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SMALL SCALE WASTE MANAGEMENT PROJECT

Predicting Life for Wastewater Absorption Systems

by

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MARCH 1998

Taken from On-site Wastewater Treatment, Proceedings of the Eighth National Symposium on Individual and Small Community Sewage Systems, ASAE Publication 03-98. American Society of Agricultural Engineers, Orlando, Fl. 1998 pp. 167-176.

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Predicting Life For Wastewater Absorption Systems

J.R. Keys, E.J. Tyler, and J.C. Converse*

ABSTRACT

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 falling head infiltration rates to determine basal area and sidewall conductivities were measured and incorporated in the model to predict loading rates and flow from within the systems.

Gravel filled systems in these sand soils have a predicted life of 11 years when loaded basally at 1.6 cm d^{-1}. The ponding depths of wastewater were found to increase an average of 27 mm yr^{-1}. At a higher loading rate of 4.1 cm d^{-1}, the expected life was 7 years and the average ponding depth increase of 44 mm yr^{-1}. 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 biologically 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^{-1}.

From the model we determined that "new" upper sidewall soil was needed for infiltration at a basal loading rate of 1.6 cm d^{-1}. The additional sidewall needed to infiltrate wastewater not passing through the basal area agrees with the observed increase in ponding depth over time.

We found that the matted sidewall and lip are 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, and should not be ignored or downsized.

A systems life is limited by sidewall height and the conductivities of 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.

Keywords: Conductivity, Disposal, Effluent, Infiltration, Soil.

INTRODUCTION

The gravel trench of an onsite wastewater treatment system provides temporary storage and exposes an infiltration surface where the wastewater can enter the soil. In time, the soil infiltration surface may become biologically clogged, reducing the infiltrative capacity. If the wastewater loading rate exceeds the infiltrative capacity of the trench basal area, effluent will pond in the gravel voids and wastewater will contact the sidewall. As wastewater infiltrates sidewall, the sidewall soil will progressively clog and continue to develop up the sidewall as the ponding depth increases. System life is then limited by the system loading rate, clogged soil infiltration rate and the depth of the trench. If the ponded effluent exceeds the trench height, effluent will back up to the source or surface above the system. Either situation is failure. Failure commonly occurs when the soil moisture is greatest and the hydraulic gradient from the system is smallest.

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Proving the validity of a proposed loading rate is time consuming and expensive, so little long-term (>10 years) field research has been attempted. Ocock and Wright (1912) proposed a domestic wastewater loading rate based upon experience. Others have also proposed loading rates based upon experience and short term testing (< 2-3 years) (Bennett, et al., 1975: Berhart, 1973: Bouma, 1975: Hardenbergh, 1924: Ocock and Wright, 1912: Tyler, et al., 1993). Several studies suggest loading rates lower than currently in use in Wisconsin (Bouma, 1975: Siegrist and Boyle, 1987: Tyler, et al. 1991 and 1993). None of these studies used expected system life as a criteria for their proposed loading rates.

Using Darcy's law, Bouma (1975) described instantaneous infiltration through a clogging mat. He did not relate this to system life either. The objective of this study was to develop a mass-balance model for predict system life and long term loading rates of gravel wastewater infiltration systems on sand soils.

THEORY

The flux, q_s, of wastewater entering the soil is defined by the volume, V, passing through a plane, A, in time, t. The hydraulic gradient, dH/dl, is the head loss per unit length in the direction of wastewater flow and the soil hydraulic conductivity, $K_s(\theta)$ which is a property of the soil and fluid. The relationship is applied to saturated and unsaturated wastewater flow in soil and is illustrated in equation 1 (Bouma, 1975).

$$q_s = V / (A^*t) \quad = K_s(\theta)\ (dH/dl) \tag{1}$$

The biological clogging at the infiltrative surface is saturated when wastewater is ponded above it. The underlying soil is unsaturated. Equation 1 can be applied to the flow through the clogging mat and into the surrounding soil. Since the fluxes are equal ($q_s = q_c$) for each material and assuming the gradient is one then the equations can be combined as in equation 2 (Bouma, 1975):

$$q_c = (K_c/z_c)(H_0 + \Psi_s + z_c) \tag{2}$$

Where q_c is the flux of the crust, z_c is the crust thickness, K_c is the saturated conductivity of the crust, H_0 the ponding height of wastewater in the gravel, and Ψ_s is the soil tension outside the bed or subcrust tension.

These variables are the controlling features of the matted or crusted interface flow (q_c). Since thickness of a clogging mat is difficult to determine, the resistivity of the mat, K_c/z_c, is sometimes used. Because it is difficult to measure variables needed in these equations a direct measure and mass-balance was used in this study.

A cross section of a gravel filled trench is in Figure 1. Along the sides and the bottom of the trench is a black zone between the gravel and soil depicting a clogging zone. As illustrated, wastewater is ponded in the gravel of the trench to a depth, H_0.

The loading rate, Q_{in}, is the volume of wastewater flowing into the system each day (basal loading rate times the basal area). The loading of wastewater added to a ponded system each day is equal to the sum of the infiltration volumes leaving each surface; basal, Q_b; sidewall, Q_{sw}; lip, Q_l; and unclogged soil, Q_{soil}; when the ponding depth is constant given in equation 3. The total surface area for effluent flux from within the trench to the soil matrix was defined as the length times the wetted perimeter.

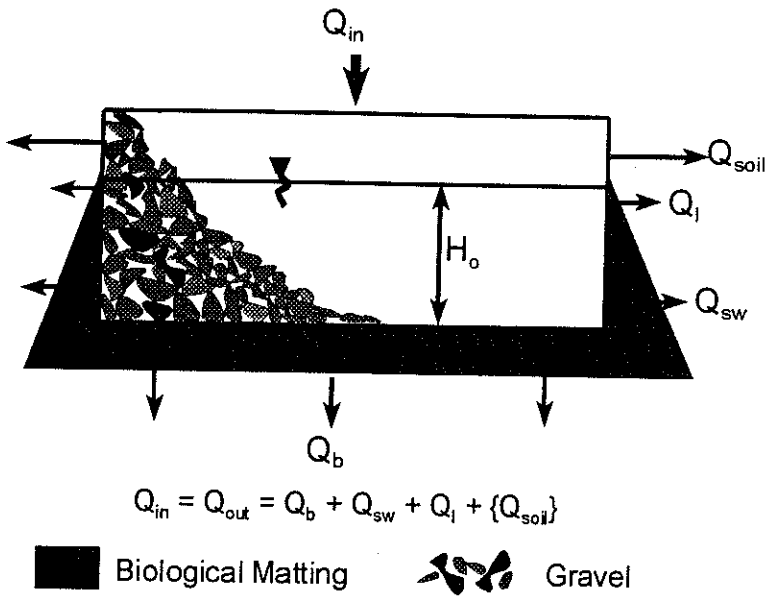

Figure 1. Cross-section of gravel filled trench onsite wastewater infiltration system. The trench has clogging along the base and part way up the sides.

$$Q_{in} = Q_{out} = Q_b + Q_{sw} + Q_l + Q_{soil} \tag{3}$$

If the wastewater added to the system is at a rate either higher or lower than the out flow then the ponding depth will increase or decrease. The mass-balance model determines the size of the trench for a fixed loading rate or the loading rate for a fixed size trench. If the volume in is greater than the volume out, then the height of effluent within the trench increased over time. Therefore, the operational flow of the system surfaces could be determined by measuring the inflow of wastewater while keeping the ponding depth constant or by maintaining constant inflow and measuring changes in ponding depth. These approaches were used in the model and this study.

MATERIALS AND METHODS

Wastewater ponding depths in each of three 1.8 m long by 0.9 m wide infiltration trenches with no flow from the ends were measured using a steel tape. The mature trenches had been loaded with typical household wastewater (BOD_5 = 171, COD = 376, TS = 464, SS = 28, VS = 237, and VSS = 50; mean values in mg L^{-1}) for 10 years. The constant basal loading rate was 4.1 cm d^{-1} from April 1987 to August 1993 and then 1.6 cm d^{-1} to August 1995. Ponding depths (PD) were measured approximately every two weeks from August 1993 to August 1995.

The predicted life is defined by equation 4, where predicted life is PL, failure depth is FD (300 mm for these trenches), and a calculated slope (mm yr^{-1}) or the rate of ponding depth increase. This calculation assumes there was no ponding initially and that there is 300 mm of height for ponding to increase before failure.

$$PL = FD / slope \tag{4}$$

Data collected for calculating the long-term falling head infiltration rate (LTFHIR) were the ponding depths at specific time increments. This was to determine the infiltration rate in the upper biologically matted lip and throughout the sidewall. The variables are ponding depth, time (t), average surface area or wetted perimeter (SA_{avg}), basal width (W), trench length(L) and the volume (V). The ponding depth at time zero ($PD_{t=0}$) and the ponding depth at time one ($PD_{t=1}$) was averaged to give PD_{avg} ($t_1 - t_0 = \Delta t \sim 2$ or 12 hours or days). This was used to calculate the volume infiltrated. Using ponding depth and time, the surface area and volume of effluent are calculated and the long-term falling head infiltration rate could then be determined. For calculations of infiltrative area or wetted perimeter, the height is doubled and added to the basal width times the length of a trench. The long-term falling head infiltration rate is calculated using equations 5 through 7 (fig. 2). The data are given in cm d^{-1}.

$$SA_{avg} = L * (W + 2(PD_{avg})) \quad (5)$$

$$V = L * W * (PD_{avg}) \quad (6)$$

$$LTFHIR = V / (SA_{avg} * \Delta t) \quad (7)$$

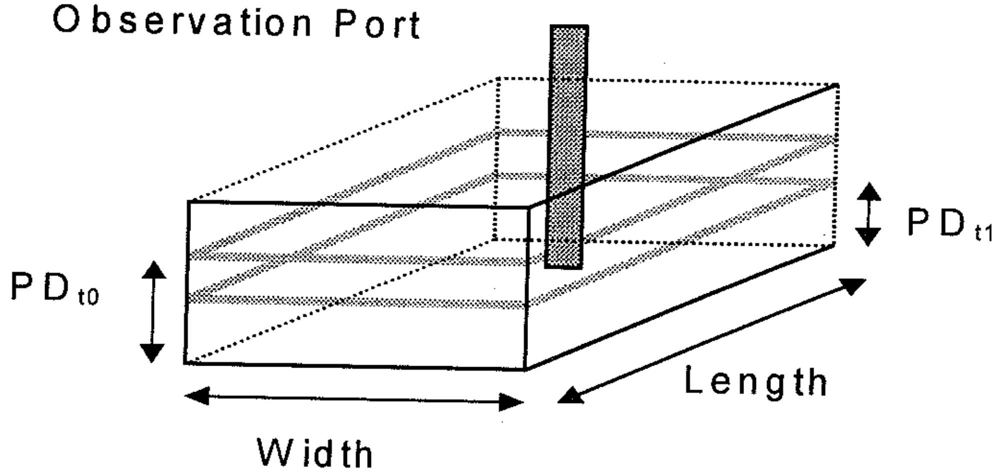

Figure 2. Long term falling head infiltration rate measurements.

Each of the systems tested had at least 190 mm of ponded effluent present. Testing length varied from nine to 23 days for the different replicates. Only infiltration through ponded and biologically matted sidewall is presented.

Before testing, the ponding depth was measured and the volume to raise the height of wastewater within the trench five centimeters was calculated. At time equal to zero, the wastewater was added and measurements were taken at half-hour intervals until the wastewater returned to its original ponding depth. The addition of approximately five centimeters of wastewater was to test the upper un-matted sidewall soil lip and was done only during the first day of testing.

Long-term falling head infiltration rate measurements were taken every 24 hours as the ponding depth dropped until it was approximately 5 cm. This was done to prevent the lower biological mat from drying out.

Crust or biological mat conductivities for the different surface areas were found from the long-term falling head infiltration rate measurements. These estimates of crust or biological mat conductivities for various portions of the system areas were used as mass-balance model variables.

RESULTS AND DISCUSSION

When the trenches were loaded at 4.1 cm d^{-1} from April 1987 to August 1993, ponding depths increased to near 300 mm, the failure depth (Table 1). One trench (replicate C) failed in March of 1993. The failed trench (replicate C) was then allowed to rest for 37 days.

The ponding depths for each replicate increased from zero (April 1987) to the maximum ponding depth (August 1993) reported in table 1. The predicted life of each replicate was calculated using equation 4 with a slope from regression of ponding depth data and time with an intercept of zero. The values calculated are in table 1. The average predicted life was 7 years with an average yearly increase in ponding depth of 44 mm yr^{-1} at a loading rate of 4.1 cm d^{-1}. Ponding depths from April 1987 to August 1993 for the three replications are shown in Figure 3.

Table 1. Predicted life of gravel systems based upon slopes of ponding depths. Replicate C failed in March of 1993.

Replicate	Maximum Ponding Depth (mm)	Slopes (mm yr^{-1})	Predicted Life (years)
	1987 to August 1993 at a LR of 4.1 cm d^{-1}		
A	212	40	9
B	239	40	8
C	300	51	6
Average		**44**	**7**
	1993 to August 1995 at a LR of 1.6 cm d^{-1}		
A	179	22	14
B	203	26	11
C	256	33	10
Average		**27**	**11**

Ponding depths from August of 1993 to August of 1995 for the three replications are shown in Figure 4. No replicates failed at a loading rate of 1.6 cm d^{-1} from August of 1993 to August of 1995. Except for some extreme exceptions when there were mechanical problems, there is a gentle upward trend with time as the ponding depth slowly increases. The data from 1987 to 1993 has a more distinct upward trend when compared with the 1993 to 1995 data.

At a loading rate of 1.6 cm d^{-1} the average predicted life of a system is 11 years with an average yearly increase in ponding depth of 27 mm yr^{-1} (Table 1) assuming that the ponding depth was zero when wastewater was first added. The same regression of ponding depth data was used for this time period. Since the data is variable, R^2 (coefficient of determination) of 0.5 or less, and since the clogging was established under the higher loading rate, the actual life may be somewhat greater than found here.

The difference in predicted life between a loading rate of 4.1 and 1.6 cm d^{-1} is approximately 4 years and a reduction in average yearly ponding depth slope of 17 mm yr^{-1}. This means that as systems are loaded at higher basal loading rates the average life expectancy is reduced. Systems at lower loading rates will have the advantage of greater a functional life than those loaded higher.

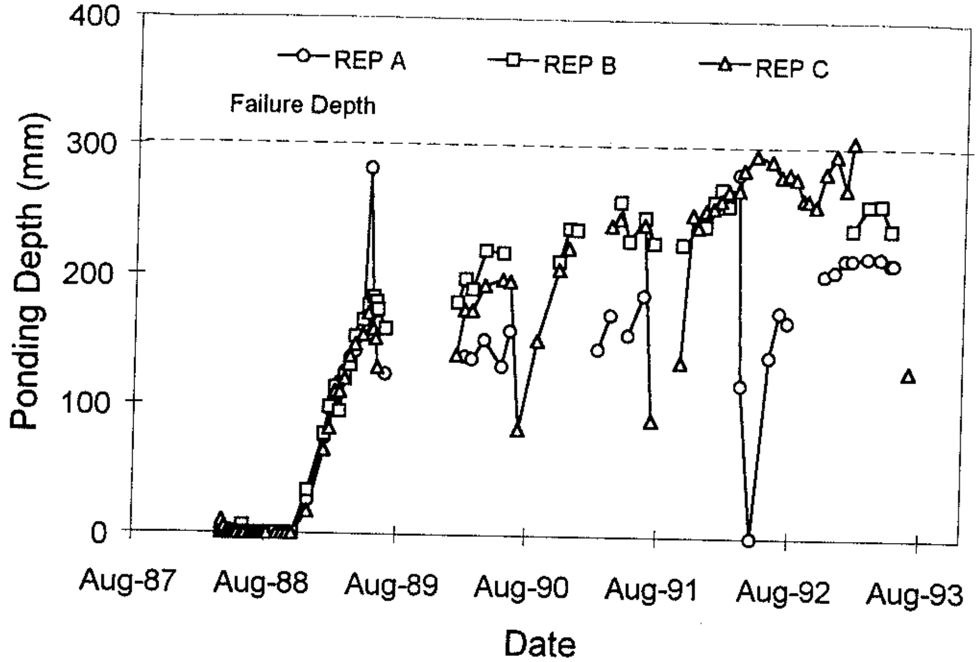

Figure 3. Wastewater ponding depths in three gravel trenches from August 1987 to August 1993. The failure depth of 300mm is shown.

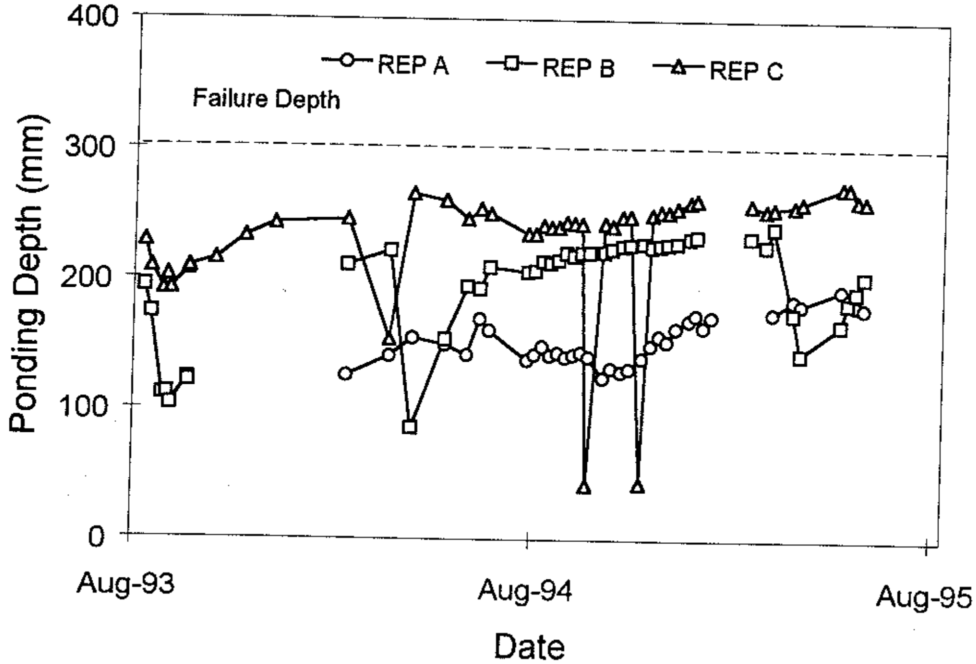

Figure 4. Wastewater ponding depths in three gravel trenches from August 1993 to August 1995. The failure depth of 300mm is shown.

Design loading rates suggested by various authors are in table 2 and range from 2.1 to 5.4 cm d^{-1}. Because of design safety factors, design loading rates are considerable higher than actual loading rates. The initial actual loading rate in this project was 4.1 cm d^{-1} which is higher than the average reported from other authors and the final actual loading rate of 1.6 cm d^{-1} is lower than any design loading rate reported. A rate of 1.6 cm d^{-1} is probably about the actual loading rate of systems installed using the suggested design loading rates of the other authors. A system should be able to handle its design loading rate since that is its maximum expected value but this is probably not the case.

Table 2. Loading rates and predicted life of gravel trenches on sand soil.

Source	Year	Loading Rate ($cm\ d^{-1}$)	Predicted Life (years)
This study	**1997**	**1.6**	**11**
Bernhart	1973	2.1	
Bennett	1975	2.2	
Tyler, et al.	1993	3.3	
Hardenbergh	1924	3.6	
This study	**1997**	**4.1**	**7**
Bouma	1975	5.0	
Ocock and Wright	1912	5.4	

If the loading rates reported in Table 2 were actual loading rates it would be expected that trenches in sand loaded at greater than 4.1cm d^{-1} would have a predicted life of less than 7 years. Those loaded between 1.6 and 4.1 cm d^{-1} would have a predicted life between 7 and 11 years. Additional trenches loaded at various rates would be needed to establish the predicted life with any statistical precision.

Table 3 gives the ranges of conductivities for the biologically matted areas of the replicates found during the long term falling head infiltration rate testing. Measurements above the matted portion in the soil were from 0.80 to 44 cm d^{-1}. We were not physically able to take measurements as fast as the water was dropping, therefore, these values were probably underestimated. The ponding depth or total matted sidewall for replicate B was 210 mm and for replicate C it was 270 mm.

Table 3. Biologically matted conductivities and associated wetted areas for gravel replicates 1.8 m long from the LTFHIR field study.

Replicate	Wetted Area	Dimension (m)	Area (m^2)	Conductivity Range ($cm\ d^{-1}$)
B	Lip (height)	0.01	0.04	0.40 - 0.78
	Sidewall (height)	0.20	0.73	0.05 - 0.40
	Basal (width)	0.91	1.67	0.02 - 0.05
C	Lip (height)	0.01	0.04	0.81 - 2.41
	Sidewall (height)	0.26	0.95	0.05 - 0.81
	Basal (width)	0.91	1.67	0.02 - 0.05

Both replicate B and C had higher conductivities in the lip (upper sidewall) than in the lower sidewall or basal areas. The data from replicate A was not used in the model and is not presented due to high variability and magnitude. A possible explanation for the high conductivity in replicate A is that some bio-mat sloughed off the sidewall creating an area of much higher relative hydraulic conductivity, compared with replicate B and C.

The length of the trench in the mass-balance model was 1 m, the width was 0.9 m, and the height was the ponding depth. Using the conductivities, geometry, and the loading rate, a mass-balance for each system was calculated.

Flow into the system, Q_{in}, is equal to the basal area times the basal loading rate. Flow out of the system, Q_{out}, the sum of Q_b, Q_{sw}, and Q_l, was calculated for each wetted surface area by multiplying surface area by conductivity from table 4.

For the model, the range of conductivities from table 3 and equation 3 were used to calculate if the model replicate was discharging the dosed effluent (Q_{in}) through the wetted area or using new soil. Minimum and maximum values of conductivities were entered into equation 3 to find the flow rates through the various wetted areas and are given in table 4. If the Q_{in} is greater than the subtotal Q_{out} then additional sidewall area soil is needed for mass-balance.

If Q_{in} is less than Q_b then the system will not pond, initially a system behaves this way. As Q_b decreases the sidewall soil is used to make up the differences needed. This sidewall soil will eventually clog, the combination of Q_b and Q_{sw} will decrease and more un-matted sidewall soil will be needed to make up the deficit. With increases in ponding depths over time, the range of conductivities in the matted sidewall will vary from the aerobically exposed lip down through the continuously ponded sidewall. If the combination of Q_b, Q_{sw}, and Q_l is equal to the Q_{in} then there is equilibrium. The system should maintain a steady state ponding depth at this time, although this will not happen though since clogging intensity will increase over time.

Table 4. Conductivities, flow rates, and associated wetted areas for gravel replicates. At a LR of 1.6 cm d^{-1}, the flow rate in to be discharged is **Q_{in} = 14830 cm³ d⁻¹**.

Model Replicate	Location	Area (m^2)	Conductivity (cm d^{-1})	Flow Rate (cm^3 d^{-1})
Minimum	Lip	0.02	0.40	80
PD = 0.21 m	Sidewall	0.40	0.05	200
	Basal	0.91	0.02	180
			Subtotal Q_{out} =	**460**
	Soil	0.01	144	14400
	Total Q_{out} with new sidewall soil used =			**14860**
Maximum	Lip	0.02	2.41	480
PD = 0.21 m	Sidewall	0.40	0.81	3240
	Basal	0.91	0.05	460
			Subtotal Q_{out} =	**4180**
	Soil	0.01	107	10700
	Total Q_{out} with new sidewall soil used =			**14880**

For the minimum case, the difference between Q_{in} (14830 cm^3 d^{-1}) and Q_{out} (460 cm^3 d^{-1}) from the model was positive (14370 cm^3 d^{-1}) which means that additional sidewall area was needed (Table 4). If an additional area (0.01 m^2) of sidewall, 0.005 meters in height, were exposed for infiltration, then the conductivity of this area would only have to be 144 cm d^{-1} to provide the flow deficit needed. This is within the range of conductivities measured for this soil type (Anderson and Bouma, 1977a & b: Baker, 1978: SCS, 1993).

The model can also be used to determine the steady state basal acceptance rate by dividing the calculated flow out by the basal surface area, assuming that the height of effluent is maintained. Using values from table 4, the calculated minimum basal loading rate is 0.05 cm d^{-1}(Q_{out} of 460 cm^3 d^{-1} / 0.91 m^2) and the maximum basal loading rate is

0.46 cm d^{-1}(Q_{out} of 4180 cm^3 d^{-1}/ 0.91 m^2), assuming no "new" soil is used for discharge of wastewater from the replicate.

Sidewall and lip areas account for most of the flow, 60% in the minimum case and 90% in the maximum. This study further stresses the importance of the sidewall in the transmittal of effluent from the replicate into the soil matrix (McGauhey and Winneberger, 1965). This does not mean that the basal area can be ignored or downsized. In the spring or fall when soils are wetter, the gradient will be smaller reducing sidewall flow. The head of effluent effecting the basal area and flow from the basal area will then become more important overall (Otis et al 1977b).

This mass-balance approach in table 4 gives an explanation of flow from a gravel trench into sand soil. Based on this information, design loading rates could be selected to match with desired system life. This example assumes constant wastewater quality and sand soil.

CONCLUSIONS

A gravel wastewater absorption system on sand soil at a loading rate of 1.6 cm d^{-1} has a predicted life of 11 years and a ponding depth increase of 27 mm yr^{-1}. At a loading rate of 4.1 cm d^{-1} the predicted life was reduced to 7 years and the ponding depth increase was 44 mm yr^{-1}. Therefore, as loading rates increase the predicted life of systems decrease. This results because of bio-mat maturation.

A mass-balance model explained increases in ponding depth over time. Model inputs included measured conductivities that ranged from 0.02 to 2.41 cm d^{-1}. It was determined that "new" or additional sidewall soil was needed to meet model conditions for the given loading rate. This agrees with the observed increase in ponding depth over time.

Sidewall is a very important part of transmitting effluent to the soil matrix. The clogged basal and sidewall areas need to accept the applied wastewater or at some point the trench will fill and the system will fail.

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