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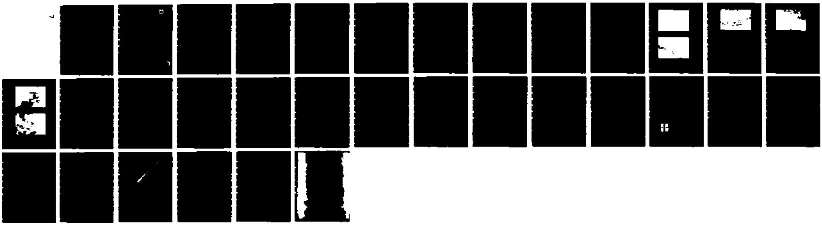

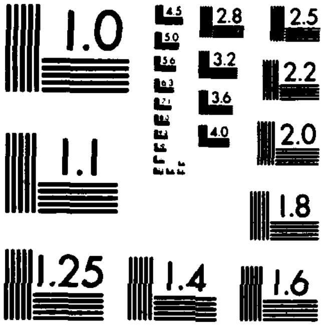

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Special Report 84-11

May 1984

US Army Corps of Engineers

Cold Regions Research &
Engineering Laboratory

Analysis of infiltration results at a proposed North Carolina wastewater treatment site

Gunars Abele and John R. Bouzoun

Prepared for
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A 6-ft-diam flooding infiltration test was conducted at a proposed wastewater land treatment site near Chapel Hill, North Carolina. The saturated infiltration rate of the soil was 0.13 in. hr^{-1}, and the reaeration rate of the saturated soil was equivalent to 1.35 in. of water after six days. A conservative wastewater application rate at this site would be between 1 and 2 in. wk^{-1}.

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PREFACE

This study was conducted by Gunars Abele, Research Civil Engineer, Applied Research Branch and John R. Bouzoun, Research Environmental Engineer, Civil Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

This work was supported by U.S. Army Engineer District, Wilmington, North Carolina, Intra-Army Order SAWEN-DF-81-90. Tom Child, Wilmington District, participated in the field test and coordinated the logistics requirements for this test.

This report was technically reviewed by Sherwood C. Reed and Robert S. Sletten of CRREL.

Appreciation is expressed to John A. Ricard, Corps of Engineers, Falls Resident Office, Neuse, N.C., for his assistance in obtaining the soil samples and in determining the soil properties at the test site.

Jonathan Ingersoll of CRREL conducted the laboratory tests on the soil samples. Dr. Harlan L. McKim, James Martel and Sherwood C. Reed, CRREL, assisted in the interpretation of the test data.

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ILLUSTRATIONS

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NOMENCLATURE

G_s	specific gravity of soil
γ	dry density of soil (g cm^{-3})
w	gravimetric water content (%) $W_w \times W_s^{-1} \times 100$
W_w	weight of water (g)
W_s	dry weight of solids (g)
γ_w	density of water (assume 1 cm^3 = 1 g)
V_T	total volume of soil-water-air matrix (100%)
V_w	volumetric water content (%) $V_w = w (\gamma \times \gamma_w^{-1})$
V_s	volume of solids (%) $V_s = \gamma \times G_s^{-1} \times 100$
V_v	volume of voids (%) $V_v = V_T - V_s$
V_a	volume of air (%) $V_a = V_v - V_w$
S	saturation (%) $S = V_w \times V_v^{-1} \times 100$
z	depth (in.)
Y	cumulative water intake (in.)
ΔY	incremental water intake between two consecutive observations (in.)
Y_u	cumulative intake, unsaturated soil condition (in.)
Y_s	cumulative intake, saturated soil condition (in.)
I	infiltration rate (in. hr^{-1})
I_u	infiltration rate, unsaturated soil condition (in. hr^{-1})
I_s	infiltration rate, saturated soil condition (in. hr^{-1})
t	time (hr)
Δt	time interval between two consecutive observations (hr)
H	height of water applied, head (in.)
h	soil moisture tension (cm of water)

SUMMARY

During 29-30 September 1981, a large-scale (6-ft-diam.) flooding infiltration test was conducted at a representative site in a proposed wastewater land treatment area in North Carolina to determine the infiltration and reaeration rates of the soil. Soil profile characteristics to a depth of 30 in. were determined from samples obtained adjacent to the infiltration test. Tensiometers, installed at various depths, were used to monitor the saturation and reaeration of the soil profile. The infiltration rates for unsaturated and saturated soil conditions were determined from observations of water head drop.

To determine the infiltration rate of the soil in the existing unsaturated condition and to saturate the soil profile, 5.2 in. of water was applied. To determine the saturated infiltration rate of the soil profile, an additional 3.2 in. of water was applied the next day after all of the initial 5.2 in. of water had percolated into the soil.

The saturated infiltration rate, which represents the rate at which water can move through a soil profile (saturated hydraulic conductivity or permeability), was 0.13 in. hr^{-1}. According to the Process Design Manual for Land Treatment of Municipal Wastewater (U.S. EPA et al. 1981), a conservative wastewater application rate for this infiltration rate is between 1 and 2 in. wk^{-1} (between 5 and 10% of the saturated infiltration rate).

The reaeration rate of the saturated soil profile was equivalent to 1.35 in. of water after 6 days. That is, in approximately one week a sufficient volume of water was displaced in the soil profile through evaporation and drainage to accept more than 1 in. of additional water. Since a saturated soil condition represents the "worst case" situation, the reaeration in unsaturated soil would be higher. At a spraying application rate of 0.1 in. per hour, a 1-in. continuous application would require 10 hr. Since the application rate (0.1 in. hr^{-1}) does not exceed the saturated infiltration rate at 10 hr (0.11 in. hr^{-1}), no surface runoff should occur even during a "worst case" (saturated soil) condition.

Based on the test results, an application rate of 1 in. per week is considered conservative. Results from double ring infiltrometer tests, conducted by others, were, in most cases, similar to those of the large-scale infiltration test.

ANALYSIS OF INFILTRATION RESULTS AT A PROPOSED NORTH CAROLINA WASTEWATER TREATMENT SITE

Gunars Abele and John R. Bouzoun

INTRODUCTION

The infiltration rate of a soil is defined as the rate at which water enters the soil from the surface. The hydraulic conductivity (permeability) is a measure of the ease with which a fluid passes through the soil (U.S. EPA et al. 1981).

The flow rate of water into soil in an unsaturated condition decreases with an increase in the soil water content, eventually becoming relatively constant after a saturated soil condition has been reached (steady state). This condition identifies the saturated hydraulic conductivity (saturated permeability), which is equal to the saturated infiltration rate, and represents the minimum infiltration capacity of the soil. Since the saturated infiltration rate represents the most conservative ("worst case") situation, the design application rates are based on this value. The current criterion (U.S. EPA et al. 1981) states that a wastewater application rate equivalent to 5 to 10% of the saturated infiltration rate of clear water is considered a safe design rate that permits sufficient drainage and evapotranspiration and thus provides sufficient reaeration between applications.

A large-area infiltration test, developed by CRREL (U.S. Army 1981), was conducted on 29-30 September 1981 as part of the planning for the proposed Chatham County Recreational Area Wastewater Treatment System 12 miles southeast of Chapel Hill, North Carolina, at a location selected by the Wilmington (North Carolina) District. Five double ring infiltrometer tests were also conducted at this site by Soil and Material Engineers, Inc., Raleigh, North Carolina, to provide a comparison between the results of the two types of infiltration tests.

The tests were conducted to determine the infiltration and reaeration rates of the soil at this site, so that appropriate wastewater application rates can be established.

DESCRIPTION OF STUDY

Test Site Preparation

The test site location (10 ft north of a survey stake with coordinates N 11+00, E 5+00) is shown in Figure 1. The soil and vegetation characteristics of the area are described in U.S. Army Corps of Engineers, Wilmington District (1980). The test site in its undisturbed condition is shown in Figure 2.

The surface vegetation and the dead litter (leaves, branches) were removed from the test area to facilitate the berm and tensiometer installation. A 6-ft-diam area was laid out, a 6-in.-deep groove was cut along the perimeter (Fig. 3), an aluminum berm was installed in the groove, and the soil was tamped on both sides of the berm to provide a good seal and, therefore, to minimize lateral water leakage.

Tensiometers, used to monitor the saturation of the soil, were installed at depths of 4, 9, 12, 15, 18, 23.5 and 30 in. A graduated marker for monitoring the water surface level was also installed. The completed test setup is shown in Figure 4.

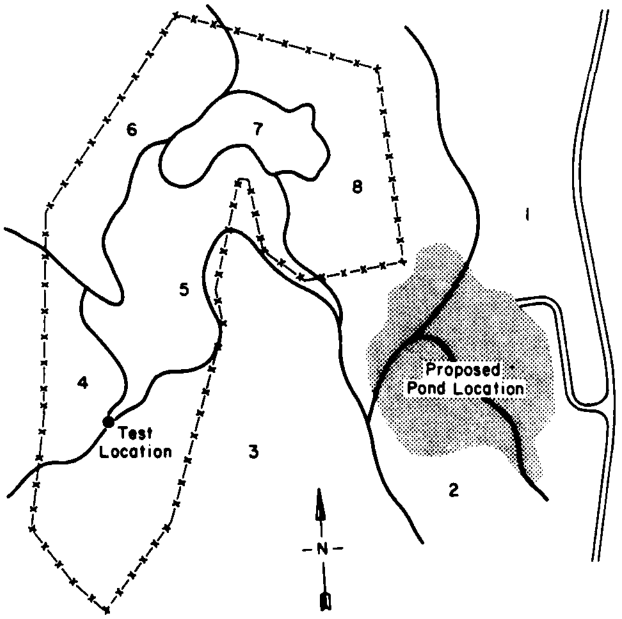


Figure 1. Test location and soil series (1-White Store series, 2-Creedmore series, 3-Wahee series, 4-Herndon series, 5-Lignum series [MWD version], 6-Enon series, 7-Lignum series [SWP-DR version], and 8-Enon-Herndon-Lignum complex).

Figure 2. Test site in undisturbed condition.

Figure 3. Test site after clearing and groove cutting.

Figure 4. Test site after berm and tensiometer installation.

The test site preparation by three men required 2.5 hr: 1.5 hr for clearing and berm installation and 1 hr for tensiometer installation. (In non-wooded areas, where installation is not hampered by subsurface tree roots, the required preparation time would be less.)

The water for the test was supplied through a hose from a water truck, stationed on a hill approximately 450 ft from the test site.

Soil Characteristics

Soil samples were obtained approximately 10 ft from the infiltration test area to a depth of 30 in. (Based on visual inspection, the soil profile characteristics between these samples and the cores from the tensiometer holes did not appear to differ.) Moisture content and density of the soil were determined at the Corps of Engineers Soils Laboratory, Neuse, North Carolina, and the specific gravity, particle size distribution and moisture retention (relationship between soil moisture tension and water content) at the CRREL soils laboratory.

Infiltration Test

Tensiometer readings were obtained prior to the water application. These readings stabilized in less than an hour after installation, and 5.2

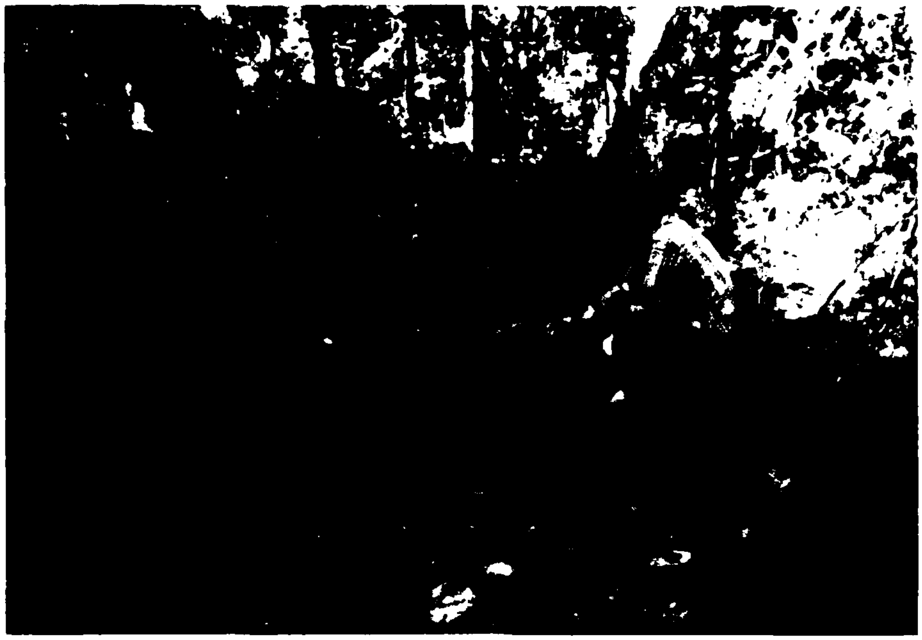


Figure 5. Water application.

in. of water was applied 4 hr after installation (Fig. 5). The actual amount of water applied was somewhat more than 5.2 in., since the application required approximately 10 min. and some of the water percolated into the soil. (This error was approximately canceled by the evaporation from the water surface during the test). The 5.2-in. value represents the water head at the end of the application (the beginning of the observation period).

Periodic readings, initially at 15-min. intervals, were made of the head drop (cumulative intake) and soil moisture tension. The 5.2 in. of water saturated the soil profile to a depth of somewhere between 24 and 30 in.

To observe the infiltration rate at saturated soil conditions, additional water (3.2 in.) was applied the following day, and cumulative intake was monitored as before. The 3.2 in. of water penetrated the soil in approximately 24 hours. The tensiometer observations were continued (at 2, 6 and 9 days) to observe the rate of drying (reaeration).

Concurrently with the saturated infiltration test (Fig. 6) double-ring infiltrometer tests (Fig. 7) were conducted nearby by Soil and Material Engineers, Inc., for comparison.

Figure 6. Infiltration test.

Figure 7. Double ring infiltrometer test.

DISCUSSION OF RESULTS

Infiltration Rate

The cumulative intake (Y) vs time (t) data are listed in Table 1. When these data are plotted on log-log paper, as shown in Figure 8, the lines of best fit for both the unsaturated and saturated soil conditions are of the following general form:

$$Y = C\,t^{n} \qquad (1)$$

where

Y = cumulative water intake (in.)
C = intercept at $t = 1$
t = time (hr)
n = slope.

Table 1. Cumulative intake.

H = 5.2 in.			H = 3.2 in.		
Clock time	Time t (hr)	Cum. intake Y (in.)	Clock time	Time t (hr)	Cum. intake Y (in.)
29 Sep (Unsaturated)			30 Sep (Saturated to between 24 and 30 in.)		
1530	0	0	0830	0	0
1539	0.15	0.4	0845	0.25	0.1
1543	0.22	0.6	0900	0.5	0.2
1550	0.33	0.7	0915	0.75	0.25
1600	0.5	0.9	0930	1.0	0.3
1615	0.75	1.1	0945	1.25	0.35
1630	1.0	1.4	1000	1.5	0.4
1645	1.25	1.55	1015	1.75	0.45
1700	1.5	1.75	1030	2.0	0.5
2045	5.25	3.2	1045	2.25	0.55
			1100	2.5	0.6
30 Sep			1130	3.0	0.65
			1200	3.5	0.7
0800	16.5*	5.2	1415	5.75	0.95
			1600	7.5	1.3
			1 Oct		
			0830	24	3.2

*Cum. intake of 5.2 in. had occurred sometime before 0800 hr on 30 Sep; therefore $t < 16.5$ hr.

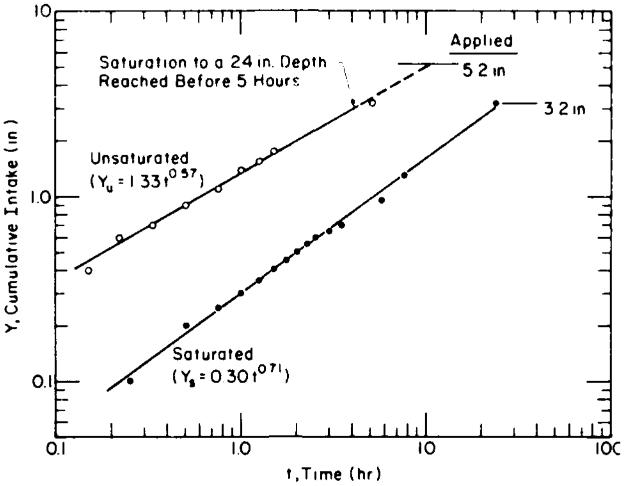


Figure 8. Cumulative intake vs time.

A regression analysis of ln Y as a function of ln t gives the following equations:

$$Y_u = 1.33\ t^{0.57} \quad \text{(unsaturated condition)} \tag{2}$$

$$Y_s = 0.30\ t^{0.71} \quad \text{(saturated condition).} \tag{3}$$

The coefficient of correlation (r) for both relationships is 0.99.

The infiltration rate (I), which is the rate of change of Y with respect to t, can then be computed by differentiating eq 1:

$$I = \frac{dY}{dt} = C\ n\ t^{n-1} \tag{4}$$

and the infiltration rates for the unsaturated (I_u) and saturated (I_s) soil conditions at the test site can be expressed by

$$I_u = 0.76\ t^{-0.43} \tag{5}$$

$$I_s = 0.21\ t^{-0.29} \tag{6}$$

The computed I vs t relationships are shown in Figure 9.

The I vs t relationship can be also obtained by calculating the incremental I values for each individual head drop and time observation ($I = \Delta Y/\Delta t$). This procedure, however, usually results in considerable data scatter, especially if the observation time increments and the corresponding head drop increments are small and therefore cause difficulties in accurately reading small increments. Computing the infiltration rate from the Y vs t relationship (eq 1) using eq 4 minimizes the effect from errors in incremental readings.

In this test, the saturated infiltration rate at 1 hr (cumulative intake 0.3 in.) was 0.21 in. hr^{-1} (refer to Fig. 8 and 9). At the end of the test (at 24 hr, cumulative intake 3.2 in.), the infiltration rate was slightly below 0.1 in. hr^{-1}.

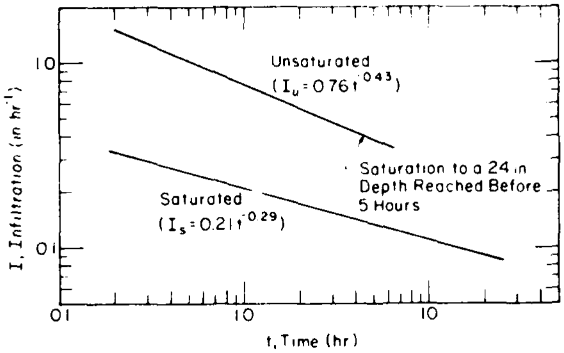


Figure 9. Computed infiltration rate vs time.

Comparison with Double Ring Infiltrometer Test Data

Double-ring infiltrometer data from five tests (Soil and Material Engineers, Inc. 1981) are listed in Table 2, and the resulting I vs t curves, drawn by eye through the data points, are shown in an arithmetical plot in Figure 10 (for clarity, the individual data points are not shown). Tests 3-5 were conducted at the surface, test 1 at a 4-in. depth, and test 2 at a 9-in. depth.

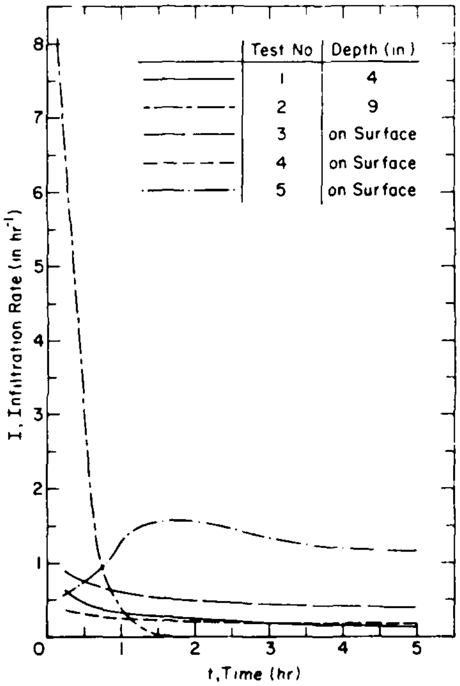


Figure 10. Infiltration rate vs time (double-ring tests).

Data from test 2 show very high infiltration rates for the first 45 min. of the test. But, after 2 hr, infiltration had virtually stopped. In test 5 the infiltration rate kept increasing for the first 2 hr, in contrast to the decrease usually observed. Results from the other three tests compare very well with each other.

The significant differences between tests 2 and 5 and the other three tests may indicate some localized peculiarities in the soil profile. This situation illustrates the advantage of a large area infiltration test, where the effects of any isolated peculiarities, not representative of the general soil profile, are minimized.

Table 2. Infiltration rates (in. hr^{-1}) determined by double-ring infiltrometer tests (Soil and Material Engineers, Inc. 1981).

Time	Test				
t (hr)	1 (4 in.)	2 (9 in.)	3 (Surf.)	4 (Surf.)	5 (Surf.)
0					
	0.522	8.056	1.04*	0.116	0.580
0.25					
	1.101	4.637	0.985	0.522	0.580
0.50					
	0.406	1.507	0.753	0.464	0.869
0.75					
	0.406	0.638	0.638	0.406	1.101
1.0					
	0.290	0.145	0.580	0.174	1.507
1.5					
	0.261	0.029	0.522	0.174	1.565
2.0					
	0.159	0.007	0.449	0.290	1.463
3.0					
	0.188	0	0.406	0.203	1.239
4.0					
	0.138	0	0.362	0.101	1.166
5.0					

*In Soil and Material Engineers, Inc. (1981) shown as 1.275 due to arithmetical error.

Incremental intake in inches can be computed by multiplying infiltration rate by the corresponding time interval between readings or by dividing observed level change by 6.9.

The cumulative intake data from double-ring infiltrometer tests 1, 3 and 4 are compared with the CRREL large area test results in Figure 11. The Y vs t relationships for these three tests could also be represented as straight lines on a log-log plot in the time range of 0.5 to 5 hr. (This type of plot was not possible with the data from tests 2 and 5.)

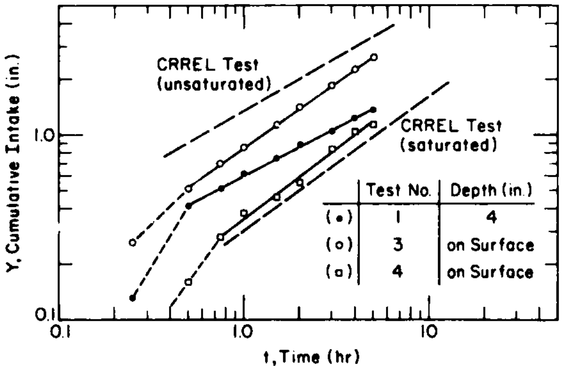


Figure 11. Cumulative intake vs time (double-ring tests) compared with CRREL test results.

The computed I vs t lines for the three tests (1, 3 and 4) are shown and compared with the CRREL test results in Figure 12. The results fall in the area between the unsaturated and the saturated CRREL test results.

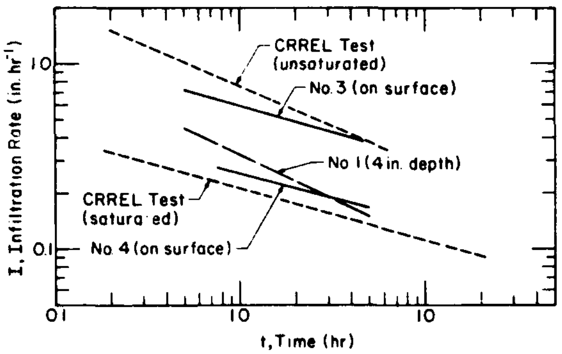


Figure 12. Computed infiltration rate vs time (double-ring tests) compared with CRREL test results.

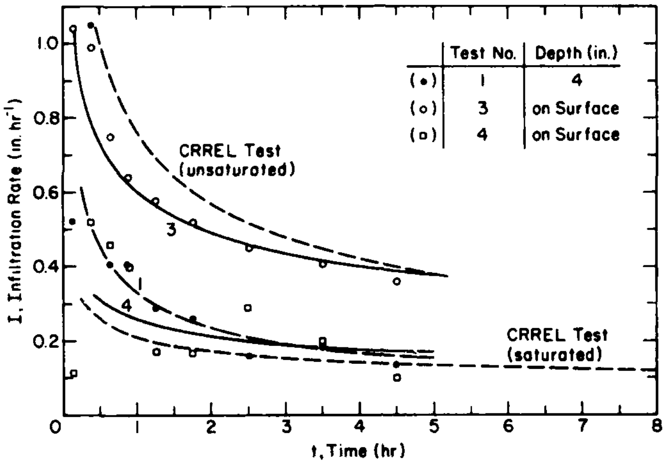


Figure 13. Infiltration rate vs time data (double-ring tests) compared with CRREL test results.

The double-ring infiltrometer test is designed for a saturated soil condition. Therefore, the relatively close agreement between the results from tests 1 and 4 and those of the CRREL test for the saturated condition is not surprising (Fig. 12). However, it is not clear why the infiltration rate for test 3 is approximately twice that of test 4 and therefore compares with the CRREL test for the unsaturated condition, unless the soil was not saturated during test 3.

The infiltration rate vs time data for tests 1, 3 and 4 are plotted on arithmetical scales in Figure 13. The computed curves from the CRREL test (both unsaturated and saturated soil conditions) are also shown for comparison. The numerical values of the infiltration rates from all the tests at 5 hr (the end of the double ring infiltrometer test) are compared in Table 3. The I values shown (for t = 5 hr) include the following:

Table 3. Comparison of infiltration rates.

Test	I ($in.\ hr^{-1}$) at 5 hr From last reading	 From curve	Location (depth)
Double-ring			
1	0.14	0.15	4 in. below surface
2	0.015	0	9 in. below surface
3	0.36	0.38	On surface
4	0.10	0.17	On surface
5	1.17	-	On surface
CRREL Test			
Unsaturated		0.38	On surface
Saturated		0.13	On surface

Double ring test:

I obtained from the last reading (Soil and Material Engineers, Inc. 1981, and Fig. 13).

I obtained from the curves drawn through the data points (Fig. 10, 12, 13).

CRREL test:

I (unsaturated and saturated conditions) obtained from the computed curves (Figs. 9, 12, 13).

In Figure 13, the calculated I represents the mean infiltration rate during the time period between the two consecutive readings and is plotted at a mean value of t. For example, if readings of the intake are taken at $t = 4$ and $t = 5$ hr, the infiltration rate is calculated by dividing the difference in the intake (change in water level) by the time interval since the previous reading ($I = \Delta Y/\Delta t$), in this case, during the 1-hour period (between $t = 4$ and $t = 5$ hr). Therefore, to be technically correct, the I is plotted at the mean t of the corresponding time interval, in this case, at $t = 4.5$ hr, rather than at the time when the readings were taken.

Soil Characteristics

The soil characteristics adjacent to the test site at the beginning of the test are listed in Table 4. The dry density and the water content (gravimetric and volumetric) profiles of the soil are plotted in Figure 14. The volumetric composition (solids, water, air) of the soil profile is shown in Figure 15 and the saturation in Figure 16. The particle size distribution data are plotted in Figure 17.

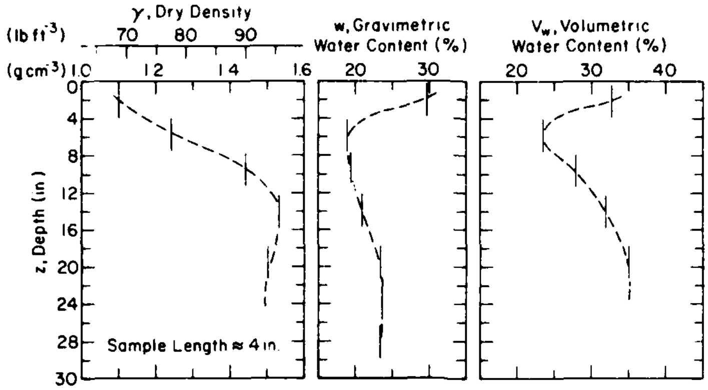


Figure 14. Dry density and water content profiles.

Table 4. Soil characteristics.

	Depth (in.)						
	0-4	4-7.5	7.5-11.5	12-16.5	17.5-21.5	21.5-26.5	26.5-30
Grav. water cont, w(%)	29.7	18.90	19.31	20.85	23.34	23.52	23.46
Dry density, γ (g cm^{-3})	1.1	1.24	1.44	1.53	1.50		
Specific gravity, G_s	2.55	2.68	2.72	2.72	2.74		
Volume of solids, V_s(%)	43.1	46.3	52.9	56.3	54.7		
Volume of water, V_w(%)	32.7	23.4	27.8	31.9	35.0		
Volume of voids, V_v(%)	56.9	53.7	47.1	43.7	45.3		
Volume (sol. + wat.), $V_s + V_w$ (%)	75.8	69.7	80.7	88.2	89.7		
Volume of air, V_a(%)	24.2	30.3	19.3	11.8	10.3		
Saturation, S(%)	57	44	59	73	77		

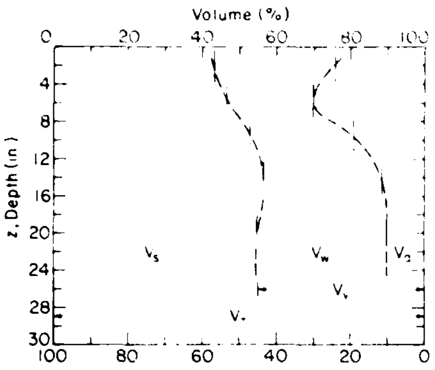


Figure 15. Volumetric composition profile.

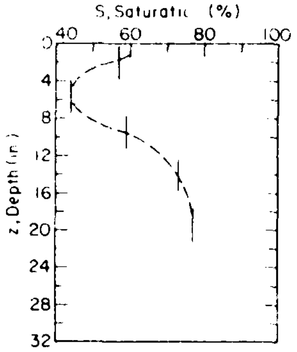


Figure 16. Saturation profile.

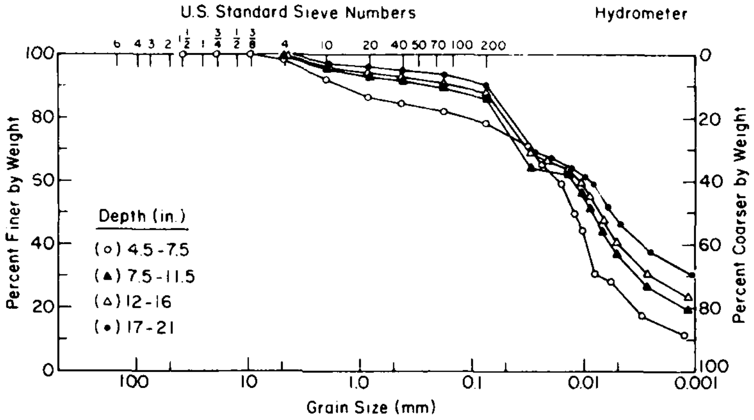


Figure 17. Particle size distribution.

The initial total air space (V_a) in the top 30 in. of the soil profile was approximately 16% of the total volume (Fig. 15). Therefore, the top 30 in. of the soil had sufficient void space to accept approximately 4.8 in. of water (30 in. x 0.16 = 4.8 in.). (This is a theoretical condition, assuming all the air pores are filled with water and there is no lateral movement or percolation below the 30-in. depth.) The cumulative available void space in terms of inches of water (calculated from Fig. 15) with depth is shown in Figure 18. This figure indicates that the actual initial application of 5.2 in. of water would have been sufficient to saturate the profile to a depth of approximately 33 in.

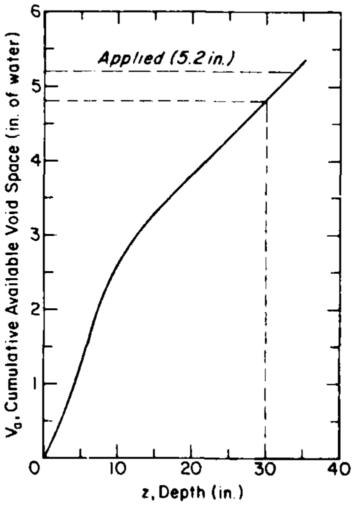


Figure 18. Cumulative available void space with depth.

It should be understood that the curve in Figure 18 is applicable only to the particular soil profile characteristics listed in Table 4 and illustrated in Figures 14 and 15. The soil profile characteristics will vary throughout the proposed spray area, and the water content in the profile will vary with the location, the time of the season and prior precipitation.

It should also be realized that complete saturation (S = 100%) of a soil profile is usually not possible in the field, regardless of the amount of water applied, because of trapped air in isolated voids. The amount of air voids remaining in an apparently saturated soil can range, depending on soil type, from 5 to 15% of the total volume (V_T).

Water Flow through Unsaturated Soil

The soil moisture tension data are listed in Table 5, and the soil moisture tension vs time at various depths is shown in Figure 19.

Figure 20 compares the calculated amount of water required to fill all available air space (from Fig. 18), shown with the solid line, and the actual amount of water (cumulative intake), shown with the dotted line, which resulted in apparent saturation (h = 0) at the various depths (time of saturation is from Fig. 19 and cumulative intake Y_u at these times is from Fig. 8).

Table 5. Soil moisture tension (cm of water).

		After 5.2-in. application (hr)									After 3.2-in. application (days)				
Depth (in.)	0*	0.25	0.5	0.75	1.0	1.25	1.5	5.25	17	0*	1	1.4	2	6	9
4	720	0	0	0	0	0	0	0	0	0	0	40	20†	50	100
9	700	700	680	580	350	190	110	0	0	0	0	0	0	40	50
12	650	590	340	200	140	70	0	0	0	0	0	0	0	30	30
15	620	330	20	0	0	0	0	0	0	0	0	0	0	20	30
18	600	590	0	0	0	0	0	0	0	0	0	0	0	20	0
23.5	320	320	320	280	230	170	120	0	0	0	0	0	0	10	10
30	440	60	60	100	110	110	150	260	170	170	90	80	80	70	60

* Prior to application.

† An undetermined amount of rainfall occurred between 1.4 and 2 days.

From Table 5 (and also Fig. 19) it can be seen that the saturation of the soil did not proceed progressively downward; that is, the apparent saturation at the 12- to 18-in. depths occurred before saturation at the 9-inch depth. Possibly the soil layer at the 9-in. depth was very permeable, allowing the water to easily pass through it and, therefore, first saturate the less permeable soil below, in this case at the 18-in. depth. After that, the saturation front would move progressively upward until the entire top 18 in. was saturated, and then eventually continue downward.

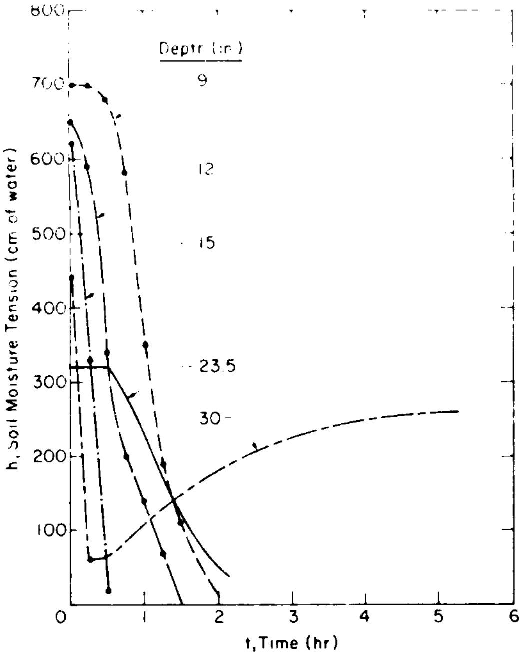


Figure 19. Soil moisture tension vs time at various depths.

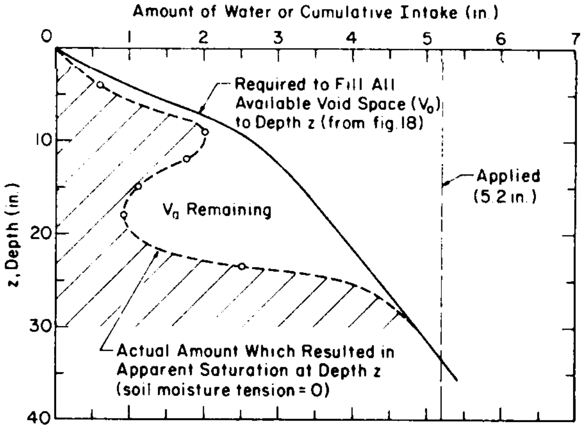


Figure 20. Comparison of available void space and actual water needed to reach apparent saturation.

This explanation is supported to some degree by the soil profile characteristics. In the top 20 in. of the soil, the density (Fig. 14), volume of solids (Fig. 15) and clay content (Fig. 17) gradually increase, implying a decrease in permeability with depth. Other characteristics that may explain the saturation progress are the initial water content (Fig. 14), saturation profiles (Fig. 16) and the initial air volume profile (Fig. 15). The least saturated section of the soil profile is between the 4- and 8-in. depth, the water content or saturation increasing gradually with depth below 8 in. At the 12- to 22-in. depth, the available air volume (V_a) is relatively low, in the 10 to 12% range, and would therefore require relatively little water to reach saturation. Significantly more water would be required to fill the available air space above the 10-in. depth (V_a at 9 in. is approximately 20% and at 6 in. approximately 30%).

The comparison of the two curves in Figure 20 permits estimation of the approximate air space remaining in the soil profile after the tensiometers indicated apparent saturation. The area under the dotted curve in Figure 20 is approximately 60% of the area under the solid curve representing the available air space. Since the air space for the 0- to 30-in. depth was approximately 16% of the total volume (refer to Fig. 15), the percentage of the total volume filled with the applied water is

$$0.16 \times 60 = 9.6\%$$

which is equivalent to

$$9.6\% \times 30 \text{ in.} = 2.9 \text{ in. of water.}$$

In other words, at the end of the initial application, 2.9 in. or 56% of the 5.2 in. of water applied was located in the soil above the 30-in. depth. Most of the remaining 2.3 in. of water had percolated below the 30-in. depth, but some of this water may have moved out laterally below the bottom of the aluminum berm (Fig. 21).

The volume that remained filled with air at the apparent saturation point was 6.4% of V_T (i.e. 16% - 9.6%) for the 0- to 30-in. depth.

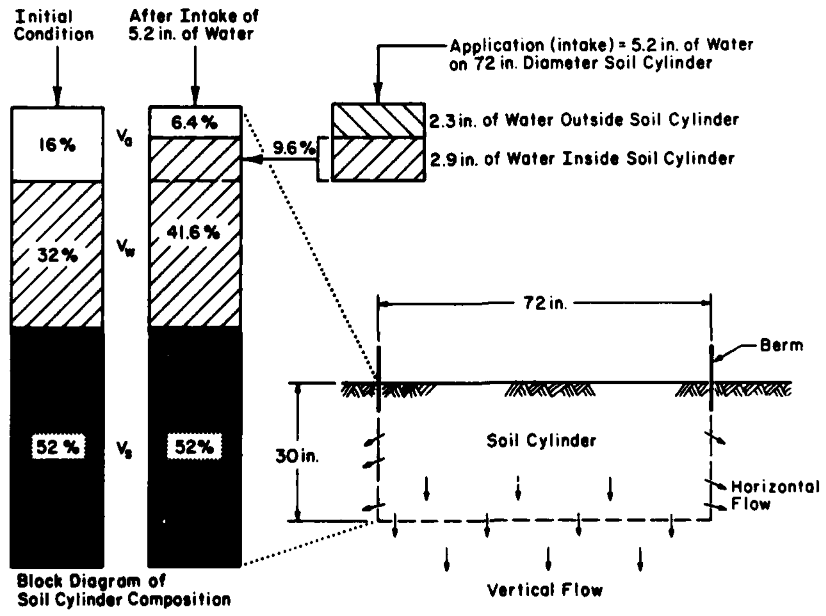


Figure 21. Schematic of water budget before and after initial application.

The initial behavior of the tensiometer at the 30-in. depth appeared very unusual. For no apparent reason, the tensiometer readings (Table 5) dropped suddenly after the initial water application and then started to increase slowly (Fig. 19). It is possible, however, that the seal around the tensiometer tube at the soil surface was not very good, allowing water to percolate quickly downward along the tube and reach the tensiometer tip.

The tensiometer at the 30-in. depth did not indicate a saturated condition at any time during or after the test (refer to Table 5). If more than 5 in. of water (most of the 2.3 in. from the initial application, plus most of the 3.2 in. of the additional application) is considered to have passed through the 30-in. depth, the tensiometer readings at this depth may not be representative of the actual water content conditions. It is, therefore, suspected that the tensiometer installed at the 30-in. depth behaved erratically because of either some deficiency in the instrument tube or its gauge or some problem at the porous tip/soil interface.

Reaeration

Unlike the infiltration rate, which can be determined by direct observation of the movement of water into the soil, rate of drying (reaeration) of soil in the field is determined indirectly by using tensiometer readings of soil moisture tension. Soil tension vs volumetric water content curves for various incremental depths of soil are developed in the laboratory and are used to convert tensiometer readings to moisture content values. The relationship between the soil moisture tension and volumetric water content of the test area soil is plotted in Figure 22. (Note that the tensiometer gauge readings are multiplied by 10 to obtain tension in units of centimeters of water.)

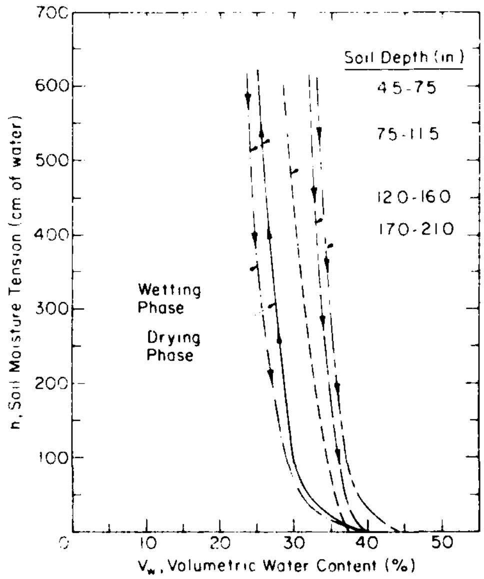


Figure 22. Soil moisture tension vs volumetric water content.

The dashed lines in Figure 22 show the soil moisture tension (h) vs volumetric water content (V_w) relationship during increasing water content (wetting stage). During decreasing water content (drying stage), the h vs V_w

relationship does not follow the same curve (hysteresis effect). Therefore, to determine soil water content from tensiometer readings, it has to be known whether the soil is in a wetting or drying phase (this can be established by comparing two consecutive tensiometer readings taken some time apart). The effect of the hysteresis phenomenon decreases as the slope of the curve increases, as is the case with the three deepest soil samples. For the sample from the 4- to 7.5-in. depth, the drying curve is noticeably different from the wetting curve (solid line in Fig. 22).

Near the saturation point (soil tension = 0), a significant change in water content can be indicated by a relatively small change in moisture tension (depending on soil type), while farther away from the saturation point, a very small change in water content in a particular soil can correspond to a very significant change in soil moisture tension.

The volumetric composition of the soil at the 4- to 7.5-in. depth before, during and after saturation is shown in Table 6 (V_w values from Fig. 22). The most significant reaeration ordinarily occurs near the soil surface; the V_a values in Table 6 show the increase in the volume of air with time at the 4- to 7.5-in. depth.

Comparison of the volumetric composition of the soil at the various depths at saturation and six days later are presented in Tables 7 and 8, respectively. The difference in the volume of air (V_a) represents the degree of reaeration of the soil profile. This difference is shown as the shaded area in Figure 23 (refer to Fig. 15 for the complete initial volumetric composition of the soil profile).

Table 6. Volumetric composition of soil at the 4- to 7.5-inch depth.

Volume (%)	Initial	Time after saturation (days) 0 & 1 day (Saturated)	2	6	9
V_s	46.3	46.3	46.3	46.3	46.3
V_w	23.4	41.5	38	33.5	31.5
$V_s + V_w$	69.7	87.8	84.3	79.8	77.8
V_a	30.3	12.2	15.7	20.2	22.2

Table 7. Volumetric composition of soil at saturation.

Volume (%)	Depth (in.)			
	4-7.5	7.5-11	12-16	17.5-21.5
V_s	46.3	52.9	56.3	54.7
V_w	41.5	37.2	39.8	44.0
$V_s + V_w$	87.8	90.1	96.1	98.7
V_a	12.2	9.9	3.9	1.3

Table 8. Volumetric composition of soil 6 days after saturation.

Volume (%)	Depth (in.)			
	4-7.5	7.5-11	12-16	17.5-21.5
V_s	46.3	52.9	56.3	54.7
V_w	33.5	36	38	41
$V_s + V_w$	79.8	88.9	94.3	95.7
V_a	20.2	11.1	5.7	4.3

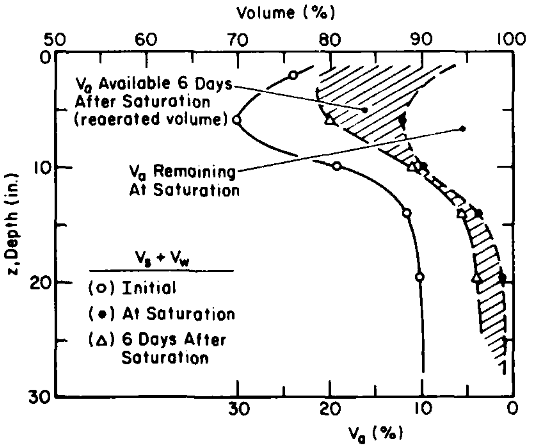


Figure 23. Volumetric composition of soil before, during and six days after saturation.

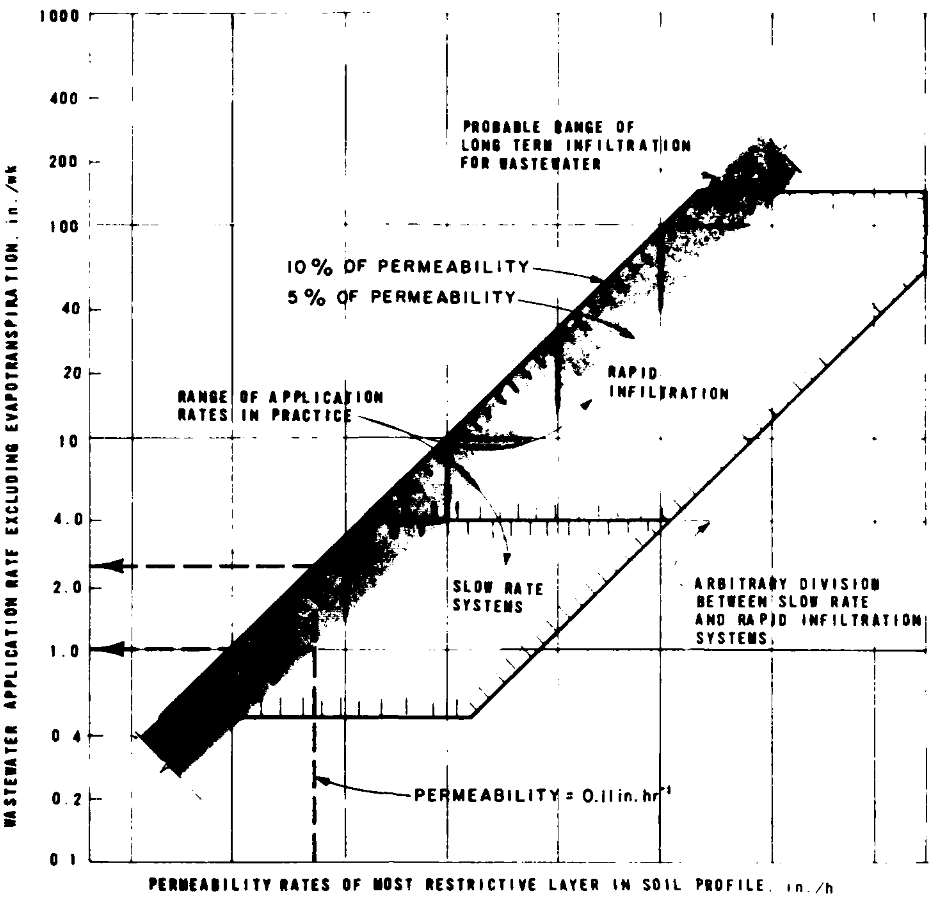
For the top 30 in., the reaerated volume is approximately 4.5% of the total volume (V_T) and is equivalent to approximately 1.35 in. of water (0.045 x 30 in. = 1.35 in.). Therefore, six days after the soil was saturated, sufficient reaeration had occurred to accept more than 1 in. of water before saturation would again be achieved. This implies that a weekly addition of water (including rain) in the amount of less than 1.35 in. would not saturate the soil. This example represents the "worst case" situation. During a spraying application in a forest, some of the water will be lost due to evaporation from tree trunks and from the surface of the understory vegetation, and some of the water entering the soil will be removed by transpiration.

CONCLUSIONS

The saturated infiltration rate of the soil at the test area was slightly above 0.1 in. hr^{-1}. This value represents the infiltration rate at the end of the test, after a total water application of 8.4 in., and therefore can be considered the saturated conductivity (permeability) of the soil. In fact, the permeability rate of 0.11 in. hr^{-1} agrees very well with the estimated subsurface permeability rate range of between 0.06 and 0.2 in. hr^{-1} (U.S. Army Corps of Engineers, Wilmington District 1980).

According to the design criteria (U.S. EPA et al. 1981), a saturated infiltration (permeability) rate of 0.11 in hr^{-1} would permit an application rate of between 1 and 2 in. per week (Fig. 24). This criterion is based on the assumption that a safe weekly wastewater application rate is from 5 to 10% of the saturated infiltration rate for clear water. In other words, the application rate should be only between 1/20 and 1/10 of the actual capability of a saturated soil to accept water. This is considered a very conservative criterion, which would assure that the soil never becomes saturated and that sufficient oxygen is available to the root system through drainage and reaeration.

The saturated infiltration rate at this site was almost identical to that at the land treatment site at Deer Creek Lake, Ohio, where infiltration tests had been performed (Abele et al. 1981). At Deer Creek, wastewater from a recreational area has been applied at the rate of 1 in. wk^{-1} for several years. The drainage water at a 30-in. depth has always met drinking water standards. It was determined that a weekly application of 2 in. of wastewater would still be a safe application rate at the Deer Creek Lake system.



PERMEABILITY* SOIL CONSERVATION SERVICE DESCRIPTIVE TERMS						
VERY SLOW	SLOW	MODERATELY SLOW	MODERATE	MODERATELY RAPID	RAPID	VERY RAPID
< 0.06	0.06-0.20	0.20-0.60	0.60-2.0	2.0-6.0	6.0-20.0	> 20.0

* MEASURED WITH CLEAR WATER

1 in./wk = 2.54 cm/wk

Figure 24. Application rate vs soil permeability.

For the top 30 in. of the soil profile, the reaeration for a saturated soil condition was equivalent to 1.35 in. of water after a period of six days.

Based on the test results and the design criteria (U.S. EPA et al. 1981), an application rate of 1 in. wk^{-1} is considered a conservative value.

At the spraying rate of 0.1 in. hr^{-1} (U.S. Army Corps of Engineers, Wilmington District 1980), a 1-in. application would require 10 hours. By referring back to Figure 9, it can be observed that even in the worst case situation (saturated soil condition), the infiltration rate at 10 hours is 0.11 in. hr^{-1}, which would be at least as high as the application rate of 0.1

in. hr^{-1} and, therefore, not create surface runoff. For an unsaturated soil condition, the infiltration rates are significantly higher. Therefore, for a 1-in. application at the rate of 0.1 in. hr^{-1}, surface runoff would not likely be a problem.

Furthermore, since the proposed site is a forested area, not all of the applied wastewater will reach the soil. A considerable amount of the wastewater applied by spraying will be deposited on the tree trunks, the branches and leaves of the understory and on the litter mat above the soil surface and will be lost to evaporation. A portion of the remaining wastewater that eventually does enter the soil will be consumed by transpiration.

The evapotranspiration rate during summer in this type of a forest is approximately 0.15 in. per day (McKim et al. 1982). This value includes only the evaporation from the soil and the transpiration through the plants; it does not include evaporation of water deposited on the vegetation. Therefore, it can be expected that 0.15 in. of an application may be lost due to evapotranspiration during the first day after application and some additional amount during the following few days.

During May through November, the mean precipitation rate in this area is approximately 0.8 in. wk^{-1} (winter rate is 1 in. wk^{-1}), and the evaporation rate is approximately 1 in. wk^{-1} (U.S. Army Corps of Engineers, Wilmington District 1980). This negative water balance during the summer season provides a favorable condition for applying additional water.

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