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Soil Acceptance of Onsite Wastewater as Affected by Soil Morphology and Wastewater Quality

by

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SOIL ACCEPTANCE OF ONSITE WASTEWATER AS AFFECTED BY SOIL MORPHOLOGY AND WASTEWATER QUALITY

E. Jerry Tyler, James C. Converse*

ABSTRACT

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 alteration of soil porosity or pore size distribution from construction activities, soil swelling and dispersion from 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. 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 wastewaters to the soil, it is likely that a rapid hydraulic failure of the soil systems will occur.

Keywords: Soil acceptance, septic tank effluent, pretreated effluents

INTRODUCTION

Soil wastewater infiltration systems receiving septic tank effluent commonly form a layer of material at the soil infiltrative surface with pores finer than the underlying soil. This layer may be partly due to alteration of the soil by construction or materials used in construction and by soil swelling, but is primarily the result of accumulation of biological substances. This fine-pored layer, often referred to as *crusting* or *clogging*, resists wastewater infiltration. The net flux of wastewater through the clogged soil system is much lower than for soil without clogging.

Careful construction procedures with good materials, along with methods to highly pretreat wastewater prior to soil infiltration, can reduce or eliminate clogging. Higher wastewater loading rates can be applied to soil when the potential for clogging is eliminated.

Although on-site wastewater treatment methods can achieve drinking or surface water standards without soil infiltration, there is reluctance to discharge these effluents to surface waters or to recycle the treated water for reuse on-site. This reluctance may result from a belief that treatment will not be adequate or that intermittent failures will occur. Therefore, highly pretreated wastewaters are added to land through soil infiltration and the soil remains the buffer to the environment and insurance against the spread of disease. Wastewater infiltration systems sized to receive highly pretreated effluent have a greater risk of failure due to rapid development of a

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severe clogging mat if the pretreatment unit fails and delivers low-quality wastewater to the soil. Also, high loading rates lead to reduced wastewater retention time in soil, reducing treatment of wastewater pollutants and allowing pollutants, such as coliforms, to move outside the treatment boundaries of the system.

This paper discusses the implications of soil clogging, the potential for increased loading rates using highly pretreated wastewaters, the need for careful construction, and the consequences should wastewaters of higher than design pollutant concentration be added to the soil.

WASTEWATER FLOW IN SOIL

Water moves in soil from a point of higher potential energy to a point of lower potential energy. In saturated soil, the gravity potential is the significant component of energy driving the water. Water moves toward the center of the earth in response to the gravity potential. During unsaturated flow, as around many clogged wastewater infiltration systems, both gravity and matric or capillary forces define potential energy differences in the soil. Matric potential energy differences can move water in all directions depending on the moisture gradient. Usually, matric forces move water from wetter to drier soil.

The constant between the flow rate, Q, and the potential energy gradient is the hydraulic conductivity or K as defined by Darcy's Law,

$$Q=KA\frac{d\psi}{dZ}$$

where Q is flow rate, K is hydraulic conductivity, A is cross-sectional flow area and $d\psi/dZ$ is hydraulic gradient. The hydraulic conductivity is a constant for a given soil and moisture status. When the soil is saturated and all pores are water filled, K is higher than for the same soil unsaturated. The relationship of the hydraulic conductivity and soil moisture potential for a sandy soil and a clayey soil is shown in Fig. 1. Unsaturated soils have fewer water-filled pores to conduct water and therefore a lower K; the drier the soil, the lower the K. Each soil has a unique saturated and unsaturated hydraulic conductivity for each moisture potential. When defining K values for soil, the moisture conditions must be defined.

As wastewater infiltrates the soil, a thin layer of material may develop that has pores finer than the underlying soil. This layer restricts wastewater infiltration and induces unsaturated soil conditions. The more intense the clogging the lower the pressure potential and hydraulic conductivity of the soil (Fig. 1). Wastewater infiltration rates depend on both the clogging layer and the soil. Flow through a clogging layer in a given soil depends on the height of ponding in the aggregate or chamber above the clogging layer, the thickness of the clogging layer, the hydraulic conductivity of the clogging layer, and the moisture pressure in the soil beneath the clogging layer (Bouma, 1975). Assuming steady infiltration, the flux through the clogging (q_c) is equal to the flux in the soil (q_s). Therefore:

$$q_s=q_c=K_{s(\psi m)}=K_c\left(\frac{H_o+\psi_m+Z_c}{Z_c}\right)$$

where $K_{s(\psi m)}$ is the hydraulic conductivity of the soil at the unsaturated moisture potential of the soil beneath the clogging mat, K_c is the hydraulic conductivity of the clogging layer, H_o is the wastewater ponding height in the aggregate or chamber, ψ_m is the matric potential of the soil next to the clogging, and Z_c is the thickness of the clogging layer. Omitting some of the equalities gives

$$q_s = K_c\left(\frac{H_o + \psi_m + Z_c}{Z_c}\right)$$

Decreasing Z_c or increasing K_c, or both, increases the flux of wastewater or the wastewater loading rate that can be applied to the soil. Therefore, assuming free drainage of the surrounding soil, factors reducing clogging in the soil allow an increase in the loading rate. Lack of a clogging layer allows wastewater application rates equal to the saturated hydraulic conductivity of the soil, assuming the soil is free draining. This discussion will not consider cases of shallow groundwater or shallow restricting horizons that prevent free drainage.

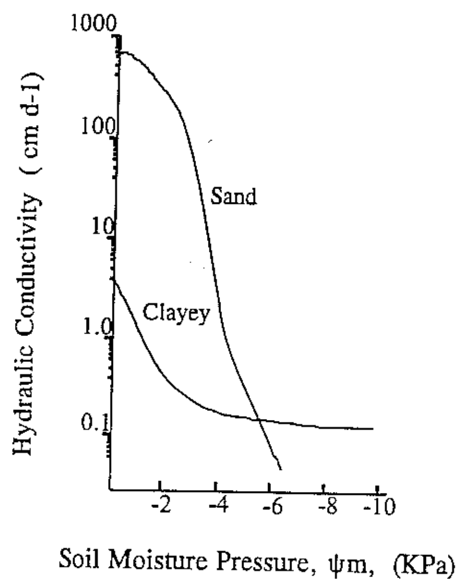

Figure 1. Hydraulic Conductivity vs. Soil Moisture Pressure for a Sandy and Clayey Soil (adapted from Bouma, 1975).

The unclogged infiltration rate or saturated hydraulic conductivity, $K_{s(\psi m=0)}$ of sandy soil, as seen at ψ_m = zero in Fig. 1, is much higher than the unclogged infiltration rate or saturated hydraulic conductivity of clayey soil. However, the clogged infiltration rates or hydraulic conductivities near ψ_m= -5 kPa are very similar for the two soils. The difference between the saturated flow rate and the clogged soil flow rate is much greater in sandy than clayey soil; therefore, the potential increase in loading rate in sandy soil using pretreated wastewater is greater than in clayey soil when compared to applying septic tank effluent.

CLOGGING

A clogging layer, or zone of lower porosity than the underlying soil, may develop at the infiltrative surface from smearing and compaction of soil by machines, the impact of falling aggregate, dust from dirty aggregate, swelling of soil minerals, suspended solids from wastewater, or biomass from organisms living on wastewater constituents. Products of bacterial growth in a carefully installed wastewater disposal system are probably the primary cause of soil clogging. Entrapment of gases may contribute to reduced flow around systems.

Soil smearing at an infiltration surface results from machine shear forces in moist or wet fine textured soil. Schoenemann (1980) showed that careful excavation of soil from over an infiltration surface using a tractor mounted backhoe resulted in infiltration rates similar to surfaces prepared carefully by hand. In that study, the use of machinery to prepare infiltration surfaces was determined to be an acceptable procedure.

Compaction forces, primarily from the weight of the machinery, results in decreased porosity if applied when soil moisture is at an intermediate level. Reduced infiltration resulted from driving a tractor on a soil infiltration surface in silt loam and clayey soils (Schoenemann, 1980). Removal of the top 10 cm of compacted soil recovered the initial infiltration rate in some cases.

In a study of falling aggregate and the dust often found attached to the aggregate, infiltration rates were significantly reduced in sandy and silt loam soils when all factors of falling aggregate, dust, and shadowing of gravel on the soil were combined (Amerson et al., 1991). In that study it appeared that the dust from aggregate used in the preparation of infiltration surfaces was a major factor in changes in infiltration. Salts, such as those from water softener backwash, are unlikely to reduce infiltration rates in clogged wastewater infiltration systems but reduced infiltration is possible in unclogged soil (Corey et al., 1978).

Organic materials, measured as biological oxygen demand (BOD) and suspended solids (SS) in wastewater, is substrate for microorganisms. The more organic substrate provided by the wastewater, the more cells and associated fibers and slimes are produced. Cells of microorganisms have been shown to physically fill the pores in the soil reducing the porosity and hydraulic conductivity (Vandevivere and Baveye, 1992). The processes of biological soil clogging formation including the natural environmental conditions and those induced by the addition of wastewater have been reviewed by Otis (1985) and Siegrist (1987b).

Although formation of clogging from construction practices and material, or swelling of soil clays may reduce the initial infiltration, the reduction is not as great as that induced by biological clogging. However, if biological clogging is eliminated, as with highly pretreated effluent, and wastewater loading rates are increased, then the importance of these factors increases. At high loading rates more attention needs to be paid to construction practices and material and the addition of hydrolyzable cation loading from water softener backwash.

LOADING RATE

As a volume of wastewater is added over time to soil, infiltration rates decrease to a percentage of the initial rates and remain at that level for an extended period. The relationship of wastewater application and infiltration rate is shown in Fig. 2. Line A represents wastewater with very high BOD and SS. As clogging initiates, infiltration rates decrease, Phase II, and continue to decrease to a very small percentage of the initial rate, Phase III, and then finally decrease to failure, Phase IV (Otis, 1985). These stages of clogging development are related to infiltration rates in Fig. 2.

Line B depicts these phases of clogging development for domestic septic tank effluent. Wastewater may continue to infiltrate for long periods of time at low rates in Phase III and is often referred to as the *long-term loading rate*. The higher the rate of application of organic matter, the faster the clogging mat develops. High organic matter application 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 amounts of organic matter.

The combination of wastewater quality, initial soil infiltration rate, actual loading rate, soil infiltration rate measured periodically, and final infiltration rate are seldom all reported in one study. Therefore, it is very difficult to determine the relationships among all soil conditions, wastewater characteristics, and infiltration rates. In a review, Tyler and Converse (1989) discussed the influence wastewater quality has on long-term infiltration rates. They concluded that very highly pretreated wastewater effluents could be applied at higher loading rates than septic tank effluent and possibly at rates equal to the soil saturated hydraulic conductivity. However, it was impossible to predict effluent loading rates for intermediate strengths of pretreated wastewaters. Loading could be as high as Phase I infiltration for clean wastewaters but for all other wastewaters Phase III infiltration rates would be needed.

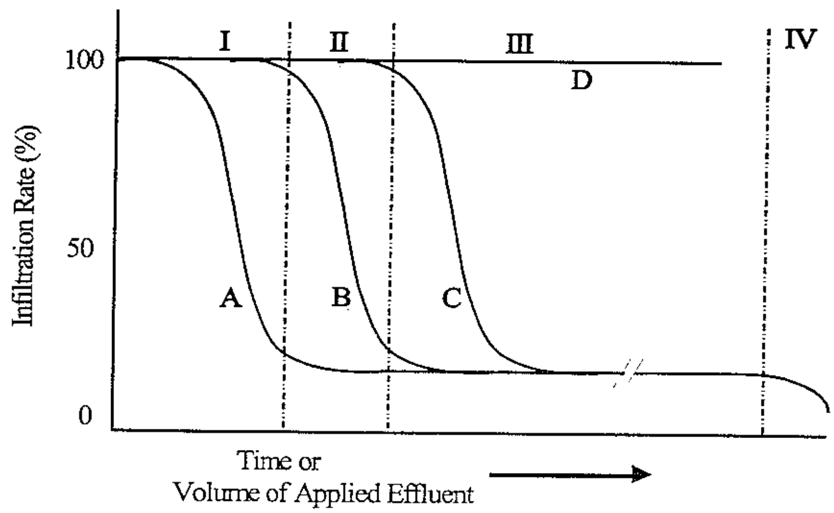

Figure 2. Infiltration vs. Time for Restaurant Effluent (A), Graywater (C), and Tap Water (D). Roman numerals refer to System B phases. (adapted from Siegrist, 1987).

Siegrist (1987a) found that septic tank effluent and graywater, as depicted by Curves B and C in Fig. 2, caused reduced infiltration rates as a clogging layer developed. Although the time of initiation of Phase II clogging was different for the wastewater types, the decrease in infiltration rates was similar. When based on BOD and SS loading instead of wastewater volume loading, the curves are more similar, suggesting that changes in infiltration are also related to cumulative BOD and SS loading and not just hydraulic loading. Results agree with findings of Laak (1976).

Long-term infiltration rates for septic tank effluent are usually in the range of the loading rates prescribed by administrative rules and codes. For example, for sandy soil in central Wisconsin infiltration rates of about 1.7 cm d^{-1} have been measured in trenches ponded with wastewater (Tyler et al., 1991b). This value is similar to the loading rate of 2.5 cm d^{-1} used in administrative code. In silt loam soil, infiltration rates of ponded systems were about 2.5 cm d^{-1} (Hargett et al. 1982). In the southern United States, higher loading rates are reported, probably because of the warmer temperatures.

Recently, wastewater loading rates have been based on soil morphology descriptions. Table 1, adapted from Tyler et al. (1991a), provides a procedure for estimating septic tank effluent wastewater loading rates. Question A identifies those soils offering little treatment and which therefore would not be used for the infiltration of septic tank effluent as indicated by the 0.0 cm d^{-1} loading rate. Questions B through F identify those soils that have very slow vertical conductivity and cannot accept precipitation and therefore additional water cannot be added. These soils frequently are seasonally saturated with natural waters and have morphological features associated with wetness.

Questions G through N identify those soil horizons that will accept the natural precipitation and have additional capacity to accept wastewater. Soil horizons within categories G through I can accept low loading rates. During wet periods these soils are naturally very wet. With a clogging mat, as might develop with the application of septic tank effluent, infiltration is reduced but by a relatively small amount compared with the saturated hydraulic conductivity. This would be similar to changes in K as the moisture pressure decreased from 0 to about -5 kPa represented by the clayey soil line in Fig. 1. For a clogging mat in a sandy soil and other soils of categories K through N in Table 1, inducing a soil moisture pressure of -5 kPa can reduce hydraulic conductivity or infiltration rate a great amount from the initial high saturated values. Therefore, there is some hydraulic advantage to reducing the clogging in soils of categories G through I. The potential for increased loading rate in soils of categories L and N is much greater than for categories G through I. Those soils in categories J, K and M would have intermediate increased loading rates.

Wastewater effluent from treatment units that result in reduced organic materials or pure water, as used as a control in research, do not have reduced infiltration rates. For example, in the study of Siegrist (1987a) tap water did not reduce the initial infiltration rate after 6 yr of application. This is similar to Line D in Fig. 2. Sand filter and aeration unit effluent may have similar results since such units produce effluents of very low organic matter. Maintenance of high infiltration rates for extended periods of time suggests the lack of clogging and higher loading rates.

Based on wastewater pollutant loadings, Siegrist (1987b) proposed adjusting wastewater loading volume rates to soil depending on the concentration of BOD and SS. Using septic tank effluent and a soil with an estimated loading rate of 1.0 cm d^{-1}, he proposed factors of 0.4 for restaurant septic tank effluent, 4.5 for aeration effluent, and 7.5 for sand filter effluent. Line A in Fig. 2 represents the restaurant system, Line B the septic tank system, Line C a graywater system, and Line D clear water or highly pretreated wastewaters. For a soil with a design infiltration rate for septic tank effluent other than 1.0 cm d^{-1}, the proportional amount would be used.

Using only the factor of 7.5 proposed by Siegrist (1987b), loading rates for sand filter effluent with BOD and SS of less than 10 mg L^{-1} each are shown in Table 1. He cautioned that factors for establishing loading rates for sand filter effluent should not be used if the determined loading rate would approach the saturated hydraulic conductivity of the soil. Soils whose loading rate would approach saturated hydraulic conductivity with septic tank effluent would be those in categories G through I in Table 1. Siegrist (1987b) also suggested that the loading rates be only 2 to 3% of the saturated hydraulic conductivity of the soil. Using this criterion on the saturated hydraulic conductivity estimated from USEPA (1991), loading rate estimates would be too high for some soil categories. It should be noted that saturated hydraulic conductivity estimates are intended to represent a possible conductivity. Soil hydraulic conductivities are highly variable.

Table 1. Loading rate from soil morphological descriptions for septic tank effluent (Tyler et al., 1991a), sand filter effluent based on Siegrist (1987b) and this paper, and estimated maximum saturated hydraulic conductivity (K) from USEPA (1991). Values have not been tested and should be confirmed before use. *Instructions*: Read questions in sequence beginning with A. The maximum loading rate in cm d^{-1} is the value corresponding to the first yes response to the questions.

	Question	Loading Rate[a] Septic: Tyler et al. (1991a)	Loading Rate[a] Sand Filter: Siegrist (1987b)	Loading Rate[a] Sand Filter: This work	Sat. K USEPA (1991)
		------ cm d^{-1} ------			
A	Is the horizon gravelly coarse sand or coarser?	0	0	0	>1000
B	Is the structure of the horizon moderate or strong platy?	0	0	0	<5
C	Is the texture of the horizon sandy clay loam, clay loam, silty clay loam or finer and structure weak platy?	0	0	0	<5
D	Is the moist consistence stronger than firm or any cemented class?	0	0	0	<5
E	Is the texture sandy clay, clay or silty clay of high clay content and structure massive or weak?	0	0	0	<5
F	Is the texture sandy clay loam, clay loam, silty clay loam or silt loam and structure massive?	0	0	0	<5
G	Is the texture of the horizon loam or sandy loam and the soil structure massive?	0.8	6	2	5
H	Is texture sandy clay, clay or silty clay of low clay content and structure moderate or strong?	0.8	6	2	5
I	Is texture sandy clay loam, clay loam or silty clay loam and structure weak?	0.8	6	2	5
J	Is texture sandy clay loam, clay loam or silty clay loam and structure moderate or strong?	1.7	13	6	50
K	Is texture sandy loam, loam, or silt loam and structure weak?	1.7	13	6	50
L	Is texture sandy loam, loam or silt loam and structure moderate or strong?	2.5	19	20	50
M	Is texture fine sand, very fine sand, loamy fine sand, or loamy very fine sand?	1.7	13	6	100
N	Is texture coarse sand, loamy sand or sand?	3.3	25	53	1000

[a]Does not account for soil with appreciable amounts of swelling clays.

It might be better to establish the ideal moisture content of the soil surrounding an operating wastewater infiltration system and then estimate the unsaturated hydraulic conductivity and therefore the loading rate. This would provide assurance of aeration. Unfortunately, the ideal moisture content would be as low as possible increasing retention time and treatment. Possibly all systems should be designed to operate at a soil matric pressure -2 kPa at 1 cm from the infiltration surface. The *K*, and therefore the loading rate, might be estimated from curves in Fig. 1. Maintaining unsaturated soil enhances aeration and increases retention time. Since soil hydraulic characteristics are so variable, however, it is very difficult to establish a loading rate based on this.

Using the logic of -2 kPa of soil matric pressure, the loading rate for soil in category N would be 200 cm d^{-1}, estimated from Fig. 1. This is very high and much greater than suggested by Siegrist (1987b). A rate between these values is suggested in Table 1 (column 3). Rates using the factor of Siegrist may be too high for soils in categories G through I which act more like clay in Fig. 1. Using -2 kPa or 3% of the saturated hydraulic conductivity would result in very low loading rates, lower than experience would suggest is necessary even for application of septic tank effluent. Some modest increase in loading rate should be possible and is suggested in Table 1. A factor of 2 was used for categories G through I, 4 for categories J, K, and M; 8 for category L; and 16 for category N (Table 1, column 3).

The third column of values in Table 1 is a possible set of loading rates to consider for highly pretreated wastewaters. These values consider the logic and suggestions of Siegrist (1987b) based on wastewater and soil characteristics procedures of Tyler et al (1991). The greatest reduction in infiltration area for using highly pretreated effluent is for the coarser soils and the least reduction in area is for the more slowly permeable soil. However, the reductions are substantial in all cases.

The analysis of these loading rates assumes that the soil is uniform to considerable depth and that shallow groundwater or flow-restricting horizons are not present. Should there be any flow restrictions within several meters of the infiltration surface, a linear loading rate should be considered. Linear loading rates have been discussed in Tyler and Converse (1984) and are incorporated in design for mounds and at-grades.

The proposed loading rates of Siegrist (1987b) and this paper have not all been tested. Field verification needs to be done before using these values. Siegrist (1987b) stated that even considering the potential for size reductions, caution should be used since wastewater and soils are highly variable. He suggested using conservative design and including a replacement area.

TREATMENT CONSIDERATIONS

The primary reason for discharging pretreated wastewaters to soil is for treatment of wastewater pollutants. 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. Because of the pretreatment, not only are constituents resulting in clogging reduced, but many of the environmental and health pollutants are reduced. Therefore, the soil is required to do less treatment than if untreated 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.

CONSEQUENCES OF PRETREATMENT FAILURE

Using design loading rates higher than domestic septic tank effluent following pretreatment units is logical. Maintaining the wastewater infiltrative surface in the soil is dependent on never exceeding the design hydraulic or BOD and SS loading rate. Design and maintenance procedures must assure that only the highly pretreated wastewaters reach the soil. Although rejuvenation of clogged and failed infiltration systems has been noted (Converse and Tyler, 1994), this has been accomplished with pretreated wastewater loaded at rates of septic tank effluent. Rejuvenation of a soil infiltration surface following clogging due to severe overloading may be difficult.

CONCLUSIONS

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. Rates for highly pretreated wastewaters might be 2 to 16 times greater than rates recommended for septic tank effluent. The higher the loading rate the more attention needs to be paid to construction practices and materials, and the addition of hydrolyzable cations. 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 wastewaters to the soil, it is likely that a rapid hydraulic failure of the soil system will occur.

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