Interim Report
Research Project Agreement No. T1803, Task 12
Stormwater Facilities

INFILTRATION CHARACTERISTICS, PERFORMANCE, AND DESIGN OF STORM WATER FACILITIES

by

Joel W. Massman
Associate Professor

Carolyn D. Butchart
Graduate Assistant

Department of Civil and Environmental Engineering
University of Washington, Bx 352700
Seattle, Washington 98195

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Tony Allen
State Geotechnical Engineer

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

May 2001

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 483.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Infiltration Characteristics, Performance, and Design of Storm Water Facilities		5. REPORT DATE May 2001 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Joel W. Massman and Carolyn D. Butchart		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) University of Washington, Box 354802 University District Building; 1107 NE 45th Street, Suite 535 Seattle, Washington 98105-4631		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Agreement T1803, Task 12
12. SPONSORING AGENCY NAME AND ADDRESS Research Office Washington State Department of Transportation Transportation Building, MS 47370 Olympia, Washington 98504-7370 Keith Anderson, Project Manager, 360-705-7931		13. TYPE OF REPORT AND PERIOD COVERED Interim report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This report provides comments and suggestions related to the Washington State Department of Ecology’s draft manual, entitled “Stormwater Management in Washington State.” These comments and suggestions are focused on those sections of the draft manual that relate to infiltration facilities. Specific issues that are addressed include the following:

- consistency in analytical approaches for estimating surface runoff and infiltration
- additional approaches for estimating infiltration rates using soil texture data
- comparison of recommended infiltration rates with selected literature values
- comparison of recommended infiltration rates with selected measurements
- field measurements for estimating infiltration rates.

17. KEY WORDS Stormwater management, infiltration	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES	22. PRICE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INFILTRATION CHARACTERISTICS, PERFORMANCE, AND DESIGN OF STORM WATER FACILITIES

INTRODUCTION

This report provides comments and suggestions related to the Washington Department of Ecology's draft manual entitled "Stormwater Management in Washington State" (WDOE, 1999). These comments and suggestions are focused on those sections of the draft manual that relate to infiltration facilities. Excerpts from the WDOE draft manual are included in Appendix A of this report. The discussions are most relevant to facilities that include infiltration ponds rather than dry wells or infiltration swales. Specific issues that are addressed include the following:

- consistency in analytical approaches for estimating surface runoff and infiltration
- additional approaches for estimating infiltration rates using soil texture data
- comparison of recommended infiltration rates with selected literature values
- comparison of recommended infiltration rates with selected measurements
- field measurements for estimating infiltration rates.

These issues are described in more detail in the sections that follow.

CONSISTENCY IN ANALYTICAL APPROACHES

The level of analytical sophistication that is required to estimate surface runoff is somewhat inconsistent with the level of sophistication recommended to estimate infiltration rates. Relatively rigorous and detailed methodologies are required to estimate surface runoff, as described in Volume III, Chapter 1, *Hydrologic Analysis*. For example, a calibrated, continuous-simulation model must be used to estimate runoff in western Washington for flow control best management practices (BMPs). In the case of infiltration facilities, the output from this runoff analysis is combined with estimates of infiltration rates to select the size and geometry of the infiltration facilities. This is described on page 141 of Volume III (included in Appendix A of this report): "The analysis must demonstrate that the BMP will completely infiltrate the design storm within 24 hours (or 48 hours for the 100-year event). If this is not the case, the surface area of the BMP will have to be increased."

The recommended approach for sizing infiltration facilities is summarized in Section 2.3.8, pages 140-142 in Volume III of the Washington Department of Ecology draft manual (WDOE, 1999a). The approach is based on using Darcy's law for saturated ground flow, assuming constant hydraulic conductivity and constant gradient. Although the manual points out that "Darcy's Law is difficult to apply to unsaturated flow conditions," it does not suggest other approaches or analytical tools for estimating infiltration rates.

In most cases, the uncertainties in estimates of infiltration rates will be significant. It would not be uncommon for the actual, long-term infiltration rate to differ from the estimated infiltration rate by factors of 2 to 10. These differences are primarily due to uncertainties in hydraulic conductivity and hydraulic gradients and because of errors in using the saturated flow equations presented on page 140 to describe infiltration. In the case of infiltration facilities, it not clear that the resources and efforts that are required to estimate surface runoff are justified, given uncertainties inherent in infiltration rate estimates. Or, from another viewpoint, it is not clear that the simplified approach recommended for sizing infiltration systems is justified given the requirements for estimating runoff. It may be appropriate in at least some cases to shift the emphasis to developing better estimates of infiltration rates. This could be accomplished with more sophisticated analytical tools for describing the infiltration process (including computer models) and with more reliable estimates of site characteristics. For example, analytical approaches for estimating infiltration rates from impoundments are presented by McWhorter and Nelson (1979). The Green-Ampt approximation to Richard's equation may also provide a more realistic description of infiltration (e.g., Mays, 1996; Ogden and Saghafian, 1997; Wang et al., 1997) in some situations. This is described in more detail in the section that follows.

The Darcy's law approach for estimating infiltration described on page 140 may over-estimate infiltration rates for facilities underlain by low-permeability layers or strata. For example, according to equation 3 on page 140, a facility with a ponded water level of 2 feet, a low-permeability layer at a depth of 15 feet, and the water table at 30 feet would result in greater infiltration than the same facility without this layer. This is because of the way the hydraulic gradient is defined. (The gradient with the low-permeability layer would be 17/15, and it would be 32/30 without the layer). In reality, the low-permeability strata would reduce infiltration relative to the un-layered or homogeneous case.

INFILTRATION IN UNSATURATED SYSTEMS

Infiltration in unsaturated systems is often described by the Green-Ampt equation (e.g., Chin, 2000). This approach assumes ponded water at the ground surface and a wetting front that extends to a depth, L, as shown in Figure 1. The wetting front is assumed to move downward as a sharp interface. The soil is assumed saturated above the wetting front (the water content is assumed equal to the porosity). The water content below the wetting front is assumed equal to some lower initial value. The rate of infiltration is approximated by the following expression:

$$f(t) = K_{sat} \frac{H_o + L + h_{wf}}{L} \qquad (1)$$

where

f(t) = the infiltration rate at time t (L/t)

K_{sat} = saturated hydraulic conductivity (L/t)

H_o = depth of water in the pond or infiltration facility (L)

L = depth of the wetting front below the bottom of the pond (L)

h_{wf} = average capillary head at the wetting front (L). Approximately equal to th eair entry pressure or bubbling pressure.

Equation (1), which was developed on the assumption that the water table is deep enough to not affect infiltration, has a very similar form to the equation presented on page 140, Volume III for estimating infiltration rates. The important difference is the interpretation of the variable, L. In equation (1), L represents the depth of the wetting front. This will change with time as water infiltrates at the ground surface. In the equations presented on page 140 of Volume III, L is a constant that represents the depth to "the water table, bedrock, impermeable layer, or soil layer of different infiltration rate."

Equation (1) can be solved to estimate infiltration rate as a function of time (e.g. Salvucci and Entekhabi, 1994). The results for several different soil types are shown in Figures 2, 3, and 4. Table 1 summarizes the values for input variables that were used to develop these results. These values were chosen on the basis of the averages reported by Carsel and Parrish (1988) for these soil types. The depth of water in the infiltration facility, H_o, is assumed to be small in these calculations. The initial infiltration rates are higher than the saturated hydraulic conductivity because of the relatively high gradients when the wetting front is shallow (L in equation (1) is small). As the depth of the wetting front increases, the gradient decreases, and the infiltration rate approaches the saturated hydraulic conductivity, K_{sat}.

The results presented in figures 2 through 4 show that short-term infiltration tests will tend to over-estimate long-term infiltration rates because of the effects of capillary forces. For sand and loamy sand, the infiltration rate decreases to within 10 percent of the saturated hydraulic conductivity within one hour. Although sandy loam is seldom used for infiltration ponds, nearly 10 hours are required before the observed infiltration rate equals the saturated hydraulic conductivity.

Note that equation (1) will over-predict infiltration rates for sites with high water tables or for sites with layers of lower-permeability materials. The gradient in these types of sites will typically be significantly smaller than one. The gradient in equation (1) is assumed to be greater than or equal to one.

ADDITIONAL APPROACHES FOR ESTIMATING INFILTRATION RATES USING SOIL TEXTURE DATA

Recommended infiltration rates based on soil textural classifications are provided in Table 2.4 of Volume III (page 135) and in Table 5.1 of volume V (page 71) in the Department of Ecology draft manual (1999a;1999b). These recommended rates are reproduced in Table 2 of this report. The WDOE manual indicates that they are based on observed infiltration rates from field sites in Thurston County. The draft manual also points out that the infiltration rates at these sites are controlled by a variety of factors and processes, including soil type, vegetation, pond geometry, depth to groundwater, and soil stratigraphy.

Methodologies have been proposed in the literature for estimating hydraulic conductivity and infiltration rates based on soil texture information. These methodologies range from relatively qualitative estimates based on soil type (e.g. Table 2.2, p. 29, Freeze and Cherry, 1979) to relatively quantitative estimates based on data from soil gradation analyses. Estimates of hydraulic conductivity from soil gradation analyses include the Hazen formula, which is based on the d_{10} grain size (Freeze and Cherry, 1979), the Krumbein and Monk equation, which is based on the mean and the standard deviation of the grain size (Davis and DeWeist, 1966), and the Fair-Hatch equation, which is based on the complete gradation curve (Freeze and Cherry, 1979). These approaches are generally applicable to relatively uniform sands.

One approach that has been proposed for estimating infiltration rates is to use regression equations based on percentage of sand, percentage of clay, and porosity. The general idea is to measure infiltration rates on a large set of samples, and to correlate these rates to measurements of the percentage of sand, percentage of clay, and porosity. The resulting regression equations are then assumed to be valid for other similar soils. This approach was used by Rawls and Brakensiek (1985). Regression equations were developed on the basis of measurements taken on more than 5,000 soil horizons from 1,323 soil types in 32 states. The data used to develop these regression equations were collected from soils with clay content ranging from 5 to 60 percent and with sand content from 5 to 70 percent. (Clay content was defined as particle sizes smaller than 0.002 mm. Sand was defined as particle sizes between 0.05 and 2 mm.) The data that were used to develop the regressions are described in Rawls et al., 1982.

The regression relationship developed by Rawls and Brakensiek for the saturated hydraulic conductivity is summarized in Table 3. The first column gives the combination of independent variables used in the regression. The symbol "C" represents percentage of clay, "S" represents percentage of sand, and "n" represents porosity. The second column gives the regression coefficients for each combination of variables. The natural logarithm of the saturated hydraulic conductivity in centimeters per hour is estimated by adding the products of the regression coefficients and variable combinations. The saturated hydraulic conductivity is then obtained by taking the exponential of this natural logarithm. An example is described in Table 4 for a soil with percentage of clay, C, equal to 15; percentage of sand, S, equal to 70; and porosity, n, equal to 0.4. The summation of products of regression coefficients and variable combinations for this example is 1.47. The hydraulic conductivity is obtained from $e^{1.47}$, or 4.3 cm/hr. This is equivalent to 1.7 inches per hour. Table 5 provides estimates of saturated hydraulic conductivity by using the regression equation developed by Rawls and Brakensiek (1985). If bulk density or porosity are not known, the approach suggested in Appendix B can be used to estimate porosity based on percentage of sand and percentage of clay.

Although the regressions developed by Rawls and Brakensiek were developed with soils that had clay contents of between 5 and 60 percent and sand contents of from 5 to 70 percent, they have been used to describe soils with higher sand contents (Carsel and Parrish, 1988; Meyer et al., 1996). The accuracy of these regressions for soils with higher sand content is not known, but the pattern described in Table 5 is consistent with other values reported in the literature (e.g., Freeze and Cherry, 1979).

Note that for layered systems, the soil texture information should be collected for each individual layer. An effective hydraulic conductivity can be calculated from the values estimated for the individual layers. For example, the effective hydraulic conductivity for flow perpendicular to the layers is given by the harmonic mean (Freeze and Cherry, 1979).

COMPARISON OF RECOMMENDED INFILTRATION RATES AND SELECTED LITERATURE VALUES.

Estimates of saturated hydraulic conductivity were developed by Carsel and Parrish (1988) using the Rawls and Brakensiek regression equation described in Table 3. Their analysis was based on a soil database of 15,737 samples of twelve USDA soil textural classifications. The results from Carsel and Parrish were used by Meyer et al. (1997) to develop probability distributions for the various soil textural classifications. These distributions are described in Table 6. The normal, lognormal, and beta distributions were used to describe the variability within each soil type. The values in the parentheses in the second column in Table 6 are the parameters of each distribution.

Figure 5 compares the distributions developed by Meyer et al. (1997) with the representative infiltration rates in the WDOE draft manual (Table 2.4, page 135, of Volume III and in Table 5.1, page 71, of volume V). The WDOE manual includes two representative rates for sands, and both are shown on the vertical bar. The average saturated hydraulic conductivities that were reported in the original data set compiled by

Rawls et al. (1982) are also included on Figure 5. The vertical bars represent the 5th and 95th percentiles for saturated hydraulic conductivity based on the distributions presented by Meyer et al. (1997). For each of the soil types shown on this graph, it can be expected that 5 percent of the hydraulic conductivity values will be less than the 5th percentile values and 5 percent will be greater than the 95th percentile values. The saturated hydraulic conductivity represents the lower bound for infiltration under saturated conditions, as described by the Green and Ampt equation. Table 7 gives the probabilities that the representative infiltration rates are exceeded based on the statistical distributions developed by Meyer et al. These results show that the exceedence probabilities for the sand and loamy sand are essentially the same (90 percent), and that the exceedence probability is lowest for sandy loam (80 percent).

Table 7 also shows the ratio of the mean values from Meyer et al. to WDOE representative rates. This ratio ranges from approximately 4 for sand to over 9 for loamy sand. This ratio might be considered as a correction factor that should be applied to field-measured infiltration rates to obtain design values. A ratio of 4 is reasonably consistent with the set of correction factors used in the King County manual to account for testing methods, geometry, and plugging (see pages 5-55 of King County Manual, 1998).

The WDOE manual specifies that the design rates should be determined by dividing the representative rate by a correction factor: "To determine design infiltration rates also apply a correction factor (CF) of 1.2 to account for variations in infiltration rates within each soil classification and micro-stratification, any unknown potential for siltation and bio-buildup, and inability to control the degree of long-term maintenance" (WDOE, 1999a, page 134, paragraph 2). This recommendation might be construed to suggest that all of these processes (siltation, stratification, poor maintenance, etc.) will reduce the infiltration rate by only 20 percent. It is not clear why the correction factor of 1.2 is needed, given that the representative rates are already a factor of 4 to 9 below what might be considered typical measured values. There may be advantages to folding the correction factor into the representative rates, and not include them as specific and identifiable numbers. An alternative approach would be to include in Table 2.4 of the WDOE Manual "typical" values from literature databases (for example, the Meyer average values or the values from Rawls et al., 1982), and then include a correction factor of 4 to 9 based on the Thurston County data. This is similar to what is done in the King County manual (King County, 1998), although it requires field measurements that are reduced by a factor on the order of 4.

The site characterization criteria described on page 132 of Volume III (WDOE, 1999a) require that the representative infiltration rates be used if they are lower than values measured in infiltration tests. If larger correction or safety factors are used to determine design values, then the site-specific data could be used in the design process. Given that the representative values are relatively low in comparison to values reported in the literature, it is likely there will be many instances in which the observed infiltration tests will result in higher values. This may result in considerable pressure to use the values based on "real" data, especially if these data show infiltration rates significantly higher than the "representative" values that are based on a relatively sparse data set from one geographical area. If larger correction factors are required, then it may make sense to allow the observed infiltration rates to be used rather than the representative rates. These observed rates would then be divided by the correction factor (perhaps on the order of 4 or so) to arrive at a design infiltration rate.

COMPARISON OF RECOMMENDED INFILTRATION RATES AND SELECTED MEASUREMENTS

Figures 6 through 9 compare the representative infiltration rates from the WDOE manual with selected measurements. The figures include infiltration rates estimated from field and laboratory tests conducted on samples from Clark, King, Kitsap, Pierce and

Thurston Counties. The soil types and testing methods are summarized in Table 8. The values described as "Stage Monitoring" represent full-scale tests. The values described as "In-situ" include constant head and falling head tests conducted in soil borings or small pits. The "Infiltrometer" values correspond to estimates made with either single-ring or double-ring infiltrometer tests. (In most cases, it is not reported whether the infiltrometer was single-ring or double-ring.)

Figures 8 and 9 show that the WDOE representative rates are lower than the observed values from small-scale field tests. However, Figure 7 shows that the WDOE representative rates are reasonably consistent with the large-scale, stage monitoring values. The stage monitoring data, which were collected at ten sites in Thurston County, two sites in Kitsap County, one site in King County, and one site in Clark County, describe infiltration for facilities that have vegetation and may have some clogging due to siltation or biological growth. As pointed out earlier, an alternative approach for setting design infiltration rates would be to use higher correction values (perhaps on the order of 4) applied to site-specific infiltration rates that are measured or estimated from soil gradation data using Table 5.

Table 9 compares observed infiltration rates and the D10 grain size parameter. This parameter is equal to the grain diameter for which 10 percent of the soil is finer, by weight. The observed rates are based on full-scale tests of infiltration ponds. These data are plotted in Figure 10. Best-fit linear trend lines are also shown in Figure 10. One trend line is drawn through the data from relatively homogeneous sites, and a second line is drawn through data from sites with layering, mottling, or bio-fouling.

FIELD MEASUREMENTS FOR ESTIMATING INFILTRATION RATES.

Pilot infiltration tests are recommended on page 131, Volume III (WDOE, 1999a), in lieu of double-ring infiltrometer tests. The advantage of the pilot scale test is that it is a larger-scale test that may better describe the actual flow conditions that will be observed during full-scale operations. One approach for making this pilot test more representative would be to reduce the depth of the water in the pit during the test. The procedure described on page 156 of the WDOE manual (1999a) , which is reproduced in Appendix A of this report, suggests a water depth of 3 to 4 feet above the bottom of the pond. With a bottom area between 100 and 150 square feet, a depth of 3 to 4 feet may cause a relatively large amount of lateral flow in comparison to vertical flow. In the full scale system the bottom area may be an order of magnitude larger than in the pilot test, but the depth will likely be similar. Vertical flow may be much larger, on a relative basis, in the full-scale system than in the pilot scale test. Lowering the water level in the pilot scale test will reduce this effect. This will also require less water.

The minimum duration for the test (1,000 minutes) is somewhat arbitrary. The results based on the Green-Ampt equation presented in figures 2 through 4 suggest that shorter tests may be sufficient for higher-permeability sites and that longer tests may be required for lower-permeability sites. An alternative approach would be to use the results in figures 2 and 4 to select a "correction factor" based on the duration of the test. A shorter test would require a larger correction factor.

An alternative approach for estimating infiltration rates at field sites is to use air flow tests. These tests, which can be conducted at more remote locations without importing large volumes of water, can be used to estimate the permeability of soils at a variety of scales. The permeability can then be related to infiltration rates. This approach is currently being evaluated as part of the current research project.

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Table 1 - Input values used to estimate infiltration rates shown in Figures 2, 3 and 4.

	Sand	Loamy Sand	Sandy Loam
Saturated hydraulic conductivity (cm/s)	$8.2\text{x}10^{-3}$	$4.0\text{x}10^{-3}$	$1.2\text{x}10^{-3}$
Capillary head at wetting front (cm)	4.1	5.8	11.2

Table 2 - Recommended infiltration rates based on soil textural classifications from Washington Department of Ecology (1999a; 1999b). Values are taken from Table 2.4 (Vol. III) and Table 5.1 (Vol. V).

	Representative Site Infiltration Rate (in./hr)	Apply Correction Factors, CF
Sandy gravel or gravelly sand	10	1.2
Sand w/< 25% finer than 0.25 mm	4	1.2
Sand w/> 25% finer than 0.25 mm	1.8	1.2
Loamy sand	0.6	1.2
Sandy loam	0.25	1.2

Table 3 - Regression variables and coefficients used by Rawls and Brakensiek (1985) to estimate the natural logarithm of saturated hydraulic conductivity in centimeters per hour.

Regression Variable	Regression Coefficient
constant	-8.96847
C	-0.028212
n	19.52348
S^2	0.0001811
C^2	-0.0094125
n^2	-8.395215
Sn	0.077718
S^2C	0.0000173
C^2n	0.02733
S^2n	0.001434
SC^2	-0.0000035
S^2n^2	-0.00298
C^2n^2	-0.019492

Table 4 - Example regression variables and coefficients for a soil with percent clay, C, equal to 15, percent sand, S, equal to 70, and porosity, n, equal to 0.4.

Variable	Value for C=15, S=70, n=0.4	Coefficient	Product
constant	1	-8.96847	-8.96847
C	15	-0.028212	-0.42318
n	0.4	19.52348	7.809392
S^2	4900	0.0001811	0.887243
C^2	225	-0.0094125	-2.1178125
n^2	0.16	-8.395215	-1.3432344
Sn	28	0.077718	2.176104
S^2C	73500	0.0000173	1.27155
C^2n	90	0.02733	2.4597
S^2n	1960	0.001434	2.81064
SC^2	15750	-0.0000035	-0.055125
S^2n^2	784	-0.00298	-2.33632
C^2n^2	36	-0.019492	-0.701712
Summation of products:			1.47

Table 5 - Saturated hydraulic conductivity estimates from regression equations

	Saturated hydraulic conductivity in inches/hour for porosity=0.2					
	S=50	S=60	S=70	S=80	S=90	S=95
C = 5	8.82E-03	1.66E-02	3.42E-02	7.66E-02	1.87E-01	3.03E-01
10	6.59E-03	1.36E-02	3.12E-02	7.95E-02	2.25E-01	
15	3.85E-03	8.71E-03	2.23E-02	6.42E-02		
20	1.76E-03	4.35E-03	1.24E-02	4.04E-02		
25	6.30E-04	1.70E-03	5.36E-03			
30	1.76E-04	5.19E-04	1.81E-03			

	Saturated hydraulic conductivity in inches/hour for porosity=0.3					
	S=50	S=60	S=70	S=80	S=90	S=95
C = 5	6.21E-02	1.26E-01	2.77E-01	6.66E-01	1.74E+00	2.91E+00
10	5.29E-02	1.17E-01	2.89E-01	7.88E-01	2.38E+00	
15	3.85E-02	9.36E-02	2.57E-01	7.93E-01		
20	2.39E-02	6.36E-02	1.94E-01	6.79E-01		
25	1.27E-02	3.69E-02	1.25E-01			
30	5.78E-03	1.83E-02	6.85E-02			

	Saturated hydraulic conductivity in inches/hour for porosity=0.4					
	S=50	S=60	S=70	S=80	S=90	S=95
C = 5	3.15E-01	6.42E-01	1.40E+00	3.31E+00	8.38E+00	1.37E+01
10	2.97E-01	6.64E-01	1.62E+00	4.34E+00	1.27E+01	
15	2.57E-01	6.28E-01	1.71E+00	5.18E+00		
20	2.03E-01	5.43E-01	1.64E+00	5.64E+00		
25	1.47E-01	4.28E-01	1.44E+00			
30	9.72E-02	3.09E-01	1.15E+00			

Table 6 - Parameter distributions from Meyer et al., 1997

Sand	**Distribution**	**Mean**	**Std. Deviation**	**Lower Limit**	**Upper Limit**
θ_s	Normal	0.43	0.06	0.245	0.615
θ_r	LN(-3.09,0.224)	0.0466	0.0106	0.0228	0.07
ψ_b	LN(1.93,0.183)	7.02	1.38	3.92	12.1
λ	LN(0.502,0.161)	1.67	0.267	1	2.72
K_s (cm/s)	Beta(1.398,1.842)	8.22E-03	4.39E-03	3.50E-04	0.0186
Loamy Sand					
θ_s	Normal	0.41	0.09	0.132	0.688
θ_r	Normal	0.0569	0.0145	0.0121	0.102
ψ_b	LN(2.15,0.401)	9.58	8.59	2.48	29.5
λ	LN(0.226,0.164)	1.27	0.209	0.756	2.08
K_s (cm/s)	Beta(0.7992,1.910)	3.99E-03	3.17E-03	3.90E-05	0.0134
Sandy Loam					
θ_s	Normal	0.41	0.0899	0.132	0.688
θ_r	Beta(2.885,2.304)	0.0644	0.0169	0.0173	0.102
ψ_b	LN(2.71,0.538)	17.7	12	2.85	79.4
λ	Normal	0.892	0.155	0.412	1.37
K_s (cm/s)	LN(-7.46,1.33)	1.17E-03	1.37E-03	9.62E-06	0.0347

θ_s = saturated moisture content θ_r = residual moisture content

ψ_b = air entry head (cm) λ = Brooks Corey parameter

K_s = hydraulic conductivity (cm/s)

Table 7 - Comparisons of infiltration rates based on parameter distributions from Meyer et al., 1997 with representative values from WDOE and from Rawls et al., 1982. All values in inches per hour.

Table 7a - Probabilities of exceeding representative infiltration rates based on parameter distributions from Meyer et al., 1997.

	Meyer et al. statistics					
	Mean	5%	95%	Mean from Rawls et al., 1982	Representative values from WDOE	Probability of exceeding WDOE values
Sand	11.31	21.83	1.70	8.27	2.9*	91%
Loamy sand	5.54	14.32	0.18	2.41	0.6	90%
Sandy loam	1.77	6.42	0.10	1.02	0.25	81%

Table 7b - Ratios of representative values and mean values from Meyer et al., 1997.

	Mean from Meyer et al.	WDOE representative values	Ratios of mean to representative values
Sand	11.31	2.9*	3.9
Loamy sand	5.54	0.6	9.2
Sandy loam	1.77	0.25	7.1

* The WDOE Manual includes two categories of sand. The average infiltration rate for these two categories is used in the tables.

Table 8 - Summary of data included in Figures 6 through 10

SCS Soil Type	WDOE Rate (in/hr)	Meyers Mean Rate(in/hr)	Reported Soil Type	Meas. Infil Rates(in/hr)	Sites	Testing Method
Sandy loam	0.25	1.66	v. silty, fine to med. sand	0.26	Clark - Clark Co.	Flood test
Sandy loam	0.25	1.66	silty fine to coarse sand	2.11	Kit - Balsam 7-11	Flood test
Sandy loam	0.25	1.66	fine to coarse sandy gravel	0.21	Kit - Krista Firs	Flood test
Indianola loamy sand	0.6	5.66	loamy sand	36	Kit- Summerhill 2	Single Ring Infiltrometer
Indianola loamy sand	0.6	5.66	loamy fine sand	36	Kit-Berger Lane	Single Ring Infiltrometer
Harstine gravelly sandy loam	0.6	5.66	loamy sand	19.2	Kit - Ponderosa Park	Single Ring Infiltrometer
Indianola loamy sand	0.6	5.66	loamy fine sand	1.11	PC - Chardonnay	Single Ring Infiltrometer
Indianola loamy sand/Kitsap silt loam	4	11.65	medium sand	2.22	PC - 143rd & Meridian	Single Ring Infiltrometer
Everett gravelly sand loam	10	11.65	very gravelly course sand	7.2	KC-Winterwood Estates	Single Ring Infiltrometer
Everett gravelly sand loam	10	11.65	very gravelly course sand	14.4	KC-Winterwood Estates 5	Single Ring Infiltrometer
sandy loam/cobbles	4	11.65	Sandy Loam/Cobbles	59.2	KC-Sno-Woodway Meadows Undis.	Double ring infiltrometer
sandy loam	0.25	1.66	Sandy Loam	16.7	KC-Woodway Meadows Dist.	Double ring infiltrometer
sandy loam/cobbles	4	11.65	Sandy Loam/Cobbles	14	KC-Tall Timbers	Double ring infiltrometer
sandy loam/cobbles	4	11.65	Sandy Loam/Cobbles	12.7	ThC-Lacey-BASIN #1	Double ring infiltrometer
sandy loam/cobbles	4	11.65	Sandy Loam/Cobbles	33	ThC-Lacey-BASIN #2	Double ring infiltrometer
	10	11.65	Coarse sand and gravel	50	ThC-State farm	Double ring infiltrometer
	10	11.65	Coarse sand and gravel	45	ThC-State farm	Double ring infiltrometer
	10	11.65	Coarse sand and gravel	83	ThC-Margaret McKinney School	Double ring infiltrometer
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	12	ThC-Woodard Glen	Double ring infiltrometer
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	6.5	ThC-Airdustrial Way	Double ring infiltrometer

	10	11.65	Coarse sand and gravel	17	ThC-Bush Middle School	Double ring infiltrometer
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	42	ThC-Lacey Lid No. 13	Double ring infiltrometer
	10	11.65	Coarse sand and gravel	45	ThC-Echo Glen	Double ring infiltrometer
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	4.5	ThC-Sweetbriar	Double ring infiltrometer
	10	11.65	Coarse sand and gravel	7	ThC-State farm	Stage
	10	11.65	Coarse sand and gravel	4	ThC-State farm	Stage
	10	11.65	Coarse sand and gravel	2	ThC-Margaret McKinney School	Stage
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	2.27	ThC-Woodard Glen	Stage
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	1.74	ThC-Airdustrial Way	Stage
	10	11.65	Coarse sand and gravel	10	ThC-Bush Middle School	Stage
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	1.1	ThC-Lacey Lid No. 13	Stage
	10	11.65	Coarse sand and gravel	13.5	ThC-Echo Glen	Stage
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	0.35	ThC-Airdustrial Way	Stage
sandy loam	1.8	11.65	Sand w/>25% finer than 0.25 mm	0.39	ThC-Sweetbriar	Stage
	10	11.65	Coarse-grained material	0.25	KC-Issaquah Highlands	Stage
	10	11.65	Coarse-grained material	1.38	KC-Issaquah Highlands	Stage
Alderwood Sandy Loam	0.6	5.66	Loamy Sand	1.18	KC-Union Hill-TRENCH (roof runoff)	Stage
silty sand loam	0.25	0.13	silty sand loam	2.7	KC-Cimarron Div. 1	Falling Head
silty sand loam	0.25	0.13	silty sand loam	3.75	KC-Sunridge Estates	Falling Head
gravel/coarse sand	10	11.65	gravel to coarse sand	66	KC-Beaver Lake	Falling Head
	4	11.65	well graded f-c sand	0.96	KC-Redmond Ridge	Falling Head
	4	11.65	well graded f-c sand	4.62	KC-Redmond Ridge	Falling Head
	4	11.65	poorly graded sand	21.6	KC-Redmond Ridge	Falling Head
Indianola Sandy Loam	0.25	1.66	sandy loam	5.51	PC-Heritage Glen	Falling Head
South Pond	0.25	1.66	sandy loam	1.1	CL Wakefield Estates, North Pond	Slug Test

	0.25	0.13	silty loam	6.4	PC-Lower Meridian	Falling head-boring
	4	11.65	fine to medium sand	13.2	KC-Toth Estates	Constant Head-boring
Test A	0.25	1.66	sandy loam	13.7	CL Rosewood Test A	Auger hole
Test B	0.6	0.41	loam	10.2	CL Rosewood Test B	Auger hole
Test C	0.25	1.66	sandy loam	8.2	CL Rosewood Test C	Auger hole
Test 3-1	0.25	1.66	sandy loam	0.73	CL RosewoodTest 3-1	Auger hole
Test 3-2	0.6	0.41	loam	0.2	CL Rosewood Test 3-2	Auger hole
Test 3-3	0.6	0.41	Loam	18	CL Rosewood Test 3-3	Auger hole
Test 3-4	0.25	1.66	sandy loam	27.53	CL Rosewood Test 3-4	Auger hole
Test 4-1	4	11.65	sand	25.8	CL Rosewood Test 4-1	Auger hole
Test 4-2	0.25	0.13	silty loam	11.3	CL Rosewood Test 4-2	Auger hole
North Pond	0.25	1.66	sandy loam	3.2	CL Wakefield Estates, South Pond	Test Pit

Table 9 – Comparison of long-term full-scale infiltration rates with the D_{10} grain size parameter

Site	Long-term, full-scale infiltration (in/hr)	D_{10} (mm)	Notes
Ridgeview,Thurston County	4	0.7	
Beaverdam, King County	2	0.5	
Echo Glen, Thurston County	13	0.4	
Margaret McKenny, Thurston County	2	0.3	evidence of mottling
State Farm, Thurston County	4	0.3	evidence of biological fouling
State Farm, Thurston County	7	0.3	
Bush, Thurston County	10	0.2	
Krista Firs, Kitsap County	0.3	0.2	
Airdustrial, Thurston County	0.4	0.1	evidence of mottling
Lacey Lid, Thurston County	1	0.1	
Wood Glen, Thurston County	2	0.1	
Sweetbriar, Thurston County	0.4	0.1	evidence of mottling
Airdustrial, Thurston County	2	0.1	evidence of mottling
Springfield, Thurston County	3	0.1	
Balsam 7-11, Kitsap County	2	0.010	
Clark County Pond	0.2	0.010	

Figure 1 - Definition of variables used in the Green-Ampt equation.

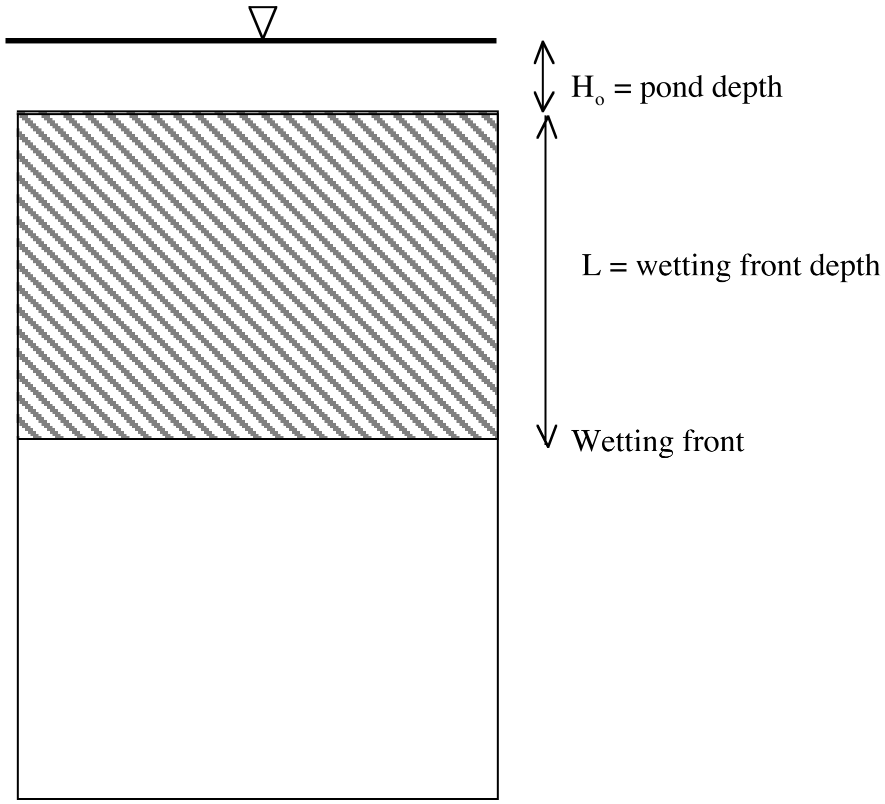


Figure 2 - Estimated infiltration rate for sand using the Green-Ampt equation

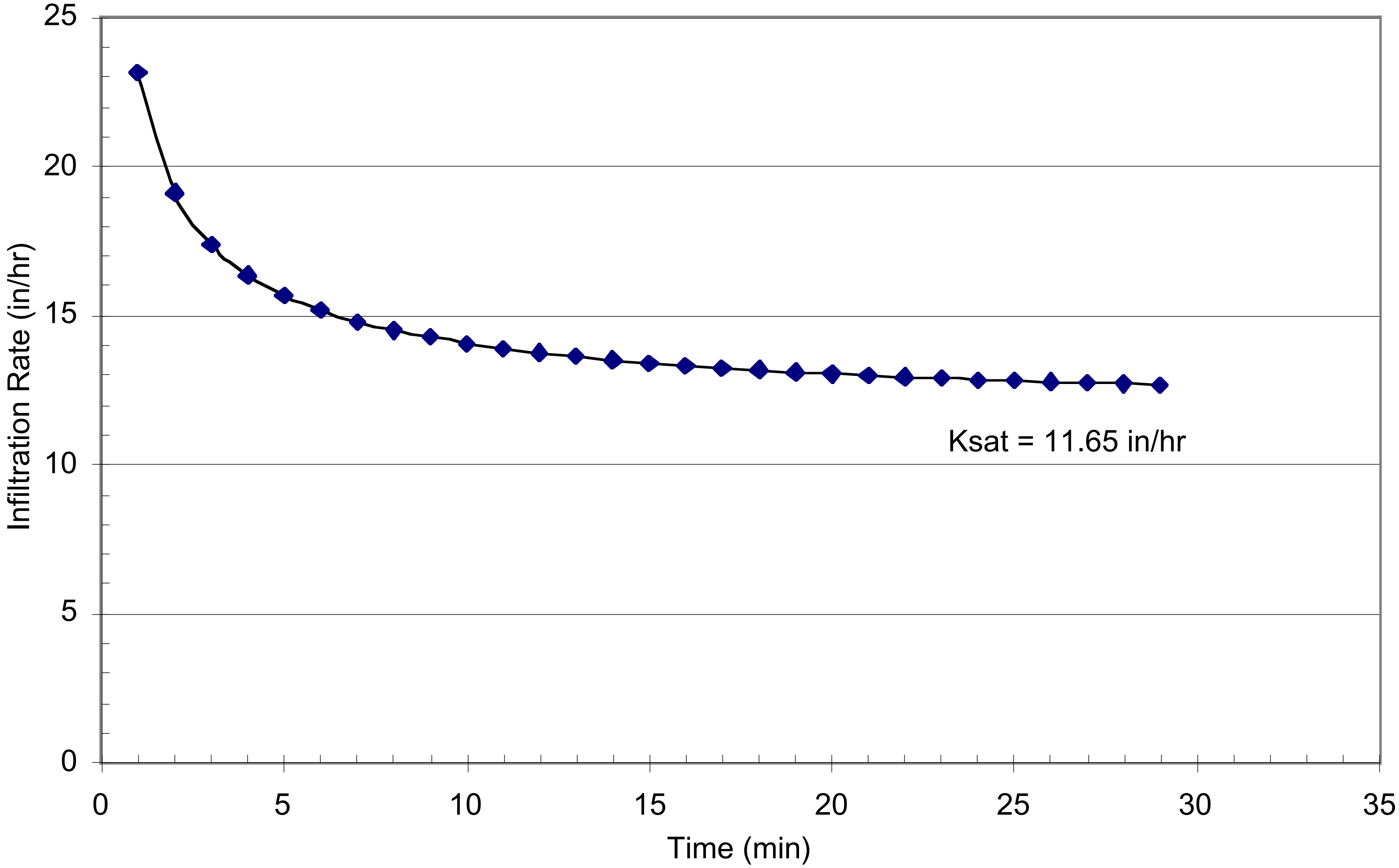


Figure 3 - Estimated infiltration rate for loamy-sand using the Green-Ampt equation

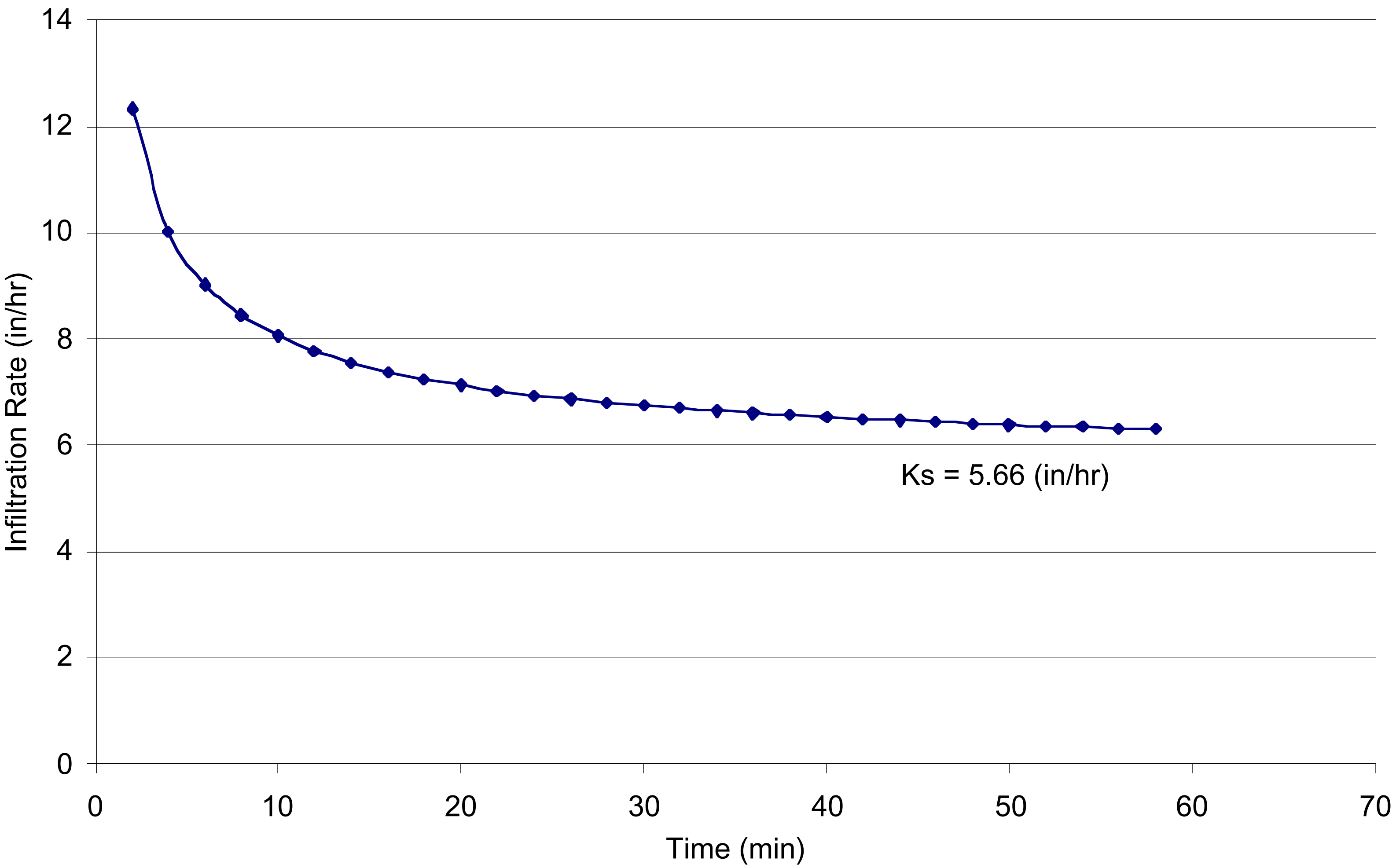


Figure 4 - Estimated infiltration rate for sandy-loam using the Green-Ampt equation

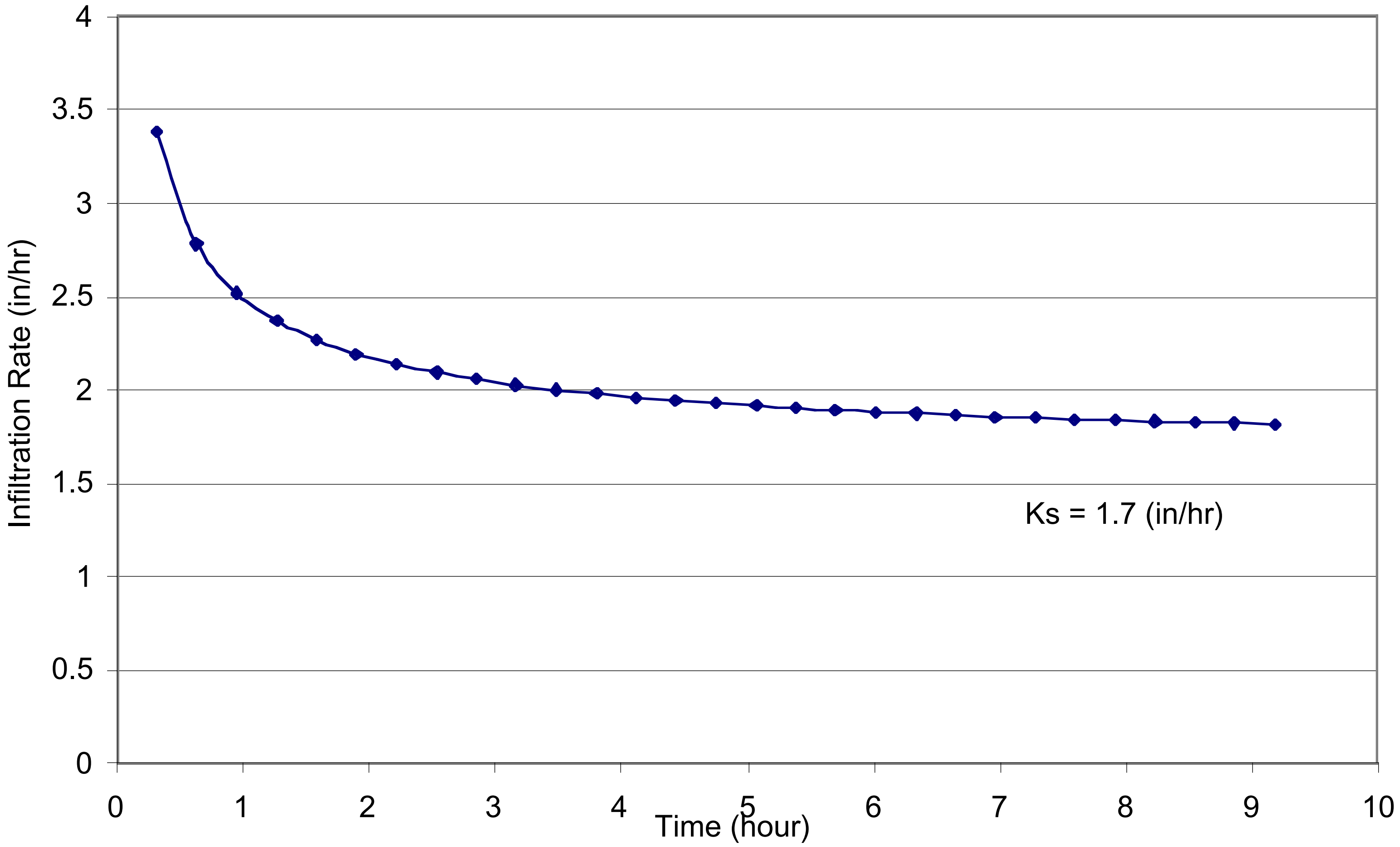


Figure 5 - Comparison of WDOE representaive values with distributions describing uncertainty in saturated hydraulic conductivity

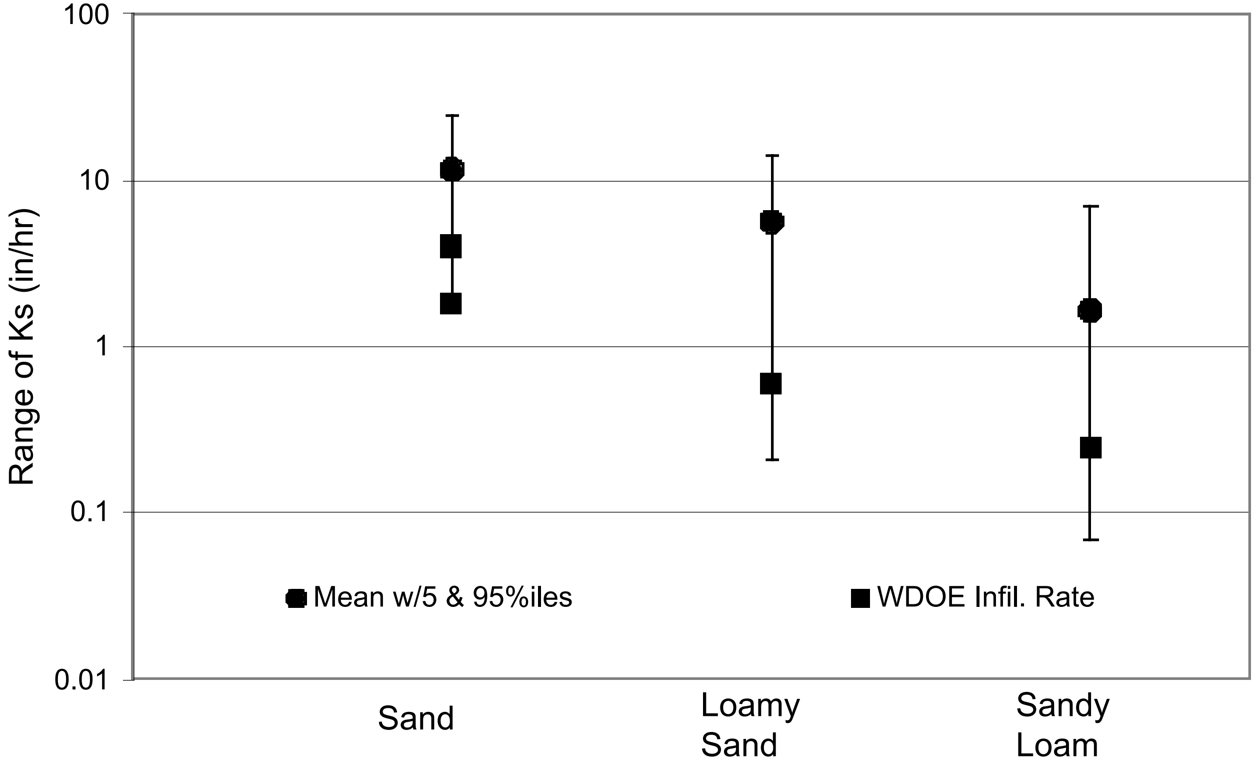


Figure 6 - Comparison WDOE representative rates with all measured values

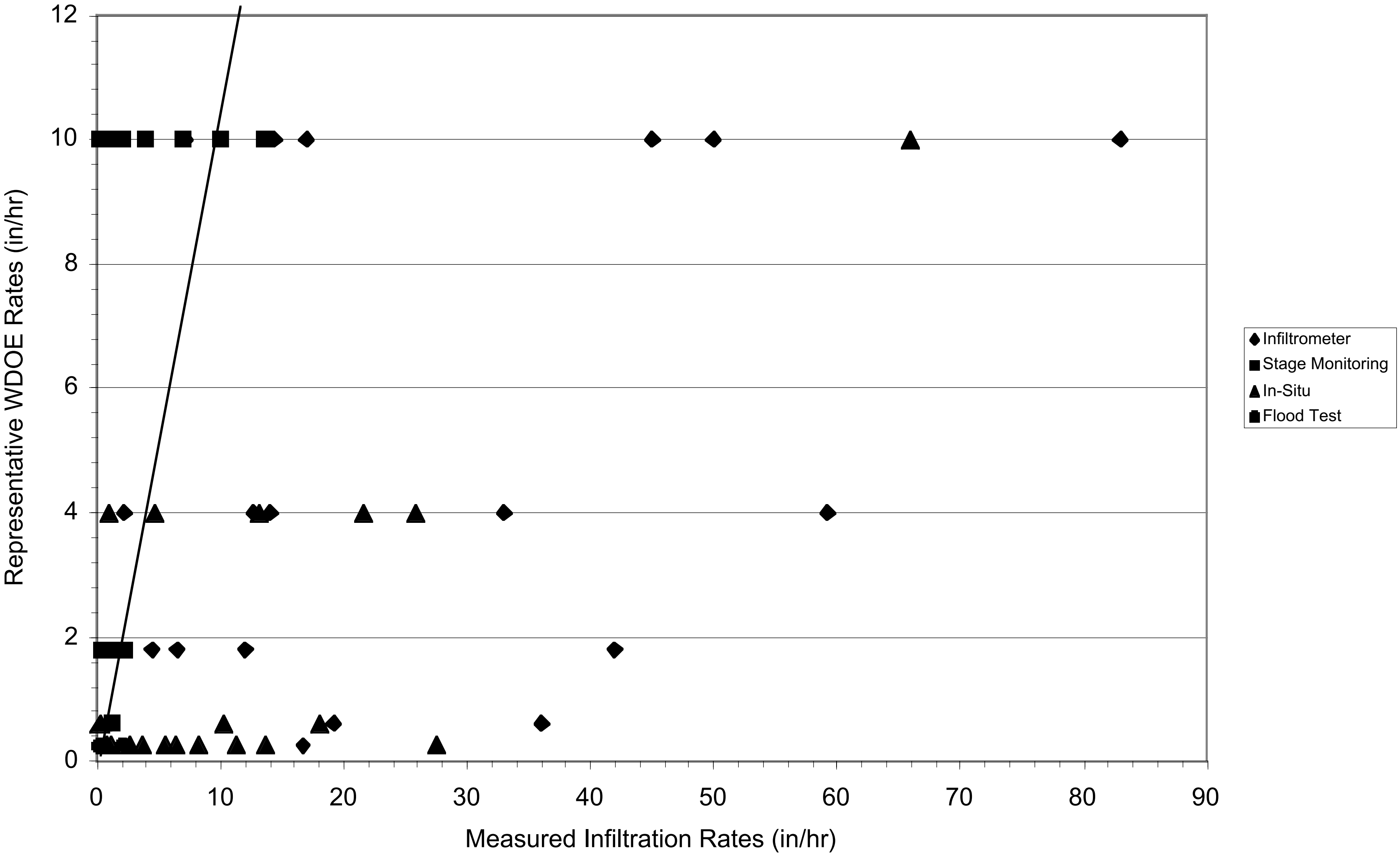


Figure 7 - Comparison of WDOE representative rates with values from stage monitoring

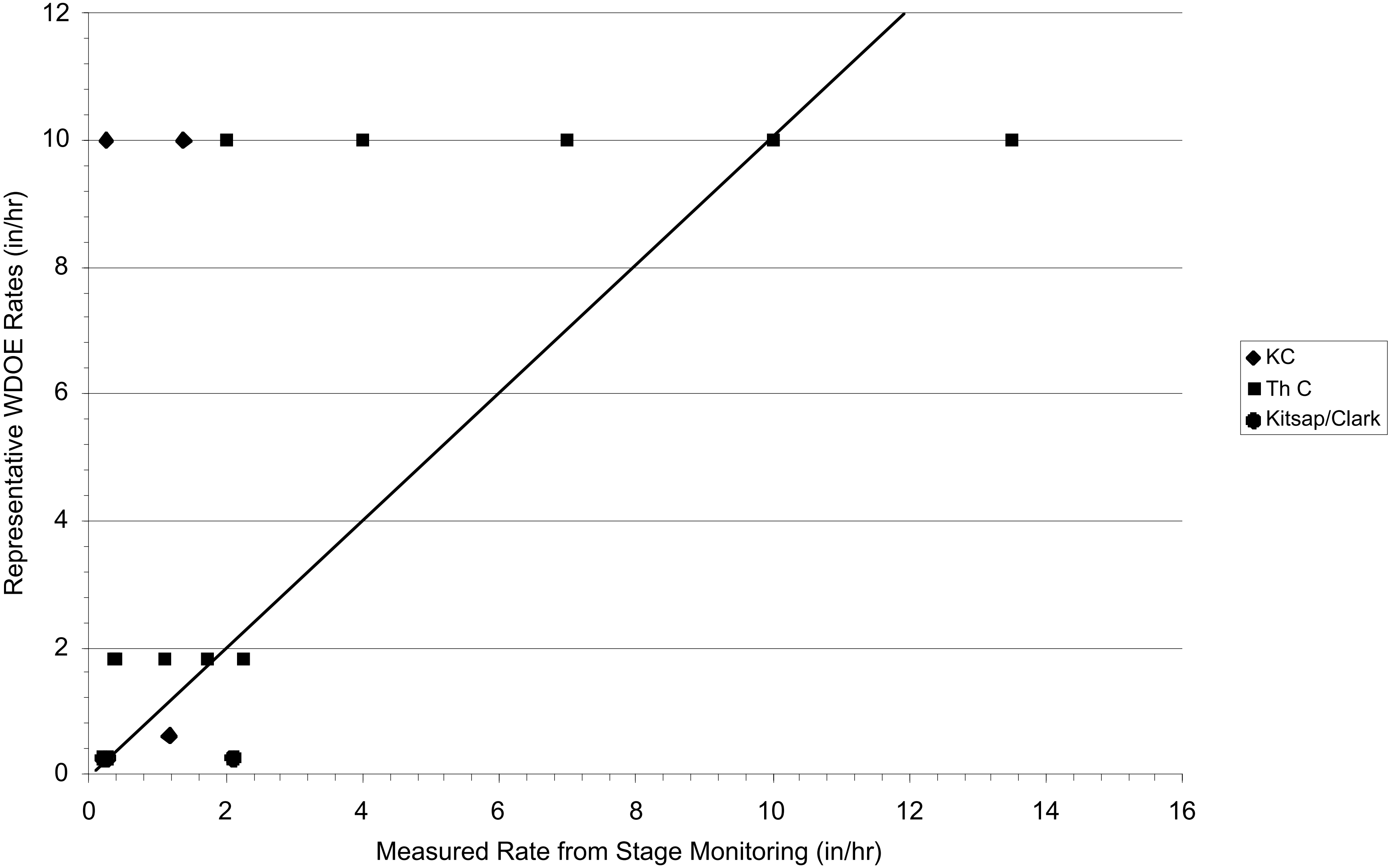


Figure 8 - Comparison of WDOE representative rates with values from infiltrometer tests

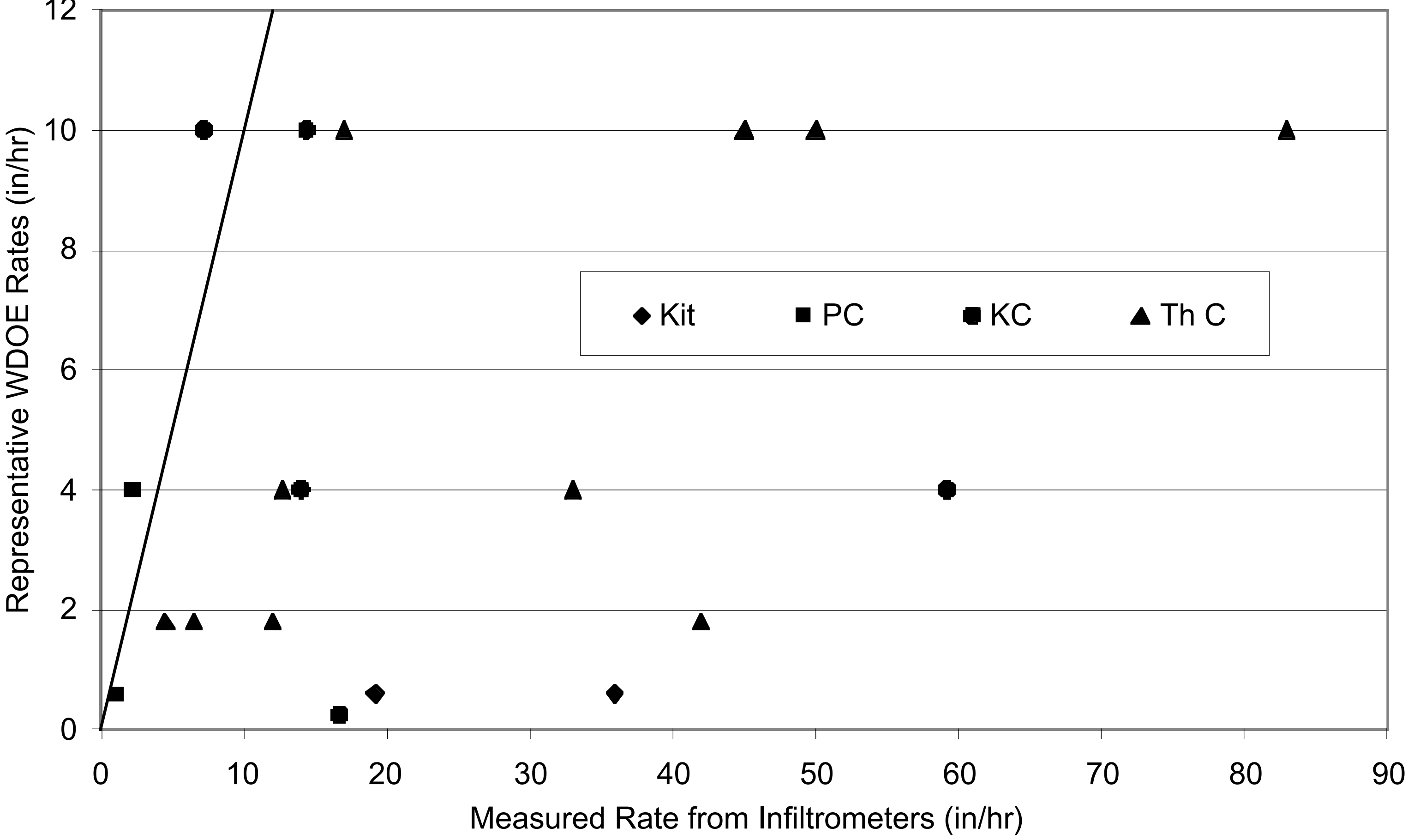


Figure 9- Comparison of WDOE representative rates with values from in-situ tests

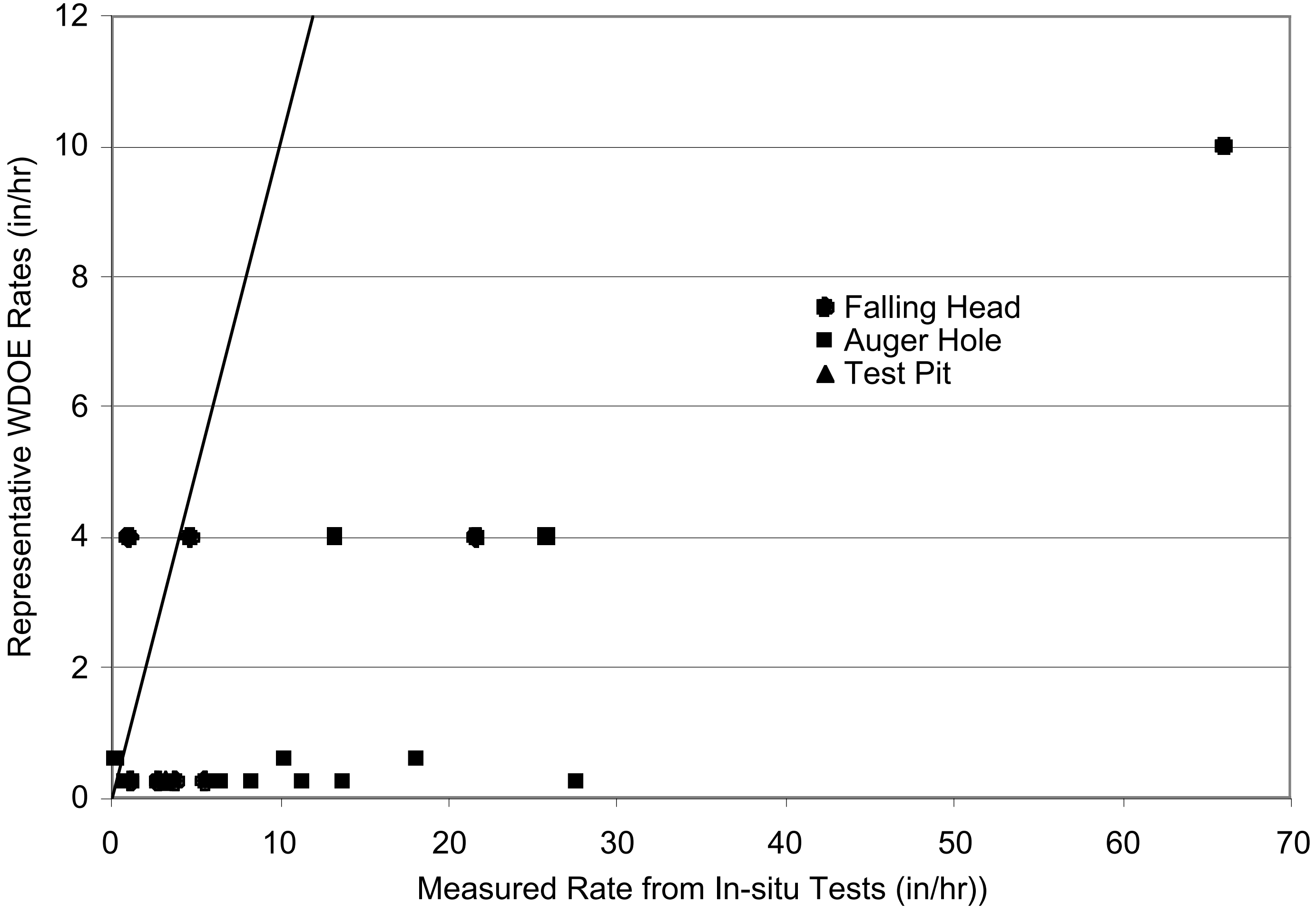
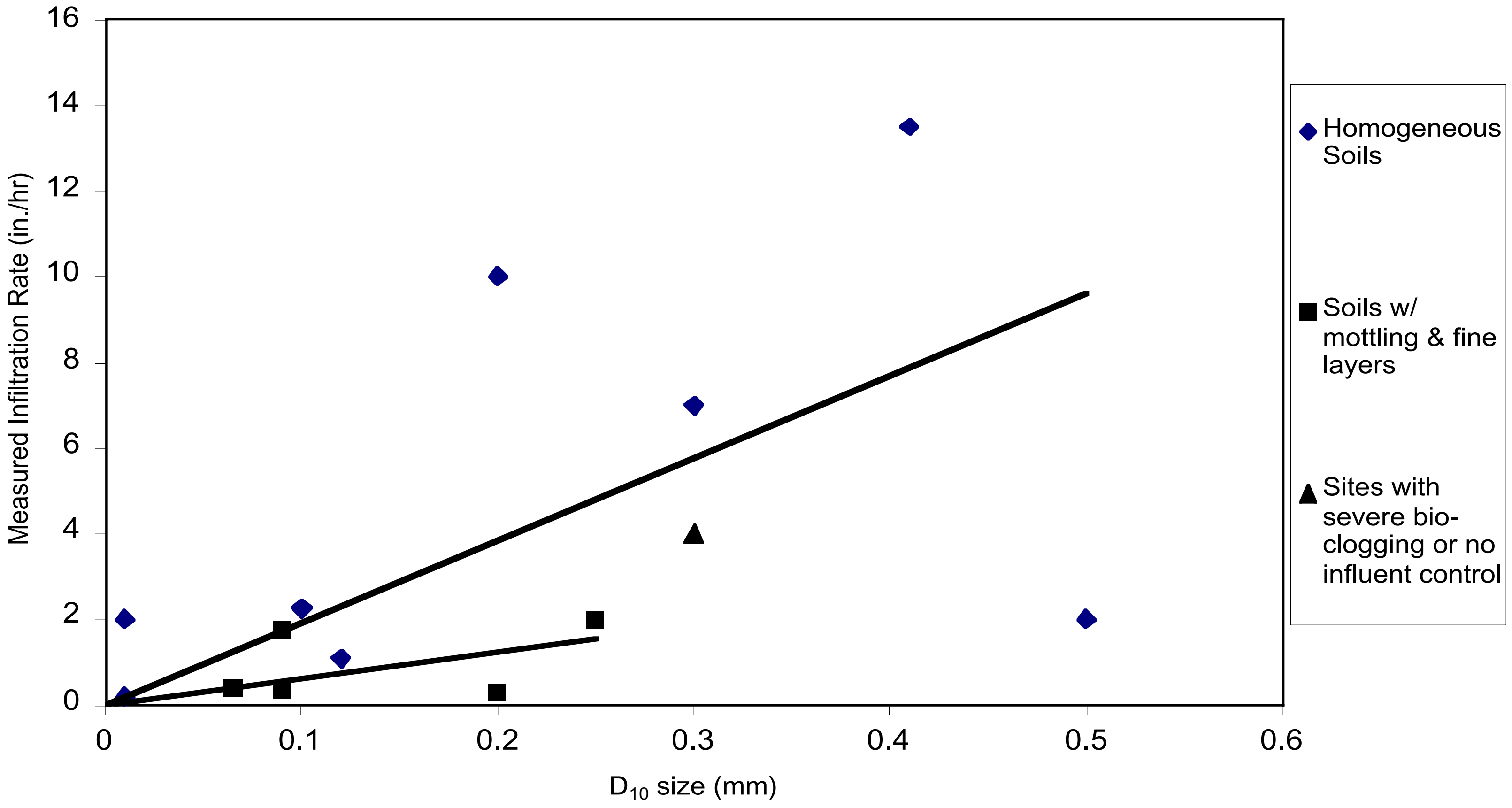


Figure 10. Measured infiltration rate vs. d_{10} size for the data in Table 8



APPENDIX A

EXCERPTS FROM "*Stormwater Management in Washington State, Volume III, Hydrologic Analysis and Flow Control Design*," Public Review Draft, Publication 99-13, October, 1999.

Table 2.4 Recommended Representative Site Infiltration Rates Based on Soil Textural Classification.

	Representative Site Infiltration Rate (in./hr)	Apply Correction Factors, CF
Sandy Gravel or Gravelly Sand	10	1.2
Sand w/< than 25% finer than 0.25 mm	4	1.2
Sand w/> than 25% finer than 0.25 mm	1.8	1.2
Loamy Sand	0.6	1.2
Sand Loam	0.25	1.2

Infiltration Rates

Ecology requests comments on:

1. The application of the CF and infiltration rates in table 2.4 and the potential requirement by local jurisdictions of an O & M and financial bonding plan.

2. Design infiltration rates for soils in other parts of the state.

3. Reliable and precise infiltrometer field test equipment and/or test procedures.

4. Applying a CF up to 5 if fine soil layering or soil mottling is observed below the site proposed for the infiltration facility.

Infiltration facilities may be made deeper to promote lateral infiltration and stormwater disposal. Therefore, Ecology also requests comments on:

1. Best method of determining lateral infiltration rates.

2. Minimum depth of the facility to obtain sufficient lateral infiltration.

3. Type of regional stratification needed to promote lateral infiltration

4. Minimum site subsurface exploration requirements for this type of design

5. Criteria needed on the lateral extent of the subsurface saturated zone and the storage volume determination for this type of design

2.3.8 Sizing Infiltration BMPs

Darcy's Law

A Darcy's Law approach is recommended for sizing infiltration BMPs. Stage-storage and stage-discharge relationships can be developed through an iterative process. The infiltration BMP size and geometry can then be determined by routing the appropriate design storm(s). A simple version of Darcy's Law of ground water movement can be used to develop the stage-discharge relationship (Figure 2.23 illustrates Darcy's Law of Ground water Movement):

$$Q = f * i * A_s, \quad (1)$$

where:

Q = flowrate at which runoff is infiltrated by BMP

f = representative site infiltration rate based on a textural analysis (table 2.4), hindcast analysis of facilities in similar soils, or large scale pilot infiltration tests

i = hydraulic gradient at saturated conditions

A_s = infiltration surface area of the infiltration BMP

Note that this version of Darcy's Law applies to saturated soil conditions. The hydraulic conductivity of unsaturated soil varies as a function of moisture content, so Darcy's Law is difficult to apply to unsaturated soil flow conditions. Also, in some cases trapped air may cause infiltration rates to be lower than would be predicted using Darcy's Law.

Apply the CF from table 2.4 or other CF acceptable to the local jurisdiction. The design infiltration rate will be labeled "f_d" where $f_d = f/CF$. The hydraulic gradient, i, is given by the equation:

$$i = \frac{h + L}{L} \quad (2)$$

where:

h is the height of the water column over the infiltration media, and, L is the distance from the top surface of the saturated infiltration medium to the water table, bedrock, impermeable layer, or soil layer of different infiltration rate. If the approximate area available for the BMP is known then a preliminary stage-discharge relationship can be developed, i.e.,

$$Q = f_d * \frac{h + L}{L} * A_s \quad (3)$$

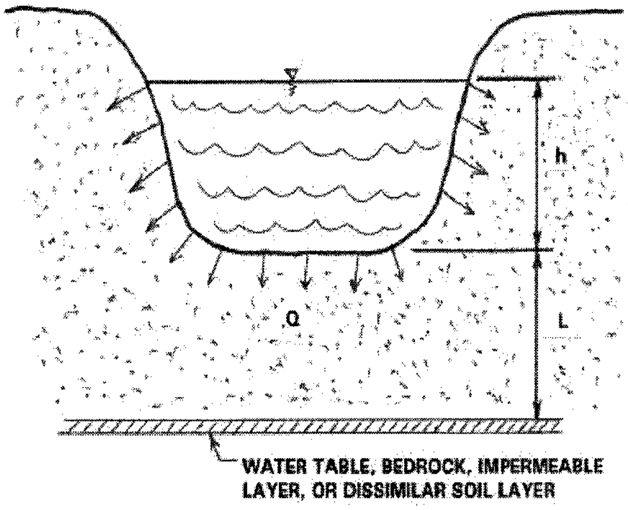


Figure 2.23 Darcy's Law of Ground Water Movement

Design Storm

The appropriate design storm can then be routed through the infiltration BMP using a level pool analysis. The analysis must demonstrate that the BMP will completely infiltrate the design storms within 24 hours (or 48 hours for the 100-year event). If this is not the case the surface area of the BMP will have to be increased. If the analysis indicates that the design storms can only be partially infiltrated the BMP should still be utilized but the additional runoff must be conveyed to another BMP.

The design criteria for quantity control infiltration BMPs are to control runoff discharged from the *developed* site such that it conforms with the flow control requirement #5 in Volume I.

Sizing Example Using Darcy's Law:

- Problem Statement: An infiltration basin is proposed to retain stormwater from a development site. A soil textural analysis of the site soils indicates that the soil is homogeneous gravelly sand for at least 8 feet below the land surface. The surface area available for the BMP is approximately 100 square feet. The depth to the water table is estimated to be 75 feet. No impermeable soil layers were detected within 10 feet of the infiltration surface and none expected within at least 50 feet. For preliminary design purposes the basin is planned to be 30 feet long, 20 feet wide, and 3 feet deep. The preliminary design calculations are as follows:

Determine the Stage-Discharge Relationship

f = 10 inches/hour (from table 2.4), thus
f_d = 10/1.2 = 8.33 inches/hour
= 0.7 ft/hr
h = variable (maximum of 2 feet)
L = *assume 10 feet*
A_s = *bottom surface area*

$= 30 * 20 = 600$ *sq. ft.*

Solving for Q in Darcy's equation gives:

$$Q = f_d * \frac{h + L}{L} * A_s$$

$$Q = 0.7 * \frac{h + 10}{10} * 90$$

$$Q = (6.3\ h) + 63$$

Determine the Stage-Storage Relationship

$$S = A_s * h * \text{Void Ratio}$$

$$S = 600 * h$$

APPENDIX B - Procedure for Conducting a Pilot Infiltration Test

The Pilot Infiltration Test (PIT) consists of a long-term, relatively large-scale infiltration test to better approximate infiltration rates for design of stormwater infiltration facilities. The PIT reduces some of the scale errors associated with relatively small-scale double ring infiltrometer or "stove-pipe" infiltration tests.

Infiltration Test

- Excavate test pit for infiltration test
- Dig the pit at least 5 feet into the infiltration receptor below the bottom of the proposed infiltration facility.
- The bottom of the pit should range from about 100 square feet to 150 square feet.
- Take care to lay back slopes sufficiently to avoid caving and erosion during the test.
- Accurately document the size and geometry of the pit.
- Install a vertical minimum 5-foot long measuring rod marked in tenth-of-a-foot increments in the center of the pit bottom.
- Use a rigid 6-inch diameter pipe with a splash plate on the bottom to convey water to the bottom of the pit and reduce side-wall erosion or excessive disturbance of the pond bottom (excessive erosion and bottom disturbance will result in clogging of the infiltration receptor and yield lower than actual infiltration rates).
- Add water to the pit at a rate that will maintain a water level between 3 and 4 feet above the bottom of the pit.
- Note: A depth of 3 to 4 feet provides for easier measurement and flow stabilization control. However, the depth should not exceed the proposed maximum depth of water expected in the completed facility.
- Periodically, record total flow and flow rate in gallons per minute necessary to maintain the water level at the same point (between 3 and 4 feet) on the measuring rod.
- Add water to the pit for a minimum of 1,000 minutes (approximately 17 hours) or until the flow rate has stabilized.
- After a 1,000 minutes and the flow rate has stabilized , turn off the water and record the rate of infiltration in inches per hour until the pit is empty.

Data Analysis

- Based on the size and geometry of the pit bottom, calculate the volume of a 1-inch thick layer of water.
- Divide the volume of the 1-inch thick layer of water by the amount of water that flowed into the pond during one hour after flow stabilized. This calculation will provide a representative infiltration rate in inches per hour.
- Note: Use statistical/trend analysis to obtain a representative, average hourly flow rate.
- Apply appropriate factors of safety for site heterogeneity, anticipated level of maintenance and treatment to determine the site-specific design infiltration rate.

Example

- The bottom of the test infiltration pit measured 8.5-feet by 11.5 feet.
- The volume of a 1-inch thick layer of water would be 14,076 cubic inches (102 inches by 138 inches by 1 inch).
- The pit holds 60.9 gallons of water for every one inch of depth (1 cubic inch times 0.004 gallons per cubic inch times 14,076 cubic inches)
- Water flow rate was measured and recorded at intervals ranging from 15 minutes to 30 minutes throughout the test. Between 400 minutes and 1,000 minutes the flow rate stabilized between 10 and 12.5 gallons per minute or 600 to 750 gallons per hour.
- 600 gallons per hour divided by 60.9 gallons per inch = 9.8 inches per hour and 750 gallons per hour divided by 60.9 gallons per inch = 12.3 inches per hour. Assume an average representative infiltration rate of 9.8 + 12.3 / 2 = 11.1 inches per hour.
- Infiltration media consisted of a gravelly sand. Therefore, from Table 1 use a minimum factor of safety of 2 to determine a design infiltration rate of 5.5 inches per hour anticipating excellent maintenance and pre-treatment.

APPENDIX B - ESTIMATING POROSITY FROM SOIL TEXTURE DATA

1. Determine Mineral Bulk Density from the following graph (from Rawls and Brakensiek, 1985):

Mineral Bulk Density Chart (g/cm^3):

						Sand					
	%	10	20	30	40	50	60	70	80	90	100
	10	1.4	1.2	1.25	1.27	1.4	1.52	1.58	1.69	1.65	1.53
	20	1.4	1.25	1.35	1.45	1.53	1.6	1.67	1.72		
Clay	30	1.4	1.3	1.4	1.5	1.57	1.63	1.68			
	40	1.4	1.35	1.44	1.55	1.61	1.68				
	50	1.4	1.35	1.44	1.53	1.62					

2. Calculate Soil Bulk Density using the following equation:

$$\text{Soil Bulk Density} = \frac{100}{\dfrac{\text{\% ORGANIC MATTER}}{\text{ORGANIC MATTER BULK DENSITY}} + \dfrac{\text{100-\%ORGANIC MATTER}}{\text{MINERAL BULK DENSITY}}}$$

AVERAGE ORGANIC MATTER BULK DENSITY = 0.224 g/cm^3 (9).

3. Determine porosity applying the following procedure:

Soil bulk density = 114.2 pcf (given)
Soil moisture content = 13.8% (given)

$$\frac{\text{Weight water}}{\text{Weight solid}} = 0.138$$

Weight water = 0.138*Weight solid
Weight water + Weight solid = 114.2 lb
1.138*Weight solid = 114.2 lb
Weight solid = 100.35 lb

Assume average specific weight (γ) of sand is 2.65

$$2.65 = \frac{\gamma\text{solid}}{\gamma\text{water}}$$

$2.65*(62.4 \text{ lbf/ft}^3) = \gamma\text{solid} = 165.36 \text{ lbf/ft}^3$

$$\text{Volume solid} = \frac{100.35 \text{ lb}}{165.36 \text{ lbf/ft}^3} = 0.61$$

porosity (n) = 1 - 0.61 = ***0.39***