaturated hydraulic conductivity, as influenced by texture, structure, and porosity, and the conductivity of the clogged layer.

Soil Structure

Soil structure refers to the relative arrangement of soil particles. The structure creates a secondary set of pores and can greatly affect the pore sizes predicted based on soil texture alone (Tyler, et al. 1991). Single grain and massive soil do not have the secondary pores. The stronger the structure, the better the aggregates or peds are defined and the more pronounced the set of secondary pores in the soil. If the pores created are in the direction of the desired wastewater movement then the soil structure enhances the wastewater movement. However, if the pores created are perpendicular to the desired wastewater flow, then the structure will be restrictive to flow. Granular, blocky and prismatic structure generally enhances vertical flow. Platy structure results in reduced vertical flow.

Even though the majority of the states use soil texture as the sole parameter in deciding the hydraulic loading rate, it is suggested that the other soil morphological factors such as structure should be included as well (Tyler et al., 1991). Soil structure and clay mineralogy have been found to have a significant impact on rate of water movement through soils (Bouma et al., 1983; Schoeneberger et al., 1995; Vepraskas et al., 1996; Vervoot et al., 1999).

Soil structure is a primary determinant in the hydraulic properties of fine textured soil, since most of the saturated flow occurs through interpedal voids and cracks of well-structured soil. Tracer experimental studies have confirmed that under initial conditions of both saturation and unsaturation that water applied in fine-textured, well-structured soil moves quickly through the interpedal voids, resulting in high dispersion values (Anderson and Bouma, 1977a,b). In a study to determine appropriate hydraulic loading rates for fine-textured soil Simon and Reneau (1987) placed emphasis on including soil structure, as a key evaluation tool. This study concluded that well drained fine-textured soils provide adequate treatment of effluent, and SSAS longevity should occur, provided that loading rates are determined relative to the structure of the soil below and around the SSAS.

Bulk Density

Soil bulk density is the ratio of the mass of the soil to its bulk or volume. In most soils, the porosity decreases as the bulk density of the soil increases. Therefore, bulk density is a direct indictor of soil compactness. Of soils with the same texture, those soils with higher bulk densities have more solids and thus less pore volume, and are consequently likely to be less permeable.

Soil consistence has to do with the strength of the soil mass, which is the degree of resistance to breaking or crushing when force is applied. The strength of soil depends in part on the contact of soil particles. Strong soil, defined in the moist condition as "firm" have reduced pores, have close contact of soil particles and therefore have high bulk density and reduced porosity (Tyler et al., 1991). Soil of high strength, generally have low infiltration rates and low hydraulic conductivity. Tyler (2001) reported when the soil consistence is stronger than "firm" the soil horizon is limiting regardless of other soil chacteristics.

Clay Mineralogy

The mineralogy of the clay particles in soils can have a very significant influence on soil permeability. Some clay minerals, such as those found in the Montmorillonite/Smectite Group, have the ability to swell upon wetting and shrink on drying. Even if present in small amount, the porosity of soils containing these swelling clay minerals can vary dramatically with varying moisture content. When dry, the clay particles shrink, opening the cracks between peds. But when wet, the clay swells, closing the soil pores.

Since on-site sewage systems are always wet, the clays remain swelled and would be expected to have low hydraulic conductivity and infiltration rates. Therefore, methods used to predict the proper loading rates must account for soils of high swelling clay mineral content. Fortunately, most soils in Washington State have mixture of clay mineral types, mostly moderately or non-swelling.

Soil Clogging

Wastewater infiltration rate into soil is dependant on the character of both the clogging layer and soil. Clogging by the accumulation of suspended solids and organic matter at the infiltrative surface of a SSAS is a phenomenon known to occur as a result of continued wastewater application (Jones and Taylor, 1965; Siegrist, 1987; Tyler and Converse, 1994; and others). This clogging zone creates an increased resistance to flow, reducing the hydraulic conductivity and rate of infiltration (Jones and Taylor, 1965; Laak, 1970; Otis, 1985; Tyler and Converse, 1994). Kristiansen (1981), Siegrist (1987) and others have shown that the development of a clog accelerates with increasing the loading rate or concentration of organic material in the septic tank effluent. All show a slow decline in infiltration rates, which approach a very low rate. This clogging phenomenon means that a SSAS cannot be designed based on the saturated hydraulic conductivity of a given soil.

A certain degree of clogging may improve the treatment of wastewater by causing more widely distributed unsaturated flow beneath the infiltrative surface, which can enhance treatment processes by increasing hydraulic retention times (Kristiansen, 1982; McCray et. al, 2000). For example, clogging leads to reduced permeability and more uniform infiltration and a concomitant unsaturated flow almost regardless of hydraulic loading. However, if soil clogging yields too great a reduction in permeability at the infiltrative surface it can be detrimental by causing hydraulic failure or adversely affecting treatment (e.g. infiltration rate less than hydraulic loading rate which causes backups or surfacing sewage) (Siegrist, 1987a,b; Siegrist and Boyle, 1987).

The rate at which wastewater infiltrates into the soil from the SSAS is limited by soil clogging and controlled by the nature of both the clogging layer and the soil (Bouma, 1975). Studies on soil clogging have shown that the flow through a clogging layer in a given soil depends on the hydraulic head above the infiltrative surface (ponding depth), saturated hydraulic conductivity of the clogged zone and the hydraulic chacteristics of the subsoil (Magdoff and Bouma, 1974; Bouma, 1975; Hargett, et al., 1982; and Huntzinger, et al., 2001).

The hydraulic loading rate and quality of wastewater can affect the rate and extent of soil clogging, which in turn affect the long-term acceptance rate (LTAR) of the SSAS (Siegrist et al., 1987b; Jenssen and Siegrist, 1990; Duncan et al., 1994; Tyler and Converse, 1994). Some investigators have reported that an equilibrium or steady-state LTAR actually evolves (Bouma, 1975; Healy and Laak, 1974, Kropf at al., 1977; Anderson et. al., 1982) while others have reported that a continuous, although slow, decrease in infiltration rate capacity occurs (Thomas et al., 1966; Okubu and Matsumoto, 1979; Jenssen and Siegrist, 1990). If an equilibrium rate exists, a system can be expected to operate indefinitely if loaded at this rate. There is evidence, however, that a steady but very slow decrease of the infiltration rate occurs. This is associated with the development and accumulation of slowly degradable material in the clogging zone (Siegrist 1987a, Siegrist et al. 2001). Therefore, a definite service life can be expected from a continuously loaded SSAS.

Many studies have investigated soil clogging to better understand the process and to find ways to prevent excessive soil clogging. There is no general agreement on which causative agents play the most active role in clogging, but most investigators agree that BOD, suspended solids and bacteria are primarily responsible. Research shows application of wastewater to soil may reduce the size of soil pores due to: (1) accumulation of suspended solids and biological growth (Rice, 1974; Daniel and Bouma 1974; Bouma, 1975), (2) deposition of organic matter on the surface of the soil pores (Jones and Taylor, 1965; De Vries, 1972; Siegrist, 1987a,b), and (3) increase in sodium concentration in the soil and associate clay particle dispersion (Amoozegar and Niewoehner, 1998).

Products of bacterial growth in carefully installed wastewater disposal system are probably the primary cause of soil clogging. Siegrist (1987b) proposed that the accumulation of organic matter by filtration and sorption followed by the formation of humic substances was the primary mechanisms responsible for the soil clogging observed in his test cells. He than noted that restricted aeration within a SSAS was one of the factors, which stimulated the process. Later, cells of microorganisms have been shown to physically fill the pores in the soil, reducing the porosity and hydraulic conductivity (Vandevivere and Baveye, 1992). Organic materials, measured as biological oxygen demand (BOD) and suspend solids (SS) in wastewater, are substrate for microorganisms. The more organic substrate provided by wastewater, the more cells and associated fibers and slimes are produced.

Factors Affecting Soil Clogging Development

The rate and extent of clogging development is dependent on several factors such as soil morphology (Jones and Taylor, 1965; Healy and Laak, 1974; Bouma, 1975), wastewater composition (or strength) and loading rate (Laak, 1976; Siegrist, 1987; Duncan et al., 1994; Tyler and Converse, 1994), application method and continuity of use (Kristiansen, 1982; Hargett et al., 1982; Otis, 1985; Siegrist, 1987). Assuming the soil is free draining, primary soil factors related to clogging include soil temperature, aeration status, and moisture content. The method of effluent application to the infiltrative surface plays an important role in influencing the soil moisture content and aeration.

Climatic Differences

Climate considerations are diverse and include air temperature, relative humidity, wind speed, and precipitation. These characteristics can influence the unsaturated soil properties with respect to temperature and water content. Air temperature and relative humidity characteristics can influence the rate of evapotranspiration. This can be an important route for water movement in our warm, dry eastern Washington climate. Precipitation in the form of snow can provide an insulating layer on the ground surface that can help maintain soil temperatures above freezing and enable shallow effluent infiltration all year round. Our high precipitation in western Washington is important as it affects the moisture regime of the soil. It is less likely that precipitation will severely affect system function on sloping sites due to runoff as opposed to infiltration. However, on some sites, precipitation events have been linked to release of virus from drainfield trenches (Rose, et al. 1999).

Season, as well as climatic difference in soil temperature will affect the development of clogging (De Vries, 1972; Simons and Magdoff, 1979, Tyler et al, 1993). The influence of temperature appears to be contradictory. Kristiansen (1981) observed a higher degree of clogging at a high temperature, while the opposite effect was observe by Simons and Magdoff (1979) and de Vries (1972).

Tyler et al. (1993) believe cold season ponding depths in wastewater infiltration cells to be related to slower microbial activity, the accumulation of a soil clog, and subsequent increasing resistance to wastewater. The soil clogging effects of soil temperature appeared to interact with effluent composition.

Where the applied effluent possessed no suspended matter, low temperature inhibited soil clogging (Siegrist, 1987). However, if the applied effluent possessed significant amount of suspended solids content such as found in domestic septic tank effluent, low temperature tended to stimulated soil clogging (De Vries, 1972; Simons and Magdoff, 1979).

Soil Aeration (Oxygen)

Oxygen in the subsoil below the infiltrative surface has been shown by numerous studies to be a critical factor impacting system performance (Otis, 1985). Without oxygen, oxidation of organic materials is incomplete, leading to soil clogging and hydraulic failure. Air must be able to diffuse freely through the soil for reaeration to occur. Air diffusion into the soil pores is promoted in soils with high permeability, good structure with low bulk densities, and low moisture status.

Healy and Laak (1974) summarized the work done by many investigators concerning the acceptance rate of septic tank effluent by soil. The major conclusions from their revaluation of earlier findings are, (1) there is not a significant difference between LTAR between a soil that is continually flooded (tend to be anaerobic) and in the same soil that is flooded intermittently (aerobic), (2) there is a stable LTAR in all of the studies which indicated a balance between bacterial growth and decomposition of clogging matter, and (3) effluent containing smaller amounts of material allows a higher LTAR.

However, some of the later research showed that having intermittent flooding and thus, aerobic conditions, is preferable to continuous flooding. Aerobic conditions maintain a stable LTAR simply because aerobic activity can decompose the clogging matter much more efficiently than the anaerobic process (Bouma, 1975; Kristiansen, 1981, Hargett, et al., 1982; Simmon and Reneau, 1987).

When wastewater is applied to a soil infiltrative surface, an oxygen demand is created by the microorganisms that breakdown the biodegradable materials in the wastewater. This oxygen demand must be satisfied by oxygen in the soil or the aerobic microorganisms cannot thrive. Anaerobic conditions are created when the applied oxygen demand exceeds what diffusion through the soil is able to supply (Otis, 1985, 1997; Mahuta and Boyle, 1991; Erickson, et al., 2001). The facultative and anaerobic microorganisms that are able to thrive in this environment are less efficient in degrading the waste. The accumulating waste materials and the metabolic by-products cause soil clogging and loss of infiltrative capacity. Further, high forms of soil fauna such as worms, insects, and non-wetland plants that are attracted to the carbon and nutrient rich infiltrative surface and help to prevent soil clogging are repelled by the anaerobic conditions. With continued applications of wastewater without ample time to reaerate the soil to satisfy the oxygen demand already applied, hydraulic failure due to soil clogging occurs (Otis, 1991).

An efficient SSAS has a balance between the amount of oxygen entering the system with the amount of oxygen needed to decompose the organic matter and meet the demand. Hydraulic and organic loadings to the infiltrative surface also impact reaeration potential. Higher hydraulic loadings increase the time for soil drainage thereby reducing the time for reaeration. High organic loadings increase the oxygen demand and, therefore, the oxygen requirements.

The SSAS design can be manipulated to help provide the proper balance. Ponding duration as influenced by dose volume and uniformity of distribution plays an important role in contributing to the development of soil clogging. Once permanent ponding occurs, aeration is inhibited and the high oxygen demand of the accumulated materials creates anaerobic conditions in the subsoil (Otis, 1985). If ponding can be avoided through proper dosing, the decomposition process can be aided by oxygen from above in the SSAS atmosphere as well as below in the soil atmosphere under the SSAS.

As part of a study of gas transport in the vadose zone below a SSAS, Mahuta and Boyle (1991) developed a model to predict oxygen concentration below infiltrative surfaces for various physical dimensions. The model was calibrated in bench-scale experiments and showed a direct relationship between oxygen concentration below SSAS and system width, unsaturated zone thickness, and wastewater strength. Using models to estimate the movement of oxygen from the ground surface to the infiltrative surface,
Erickson and Tyler, (2001) concluded that to increase the oxygen flux to the infiltrative surface, the system design must be long, narrow, and located close to the oxygen source. These models agree with the findings of Otis (1985) and Loudon (1998).

Methods of Wastewater Application

The method of delivery and frequency that wastewater is applied to soil infiltrative surfaces is an important design element. Good wastewater application aids in maintaining unsaturated flow below the infiltrative surface, which results in wastewater retention times in the soil that are sufficiently long to effect treatment and promote subsoil reaeration. Good distribution design also results in more complete use of the infiltrative surface.

In the early stages of SSAS operation, hydraulic loadings may often result in rapid, nearly saturated flow during dosing. Studies have shown that a large percentage of bacteria remain near the infiltrative surface when effluents are applied to porous media (Kristiansen, 1991; Emerick et al., 1997). If hydraulic loading rates are too high or the dosing frequency is too low, some pathogens can be transported to lower regions in the soil, posing a treatment concern in systems that are too shallow to ground water.

Typically, systems with gravity distribution do not provided uniform distribution of effluent throughout the drainfield. Increased application rates may be observed during start up of gravity distribution where daily loadings may be focused on a small portion of the infiltrative surface prior to the development of a clogging layer at this surface. This results in localized infiltration rates much higher than design hydraulic loading rates. Due to high permeability of coarse-grained soils, this type of distribution can result in saturated flow through the soil below areas of the field that do receive effluent. Coarser soils loaded at high rates may result in retention times too short for treatment processes to take place. Ver Hey and Woessner (1987) reported that in a conventional gravity drainfield installed in coarse-grained soils only a small portion of the field received effluent, and effluent reaching the drainfield appeared to infiltrate rapidly, which resulted in poor bacterial removal.

The apparent advantage of dosing appears to be in prolonging the life of the infiltration system rather than increasing its hydraulic capacity. Research has shown non-dosed systems exhibit more rapid soil clogging than dosed systems (Hargett et al., 1982). Intermittent daily dosing can reduce the rate of formation and the severity of the clogging. In sands (Kristiansen, 1981) and in silt loams (Hargett et al., 1982), less frequent daily applications of larger doses retarded soil clogging development.

Hargett et al, (1982) reported results of a 21 month study that examined rate and frequency of application under a controlled, replicated loading regime, yet in natural undisturbed soil conditions. They concluded from the study that loading rates higher than those appropriate for soil conditions cause the most rapid and continuous long-term decline in infiltrative capacity. Generally, the higher the loading rate the more rapid and severe the loss in permeability. Gravity flow application even at conservative rates is likely to result in some degree of system ponding. Dosing results in higher infiltration rates as long as the application rate is not so high as to induce persistent ponding, thereby negating the advantages of dosing.

The lower resistance of the clogged zone under a dosing regime is attributed to the aeration the infiltrative surface receives when it is exposed to air between doses. This was demonstrated in studies by Roats (1975) and Simons and Magdoff (1979). Uniform application over the infiltrative surface with periods between applications for reaeration to occur maximizes the potential for soil reaeration. After each dose, air enters behind it, maintaining aerobic conditions within the infiltrative surface.

Uniform distribution of the wastewater in the SSAS during dosing is important to achieve adequate treatment. Pressure distribution will provide a more uniform application of the effluent, providing better treatment by the soil, especially in highly permeable soils (Converse et al. 1974). Simons and Reneau (1987) concluded later that it is imperative that uniform distribution of effluent in fine textured soils be a design factor or else localized overloading may eventually result in system failure.

Early research led to guidance that dosing frequencies should be 1 to 4 times per day based on the soil characteristics and pressurized dosing networks should be designed to achieve relatively equal headloss and flow rates among the orifices (Otis et al., 1978). More frequent application of small doses of septic tank effluent uniformly applied to soil with macropores was later found to improve treatment with respect to chemical and microbiological constituents (Siegrist and Boyle, 1987; Emerick et al, 1997; Loudon and Mokma, 1999). This is due to facilitating an unsaturated thin film flow over particle surfaces and enabling more intimate contact between wastewater and soil surface. Thin film flow allows longer retention time between a given amount of applied wastewater and attached microbes than would occur under flow resulting from a large dose volume. This type of flow can be achieved by intermittent dosing (e.g., 4-24 times/d), by daily hydraulic loadings limited to a small fraction of the soil's saturated hydraulic conductivity (K_{sat}) (e.g.; <5 cm/d), and by pressurized uniform application (Siegrist and Van Cuyk, 2001).

Uniform dosing in space and time can be achieved through surge storage and timed dosing. A recent innovation includes the concept of time dosing through pressurized distribution networks where the septic and pump tanks provides surge capacity to permit frequent dosing. This is thought to enable more uniform application over time and provide more unsaturated flow through the unsaturated zone beneath the infiltrative surface, thereby aiding treatment.

Wastewater Strength and Hydraulic Loading

The applied wastewater quality and hydraulic loading rate are two parameters that can be controlled through wastewater pretreatment or SSAS sizing. Research has shown that the clogging, which forms in a SSAS, is accelerated under increasing concentration of organic matter and suspended solids in the effluent. Improving the quality of the wastewater (reduced wastewater strength) applied to the infiltrative surface is often suggested as a means to control clogging. In the absence of soil clogging, wastewater loading rates to soil have the potential to be higher.

While soil factors such as temperature and soil aeration play a role in soil clogging development, research has shown that the major factor influencing soil clogging is the per unit area loading of organic matter to the infiltrative surface resulting from the combination of wastewater quality and hydraulic loading rate (mass loading). Soil clogging can be retarded by reducing the applied mass loading of total BOD and TSS either through lower hydraulic loading rates or reduced effluent concentrations (e.g. high mass loading rates could occur from additions of a low volume of wastewater with high amounts of organic matter or a high volume of wastewater with lower of organic matter).

There is growing evidence from research and practical experience supporting on-site sewage systems design practice that accounts for wastewater effluent quality as well as hydraulic loading. Numerous studies have shown that applied wastewaters with low BOD concentrations can be applied to soils at rates 2 to 16 times the typical hydraulic loading rate for recommended septic tank effluent (Jones and Taylor, 1965; Laak, 1970, 1976; Loudon et al. 1991, 1998; Otis, 1984; Siegrist and Boyle, 1987; Tyler and Converse, 1994; Tyler et al. 1995).

Daniel and Bouma (1974) showed that aerated pretreatment produced a lower load of BOD compared with septic tank pretreatment, but more rapid and heavy clogging took place due to a smaller size of suspended solids. This was explained by the different sizes and shapes of suspended solids in the two types of effluent. It was suggested that finer particles in the aerobically treated effluent penetrate the more porous upper soil horizons and blocked the pores deeper in the profile.

Later, Siegrist (1987a) showed wastewater effluent from pretreatment systems that result in reduced BOD and TSS or pure water, as used as a control in research, do not have reduced infiltration rates. Silty clay loam soils intermittently dosed with tap water at a rate of 1.3 to 5.2 cm/d (0.3-1.2 gpd/ft^2) showed no soil clogging for a period of 70 months. Maintenance of high infiltration rates for extended periods of time suggests the lack of clogging and high loading rates. Other work has shown that clogging in soils dosed with septic tank effluent was correlated with the cumulative loading of organic matter, as measured by BOD_5 and TSS (Jones and Taylor 1985; Laak 1970).

With the previous work demonstrating a relationship between effluent total mass load of BOD and TSS and the rate and extent of soil clogging, design approaches have emerged that use high pretreatment (e.g. ATU or sand filter technology) to retard or eliminate wastewater-induced soil clogging. This is increasingly being done to permit much higher hydraulic loading rates to be used (0.4 to 2.0 gpd/ft^2 rather than 0.20 to 1.2 gpd/ft^2) and to reduce the required infiltration area or vertical separation by 50% or more.

These practices have raised concerns for bacteria and virus transport, especially with systems in coarse soil systems where removal of pathogens might be lower based on soil characteristics and decreased adsorption and higher wastewater doses being applied to the system (Siegrist, 2001). While wastewater pretreatment systems can reduce constituents such as BOD_5 and suspend solids loadings in addition to retarding wastewater induced clogging development, the concentration of pathogens may not be markedly reduced in the pretreatment system and the absence of a clogging zone might impact the treatment capability of the SSAS, particularly if higher application rates are used.

Increasing loading rates when using wastewaters that are not likely to cause clogging will decrease wastewater retention times in the soil and could reduce treatment efficiencies (Converse and Tyler, 1998, Siegrist et al., 2001; Tyler and Converse, 1994). Therefore, longer travel distance or separation distances may be needed to reach acceptable treatment. Converse and Tyler, 1998 studied fecal coliform concentrations in soil profile beneath 3 cells loaded at 1,3 and 6 gpd/ft^2 to a well drained, moderate structured silt loam receiving aerobically treated effluent. The fecal coliform concentrations were found to be higher for the 3 and 6 gpd/ft^2 than for the 1gpd/ft^2 loading rate, showing that the soil may not be capable of adequately treating the effluent to acceptable levels at the higher loading rates. The study cautioned about downsizing the soil absorption unit to the point where the loading rate exceeds the soil's ability to adequately treat the effluent.

However, reduced retention time may be compensated for by improved wastewater quality achieved by higher levels of pretreatment. Because of the pretreatment, not only are clogging forming constituents reduced, but many of the environmental and health pollutants are reduced. Therefore, the soil is required to do less treatment than if septic tank effluent were applied to the soil. Treatment needs should be assessed for each type of wastewater and a balance attained between the treatment capabilities of the soil and the goals of treatment (Tyler, et al., 1995). However, there is little current research that has clearly demonstrated effective pathogen removal in hydraulic loaded SSAS with retarded clogging development.

Additionally, well-tested organic loading rates for various classes of soils and system design configurations have not been fully developed. Most organic loading rates have been derived directly from the hydraulic loadings typically used in design by assuming a BOD_5 concentration. The derived organic loading rates also incorporate the implicit factor of safety found in the hydraulic loading rates. In a review, Tyler and Converse (1989) discussed the influence wastewater quality has in LTARs. They concluded that very highly pretreated effluents could be applied at higher loading rates than septic tank effluent and possibly at rates equal to the soil saturated hydraulic conductivity. However, they also concluded it was not possible to predict effluent loading rates for intermediate strengths of pretreated wastewaters.

Organic loadings appear to have less of an impact on slowly permeable soils because the resistance of the biomat that forms at the infiltrative surface presents less resistance to infiltration of the wastewater than the soil itself. (Bouma, 1975). The unclogged infiltration rate or saturated hydraulic conductivity of soil with large pores (sandy soil) is much higher than the unclogged infiltration rate or saturated hydraulic conductivity of soil with fine pores (clayey soil). The increase in infiltration loading rate for reduced strength wastewater and low BOD wastewater is not uniform or linear, and is much greater for soil with larger pores than for those with fine pores. Therefore, a single factor between loading rates for clogged and unclogged soils cannot be used (Tyler, 2001). For example, sandy soil loading rates are much greater without clogging than with clogging while in clayey soils the loading rate difference is small between clogged and unclogged soil. As with loading rates for clogged soil, loading rates for soil receiving wastewater of low organic strength are related to the pores and therefore the described soil morphology (Tyler and Converse, 1994).

Siegrist (1987b) analyzed research information available in the literature and made recommendations on relative design loading rates for different types of effluent. His results suggest that if domestic septic tank effluent can be loaded at a rate of 1.0 cm/d (0.24 gpd/ft^2) to a given soil, then more concentrated effluent such as restaurant septic tank effluent should be loaded at a lower rate, specifically 0.4 cm/d (0.01 gpd/ft^2). He further suggested that sand filter effluent could be loaded at 7.5 cm/d (1.8 gpd/ft^2) and provide contaminant mass loadings that are equal to or lower than those associated with domestic septic tank effluent. The allowable loading rates for sand filter effluent are based primarily on hydraulic considerations associated with soil clogging. He cautioned that factors for establishing loading rates for sand filter effluent should not be used if the determined loading rates would approach the saturated hydraulic conductivity of the soil.
A method for predicting loading rates for wastewater of reduced organic strength based on soil

morphological description has been reported (Tyler and Converse, 1994). These values consider the logic and suggestions of Siegrist (1987b) based on pollutant loadings and based on Tyler et al. (1991), soil characteristics procedures. Using only the factor of 7.5 proposed by Siegrist (1987b), loading rates for sand filter effluent with BOD and TSS of less than 10 mg/l were presented. The maximum allowable hydraulic loadings were well below the soil K_{sat} (3 to 5% of K_{sat}) in order to maintain low soil moisture contents and adequate soil aeration (Siegrist, 1987b). The greatest reduction in infiltration area for using highly pretreated effluent is for the coarser soils and the least reduction in area for the more slowly permeable soil. However, the proposed loading rates were not tested and the authors suggested they should be confirmed before use.

Later, Tyler (2001) prepared a table (see Table 1) for estimating hydraulic loading rates into the soil from septic tank effluent (>30 mg/L BOD) or low organic strength wastewater (<30 mg/l BOD) based on field described soil characteristics of texture, structure, consistence, and mineralogy. The logic and trends in values presented in the table fit with scientific basis and with experience and were prepared for field practitioners. Values assume wastewater volume of >150gpd/bedroom. If the horizon consistence is stronger than firm or any cemented class or the clay mineralogy is smectitic, the horizon is restrictive regardless of other soil characteristics. The authors indicated further research and testing were needed to verify the values.

Table 1. **Suggested Hydraulic Loading Rates for Sizing Infiltration Surfaces (After Tyler, 2001)**

TEXTURE	STRUCTURE		HYDRAULIC LOADNG (gpd/ft^2)	
	SHAPE	GRADE	BOD>30 mg/L	BOD<30 mg/L
Coarse sand, Sand, Loamy coarse sand, Loamy sand	Single grain	Structureless	0.8	1.6
Fine sand, Very fine sand, Loamy fine sand, Loamy very fine sand	Single grain	Structureless	0.4	1.0
Coarse sandy loam, Sandy loam	Massive	Structureless	0.2	0.6
	Platy	Weak	0.2	0.5
		Moderate, Strong		
	Prismatic, Blocky, Granular	Weak	0.4	0.7
		Moderate, Strong	0.6	1.0
Fine sandy loam, Very fine sandy loam	Massive	Structureless	0.2	0.5
	Platy	Weak, Mod., Strong		
	Prismatic, Blocky, Granular	Weak	0.2	0.6
		Moderate Strong	0.4	0.8
Loam	Massive	Structureless	0.2	0.5
	Platy	Weak, Mod., Strong		
	Prismatic, Blocky, Granular	Weak	0.4	0.6
		Moderate	0.6	0.8
Silt Loam	Massive	Structureless		0.2
	Platy	Weak, Mod., Strong		
	Prismatic, Blocky, Granular	Weak	0.4	0.6
		Moderate, Strong	0.6	0.8
Sandy clay loam, Clay loam, Silty clay loam	Massive	Structureless		
	Platy	Weak, Mod., Strong		
	Prismatic, Blocky, Granular	Weak	0.2	0.3
		Moderate, Strong	0.4	0.6
Sandy clay, Clay, Silty clay	Massive	Structureless		
	Platy	Weak, Mod., Strong		
	Prismatic, Blocky, Granular	Weak		
		Moderate, Strong	0.2	0.3

Sidewall vs. Bottom Area

There is general agreement of the importance of both bottom and sidewall infiltrative surfaces. Our current hydraulic loading rates for the various soil textures are based on the use of the bottom area of the SSAS. The sidewall area is reserved as a design safety factor whereby this surface is excluded in SSAS sizing.

Numerous studies have shown sidewall area acts as an important infiltrative surface (McGauhey and Winneberger, 1965; Kropf et al., 1977; Keys, 1998; Dix, 2001). If the wastewater hydraulic loading rate exceeds the infiltrative capacity of the SSAS bottom area, effluent will pond from soil clogging and wastewater will contact the sidewall thereby causing the sidewall to become available for infiltration. As wastewater infiltrates the sidewall, the sidewall soil will progressively clog and continue to develop up the sidewall as the ponding depth increases (Bouma, 1975; Otis, 1985; Keys et. al., 1998;). The sidewall appears to clog less severely or slower than the bottom area (Winneberger, 1984). However, if the sidewall is to be an active infiltration surface, the bottom surface must be ponded.

A mass balance model was developed to predict system life and loading rates of gravel wastewater infiltration systems on a sandy soil (Keys et al, 1998). It was determined that “new” upper sidewall soil was needed to meet model conditions for the given hydraulic loading rate. The additional sidewall needed to infiltrate wastewater not passing through the bottom area agreed with observed increase in ponding depth over time. It concluded that sidewall is a very important part of transmitting effluent to the soil environment. The clogged bottom and sidewall area need to accept the applied wastewater or at some point the trench will fill and the system will fail.

The reaeration potential at the sidewalls is greater than below the SSAS bottom, but for sidewalls to be active, the SSAS must be ponded (Otis, 1997). Once the SSAS becomes ponded, the decomposition process likely occurs largely from below, since ponded effluent is anaerobic and oxygen cannot reach the organisms in the clogging layer from above. If the oxygen consumption rate exceeds the maximum flux of soil oxygen at the infiltrative zone, then the surface will become anaerobic (Erickson et al., 2001).

When infiltrative surface ponding persists for several days, reaeration is inhibited and the high oxygen demand of the accumulated materials creates anaerobic conditions in the subsoil. As a result, the infiltration rate declines more rapidly resulting in loss of hydraulic capacity to well below the design rate because anaerobic decomposition of the clogging agents is less efficient. Anaerobic conditions are created that ultimately will rise along the sidewall to cause hydraulic failure. Increasing the height of the sidewall only prolongs the time to failure (Otis, 1997).

Cost Information: Not applicable.

Conclusions

A comprehensive review of the literature to address identified key issues on the subject of hydraulic loading rates for on-site sewage systems was conducted. The following conclusions can be drawn from the information available in the literature:

- When wastewater is applied continuously to the soil, soil pore clogging (with suspended solids and the residues of microorganisms) usually develops at the infiltrative surface resulting in lower hydraulic conductivity than the underlying soil. Wastewater infiltration rates into soil are dependant on the character of both the clogging layer and soil.

- Not only does soil clogging cause more of the infiltrative surface to be used and yield an unsaturated flow regime in the underlying soil, it can enhance treatment at the infiltrative surface. However, severe clogging, for example due to application of high-strength effluents (e.g. restaurant wastewater), can reduce permeability at the infiltrative surface to a point of hydraulic failure, anoxic soil conditions and reduced wastewater treatment.

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- Reducing the total mass load of BOD and TSS with wastewater pretreatment systems reduces or eliminates soil clogging of an infiltrative surface. Higher wastewater loading rates can be applied to soil when the potential for clogging is eliminated.

- High hydraulic loading that highly treated (in terms of TSS and BOD) wastewater may permit lead to reduced wastewater retention times in the soil, and could reduce treatment efficiencies.

- Reduced retention time may be compensated for by improved wastewater quality achieved from the pretreatment system combined with uniform wastewater application (in space and time) to the soil to ensure that unsaturated flow conditions are maintained below the infiltrative surface.

- For the sidewall is to be an active infiltration surface, the bottom SSAS surface must be ponded. Once permanent ponding occurs, soil reaeration is inhibited and the high oxygen demand of the accumulated materials creates anaerobic conditions in the subsoil. Therefore, including sidewall area as an active infiltrative surface in SSAS design should be avoided.

- The potential increase in loading rate for soil with larger pores (sandy soil) using pretreated wastewater is greater than for those with fine pores (clayey soil) when compared to applying septic tank effluent. Therefore, a single factor between loading rates for clogged and unclogged soils should not be used.

- Since soil is a factor in infiltration rates through a clogging layer, hydraulic loading rates will vary from soil-to-soil with the same clogging. The differences in infiltration rates are related to soil characteristics defining pore sizes and pore size distribution. Soil morphological chacteristics, including texture, structure, bulk density, and clay mineralogy all provide information about soil pores.

- Even though majority of the states use the soil texture as the only parameter in deciding the hydraulic loading rate, the literature suggests that the other soil morphological factors such as structure, bulk density, clay mineralogy be included.

- Wastewater quality, and treatment requirements should be considered with soil morphology in predicting the hydraulic loading rate and incorporated into a rational design practice for SSAS. Although the literature is not very clear on how to obtain these loading rates.

- Table 1 presents recommended allowable hydraulic loading rates for septic tank effluent and low organic strength wastewater based on field described soil morphology. The logic and trends in values presented in the table fit with scientific basis and with experience and were prepared for field practitioners.

- It is important to realize that there are few papers that demonstrate effective pathogen removal in high hydraulic loaded SSAS with retarded clogging development. Since wastewater and soils are highly variable, conservative system design, including replacement area is recommended. Further research is needed to establish treatment efficiencies and design criteria for systems operated without a soil clog.

References:

Amerson, R.S., E.J. Tyler and J.C. Converse. 1991. Infiltration as Affected by Compaction, Fines, and Contact Area of Gravel. In On-Site Wastewater Treatment: Proceedings of the Sixth National Symposium On Individual and Small Community Sewage Systems, ASAE, St. Joseph, MI. p. 243-247.

Traditional onsite wastewater treatment systems utilize gravel, to support the sidewalls of the soil excavation preventing its collapse, to dissipate energy from incoming wastewater which might erode the infiltrative surface, to provide storage of peak wastewater flows, to support the distribution pipe, and to provide a media through which the wastewater can flow from the pipe to reach the infiltrative surface. Some have questioned the effect gravel has upon the infiltration rate of wastewater into soil. The supposed problems caused by gravel include the compaction of the soil infiltrative surface by falling gravel during system construction, the presence of excessive fine earth material, or "fines", on the gravel which can wash off and form a restrictive layer on the soil surface, and the 'masking' of a portion of the soil infiltrative surface by contact with the gravel. The objective of this study was to evaluate the effect of gravel on soil infiltration rates, and thus on the operation of newly constructed onsite wastewater treatment systems. Specifically, 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.

Amoozegar A. and C.P. Niewoehner. 1998. Soil Hydraulic Properties Affected by Various Components of Domestic Wastewater. In On-Site Wastewater Treatment: Proceedings of the Eight National Symposium On Individual and Small Community Sewage Systems, ASAE, St. Joseph, MI. p.155-166.

Hydraulic failure of a septic system may be attributed to the formation of a biomat in its trenches, but the chemical composition of wastewater may also significantly contribute to the failure of the system. The effects of various components of domestic wastewater on the hydraulic properties of three soils were studied. The soils were a sandy soil, the clayey Bt horizon of a soil, and a commonly occurring saprolite (C horizon) from North Carolina. Saturated hydraulic conductivity (K_{sat}) and infiltration rate (IR) of the soils and saprolite for tap water, simulated wastewaters from a washing machine, kitchen sink, bathroom sink and shower, and car wash with a water softener were measured in situ for five consecutive days using three replications. The simulated wastewaters affected the K_{sat} and IR differently. Simulated wastewater from a laundry machine had the most deleterious impact on soil hydraulic properties. In some cases, application of a $CaCl_2$ solution to the soil resulted in restoration of infiltration rate and hydraulic conductivity.

Anderson J. and J. Bouma. 1973. Relationships Between Saturated Hydraulic Conductivity and Morphometric Data of an Argillic Horizon, Soil Science Society of America Proceedings. 37(3): 408-413.

A method of calculating K_{sat} in pedal soil materials on the basic of morphometric data yielded reproducible results for seven soil peels sampled in the argillic horizon of a Batavia silt loam. Calculated values were reasonably close to those measured in situ with the double tube method. The method was also successfully applied to impregnated horizontal sections through soil cores. Dye studies demonstrated the validity of some of the underlying assumptions of the method, which predicts a strong relationship between core height and measured hydraulic conductivity in pedal soil materials. Experiments confirmed this relationship and a representative core size was defined for the studied horizon using the morphometric data.

Anderson J.L. and J. Bouma. 1977a.& b. Water Movement Through Pedal Soils I & II. Saturated and Unsaturated Flow. Soil Science Society of America Journal. 41:413-423.

Demonstrates the potential usefulness of routine soil structure descriptions as a correlative tool for predicting certain aspects of physical behavior. Provided are two separate articles that study water

movement through pedal soil with saturated and unsaturated flow conditions. All soils have a silty clay texture. Five medium subangular blocky structures were compared with five prismatic structures. Application of an unlimited quantity of traced water to drained columns resulted in very high dispersion, particularly for subangular blocky structures. Breakthrough curves for different flows are provided.

Anderson J.L., R.E. Machmeier and M.J. Hansel. 1982. Long Term Acceptance Rate of Wastewater. In On-Site Wastewater Treatment: Proceedings of the Third National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 93-100.

A review of literature concerning soil absorption system failures was conducted to determine whether such failure is inevitable for any system or whether soils possess a long-term acceptance rate which would permit a system to function indefinitely at its design capacity. The bulk of evidence supported the long-term acceptance rate concept. Proper site evaluation, construction, and maintenance are key factors in maintaining a system's capacity to absorb and treat sewage. Hydraulic properties obtained from soil survey reports can be used to estimate the long-term acceptance rates of most soils.

Bouma, J. 1971. Evaluation of the Field Percolation Test and an Alternative Procedure to Test Soil Potential for Disposal of Septic Tank Effluent. Soil Science Society of America Proceedings. 35: 871-875.

In order to provide a reliable alternative to the conventional percolation test, an alternative procedure was researched in Wisconsin. Measurement of K values in-situ, as a function of soil moisture tension, is proposed as a field test to determine soil potential for effluent disposal. A field experiment with dosing of effluent was made to demonstrate that system management will determine which K values from the measured range will apply to the flow system at any given time.

Bouma, J. 1975. Unsaturated Flow During Soil treatment of Septic Tank Effluent. J. Environ. Eng. Div., ASCE 101(6): 967-983.

Unsaturated flow as a parameter to achieve adequate purification of septic tank effluent is discussed. Column studies and field monitoring of homes in Wisconsin showed that the capacity of the soil to accept, conduct, and purify septic tank effluent is determinable only if appropriate hydraulic conductivity (k) curves are available for the soil in question. A suggested empirical design criteria for field systems is presented.

Bouma J. and J.L. Anderson. 1973. Relationships Between Soil Structure Characteristics and Hydraulic Conductivity, Field Soil Water Regime, Bruce, R.R. (ed.) Soil Science Society of America Special Publication No. 5, Chapter 5. 1973. p.77-105.

Relationships between soil structure, as characterized by morphometric methods, and hydraulic conductivity (K) were explored for a series of six artificial sand-clay mixtures with characteristics basic fabrics and four pedal soil horizons. The hydraulic behavior was strongly affected by differences in basic fabrics. Pore size distributions (measured with a point-count technique in thin sections) could be used to predict K values of the soil mixtures, but a pore continuity model and large matching factors were used. A physical model, using moisture retention data, yielded comparable results with less effort. Morphometric analysis was shown to have a specific function in studying the occurrence of pore types, such as planar voids and channels, that constitute only a small fraction of total pore volume, but strongly affect K_{sat}. Results were used to construct simple models of natural soil structures. A planar-void model, assuming vertical plane continuity, was used to calculate K_{sat} of the four natural pedal soil materials. Results obtained were close to experimental values measured *in situ* by the double-tube method.

Bouma, J., C. Belmans, L.W. Dekker and W..M.J. Jeurissen. 1983. Assessing the Suitability of Soils with Macropores for Subsurface Liquid Waste Disposal. J. Environ. Quality 12(3): 305-311.

The associated transient soil physical conditions, which govern purification processes, were measured experimentally in soil columns and in situ, and were predicted by simulation in three soils, two of which had macropores. Predictions involved computer simulation of pressure heads during infiltration and redistribution, and of outflow rates in the columns. Ponding times and drainage rates can be predicted using the computer program's algorithm.

Brown, D.F., L.A. Jones, and L.S. Wood. 1994. A Pedologic Approach for Sitting Wastewater Systems in Delaware. In On-Site Wastewater Treatment: Proceedings of the Seventh International Symposium On Individual and Small Community Sewage Systems. ASAE. St. Joseph, MI. p. 229-237.

Extensive housing development in the 1970's supported by on-site wastewater disposal systems (OWDS), often sited on soils having low suitability for such use, caused contamination of the phreatic zone. The State of Delaware decided to reevaluate its OWDS permitting procedures. The Department of Natural Resources and Environmental Control (DNREC) hired a consultant to develop a set of working papers that documented several methods for evaluating parcels for OWDS suitability (Tatman & Lee 1983). The method chosen had to maintain groundwater quality. Studies within the State confirmed that OWDS were partly responsible for contaminated groundwater. Percolation testing, as an indicator of suitability of OWDS was eliminated due to unreliability. A soil-based approach was chosen that used site evaluators to determine OWDS suitability. Licensing of site evaluators was modeled after the requirements of the American Registry of Certified Professionals in Agronomy, Crops and Soil Science (ARCPACS) for soil scientists. A site evaluator must assess the soils and site conditions of the parcel on which an OWDS is proposed. This approach takes into account geomorphology, stratigraphy and hydrology of the site. Based on this work, permeability rates are assigned and an OWDS type is prescribed. Standard OWDS include gravity fed, elevated sand mound, low pressure pipe, and pressured-dosed technologies. Alternative technologies are recirculating sand filters and biological rotating contactor units. The alternative technologies are used on sites with severe limitations for the standard OWDS. Siting an OWDS based on a soil based approach allows the OWDS to be designed to operate within specific soil limitations. Large (community) systems, commercial systems and difficult sites require a more systematic evaluation. Over 50,000 site evaluations have been performed during the eight years of this program's existence. In that time, OWDS failures have been reduced to less than four (4) percent annually.

Converse, J.C., J.L. Anderson, W.A. Ziebel and J. Bouma. 1974. Pressure Distribution to Improve Soil Absorption Systems. In Home Sewage Disposal: Proceedings of the National Disposal Symposium. ASAE, St. Joseph, MI. p. 104-129.

Soil absorption systems can be improved through the use of pressure distribution. The authors stress the importance of using properly sized, submersible pumps to distribute the effluent evenly over the field. Seven distribution systems were studied; five of them for two years for system evaluation. General recommendations for best system performance are included. Tables and graphs represent system data.

Converse, J.C. and E.J. Tyler. 1998. Soil Treatment of Aerobically Treated Domestic Wastewater with Emphasis on Modified Mounds. In On-Site Wastewater Treatment: Proceedings of the Eighth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 306-319.

Wastewater treatment by soil beneath 35 modified mounds and 4 at-grade soil absorption units receiving aerobically treated wastewater was determined. The soil texture ranged from sand to clay loam and estimated seasonal saturation was just below ground surface in many cases. Thirty-six of the dispersal units received wastewater from aerobic units and two from single pass sand filters.

Effluent was distributed via pressure distribution to all systems. On approximately 50% of the soil absorption units, effluent was delivered to only half of the unit which increased the effluent loading to the other half of the unit. To evaluate the treatment effectiveness, soil cores were taken from beneath and adjacent to the system at 15 cm (6 in.) increments to a depth of 105 cm (42 in.). Fecal coliforms, nitrogen compounds and chlorides were evaluated. Median (50% above and 50% below) fecal coliform in the aerated wastewater was 10^3 counts/100mL. Wastewater fecal coliform counts ranges from <1 (not detectable) to >10^5 counts/100 mL. Median fecal coliform counts were below detection limits at 30 cm (1 ft) beneath the infiltrative surface. At 105 cm (42 in.) below the infiltrative surface <10% of the samples contained fecal coliform >1 MPN/g dry soil. When wastewater with <10^3 counts/100 mL was added, median soil fecal coliform counts were <1 MPN/g dry soil within 15 cm (6 in.) of the infiltrative surface and at 60 cm (2 ft) below the infiltrative surface <10% of the samples contained fecal coliform > 1 MPN/g dry soil. Separation from the wastewater infiltrative surface might be based on the odds of meeting a treatment goal for the soil. For example, based on median values fro all samples collected being below detection limits, it may be reasonable to set the separation distance at 30 com (1 ft). Based on only 10% of the values exceeding the detection limits, a separation limit of 60 cm (2 ft) may be selected. Similar separation distance could be assigned based of the ability of the treatment unit reducing fecal coliforms. Median total nitrogen concentration of the aerobically treated wastewater was 32 N/L. Median soil nitrated concentrations was 26 N/L at 105 cm (42 in.) and similar to amounts found beneath mounds and at-grade systems receiving septic tank effluent.

Daniel, T.C. and J. Bouma. 1974. Column Studies of Soil Clogging in Slowly Permeable Soils as a Function of Effluent Quality, J. Env. Quality 3(4): 321-326.

Clogging as a function of effluent quality was investigated in cores of the very slowly permeable Almena silt loam soil which offers problems for conventional on-site liquid waste disposal. Undisturbed 60 cm long cores were subjected for approximately 120 days to constant ponding with simulated septic tank effluent, extended aeration effluent and distilled water. Column influents and effluents were monitored with respect to chemical oxygen demand (COD), biochemical oxygen demand (BOD), and solid residue fractions. Column influents differed markedly in COD and BOD content but column effluent had consistently low contents indicating the high renovative capacity of the soil. In situ tensiometric, redox, and flow rate measurements indicated development of the most severe barriers to flow in columns ponded with low BOD aerated effluents, followed closely by those ponded with high BOD septic tank effluent. No barriers developed in columns ponded with water. Total concentrations of solid residue fractions in the two effluents and the cumulative load of solids applied to the columns did not differ significantly, but particle sizes in the aerated effluent were smaller. Increased pore clogging in aerated influent treatment points to the significant role of effluent solids in the clogging process in slowly permeable clayey soils. Additional studies are in process to better define critical waste characteristics as related to soil clogging.

De Vries, J. 1972. Soil Filtration of Waste Water Effluent and the Mechanism of Pore Clogging. Journal Water Pollut. Control Fed. 44(4): 565-573.

Dix, S.P. 2001. Affects of Sand Texture on Sidewall Absorption of Septic Effluent. In On-Site Wastewater Treatment: Proceedings of the Ninth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 159-170.

Side by side comparison of sidewall absorption in medium sand and fine sand shows that sidewall absorption plays a significant role in the release of effluent from a soil absorption system. Chamber sidewall is also compared to an aggregate sidewall, with a significant difference in upper sidewall evident using this media. Variation in absorption with depth indicates that fringe length will have a greater influence than sidewall height in the performance of a trench in the two sand media tested. Fines sand run consistently slower over the range of depth without the upper fringe efficiency observed in the coarser media.

Duncan, C.S., R.B. Reneau, and C. Hagedorn. 1994. Impact of Effluent Quality and Soil Depth on Renovation of Domestic Wastewater. In On-Site Wastewater Treatment: Proceedings of the Seventh National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 219-228.

Many soils are marginally suited for installation of on-site wastewater disposal systems. With soil limitations, additional wastewater treatment prior to soil application may allow for a reduction in soil depth. Undisturbed 20-cm-diameter soil columns (fine loamy, mix, mesic Typic Hapludult), in a factorial arrangement between depth of soil (15, 30, and 45 cm) and type of effluent (septic tank, constructed wetlands, and recirculating sand filter), were used in this study. Effluent (670 cm3/d) was applied 6 times daily. Additional treatment of septic tank effluent by a constructed wetland and a recirculating sand filter resulted in 30 and 70% higher average soil infiltration rates, 92 and 96% reduction in fecal coliforms, 34 and 44% reduction in total nitrogen, and a 60 and 94% reduction in BOD5, respectively. Fecal coliforms were present only in soil leachate from the 15 and 30 cm soil depths receiving septic tank effluent and the 15 cm depth that received constructed wetland effluent. Average soil leachate NO3- -N concentrations were 19, 10 and 14 mg/L from soil columns receiving septic tank, constructed wetland, and recirculating sand filter effluents, respectively. Soil leachate contained <5 mg/L TKN and 1.8 mg/L NH4+-N. Total nitrogen losses were 55,73, and 66 for the septic tank, constructed wetland, and recirculating sand filter treatments, respectively. BOD5 averaged less than 4 mg/L in the soil column leachate, despite a 10 fold difference among influent types. In comparing the 1993 and 1994 growing seasons, average plant tissue dry weight, percent N, and percent P were greater during the 1994 growing season. The results from this study indicate that additional treatment of septic tank effluent can be substituted for soil depth.

Emerick, R.W., R.M. Test, G. Tchobanoglous, and J. Darby. 1997. Shallow Intermittent Sand Filtration: Microorganism Removal. In The Small Flows Journal. 3(1): 12-22.

Twelve shallow circular sand filters (0.38 m deep, nominal diameter of 1.2 m) were loaded intermittently with primary effluent to evaluate the effects of hydraulic loading rate (HLR) -coupled with a high dosing frequency (DF) -and filter medium characteristics on the removal of indigenous coliphages, total coliforms, turbidity, chemical oxygen demand (COD), and total suspended solids (TSS). HLRs between 0.041 and 0.162 m/d were applied during an 84-day period at a DF of 24 doses/d. Two types of filter media were investigated: medium-size and coarse sand and crushed glass. Effective sizes ranged from 0.44 to 3.3 mm, and uniformity coefficients ranged from 1.3 to 5.0. Average removal rates greater than 94, 96, and 92 percent occurred for turbidity. TSS, and COD, respectively, regardless of medium characteristics. Removal of microorganisms was found to be affected by the combination of HLR and DF, with an increase in HLR at a constant DF resulting in a decrease in the log removal of both total coliforms and indigenous coliphages. Indigenous coliphage appeared to be more sensitive to changes in HLR than seeded polioviruses.

Erickson, J. and E.J. Tyler. 2001. A Model for Soil Oxygen Delivery to Wastewater Infiltration Surface. In On-Site Wastewater Treatment: Proceedings of the Ninth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 11-17.

Soil could accept onsite wastewater at rates two to three orders of magnitude higher than the current design loading rates if a clogging mat at the wastewater infiltration surface was limited or not present. The clogging mat controls system design, loading rate and life. Maintaining aerobic conditions at the wastewater infiltration surface could substantially reduce or eliminate clogging. This project is studying soil oxygen supply to the zone of clogging in soil. A model based on a form of Fick’s Law for diffusive transport is being applied to oxygen diffusion to the wastewater infiltration surface. Gas filled porosity controlled by soil characteristics of texture, structure, consistence and water content as well as the distance to the supply of oxygen and rate of oxygen consumption control the flux, F, of oxygen. If the oxygen consumption rate exceeds the maximum flux of soil oxygen then the soil infiltration surface will become anaerobic. To maximize delivery of oxygen, soil components should be shallow, narrow and have separated infiltration areas. Using models that incorporate system depth, geometry, and oxygen diffusion coefficients in soil, efficient loading rates can be estimated. Design of wastewater infiltration surfaces should be based on both oxygen transport and hydraulics. In many cases, oxygen transport will be limiting and therefore the basis for design.

Gross, M.A., P.R. Owens, N.D. Dennis, A.K. Robinson and E.M. Rutledge. 1998. Sizing Onsite Wastewater Treatment Systems Using Soil Characteristics as Compared to the Percolation Test. In On-Site Wastewater Treatment: Proceedings of the Eighth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 52-59.

Hantzsche, N.N., T. Neikirk and T.V. Wistrom. 1974. Soil Textural Analysis For On-Site Sewage Disposal Evaluation. In On-Site Wastewater Treatment: Proceedings of the Third National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 51-60.

Describes a procedure which utilizes soil textural analysis as a primary tool for judging site suitability. Comparison of field and laboratory data show a significant correlation between percolation test results and position of soil within defined suitability zones on the textural triangle. In cases of marginal or unacceptable textural classification, wet-weather percolation testing is relied upon as a final determinant of a site's percolation suitability. Although the procedures reduce the dependence on the percolation test, they do not totally eliminate its use as an evaluation tool.

Hargett, D.L., E.J. Tyler and R.L. Siegrist. 1982. Soil Infiltration Capacity as Affected by Septic Tank Effluent Application Strategies. In On-Site Wastewater Treatment: Proceedings of the Third National Symposium on Individual and Small Community Sewage Systems. ASAE. St. Joseph, MI. p. 72-84.

The effect of method and rate of application of septic tank effluent to replicated soil absorption systems in an undisturbed silty clay loam subsoil were studied. Methods of application include convention (simulated) and dosed (uniformly, once daily). Application rates were 2, 4 and 8 com/day. The experiment was limited duration (21 months) under specific soil conditions. The following conclusions were stated: Loss of infiltrative capacity is related to amount and frequency of application over time. Initial loss in permeability is very rapid regardless of application rate or method. Loading rates higher than those appropriate for soil conditions cause the most rapid and continuous declines in filtration capacity. Conventional application is likely to produce system ponding. At reasonable application rates dosing can be useful in maintaining higher infiltrative capacity than conventional loading. For high loading rates, dosing has little long-term advantage over conventional application.

Healy, K.A. and R. Laak. 1973. Factors Affecting the Percolation Test. Journal of Water Pollution Control Federation. 45(7): 1508-1516.

Healy, K.A. and R. Laak. 1974. Site Evaluation and Design of Seepage Fields. Journal of Environmental Engineering, American Society of Civil Eng. 100(EE5): 1132-1146.

Septic tank effluent can be indefinitely absorbed by soil if the application rate is kept below a certain level, which is a function of the soil permeability. This acceptance rate is independent of whether the soil is flooded continuously or intermittently. Groundwater flow below a seepage field is, in many cases, a function of the hydraulic conductivity of the ground surrounding the field. Techniques for site evaluation of soil permeability, depth to water table, and depth to any impervious strata are presented along with design examples.

Huntzinger, D., J. McCray, S. VanCuyk and R. Siegrist. 2001. Mathematical Modeling of Unsaturated Flow in Wastewater Soil Absorption Systems with Clogging Zones. In On-Site Wastewater Treatment: Proceedings of the Ninth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 106-115.

It is common practice in the United States to use wastewater soil absorption systems (WSAS) to manage and treat domestic wastewater. These systems are expected to provide efficient, long-term removal of wastewater contaminants prior to groundwater recharge. Soil clogging by the accumulation of suspended solids, organic matter, and chemical precipitates at the infiltrative surface of WSAS is a phenomenon known to occur as a result of continued wastewater infiltration. This clogging creates an impedance to flow, restricting the hydraulic conductivity and rate of infiltration. A certain degree of clogging may improve the treatment of wastewater by enhancing purification processes, in part because unsaturated flow is induced and residence times are significantly increased. However, if clogging becomes too excessive, the height of ponding can rise to a level where system failure occurs. The numerical model HYDRUS2D and representative hydraulic properties for clogging zones obtained from the literature are used to hypothetically simulate unsaturated flow within WSAS to better understand the effect of clogging zones on unsaturated flow behavior and hydraulic retention times in sandy and silty soil. The simulations indicate that sand-based WSAS with mature clogging zones are characterized by a more widely distributed flow regime and longer hydraulic retention times. The impact of infiltrative surface clogging on water flow within the silty soils is not as substantial. In the sand case by increasing the hydraulic resistance of the clogging zone by a factor or 2 to 3, ponding levels required to accept the same wastewater loading increase by as much as a factor of 5. Since the degree of clogging zone resistance directly impacts the level of ponding within a system, knowledge of the genesis and properties of the clogging zone and its impact on flow regimes within these systems is critical in optimizing system design to achieve a desired pollutant treatment efficiency.

Jenssen, P.D. and R.L. Siegrist. 1990. Technology Assessment of Wastewater Treatment by Soil Infiltration Systems. Water Science & Technology. 1990 22(3/4): 83-92.

Successful performance starts with thorough site investigations, where large scale infiltration tests or tracer studies might be needed. The hydraulic loading rate is a principal design parameter. An integrated approach for assessment of the hydraulic loading rate based on soil type and wastewater quality is suggested. In general, trench design should be preferred over beds, but rational criteria for selection of optimal geometry is lacking. Purification performance of subsurface wastewater system is generally good. Estimates of purification on the basis of soil grain size, soil depth and loading rate can be given.

Jenssen, P.D. and R.L. Siegrist. 1991. Integrated Loading Rate Determination for Wastewater Infiltration System Sizing. In On-Site Wastewater Treatment: Proceedings of the Sixth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 182-191.

One of the principal parameter used in wastewater system design is the hydraulic loading rate. Historically the determination of the loading rate has been a straight forward process involving selection of a rate based on soil texture or water percolation rate. Research and experience over the past decade has provided additional insight into the complex process occurring within wastewater-amended soil systems and has suggested the fallacy of this approach. A mean grain size vs. sorting (MESO) diagram constitutes a new basis for soil classification for wastewater infiltration system design. Crude characterization of the soil hydraulic properties is possible according to the MESO Diagram and loading rate as well as certain purification aspects can be assesses from the diagram. In this paper, an approach is described based on the MESO Diagram, which integrates soil properties and wastewater pretreatment to yield a loading rate.

Jones, J.H. and G.S.Taylor. 1965. Septic Tank Effluent Percolation Through Sands Under Laboratory Conditions. Soil Science. 99(5): 301-309.

Laboratory investigations were conducted to evaluate the effect of septic tank effluent application on the clogging process in sand media. Emphasis was place on the cumulative effect of such application when made over a period of several months. This report is principally concerned with changes in hydraulic conductivity of the sand that resulted form effluent application. Soil clogging under effluent loading occurs 3 to 10 times faster under an anaerobic environmental than under an aerobic one, and sands of high initial hydraulic conductivities are clogged at a much slower rate than ones of low initial conductivity.

Keys, J.R., E.J. Tyler, and J.C. Converse. 1998. Predicting Life for Wastewater Absorption Systems. In On-Site Wastewater Treatment: Proceedings of the Eighth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 167-176.

A mass-balance model to predict system life and loading rates of gravel wastewater infiltration systems on a sand soil was developed. The functional life of a system was predicted using multiple regression analysis of ponding depths of wastewater versus time. Long term failing head infiltration rates to determine basal area and sidewall conductivities were measured and incorporated in the model to predict loading rates and flow from with the systems. Gravel filled systems in these sand soils have a predicted life of 11 years when loaded basically at 1.6 cm/d. The ponding depths of wastewater were found to increase an average of 27 mm/yr. At a higher loading rate of 4.1 cm/d, the expected life was 7 years and the average ponding depth increase of 44 mm/yr. The loss of “new” sidewall infiltrative area for a fixed length system is the limit or life expectancy measure. The mass-balance model explained differences in flow rates for various biological matted surface areas. Conductivities for these surface areas ranged from 0.02 (basal and lower sidewall areas) to 2.41 (upper sidewall and lip areas) cm/d. From the model, “new” upper sidewall soil was determined needed for infiltration at a basal loading rate of 1.6 cm/d. The additional sidewall needed to infiltrate wastewater not passing through the basal area agrees with the observed increased in ponding depths over time. The matted sidewall and lip was found to be the most efficient for movement of wastewater into the soil. The basal area had a lower conductivity than either the sidewall or lip areas. It still accounted for a significant amount of wastewater removal, is an important part of the system, should not be ignored or downsized. A system life is limited by sidewall height and the conductivities of the clogged areas. The clogged basal and sidewall areas need to accept the applied wastewater or eventually the trench will fill causing the system to fail.

Kommalapati, R.R. and A. Noman. 1999. A Literature Review on Effects of Long-Term Effluent Infiltration Rates At On-Site Sewage Disposal Systems. Texas On-Site Wastewater Treatment Research Council. 29 pages.

This report summarizes the literature available on the topic of effect of long-term effluent rate at on-site sewage disposal systems. Its objective was to perform a comprehensive review of all the literature available on the subject of on-site wastewater or sewage treatment facilities with focus on the long-term effluent infiltration rates. Review the literature on the subject of long-term infiltration rate with respect to hydraulic and organic loading for different types of soils and onsite sewage facilities surface disposal systems.

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

This is the first of three articles on sand filter trenches for treating septic tank effluent. Three pilot plant sand filters, one heated and two at ambient temperatures, were observed to explain the relationship between clogging and soil physical and chemical environment in the sand filters. Discusses ponding rates, C/N ratio, bacteria and bacterial exudates, redox potential, and atmosphere within the sand filters.

Kristiansen, R. 1982. The Soil as a Renovating Medium-Clogging of Infiltrative Surfaces. In Proceedings of the Conference on Alternative Wastewater Treatment, Low-Cost Small Systems, Research and Development., held in Oslo, Norway, Sept. 7-10, 1981. D. Reidel Publishing Co., Boston, MA. p. 105-120.

Presents an overview of research associated with the clogging layer which develops on infiltrative surfaces in septic tank leaching systems. Discusses the three clogging phases, the causes of clogging, and the effect of loading conditions, wastewater, soil type, temperature and redox conditions on clogging. Systems may be restored by resting.

Kropf, F.W., R. Laak, and K.A. Healy. 1977. Equilibrium Operation of Subsurface Absorption Systems. J. Water Pollut. Control Fed., 49(9): 2007-2016.

This investigation examined the infiltration rate through the clogging mat of a soil absorption system and involved development of a design criteria for the construction of a system that would function at its equilibrium point, offering successful long-term operation. Soil column samples were tested under a constant hydraulic head and with/without a groundwater table within a few inches of the infiltration surface. The samples were flooded at different frequencies. Results showed that the infiltration rate is related to the prevailing gradient, but it is independent of the permeability of the supporting soil matrix. Continued inundation of the infiltrative surface for 80 weeks in an anaerobic environment did not affect the LTAR.

Laak, R. 1970. Influence of Domestic Wastewater Pretreatment on Soil Clogging. Journal of Water Pollution Control Federation, 42(8): 1495-1500.

A soil column experiment was designed to determine if the total weight of TSS and BOD-5 applied to the soil was directly related to soil failure or ultimate clogging. Half of the columns were loaded with septic tank effluent and the other half with extended aeration plant effluent. Results showed that TSS removal differed between the two systems, indicating that BOD-5 could be a contributing parameter in clogging. Analysis of the clogging material showed that it did not contain sufficient amounts of ferrous sulfide to be considered a major clogging component, as was previously thought. The experiment concluded that increasing the pretreatment of domestic wastewater prior to soil application increases the service time of the soil surface.

Laak, R. 1976. Pollutant Loads from Plumbing Fixtures and Pretreatment to Control Soil Clogging. J. Environ. Health 39:48-50.

Three areas of concern in the disposal of domestic wastewater are discussed: soil clogging, pollution loads and pretreatment efficiencies. Presents material dealing with effects of these areas on development of a clogging mat on the soil surface. Attempts to update existing codes of practice for on-site disposal of domestic wastewaters.

Loudon, T.L. and G.L. Birnie, Jr. 1991. Performance of Trenches Receiving Sand Filter Effluent in Slowly Permeable Soils. In On-Site Wastewater Treatment: Proceedings of the Sixth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 313-323.

In a conventional septic tank-soil absorption system the soil system receiving septic tank effluent will exhibit clogging and reduction in effluent absorption capacity over time. The rate and severity of clogging varies with the hydraulic loading rate, quality of the applied effluent, application methods, and soil factors such as temperature, moisture content, and aeration status. Sand filters can greatly improve the quality of the septic tank effluent. The purpose of this paper is to discuss field experiences with systems involving subsurface soil absorption of effluent from recirculating sand filters

in very slowly permeable soils. Two systems involving the use of shallow, narrow trenches are discussed. Soil absorption performance data are presented.

Loudon, T.L., G.S. Salthouse, and D.L. Mokma. 1998. Wastewater Quality and Trench System Design Effects on Soil Acceptance Rates. In On-Site Wastewater Treatment: Proceedings of the Eight National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 182-194.

An automated system was developed to monitor ponding in absorption trenches and to control dosing of individual trenches as they become unponded. The PC-based system controls pumps and valves, and keeps track of the amount of wastewater each trench accepts. Various trench designs are compared for their ability to accept septic tank (ST) 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 threes different depths. Soil acceptance rates through the bottom of the trenches are 7 to 12 times greater for trenches receiving sand filter effluent than for trenches receiving septic tank effluent. 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 than the others.

Loudon, T.L. and Mokoma, D.L. 1999. Trench Infiltration as Influenced by Soil Type, Depth, Application Method and Effluent Quality. In Proceedings Ninth Northwest On-Site Wastewater Treatment Short Course, September 1999,College of Engineering, University of Washington, Seattle, p. 341-352.

Magdoff, F.R. and J. Bouma. 1974. The Development of Soil Clogging in Sands Leached With Septic Tank Effluent. In Home Sewage Disposal: Proceedings of the National Disposal Symposium. ASAE, St. Joseph, MI. p. 37-47.

Describes an experimental study of crust development in sand columns dosed with septic tank effluent. Field and laboratory tests reveal soil clogging is caused by isotropic organic compounds and opaque organic fragments in the soil pores. Tensiometers measured the hydraulic conductivity through crusts, while their resistance to flow was evaluated using a physical flow computer model.

Mahuta, F. and W.C. Boyle. 1991. Gas Transport in the Unsaturated Zone of Soil Absorption Systems. In On-Site Wastewater Treatment: Proceedings of the Sixth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 233-242.

The major objective of this research was to obtain a better understanding of gas transport associated with the biochemical transformations of pollutants occurring in the unsaturated zone of soil absorption systems. To meet this objective, research activity was conducted in two main areas: first, a two dimensional mechanistic model of the transport of oxygen and other gases in SAS's was developed; and second, bench-scale experiments were performed to collect quantitative data on these processes which could be used to verify the model. One potential application for a model such as this would be to estimate the composition of the soil-gas phase, and thus the potential for anaerobiosis to occur, within full-scale systems as a function of various system design parameters such as the physical characteristics of the underlying soil and the geometry of the SAS.

McCray, J.E., D.H. Huntzinger, S. Van Cuyk, and R. Siegrist. 2000. Mathematical Modeling of Unsaturated Flow and Transport in Soil-based Wastewater Treatment Systems. Proc. WEFTEC 2000. Water Environment Federation, Washington D.C. pp. 20.

A numerical model is used to investigate the impact of the infiltrative-surface crust on the hydraulic-treatment volume and on unsaturated transport and transformation of orthophosphate and ammonium in soil-based wastewater treatment systems (SWTS). The simulated SWTS is a subsurface trench underlain by a natural soil. Crusts at the base and on the sidewall of the trench are incorporated in the model. Unsaturated water-flow and contaminant-transport parameters are selected from the ranges of values measured in field and laboratory experiments that have been reported in the literature. The process of contaminant sorption to soil is included for both contaminants. Biochemical ammonium transformation and phosphate precipitation are simulated assuming first-order kinetics. The simulations illustrate that the presence of an infiltrative-surface crust greatly improves treatment of orthophosphate and ammonium. The infiltrative crust causes reduced infiltration velocities and a somewhat larger hydraulic-treatment volume. The slower velocities result in longer hydraulic residence times and thus allow more time for biochemical removal. Increased hydraulic volumes are due mainly to infiltration through the sidewall crust in mature systems. Slower contaminant velocities due to sorption also improve biochemical treatment. The impact of two septic-tank effluent (STE) -application methods on treatment is evaluated for an uncrusted system. Uniform application across the infiltration trench resulted in improved treatment due to a larger overall hydraulic residence time compared to a focused application in the center area of the trench. This research illustrates that numerical models are useful for gaining a better understanding of crust development and the associated impact on contaminant treatment.

McGauhey, P.H. and J.H. Winneberger. 1964. Studies of the Failure of Septic Tank Percolation Systems. Journal of Water Pollution Control Federation. 36(5) 593-606.

The objectives of the studies herein reported were to determine the causes of loss of infiltrative capacity of a soil which results in failure of a percolation system; gain an understanding of the mechanisms of soil clogging; and explore the ways in which soil clogging can be overcome or minimized in practice. To attain these objectives the investigation included a review of existing literature, a re-interpretation of data from previous work on groundwater recharge, laboratory and pilot scale experiments, and field observations.

National Small Flows Clearinghouse, 1996. Application Rates and Sizing of Effluent Drainfields, From State Regulations, Publication No. WWBKRG19, National Small Flows Clearinghouse, West Virginia University.

This document compiles the application rates and sizing requirements for drainfields from state regulations as of 1996.

Okubo, T. and J. Matsumoto. 1979. Effect of Infiltration Rate on Biological Clogging and Water Quality Changes During Article Recharge, Water Resources Research 15(6): 1536-1542.

The effect of infiltration rate on biological clogging and water quality changes is investigated experimentally using a sand column. The concentration of soluble COD in the effluent is stable during 3 months of infiltration, and the lower the initial infiltration rate is, the higher the average percentage of the reduction of soluble COD becomes. The soluble COD is primary removed in the surface layer. The hydraulic conductivity in the bottom layer decreases at the highest infiltration rate. The variation of infiltration rate is divided into four stages, In addition, the biological-clogging model is proposed, and the mechanism of biological clogging is discussed.

Okubo, T. and J. Matsumoto. 1983. Biological Clogging of Sand and Changes of Organic Constituents During Article Recharge. Water Research 17(7): 813-821.

Biological clogging during artificial ground water recharge is divided into three stages, i.e. aerobic period, transitional period form aerobic conditions to anaerobic conditions and anaerobic period. During the transitional period, the infiltration rate is almost constant or increases slightly because of the transient decrease of microbial accumulation in the sand column. Experimental result shows that the secondary effluent infiltrated through the sand must have suspended solids of <2 mg/l and soluble organic carbon of <10mg/l to maintain a high infiltration rate during a long inundation period. The gel chromatogram data show that the biological clogging plays an important role in preventing contamination of an aquifer recharge by polluted water.

Otis, R.J. 1985. Soil Clogging Mechanisms and Control. In On-Site Wastewater Treatment: Proceedings of the Fourth National Symposium on Individual and Small Community Sewage Systems. ASAE. St. Joseph MI. p 238-250.

A survey and comparison of past research on the phases and mechanisms of soil clogging is reviewed. Each of four infiltration rate studies confirmed that there are three to four distinct declining infiltration rate phases. Similarly, from clogging mechanisms studies it was concluded that microbial activity (resulting in slime, gas, and other void-filling by-products) is the main cause of clogging. A section on the control of clogging follows and includes a discussion of each contributing factor. Past research is reviewed for many factors including hydraulic loading, geometry and depth of the infiltration surface, wastewater application via dosing, pretreatment, resting, and chemical oxidation. Recommendations for onsite system design and further study are given.

Otis, R.J., 1997. Considering Reaeration. In Proceedings Ninth Northwest On-Site Wastewater Treatment Short Course, College of Engineering, University of Washington, Seattle, 1997. p. 119-125.

Pell, M. and H. Ljunggren. 1984. Reduction of Organic Matter with Focus on the Clogging Phenomenon. In Proceedings of the International Conference on New Technology Wastewater Treatment and Sewerage in Rural and Suburb Areas, Tampere Univ of Tech., Tampere, Finland. p.311-327.

The influence of wastewater quality, especially its content of organic matter, on the clogging mechanism and the hydraulic capacity of infiltration systems was investigated. The active bacterial population and its possible adaptation to various compositions of wastewater were also studied. Small columns packed with sand were loaded once a day with an artificial septic tank effluent containing different concentrations of protein, starch or fat. Six columns loaded with protein-rich water, ranging in COD from 100 mg/l to 3200 mg/l, gave a straight-line relationship, showing that if high concentrations were dosed, larger amounts of organic matter could be accepted by the surface before ponding. It was found that the bacterial population did not adapt to the quality of the water loaded on the columns.

Rice, R.C. 1974. Soil Clogging During Infiltration of Secondary Effluent. Journal of Water Pollution Control Federation. 46(4): 708-716.

Roats, G.G. 1974. Effects of Domestic Wastewater Pretreatment on Soil Clogging and Aerobic and Anaerobic Conditions. M.S. Thesis, University of Washington, Dept of Engineering. 76 pages.

A tarnished image of septic tank systems has resulted from widespread failures which became particularly noticeable during the building boom following World War II. Small aerobic tank systems, developed as an alternative to septic tank systems, are viewed with suspicion by many public health officials and have found only limited application. Rational design criteria for both systems and their accompanying subsurface disposal fields are lacking, and a controversy exists over the relative severity of soil clogging produced by septic and aerobic effluents. This thesis, in a literature review and laboratory investigation, focuses on the soil clogging problem and attempts a partial clarification of the controversy. Review of the technical literature reveals that the clogging process is extremely complex, influenced by effluent characteristics, soil type, loading conditions, soil conditions and several other variables. The laboratory experiment compares the clogging characteristics of septic tank liquor and extended aeration unit effluent in a common King County soil contained in plastic columns. Both aerobic and anaerobic soil conditions are artificially induced in separate columns. The study cautiously concludes that soil clogging in the soil chosen is more severe under application of extended aeration effluent than septic tank liquor, and more severe under anaerobic than under aerobic soil conditions. The importance of the relation between the sizes of effluent suspended solids and soil pores is emphasized, as is the maintenance of aerobic soil conditions, with regard to subsurface effluent disposal. Intermittent dosing of effluent and alternation of soil systems are recommended.

Rose, J.B., D.W. Griffin and L.W. Nicosia. 1999. Virus Transport form Septic Tanks to Coastal Waters. In Proceedings Tenth Northwest On-Site Wastewater Treatment Short Course, College of Engineering, University of Washington, Seattle, 1999. p. 71-80.

Schoeneberger, P.J., A. Amoozegar and S.W. Boul. 1995. Physical Property Variation of a Soil and Saprolite Continuum at Three Geomorphic Positions. Soil Science Society of America Journal. 59: 1389-1398.

Siegrist, R.L. 1987a. Soil Clogging During Subsurface Wastewater Infiltration as Affected by Effluent Composition and Loading Rate, Journal of Environmental Quality, 16(2): 181-187.

The soil clogging effects of wastewater effluent composition and loading rate were investigated in pilot-scale infiltration cells installed in situ in the structured silty clay loam subsoil of a Typic Argiudoll (fine-silty, mixed, mesic). Over a 70-month period domestic septic tank effluent (DSTE), graywater septic tank effluent (GSTE) and tap water (TW) were intermittently applied in an average of 5.2 doses/d to yield daily loading rates of 1.3, 2.6, and 5.2 cm/d. Soil clogging was negligible in all TW treatments and in the GSTE treatment at 1.3 and 2.6 cm/d. In the GSTE treatment at 5.2 cm/d and in all DSTE treatment, severe soil clogging led to continuous ponding of the soil infiltrative surfaces. A logistic model fit to the experimental data confirmed that soil clogging development was highly correlated with the cumulative mass density loadings of total biochemical oxygen demand and suspended solids. After 62 and 70 months of loading, soil properties were determined with depth. Clogged infiltrative surface zones exhibited significant accumulations of organic materials at the infiltrative surface and within the first few millimeters of the soil matrix. This field study demonstrated that higher quality wastewater effluents can be discharged to subsurface infiltration systems at hydraulic loading rates in excess of those utilized for DSTE without stimulating soil clogging development.

Siegrist, R.L. 1987b. Hydraulic Loading Rates for Soil Absorption Systems Based on Wastewater Quality. In On-Site Wastewater Treatment: Proceedings of the Fifth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 232-241.

This paper reviews the phenomenon of soil clogging induced by wastewater application and its importance to soil absorption system performance. The author proposes mass density loadings of BOD and TSS as a basis for design. Pretreatment of septic tank effluent appears to have a significant impact on soil clogging. The proposed alternative design approach does not provide firm guidance but serves to stimulated further consideration and research. Using this approach, sand filters seem desirable for commercial and community scale facilities where incentives to increase loadings or reduce risk are substantial.

Siegrist R.L. and W.C. Boyle. 1987. Wastewater Induced Soil Clogging Development, J. Environ. Eng. ASCE. 113(3):550-566.

The development of wastewater-induced soil clogging in subsurface wastewater infiltration systems is investigated in the field over a 70-month period. Domestic septic tank effluent (DSTE), graywater septic tank effluent (GSTE), and tapwater (TW) are intermittently applied at 1.3, 2.6, and 5.2 cm/day to replicate 0.9-m diameter pilot-scale wastewater infiltration systems installed in situ in a structured silty clay loam subsoil. Soil clogging development is negligible under all TW loadings and under GSTE loadings at 1.3 and 2.6 cm/day. Under GSTE loadings at 5.2 cm/day and under all DSTE loadings severe soil clogging development leads to continuous ponding of the soil infiltrative surfaces. A logistic model fit to the experimental data confirms that soil clogging development is highly correlated with the cumulative mass density loading of total biochemical oxygen demand and suspend solids (R^2=0.95). Wastewater composition as well as hydraulic loading rate need to be considered in system design and management.

Siegrist, R.L. and S. Van Cuyk. 2001. Wastewater Soil Absorptions Systems: The Performance Effects of Process and Environmental Conditions. In On-Site Wastewater Treatment: Proceedings of the Ninth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 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.

Simon, J.J. and R.B. Reneau, Jr. 1987. Recommended Septic Tank Effluent Loading Rates for Fine-textured, Structured Soils with Flow Restrictions. In On-Site Wastewater Treatment: Proceedings of the Fifth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p 394-411.

Soil structure is a primary determinant in the hydraulic properties of fine textured soils. In contrast to many studies, which have emphasized texture or percolation rates, this study draws on direct relationships between observed soil structure and performance of prototype septic tank drainfields in which low pressure distribution was simulated. Trench bottoms should be placed at the depth in the soil profile which is well drained and is underlain by the best structure. Loading rated low pressure distribution systems installed in fine textured subsoils are recommended based on relationships between structure, coarse fragment content and depth to restrictive layers.

Tyler, E.J. 2001. Hydraulic Wastewater Loading Rates to Soil. In On-Site Wastewater Treatment: I Proceedings of the Ninth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p 80-86.

Onsite wastewater infiltration rate into soil depends on the nature of soil clogging and soil characteristics. The rate of transmission of the infiltrated water through the soil away from the infiltration surface when a vertical flow restriction is present depends on the characteristics of the soil, depth of the permeable soil horizon and the slope. A single table is presented to estimate design infiltration loading and hydraulic linear loading rates for onsite wastewater treatment systems using soil.

Tyler E.J., and J.C. Converse. 1989. Hydraulic Loading Based Upon Wastewater Effluent Quality. In Proceedings Sixth Northwest On-Site Wastewater Treatment Short Course, College of Engineering, University of Washington, Seattle, 1989. p. 163-172.

Four phases of soil clogging are identified and discussed. These phases are identified as phrase 1, the period when the infiltration rate of the natural soil is maintained; phrase 2, the period in which the clogging layer begins to form and intensifies; phrase 3, the period when the clogging mat accepts wastewater at a rate that is acceptable for wastewater absorption systems; phase, 4 failure. The time that each of these phases exists may depend on the wastewater quality applied. It is noted that changes in infiltration are related to cumulative BOD and SS loading and not just to the hydraulic loading. It appears that pretreated effluent of high quality can be applied at higher rates than septic tank effluents. However, it is impossible to predict effluent loading rate for intermediate strengths of pretreated wastewater effluents.

Tyler E.J., and J.C. Converse. 1994. Soil Acceptance of Onsite Wastewater as Affected by Soil Morphology and Wastewater Quality. In On-Site Wastewater Treatment: Proceedings of the Seventh International Symposium On Individual and Small Community Sewage Systems. ASAE. St. Joseph, MI. p. 185-194.

Maximum possible soil acceptance of on-site septic tank effluent is less than the saturated hydraulic conductivity or infiltration rate of the natural soil. Reduced wastewater infiltration rates are caused by alternation of soil porosity or pore size distribution form construction activities, soil swelling, and dispersion form added wastewater, and the plugging of soil pores by organisms and their metabolic byproducts. Soil without free drainage or with high groundwater has reduced hydraulic gradient and reduced infiltration but is not considered in this report. Reducing organic materials with wastewater pretreatment systems reduces soil pore plugging and has the potential for higher long-term infiltration or loading rates. Loading rates of pretreated wastewater in sands can be increased more than in clayey soil. Wastewater loading rates are suggested considering wastewater quality and soil factors. Rates for highly pretreated wastewaters might be 2 to 16 times greater than rates recommended for septic tank effluent. High loading rates, however, reduce the wastewater retention time and therefore wastewater treatment in soil. In the event a pretreatment system fails to deliver highly pretreated wastewaters to the soil, it is likely that a rapid hydraulic failure of the soil systems will occur.

Tyler E.J., J.C. Converse and J.R. Key. 1995. Soil Acceptance of Wastewater Affected by Wastewater Quality. In Proceedings Eighth Northwest On-Site Wastewater Treatment Short Course, College of Engineering, University of Washington, Seattle, WA. p. 96-109.

Reducing organic materials with wastewater pretreatment systems reduces soil pore plugging and has the potential for higher long-term infiltration or loading rates. Loading rates of pretreated wastewater in sands can be increased more than in clayey soil. Wastewater loading rates are suggested considering wastewater quality and soil factors. Rates for highly pretreated wastewater might be 2 to 16 times greater than rates recommended for septic tank effluent. Higher loading rates, however, reduce the wastewater retention time and therefore wastewater treatment in soil. In the event a pretreatment system fails to deliver highly pretreated wastewater to the soil, it is likely that a rapid hydraulic failure of the soil system will occur.

Tyler E.J., E.M. Drozd, and J.O. Peterson. 1991. Estimating Wastewater Loading Rates Using Soil Morphological Description. In On-Site Wastewater Treatment: Proceedings of the Sixth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p 192-200.

A procedure for establishing design loading rates for subsurface wastewater infiltration systems based solely on field description of soil texture, structure, and consistence is being instituted in Wisconsin. To translate from morphology to loading rates, a sequence of questions is posed. The first question of the sequence with a positive response corresponds to an acceptable predicted loading rate based on treatment and disposal criteria. One group of questions contains criteria which predict soil hydraulic properties unsuited for acceptance of wastewater. The remainder establish design loading rates from 0.8 cm/day (0.2 gpd/ft^2) to 3.3 cm/day (0.8 gpd/ft^2) based on soil texture and structure. The

procedure has been reviewed by hundreds of field personnel while it was being used for training of soil and site evaluators. The procedures have been through public hearings in Wisconsin as part of the process for inclusion in Administrative Rules. A version of this procedure was included in the Wisconsin Administrative Code July 1, 1991 to replace the percolation test after a three year phase out of the use of the percolation test.

Tyler E.J., M. Milner and J.C. Converse. 1993. Soil Acceptance of Wastewaters From Chamber and Gravel Infiltration Systems. University of Wisconsin-Madison, SSWMP Publication. 12 pages.

Wastewater ponding depths and infiltration rates for chamber and gravel cells approximately 90 cm wide by 180 cm long simulating full-sized wastewater infiltration systems have been determined for more than 4 years. Three chamber systems and three gravel trenches have been installed in a sand and silt loam soil. The actual loading rates of domestic septic tank effluent are 4.2 cm/day (1.0 gpd/ft^2) and 2.5 cm/day (0.6 gpd/ft^2) for the sand and the silt-loam soils, respectively. In all ponded trenches, wastewater depth is frequently measured. Infiltration rates are periodically determined using a constant head infiltrometer in the silt-loam soil and by measuring rate of decreasing wastewater ponding height in the sand soil systems. There is no ponding in the chamber or gravel trenches in the silt loam soil and infiltration rates remain much higher than the long-term acceptance infiltration rate for each cell type. The within cell type variability is too great to establish differences between cell types. Ponding of wastewater occurred within the first year of operation in all chamber and gravel cells installed in sand soil and depths fluctuated seasonally with maximum ponding depths during the winter. Ponding depths generally increased each year.

U.S. EPA . 1980. Onsite Wastewater Treatment and Disposal Systems: Design Manual. EPA 625/1-80-012. U.S. EPA, Cincinnati, OH. p. 211-215.

This document provides information on standard types of on-site wastewater treatment and disposal systems. The design information presented is intended as technical guidance reflective of sound, professional practice. The intended audience for the manual includes those involved in the design, construction, operation, maintenance, and regulation of on-site systems. Major topics considered include site evaluation procedures, wastewater characteristics and modification, on-site treatment and disposal methods, residuals disposal and management of on-site systems.

Van Cuyk, S. and R.L. Siegrist. 2001. Pathogen Fate in Wastewater Soil Absorption Systems as Affected by Effluent Quality and Soil Clogging Genesis. In On-Site Wastewater Treatment: Proceedings of the Ninth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 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., R.L. Siegrist, A. Logan, S. Masson, E. Fischer and L. Figueroa. 2001. Hydraulic and Purification Behaviors and Their Interactions During Wastewater Treatment in Soil Infiltration Systems. Water Research. 35(4): 953-964.

Four three-dimensional lysimeters were established in a pilot laboratory with the same medium sand and either an aggregate-laden (AL) or aggregate-free (AF) infiltration surface and a 60- or 90-cm soil vadose zone depth to depth to ground water. During 48 weeks of operation, each lysimeter was dosed 4 times daily with septic tank effluent (STE) at 5 cm/d (AL) or 8.4 cm/d (AF). Weekly monitoring was done to characterize the STE, percolate flow and composition, water content distribution within the lysimeters. Bromide tracer tests were completed at weeks 0, 8, and 45 and during the latter two times, ice nucleating active (INA) bacteria and MS-2 and PRD-1 bacteriophages were used as bacterial and viral surrogates. After 48 weeks, soil cores were collected and analyzed for chemical and microbial properties. The observations made during this study revealed a dynamic, interactive behavior for hydraulic and purification process that were similar for all four lysimeters. Media utilization and bromide retention times increased during the first two months of operation with the median bromide breakthrough exceeding one day at start-up and increasing to two days or more. Purification process were gradually established over four months or longer, after which there were high removal efficiencies (>90%) for organic constituents, microorganisms, and virus, but only limited removal of nutrients. Soil core analyses revealed high biogeochemical activity with the infiltrative zone form 0 to 15cm depth. All four lysimeters exhibited comparable behavior and there were no significant differences in performance attributable to infiltrative surface character or soil depth. It is speculated that the comparable performance is due to a similar and sufficient degree of soil clogging genesis coupled with bioprocesses that effectively purified the wastewater effluent given the adequate retention times and high volumetric utilization's of the sand media.

Vandevivere, P. and P. Baveye. 1992. Saturated Hydraulic Conductivity Reduction caused by Aerobic Bacteria in Sand Columns, Soil Science Society of America Journal. 56(1);1-13

Bacterial reductions of the saturated hydraulic conductivity, K_s , of natural porous media have been traditionally associated with the development of anaerobic conditions and the production of large amounts of extracellular polymers by the bacteria. Various researchers have also reported that these reductions occur predominantly at or very near the surfaces of injection of nutrients within the porous media. Attempts to describe mathematically the resulting clogging process have, in the past, been based on the assumption that bacteria cells form impermeable biofilms uniformly covering pore walls. A series of percolation experiments was carried out to determine the extent to which an obligately aerobic bacterial strain, *Arthrobacter* sp.;' is able to clog permeameters filled with fine sand. A second objective was to elucidate the mechanism(s) responsible for this process. The experimental results indicate that strictly aerobic bacteria are able to reduce K_s by up to four orders of magnitude. Rapid reductions in K_s are associated with the formation of a bacterial mat at the inlet boundary of the sand columns. When the colonization of the inlet is prevented, clogging proceeds within the bulk of the sand at a noticeably slower rate. Under O_2 or glucose-limited growth conditions, this decrease in K_s within the sand does not appear on scanning electron micrographs to be caused by exopolymers, which are entirely absent, but rather seems to be due to the presence of large aggregates of the cells that form local plugs within the pores. Under conditions of severe N limitation, the same mechanism seems to be largely responsible for the observed clogging, in spite of the production by the cells of extracellular substances, visible under light microscopy and on scanning electron micrographs. In all cases, the coverage of the solids surfaces by the bacteria cells is sparse and heterogeneous, contrary to the basic tenets of the biofilm model.

Vepraskas, M.J., W.R. Guertal, H.J. Kleiss and A. Amoozegar. 1996. Porosity Factors that Control the Hydraulic Conductivity of Soil-Saprolite Transition Zones. Soil Science Society of America Journal. 60: 192-199.

Ver Hey, M.E. and W.W. Woessner. 1987. Documentation of the Degree of Waste Treatment Provided by Septic Systems, Vadose Zone and Aquifer In Intermontane Soils Underlain by Sand and Gravel. In On-Site Wastewater Treatment: Proceedings of the Fifth National Symposium On Individual and Small Community Sewage Systems. ASAE, St. Joseph, MI. p. 77-93.

Focus of this study lies in documenting the effectiveness of the septic tank, drainfield, vadose zone, and the groundwater system in treating septic system wastes that are applied to the coarse soils of the northwestern alluvial valleys. It was found that the traditional septic system design is ineffective in treating domestic wastes in these soils. Reason given are lack of appreciable retention time, large interstitial pore spaces, minimal exchange sites below the drainfield, coliforms found in all down gradient wells, and the fact that only a small portion of the drainfield area is used for effluent treatment.

Vervoot, R.W., D.E. Radcliffe, and L.T. West. 1999. Soil Structure Development and Preferential Solute Flow. Water Resources Research. 35(4): 913-928.

Winneberger, J.T. 1984. Septic-tank Systems, A Consultant Toolkit. Butterworth Publishers, Boston, MA. pp. 222.