UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS LABORATORY
Engineering, Environmental and Geophysical Fluid Dynamics

Project Report No. 560

Performance of Low Impact Development Practices on Stormwater Pollutant Load Abatement

Objective B: Infiltration capacity of LID practices

By

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Prepared for
Minnesota Pollution Control Agency

August, 2011
Minneapolis, Minnesota

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1. Introduction:

Stormwater runoff is a major contributor to the impairment of surface waters in the United States. With high connected impervious surfaces and concentrated human activities, urban land uses are involved in discharging most of the stormwater volume and pollutant loadings during a storm. Stormwater pollution prevention involves the installation and maintenance of stormwater low impact development (LID) practices in urban areas. These include infiltration basins and trenches, porous pavements, rain gardens, vegetative swales, and filter strips. LID practices infiltrate and detain stormwater to reduce stormwater runoff volume and improve water quality via filtration and other processes. The reasons for assessing the performance of the LID practices include fulfilling stormwater permit regulatory requirements, engineering and design due diligence, scheduling maintenance and TMDL studies. The results of the assessment allow for an improved understanding of the role of the various system components (i.e. soil, plants, etc.) in pollutant removal and volume reduction.

This project is designed to assist MS4s in the assessment of their stormwater BMPs and the utilization of these BMPs in watershed TMDL analyses. Objective B of this project focuses on the infiltration performance of low impact development (LID) practices. The infiltration capacity testing developed for rain gardens (Asleson, et al. 2009) was to be refined, altered and expanded for other types of LID practices including infiltration basins and trenches, vegetative swales and filter strips. The Modified Philip Dunne (MPD) infiltrometer is implemented as a low-effort, low-cost method to determine saturated hydraulic conductivity, a predictor of infiltration capacity. This infiltration tests have been performed on rain gardens, infiltration basin, swales and turf areas.

2. Objectives:

I. The goal of objective B is to apply previously developed infiltration capacity testing to other LID infiltration practices, such as infiltration basins and trenches, swales, pervious pavement and filter strips, and to adjust the capacity testing methodology as needed for each practice.
II. To develop a relatively rapid, low-effort and low-cost approach for assessing the performance of these practices.
III. Capacity testing with the MPD infiltrometer developed for rain gardens is to be refined and expanded to other types of LID practices.

3. Infiltration capacity testing sites:

Infiltration measurement have been performed on six rain gardens, three turf areas, three swales, an infiltration basin and proposed rain garden/infiltration areas. These infiltration practices are the following:

1. Burnsville rain garden,
2. Cottage Grove rain garden,
3. RWMWD rain garden,
4. Thompson Lake rain garden,
5. U of M Duluth rain garden,
6. U of M St. Paul rain garden,
7. Stillwater infiltration basin,
8. Albertville swale,
9. Hwy 47 swale,
10. Hwy 212 swale,
11. French Regional Park turf area,
12. Lake Minnetonka Regional Park turf area,
13. Maple Lakes Park turf area,
14. Proposed Minnetrista rain gardens.

4. Methods and procedure:

To estimate the infiltration capacity of the LID infiltration practices, saturated hydraulic conductivity (K_{sat}) was measured at multiple locations from each site using the MPD infiltrometer. The material of the MPD infiltrometer was converted from aluminum tubing to a steel base and clear acrylic pipe to make it more durable and easier to operate. The revised MPD infiltrometer, shown in Figure1, is an open ended, 6 mm thick, 10 cm inner diameter cylinder that comes in two parts. The top is 37cm long constructed of clear acrylic pipe and the detachable bottom is 7cm long made of finished steel. A metric tape is adhered at the outside of the infiltrometer cylinder. A stop watch is used with each MPD infiltrometer to record the drainage time.

Figure 1: Revised Modified Philip-Dunne Infiltrometer

The procedure of the test is as follows:

1. A grid is made to plan where to take the measurements in the infiltration practice.
2. At each grid location the cylinder is pounded 5 cm into the soil.
3. The cylinder is filled with water, the stop watch is started and the initial water level is noted in writing by the operator.
4. The water levels at a given stop watch times are recorded. Depending on the infiltration rate, the time interval between readings varies, but 12 to 15 readings were recorded to eventually calculate a value for saturated hydraulic conductivity (K_{sat}).
5. Both the initial and the final volumetric moisture content are needed to calculate the saturated hydraulic conductivity. As a part of these analyses, a bulk density value was obtained, following the procedure described by ASTM (2004). More than one bulk density sample was taken at each site, using a cylindrical core sampler and a metal driver.
6. Using software developed by St. Anthony Falls Laboratory (Asleson, et al., 2009), the recording of the water level vs. time together with the initial and final moisture content in the soil were used to calculate values for K_{sat} and the soil suction pressure head.

The original MPD infiltrometer is shown in Figure 2. These were composed of thin-walled aluminum tubing with a piezometer tube attached to the side of the tube and connected to the inside of the aluminum tube 5 cm above the bottom of the tube.

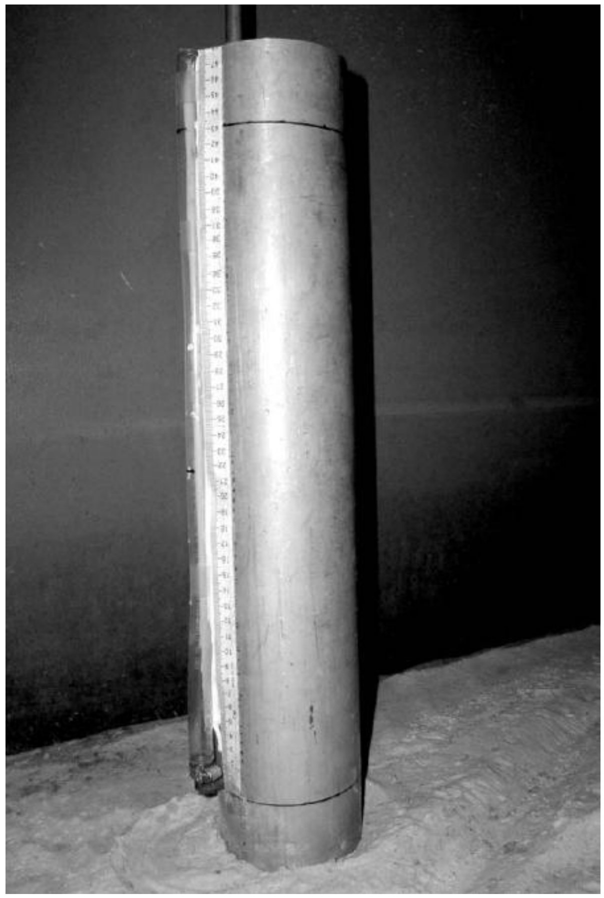

Figure 2: Original Modified Philip Dunne Infiltrometer (Nestingen, 2007)

Most of the infiltration measurements were performed using the original MPDs. The performance of the original and revised MPD infiltrometers are equal, except that the revised MPDs were developed to ease the insertion procedure into a hard soil and to eliminate the need to clean the piezometer tube. From each site sufficient numbers of measurements were taken to perform statistical analyses. These analytical results provide the assessment of the infiltration performance.

(a) (b)

(c)

Figure 3: Performing infiltration test using modified Philip Dunne infiltrometer at
(a) a rain garden,
(b) a proposed raingarden and
(c) turf grasses.

5. Results and analysis:

A sufficient number of infiltration measurements were taken for each of the infiltration practices to facilitate statistical analyses for assessment of the performance of the infiltration practices. The arithmetic mean, geometric mean, standard deviation and coefficient of variance were calculated for each site. The equations that were used are as follows:

Arithmetic mean $$\overline{a_A} = \frac{1}{n}\sum_{i=1}^{n} a_i \quad (1)$$

Geometric mean $$\overline{a_G} = \sqrt[n]{a_1 a_2 \ldots\ldots\ldots a_n} \quad (2)$$

Standard deviation $$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(a_i - \overline{a_A}\right)^2} \quad (3)$$

Coefficient of variance $$COV = \frac{\sigma}{\overline{a_A}} \quad (4)$$

Standard deviation of log $$\sigma_{\log} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\log a_i - \log \overline{a_G}\right)^2} \quad (5)$$

Upper limit $$UL = 10^{\overline{a_G} + t\frac{\sigma_{\log}}{\sqrt{n}}} \quad (6)$$

Lower limit $$LL = 10^{\overline{a_G} - t\frac{\sigma_{\log}}{\sqrt{n}}} \quad (7)$$

where, n = number of measurement,

a_i = K_{sat} at a specific location,

t = Student's t distribution,

σ_{log}= Standard deviation in log space.

The arithmetic mean, standard deviation and coefficient of variance all give more weight to the largest K_{sat} values and the largest variations from the mean. The geometric mean is similar to the mean of the log values, and gives equal weight to each K_{sat} value. The upper limit, *UL* and the lower limit, *LL,* are the 95% confidence interval assuming a log-normal distribution of K_{sat}, which most of the data follow. The K_{sat} values determined by the MPD software from these measurements are provided in Appendix B.

5.1. Statistical analysis of infiltration measurements in LID infiltration practices with engineered soil

The K_{sat} values provided in Appendix B allow the use of statistics to determine the spatial mean K_{sat} value to use in infiltration computations. In addition, the coefficient of variation and confidence intervals for this mean can be computed to a given probability. The value of these confidence intervals is that it is known, within the stated probability that the geometric mean value will lie between the confidence intervals. For example, a 95% confidence interval on the geometric mean value indicates that the actual geometric mean value will be between the confidence interval 19 out of 20 times. The one assumption is that the log of the K_{sat} data is distributed in a Gaussian (normal) manner (it is a log-normal distribution).

In this section the statistical analyses on engineered (chosen and placed by the designer and developer) soil are given for MPD measurements in rain gardens (Table 1) conducted with funding from the Minnesota Pollution Control Agency (MPCA) and the Metropolitan Council Environmental Council (MCES) an infiltration basin (Table 2) and swales (Table 3).

Table 1: Statistical analysis of infiltration measurement in rain gardens (Asleson et al., 2007)

Location	# of measurement	Geometric mean of K_{sat} (cm/hr)	Arithmetic mean of K_{sat} (cm/hr)	St. dev. of K_{sat} (cm/hr)	COV	Upper limit of mean K_{sat} (cm/hr)	Lower limit of mean K_{sat} (cm/hr)
Burnsville	23	40.96	63.99	64.15	1.00	64.95	25.83
Cottage grove	20	71.80	85.51	49.12	0.57	97.44	52.91
RWMWD	31	7.18	17.64	21.04	1.19	13.44	3.83
Thompson lake	29	13.27	44.98	53.71	1.19	33.13	5.31
U of M Duluth	33	9.71	33.61	58.65	1.75	17.01	5.54
U of M St. Paul	39	8.76	15.58	13.83	0.89	14.88	5.16

Table 2: Statistical analysis of infiltration measurements in the Stillwater infiltration basin

Location	# of measurement	Geometric mean of K_{sat} (cm/hr)	Arithmetic mean of K_{sat} (cm/hr)	St. dev of K_{sat} (cm/hr)	COV	Upper limit of mean K_{sat} (cm/hr)	Lower limit of mean K_{sat} (cm/hr)
Stillwater	68	3.18	11.61	18.07	1.56	5.78	1.75

Table3: Statistical analysis of infiltration measurement in swales

Location	# of measurement	Geometric mean of K_{sat} (cm/hr)	Arithmetic mean of K_{sat} (cm/hr)	St. dev of K_{sat} (cm/hr)	COV	Upper limit of mean K_{sat} (cm/hr)	Lower limit of mean K_{sat} (cm/hr)
Albertville	8	6.88	32.41	34.04	1.05	86.45	0.55
Hwy 47	18	2.14	9.95	15.27	1.54	6.99	0.66
Hwy 212	19	0.96	16.26	30.98	1.90	5.18	0.18

5.2. Statistical analysis of infiltration measurements in native soil:

A field experiment was conducted on turf to determine the effectiveness of remediation techniques to alleviate soil compaction and increase infiltration. The MPD was used before and after the soil remediation techniques were applied to assess the effectiveness of each technique to improve infiltration capacity. Funding was provided by the Minnesota Pollution Control Agency (MPCA) under the title, "Quantifying Stormwater Infiltration Rates on Developed Soils Amended with Tillage and Compost." Additional funding was provided by the University of Minnesota Center for Urban and Regional Affairs (CURA). Table 4 shows the statistical analysis that was performed on the data collected from three turf areas. In this case the geometric mean represents the mean more accurately than arithmetic mean. The geometric mean emphasizes the exponent of the K_{sat} instead of the actual numeric value and achieves a more equal weight of the low K_{sat} values.

Table 4: Statistical analysis of infiltration measurements on turf (Olson et al., 2010)

Location	# of measurement	Geometric mean of K_{sat} (cm/hr)	Arithmetic mean of K_{sat} (cm/hr)	St. dev of K_{sat} (cm/hr)	COV	Upper limit of mean K_{sat} (cm/hr)	Lower limit of mean K_{sat} (cm/hr)
French Regional Park	54	3.65	6.73	8.12	1.21	5.16	2.58
Maple Lake Park	93	1.80	2.27	1.71	0.75	2.08	1.55
Lake Minnetonka Regional	40	2.35	6.20	9.80	1.58	3.92	1.41

A number of infiltration measurements were performed at several locations clustered at different sites in Woodland Cove area. Woodland Cove is a planned development along the western shore of Lake Minnetonka, within the City of Minnetrista. To meet regulatory requirements, the developer is designing a series of infiltration practices to capture stormwater runoff. So to predict the efficiency of the planned practices the infiltration measurements were performed. This project was funded by James R. Hill Engineers. There were thirteen different sites in that area where the proposed infiltration practices is supposed to be built. Six to twelve MPD measurements were taken from each site and then all of the data were combined. Table 5 shows the statistical analysis performed on these combined data.

Table 5: Statistical analysis of infiltration measurements in proposed rain gardens

Location	# of measurement	Geometric mean of K_{sat} (cm/hr)	Arithmetic mean of K_{sat} (cm/hr)	St. dev of K_{sat} (cm/hr)	COV	Upper limit of mean K_{sat} (cm/hr)	Lower limit of mean K_{sat} (cm/hr)
Minnetrista	138	0.73	5.09	11.60	2.28	1.13	0.45

From Tables 1 through 5 we can conclude that both native soil and engineered soil typically have a high coefficient of variance of K_{sat} values. COV usually varies from 0 to 1. But the distribution of K_{sat} values tends towards a log-normal distribution (the log of the K_{sat} values is normally distributed), and we thus get COV values greater than one because the high end of the distribution has a long tail.

From the results it is noticeable that the K_{sat} of the rain gardens of our study has a higher value than the K_{sat} value of infiltration basin and swales. The reason may be that the top 36 inch of the soil of the infiltration basin contains significant amount of silt and clay which resulted in low K_{sat} value. In swales sediment was accumulated on the soil surface along the central low spot in the swales. The K_{sat} at the side of the swales was very high but the low K_{sat} at the center lowered the mean K_{sat}. However, Barrett (1998) found from his research that the majority of pollutant removal and infiltration occurs on the side slope as opposed to at the center of the grassed swale. The slope parallel to the highway is not critical for performance. A similar conclusion can also be made from our study on swales. The turf had lower K_{sat} value because the soil was compacted. The K_{sat} at the proposed rain garden is also low because the soil type was mostly silty or clayey.

Regardless of whether the soil is engineered or not, the COV of K_{sat} is high. This indicates that one infiltration measurement at each site may not represent the infiltration rate of the whole area. In general, roughly 10 to 20 measurements of infiltration are required to capture this high spatial variation of K_{sat} and compute the mean K_{sat} values. Appendix A shows the procedure of estimating the number of measurement that need to be taken in an infiltration practice for different margins of error and for different confidence intervals.

6. Conclusion

Overall the modified Philip Dunne infiltrometer performed well in all of the infiltration practices. As discussed earlier in the result section, the K_{sat} value was found to be higher in rain gardens than other practices. The only modification is the material composition of the infiltrometer to make it easier to set up and to take the readings. A manual (Appendix C) and software has also been developed for the MPD infiltrometer.

7. References

A.S.T.M. D 2937-04, 2004. Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method. ASTM International Ed.

Asleson B. C., “The development and application of a four level rain garden assessment” M.S. Thesis, University of Minnesota, August 2007.

Asleson, B.C., R.S. Nestingen, J.S. Gulliver, R.M. Hozalski, and J.L. Nieber, “Assessment of Rain Gardens by Visual Inspection and Controlled Testing,” *Journal of the American Water Resources Association,* 45(4), 1019-1031, 2009.

Nestingen R.S., “The Comparison of Infiltration Devices and Modification of the Philip-Dunne Permeameter for the Assessment of Rain Gardens,” M.S. Thesis, University of Minnesota, November 2007.

Olson N. C., “Quantifying the effectiveness of soil remediation techniques in compact urban soil”, M.S. Thesis, University of Minnesota, December 2010.

8. Appendix A: Estimation of the required number of infiltration measurements in LID infiltration practices and in native soil:

It is important to estimate the number of infiltration measurement to estimate the true mean of the infiltration practice. With fewer infiltration measurements there is more uncertainty associated with. Figures 4 and 5 give the relation between the number of measurements and fraction margin of error (M.E.) for 67% and 95% confidence intervals, respectively. The number of measurement was obtained from the following equation (Moore and McCabe, 2009):

$$n = \left(\frac{z * \sigma}{m} \right)^2 \qquad (6)$$

where,
n= number of measurements,
z = Standardizing normal random variable,
σ = standard deviation,
m = margin of error (M.E.),
.
The graphs shown in Figures 4 and 5 were developed based on the infiltration measurement performed on rain gardens, infiltration basin and swales; however, for native soil these values were obtained from the data of turf grasses and proposed rain gardens. The data were highly skewed, so they were transformed into log scale which was normally distributed because equation 6 is applicable for normally distributed data. Margin of error expresses half the interval of the confidence interval and for this analysis it is assumed to be equal to a certain fraction of the arithmetic mean of the measured infiltration data. The margin of error had been varied from 10% to 50% of the arithmetic mean of the measured data. For each site the number of measurements was calculated for different values of M.E. and for 67% and 95% confidence interval. Then the average number of measurements was calculated for all LID practices that are constructed of engineered soil and for all practices that have the native soil separately. This average number of measurements has been shown for different M.E. in Figure 4 and 5 for 95% and 67% confidence interval respectively.

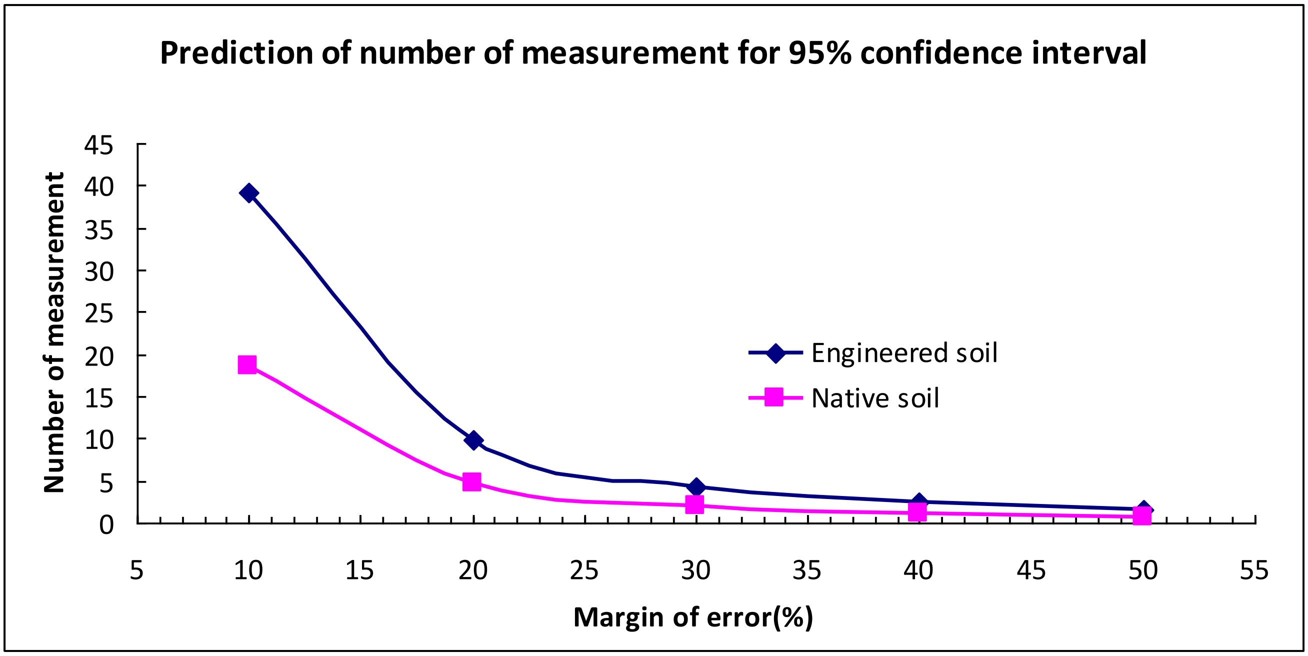

Figure 4: Number of infiltration measurement vs margin of error graph for 95% confidence interval for the practices in this report.

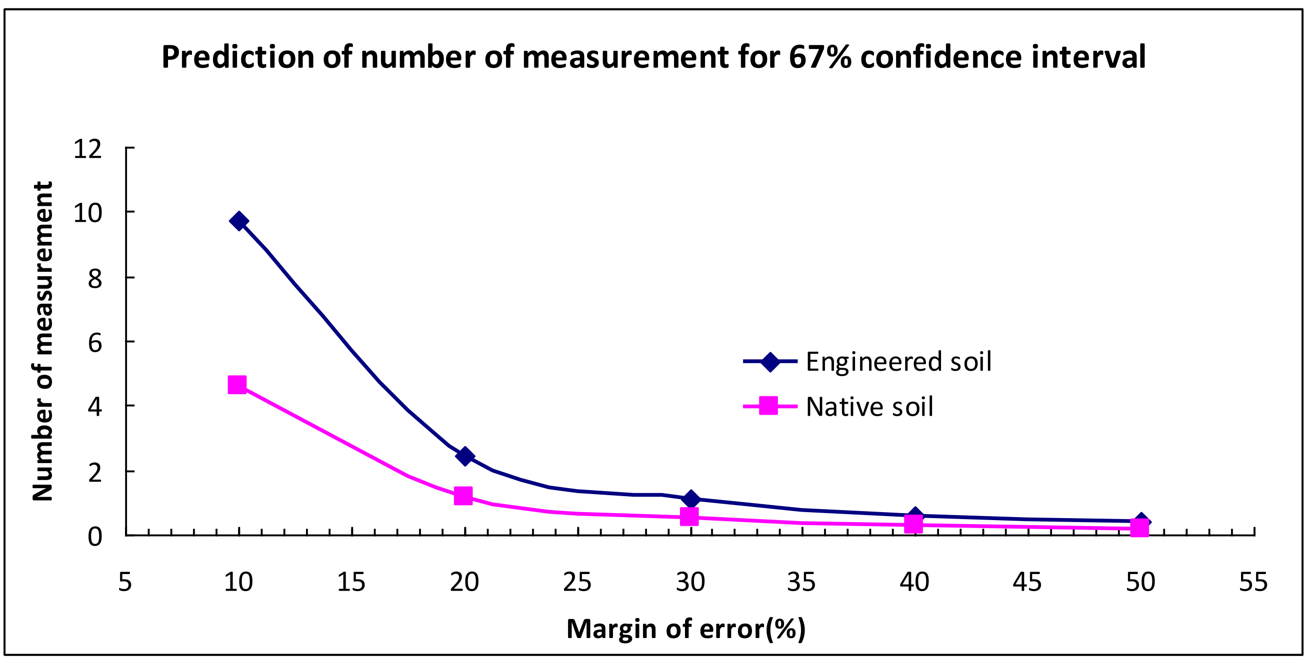

Figure 5: Number of infiltration measurements vs margin of error graph for 67% confidence interval for the practices in this report.

8.1 Reference:

Moore, McCabe, Craig. Introduction to the Practice of Statistics. Sixth edition. New York: W.H. Freeman and Company, 2009

9. Appendix B: Measured K_{sat} values in LID infiltration practices

The measured value of K_{sat} obtained from different infiltration practices (Asleson, 2007) has been shown in the following tables. The K_{sat} values of turf and proposed rain gardens are not incorporated in the report because of the large number of measurements.

Table 6:Burnsville rain gardens:

ID	Ksat (cm/hr)
1	22.464
2	126.756
3	29.628
4	293.328
5	137.520
6	17.496
7	8.784
8	55.728
9	32.904
10	76.968
11	30.708
12	1.980
13	48.096
14	19.728
15	34.848
16	76.032
17	118.188
18	51.876
19	127.908
20	13.608
21	69.336
22	46.548
23	31.248

Table 7:Cottage Grove rain garden:

ID	Ksat (cm/hr)
1	76.86
2	175.212
3	14.508
4	79.2
5	48.06
6	66.708
7	63.216
8	62.316
9	54.792
10	103.32
11	72
12	73.656
13	143.568
14	67.644
15	49.572
16	163.872
17	115.02
18	192.888
19	68.976
20	18.72

Table 8: RWMWD rain garden:

ID	Ksat (cm/hr)
1	0.972
2	4.932
3	17.316
4	7.956
5	0.864
6	56.52
7	2.628
8	5.94
9	0.684
10	30.276
11	42.804
12	0.648
13	2.484
14	0.936
15	2.916
16	8.604
17	15.948
18	2.952
19	92.808
20	5.436
21	13.968
22	56.592
23	36.828
24	25.956
25	22.572
26	26.028
27	15.444
28	15.084
29	16.812
30	13.752
31	0.036

Table 9: Thomson Lake rain garden:

ID	Ksat (cm/hr)
1	24.768
2	13.572
3	47.412
4	2.196
5	0.00252
6	15.876
7	194.58
8	2.7
9	6.912
10	40.968
11	82.944
12	0.108
13	22.608
14	18
15	81.72
16	1.188
17	10.476
18	5.328
19	20.196
20	88.956
21	67.356
22	7.668
23	14.436
24	0.828
25	172.44
26	155.988
27	55.8
28	91.26
29	58.104

Table 10: U of M Duluth rain garden:

ID	Ksat (cm/hr)
1	3.49
2	3.92
3	6.23
4	0.50
5	3.42
6	3.20
7	103.75
8	2.48
9	19.58
10	5.58
11	9.18
12	23.44
13	34.63
14	7.20
15	3.74
16	9.47
17	1.19
18	2.66
19	125.42
20	1.44
21	3.38
22	59.80
23	59.29
24	229.07
25	5.87
26	5.47
27	213.23
28	8.28
29	32.58
30	1.98
31	5
32	109.76

Table 11: U of M St. Paul rain garden:

ID	Ksat (cm/hr)
1	45.86
2	17.68
3	0.003
4	54.54
5	37.73
6	48.06
7	15.37
8	5.26
9	16.78
10	19.40
11	6.44
12	5.54
13	5.11
14	26.96
15	23.90
16	4.28
17	9.36
18	25.74
19	6.30
20	5.36
21	4.46
22	20.41
23	4.54
24	5.98
25	10.37
26	32.00
27	17.50
28	1.12
29	1.80
30	10.76
31	32.80
32	2.30
33	5.08
34	5.98
35	18.43
36	23.98
37	9.94
38	14.69
39	5.83

Table 12: Stillwater infiltration basin:

ID	Ksat (cm/hr)
1	34.30
2	44.10
3	5.23
4	2.58
5	6.33
6	0.435
7	45.10
8	49.40
9	35.80
10	11.10
11	7.40
12	8.71
13	15.60
14	14.60
15	4.49
16	45.10
17	1.36
18	14.30
19	44.10
20	2.67
21	7.41
22	6.40
23	8.78
24	1.76
25	1.40
26	4.85
27	3.71
28	11.40
29	2.99
30	6.88
31	0.003
32	2.46
33	5.67
34	3.04
35	1.75
36	4.22
37	5.51
38	5.11
39	0.001
40	3.44
41	0.855
42	0.004
43	2.41
44	0.16
45	17.10
46	5.36
47	6.96
48	3.04
49	2.13
50	0.915
51	43.10
52	1.41
53	0.001
54	17.50
55	1.77
56	2.84
57	1.52
58	8.12
59	12.80
60	2.70
61	111
62	24.70
63	1.65
64	7.93
65	28.60
66	3.80
67	0.003
68	1.75

Table 13: Alberville swale:

ID	Ksat (cm/hr)
1	88.10
2	0.11
3	65.20
4	38.00
5	7.09
6	28.20
7	0.15

Table 14: Hwy 47 swale:

ID	K_{sat} (cm/hr)
1	7.851
2	15.955
3	0.236
4	0.655
5	2.768
6	0.866
7	12.815
8	62.925
9	0.018
10	3.589
11	25.611
12	18.515
13	11.453
14	12.073
15	2.830
16	0.020
17	0.140
18	0.720

Table 15: Hwy 212 swale:

ID	Ksat (cm/hr)
1	3.429
2	16.448
3	0.033
4	49.651
5	0.120
6	0.090
7	4.190
8	12.483
9	20.750
10	1.085
11	5.148
12	116.941
13	72.270
14	0.007
15	0.022
16	3.860
17	2.487
18	0.004
19	0.002

10. Appendix C: Manual for the Modified Philip-Dunne (MPD) Infiltrometer

I. Introduction

The Modified Philip-Dunne (MPD) Infiltrometer is a modification of the Philip-Dunne Permeameter (*Nestingen,2007*) to measure the saturated hydraulic conductivity of the soil surface. Knowledge of the saturated hydraulic conductivity is important to model infiltration rates for a range of storms and antecedent soil moistures. This falling head device is suitable for infiltration practices because it can be performed relatively quickly to capture the large spatial variability that commonly occurs with infiltration rates. In the analysis, a Green-Ampt formulation for infiltration is assumed in that wetting front for infiltrating water is assumed to be sharp between the initial value ahead of the front and the saturated soil behind the front.

The MPD infiltrometer is suitable for assessment of the required maintenance of an infiltration practice because accumulation of fine particles can limit the infiltration rate. Using the spreadsheet program and the initial and final moisture content of the soil, the saturated hydraulic conductivity of the soil, *K*, can be determined, along with the capillary pressure at the wetting front, *C.* Because *K* values typically have a large variability (*Warrick and Nielson, 1980; Asleson, et al., 2009)* it is useful to have a number of measurements to estimate the mean infiltration rate of the practice. The MPD infiltrometer has been used at up to 20 locations simultaneously, allowing for up to 40 measurements per day, with a three-person team. The MPD infiltrometer, however, is designed to measure only the hydraulic conductivity of the top 30 cm of media and does not typically detect a confining layer below 20 cm. To detect confining layers below 20 cm of depth, permeameter measurements in boreholes cored to the depth of interest are recommended (*Philip, 1993*).

II. Description of the MPD Infiltrometer

The MPD infiltrometer, shown in Figure.1, is an open ended, 6 mm thick, 10 cm inner diameter cylinder that comes in two parts. The top is 37cm long constructed of clear acrylic pipe and the detachable bottom is 7cm long made of finished steel. The bottom portion has been lathed from steel pipe to form a “collar,” with inner diameter equal to the inner diameter of the clear acrylic pipe and a thickness of 1cm. The MPD is ready for operation when the two parts are attached, using vacuum grease to eliminate leakage between the outer face of the acrylic and the inner face of the collar. The bottom edge of the cylinder is beveled from the outside to ease the process of inserting the device into the soil surface. A metric measuring tape is adhered to the outside of the clear acrylic cylinder.

Figure 1: Modified Philip-Dunne Infiltrometer

III. Device Operation:

1. If the ground is dry and hard, the steel collar of the MPD infiltrometer is pounded into the soil to the bottom edge of the collar, so that it will rest on the soil surface at a depth of 5cm (Figure 2). The top of the collar should be close to horizontal, which can be arranged with a small level. The inner face of the collar must be clean to form a tight seal.

(a) Place the permeameter base in an area that permeability (K_{sat}) is to be measured.

(b) Place ring weight inside the base and use a hammer to force the permeameter base into the soil up to the bottom of upper ring.

Figure 2. Placement of steel collar.

2. Place a small amount of vacumn grease around the inside of the collar to result in a tight seal when the acrylic is inserted.

3. The acrylic portion of the MPD is then inserted into the collar. The arrangement is such that the bottom of the acrylic is in contact with the screen and the screen is in contact with soil surface (Figure 3a).

a) Place the permeameter clear tube on the secured base and use gentle force to fully insert clear tube into the base, level it evenly and fill with water.

(b) Wait for water surface to stabilize, read water level and start timing. Continue to read water level and time.

Figure 3 Operation of the Modified Philip-Dunne Infiltrometer

4. If the soil is wet, a rubber mallet can be used with a block of wood to pound both sections of the MPD together into the soil. In this case, item 1 is unnecessary, and item 2 and 3 can be completed before insertion into the soil.

5. Initial soil moisture content needs to measured (Sections V, and VI) or estimated (Sections VII). The measurements are typically made gravimetrically. One also needs to know the dry bulk density of the soil (Section IV) to convert the gravimetric moisture content into volumetric soil moisture (*Klute, A. 1986*).

6. The infiltration test is performed by filling the device with water within 5~10 sec up to a predetermined height (H_0). H_0 should be at least 20 cm (Figure 3a).

7. As soon as the device is filled to the desired level, a stopwatch is started and the height of water in the cylinder is recorded with respect to time. The height of the water at time zero is H_0 (Figure 3b). The 2nd reading should be made when water level drops by approximately 1 cm. All subsequent readings should be collected at regular intervals, the length of which can be determined from Table i.

Table i. Guideline for the time between head measurements of the MPD infiltrometer

Initial time required to drop 1cm	<10 s	10 s	20 s	40 s	1 min	2 min	5 min	≥ 10 min
Time interval between 2 subsequent head measurements	20~ 30 s	40 s	1 min	2 min	4 min	6 min	10 min	30 min

8. Typically, 12~15 readings for a location are desired for an accurate optimization of *K* and *C*. A large water level drop over the test will incorporate more soil depth into the optimization of *K* and *C* and is thus recommended. If the water surface drop is slow, head versus time data should be taken until the water level is at least 10 cm from H_0.

9. The gravimetric final moisture content is measured from the porosity of the soil and then converted to the volumetric moisture content by multiplying it with the dry bulk density of the soil.

10. The head vs. time readings, initial and final volumetric moisture contents, are then entered into the MPD software to determine hydraulic conductivity and capillary pressure at the wetting front.

The MPD infiltrometer has been used on land surface slopes up to 4:1. The device may not function properly, however, if the soil is saturated because the soil may not have sufficient strength to hold the MPD.

IV. Determination of Bulk Density of the Soil Sample

(Revised from ASTM, 2004):

Soil dry bulk density is the ratio of the mass of dry solids to the bulk volume of the soil. The bulk volume includes the volume of the solids and the pore space. It is needed for converting water percentage by weight to content by volume. The mass is determined after drying to constant weight at 105 °C and the volume is that of the sample as taken in the field.

There are four methods of determining the dry bulk density of soil: core method, clod method, excavation method, and radiation method. The determination usually consists of drying and weighing a soil sample, the volume of which is known (core method) or must be determined (clod method and excavation method). A different principle is employed in the radiation method. The core method (A.S.T.M. D 2937-04, 2004) is the most straightforward. This method is not recommended for use in organic or friable soils, and may not be applicable if the soil cannot be retained in the drive cylinder.

The MPD test and the bulk density sample collection should not be done at the same time if these two locations are very close to each other. This is due to the fact that driving the sampler through the soil might cause disturbance in the soil which will affect the MPD test (for example, the water might move more quickly through the soil). But if someone is doing the bulk density sample collection 10~15 m or more from the MPD location then the vibration during the sampling should not affect the MPD test.

V. Determination of Initial Moisture Content of the Soil Sample

(Revised from Klute, 1986)

Moisture content of soil is the ratio of mass of water contained in the soil's pore space to the solid mass of particles in the soil, expressed as a fraction or percentage. A test specimen is weighed, and then dried in an oven at a temperature of 110 ± 5 °C until the mass is constant. The loss of mass due to drying is considered to be water. The water content is calculated using the ratio of the mass of water and the mass of the dry specimen.

Specimen containers- Choose a suitable container made of materials resistant to corrosion and change in mass upon repeated heating, cooling, and exposure to materials of varying pH and cleaning. Containers with close-fitting lids are required for testing specimens having a mass of less than about 200g. For specimens having a mass of greater than 200g, containers without a lid may be used. The purpose of close-fitting lids is to prevent loss of moisture from specimens before initial mass determination and to prevent adsorption of moisture from the atmosphere following drying and before final mass determination.

Test specimen selection- To measure initial moisture content, take 3~5 soil samples in the vicinity of the the device at the soil surface and combine all of the soil samples to prepare the test specimen. The samples should be taken at a distance of at least 30 cm from the edge of the MPD wall to prevent disturbance of the soil volume being tested for infiltration.

Procedure- Determine and record the mass of the clean and dry specimen container and its lid, along with its identification number. Place the moist test specimen in the container and set the lid securely in position. Determine the mass of the container and moist specimen using a balance and record the value.

Remove the lid (if used) and place the container with the moist specimen in the drying oven. Dry the specimen to a constant mass. Maintain the drying oven at 110 ± 5 °C. In most cases, drying a test specimen overnight (about 12 to 16 hr) is sufficient. As a rapid check to see if a relatively large specimen (> than about 100g of material) is dry, place a small strip of torn paper on the top of the material while it is in the oven or just upon removal from the oven; if the paper strip curls the material is not dry. Sand may often be dried to a constant mass in a period of about 4 hr. Because some dry materials may absorb moisture, dried specimens shall be removed before placing moist specimens in the same oven; unless they are being dried overnight.

After the specimen has dried to constant mass, remove the container from the oven (and replace the lid if used). Allow the specimen and container to cool to room temperature or until the container can be handled comfortably with bare hands and the operation of the balance will not be affected by convection currents and/or being heated. Determine the mass of the container and the oven-dried specimen. Record this value. Calculate the moisture content with the following equation:

Calculation

$$w = [(M_{cms} - M_{cds})/(M_{cds} - M_c)] \times 100 = (M_w / M_s) \times 100$$

where,
w = water content, %,
M_{cms} = mass of container and moist specimen, g,
M_{cds} = mass of container and oven dry specimen, g,
M_c = mass of container, g,
M_w = mass of water, g,
M_s = mass of oven dry specimen, g.

VI. Determination of Final Moisture Content of the Soil Sample

(Revised from Jury and Horton, 2004)

After the test has been performed the soil surface is assumed to be fully saturated, which means that the pores of the soil surface are filled with water. There are two techniques that can be used to determine the final moisture content of the soil:

1. Run a gravimetric moisture content procedure similar to the procedure for acquiring initial moisture content. The saturated moisture content occurs when the soil is saturated, but neither liquefied nor drained. It can be difficult to wait until the soil has drained the excess water, but is still saturated. There can be considerable scatter in the resulting final moisture content.
2. The final moisture content of the soil sample can be considered to be the effective porosity of that soil, which is determined using the following equation:

   $$\phi = 1 - \frac{\rho_b}{\rho_s}$$

   $$\phi_{eff} = \phi - \phi_{air}$$

   where,
   Φ = Total porosity
   Φ_{eff} = Effective Porosity of the soil
   ρ_b = Dry bulk density of the soil
   ρ_s = Soil particle density
   Φ_{air} = Fractional porosity of air (Table 4)

The dry bulk density of the soil can be measured once for every three locations following the ASTM standard. The particle density of the soil can be estimated from the weighted average of the solid component using the following equation:

$$\rho_s = \rho_m X_m + \rho_{om} X_{om}$$

where,
ρ_{om}= Density of the organic matter = 2.65 g/cm^3
ρ_m= Density of the mineral= 1.3 g/cm^3
X_{om}= Organic volume fraction
X_m= Mineral volume fraction=1-X_{om}

The organic volume fraction in soil varies from 1 to 10%, but typically less than 5%. Some typical values for organic fraction in different types of soil are provided in Table ii.

Table ii. Typical values for organic fraction of soil (Weiner, 2008).

Type of soil	Organic volume fraction (%)
Coarse soil	7
Silty loam	8.5
Silty Clayey loam	5
Clayey silty loam	0.9
Clayey loam	0.7
Sand	0.09
Glaciofluvial	0.017

Some typical values of porosity of different types of soil are given later. This second technique will result in improved precision in the final soil moisture values, if the porosity of the soil is known.

VII. Estimation of Moisture Content of the Soil Sample:

If the tools required to determine the bulk density and the gravimetric moisture content are not available, then one can estimate the initial volumetric moisture content of the soil by using Table iii. It has been found that the change in moisture content has a less than a 20% effect on saturated hydraulic conductivity which can be considered as minor relative to the orders of magnitude spatial differences (Regalado et. al., 2005). In Table iii one can estimate the volumetric moisture content of the soil by feeling the soil by hand.

Table iii. Guide for estimating soil water moisture content based on soil feel and appearance for several soil textures

Loamy Sand	Θ (%)	Sandy Loam	Θ (%)	Loam	Θ (%)	Clay Loam	Θ (%)
Leaves wet outline on hand when squeezed	15	Appears very dark, leaves wet outline on hand, makes a short ribbon	20	Appears very dark, leaves wet outline on hand, will ribbon out above one inch	28	Appears very dark, leaves slight moist. on hands when squeezed, ribbon out about 2”	29
Appears moist, makes a weak ball	12.5	Quite dark color, makes a hard ball	17.5	Dark color, forms plastic ball, slicks when rubbed	25	Dark color, will slick and ribbons easily	27
Appears slightly moist, sticks together	10	Fairly dark color, makes a good ball	15	Quite dark, forms a hard ball	22	Quite dark, will make thick ribbon, may slick when rubbed	25

Appears to be dry, will not form a ball under pressure	7.5	Slightly dark color, makes a weak ball	12.5	Fairly dark, forms a good ball	19	Fairly dark, makes a good ball	23
Dry, loose, single grained flows through fingers	5	Lightly colored by moisture, no ball	10	Slightly dark, forms a weak ball	16	Will ball, small clods will flatten out	21
		Very slight color due to moisture, loose, flows through fingers	7.5	Lightly colored, small clods crumble fairly easily	13	Slightly darks, clods crumble	19
				Slightly colored due to moisture, powdery, dry, sometimes slightly crusted but easily broken down in powdery condition	10	Some darkness due to unavailable moisture, hard, baked, cracked sometimes has loose crumbs on surface	17

* Jerry Wright, Fred Bergsrud (1991); Irrigation Scheduling Checkbook Method

After the identification of the soil type and the initial moisture content from Table iii, the final moisture content is assumed to be the effective porosity for that soil, which can also be estimated from the Table iv, given in Section XI.

VIII. MPD Software:

Microsoft Excel (2003 or 2007) with Microsoft Visual basic is needed to run the MPD software because the necessary equations used for optimization are written in this language. Windows XP or later is needed to run the software.

IX. Spreadsheet Recipe:

1. Open the *MPD spreadsheet(for 2007 excel)* or *MPDspreadsheet(for 2003 excel).*xls file. If a Security Warning window appears select the “Enable Macros” option.

2. Click the *Check Solver Installation* button. If a message window appears that says “The solver add-in is not installed” click *OK* and continue with step 3. If the message window says “The solver add-in is installed” click *OK* and skip to step 4.

3. To install the Solver Add-in go to the *Tools* menu, select “*Add-Ins”*, check the *Solver Add-in* box, and select *OK*. If Solver Add-in is not listed click *Browse* to locate it. If you see a message that tells you the Solver Add-in is not currently installed on your computer, click *Yes* to install it.

4. Enter initial and final volumetric moisture content(%), and initial height of the water into cells C2:C6. Enter the stopwatch time (h: mm: sec) and height (in centimeters) below the appropriate column headings in cells I1 and K1.

5. In M2 specify the number of cells of data for a cubic spline curve fit of the original data. For example, if the time and height data set ranges from I2 through I15 and from K2 through K15 respectively then in M2 the function would be written as *cubic_spline ($J$2:$J$15,$K$2:$K$15,L2)*. Click *"Autofill for Cubic Spline"* located in cell A22 to calculate the midpoint between two successive times and the corresponding head data.

6. Automatically fill all the rows in the remaining columns by clicking the "*Auto-fill Columns"* button located in cell A23.

7. Calculate the distance to the wetting front at each time step by clicking the *"Solve for R(t)"* button located in cell A24.

8. Find values for mean hydraulic conductivity (*K*) and capillary pressure at the wetting front (*C*) by clicking the "*Solve for K and C for T"* button located in cell A25. Solver's solution for *K* and *C* will appear automatically in cells C11 and C12, respectively.

9. Repeat step 8 until the 3rd digit of *K* and *C* remain constant.

10. Again find values for mean hydraulic conductivity (*K*) and wetting front potential (*C*) by clicking the "*Solve for K and C for H"* button located in cell A26. Solver's solution for *K* and *C* will appear automatically in cells E11 and E12, respectively.

11. The root mean square error for optimization with *ΔH* and for optimization with *Δt* will appear in cells C14 and E14, respectively. The corresponding head vs. time curve will also appear on the spreadsheet at the same time. Both graphs show the comparison between head vs. time curve of spline fit and optimized data. The spreadsheet will compare C14 and E14 and choose the values of *K* and *C* that correspond to the smallest error. The result will be shown in C20 (*K*) and C22 (*C*) cells.

12. Record values for *K* and *C* from cells C20 and C22, respectively, and then click the *Clear Template* button. To perform another calculation, repeat the procedure beginning at step 4.

X. Graphical Representation of Optimized Curve Fits

The spreadsheet shows two graphs for optimizing *K* and *C*, one by minimizing the RMS error in *Δt* and the other by minimizing the RMS error in *ΔH*. *Δt* is the difference between two successive times while *ΔH* is the difference between two successive head values. Each graph shows two curves, spline fit and optimized curve of H vs t data. The purpose of the cubic spline fit of the original data is to give a more accurate gradient of H vs t. A cubic spline fit with the original data is first performed and this is then to interpolate to the midpoint between two successive data points.

These midpoint data will be used for optimization. Both the spline fit and the optimized data should be exponential curves. The optimized value of *K* and *C* should result in curves that approximate the spline fit because optimization was performed using spline fit data. Two values of *K* and *C* are determined, one by optimizing Δt and other by optimizing ΔH. One should select the *K* and *C* for which the optimized data and spline data are the most similar (minimum RMS error); the spreadsheet does this automatically.

XI. Interpretation of the results:

Typical values of porosity, saturated hydraulic conductivity and capillary pressure are given in Table iv (Rawls, Brakensiek, Miller, 1983). Two thirds of the values that result from the optimization should be within the values given in the parenthesis.

Table iv. Typical measurements taken on soils. Two thirds of the measurements are within the values given in parenthesis.

Soil type	Porosity	Φ_{air}	Capillary pressure (cm)	Hydraulic conductivity (cm/sec)
Sand	0.437 (0.374~0.5)	0.02	-4.95 (-0.97~-25.36)	$3.25*10^{-3}$
Loamy sand	0.437 (0.363~0.506)	0.036	-6.13 (-1.35~-27.94)	$8.3*10^{-4}$
Sandy loam	0.453 (0.351~0.555)	0.041	-11.01 (-2.67~-45.47)	$3*10^{-4}$
Loam	0.463 (0.375~0.551)	0.029	-8.89 (-1.33~-59.38)	$9.4*10^{-5}$
Silt loam	0.501 (0.42~0.582)	0.015	-16.68 (-2.92~-95.39)	$1.8*10^{-4}$
Sandy clay loam	0.398 (0.332~0.464)	0.068	-21.85 (-4.42~-108)	$4.2*10^{-5}$
Clay loam	0.464 (0.409~0.519)	0.155	-20.88 (-4.79~-91.1)	$2.8*10^{-5}$
Silty clay loam	0.471 (0.418~0.524)	0.039	-27.3 (-5.67~-131.5)	$2.8*10^{-5}$
Sandy clay	0.43 (0.37~0.49)	0.109	-23.9 (-4.08~-140.2)	$1.7*10^{-5}$
Silty clay	0.479 (0.425~0.533)	0.056	-29.22 (-6.13~-139.4)	$1.4*10^{-5}$
Clay	0.475 (0.427~0.523)	0.09	-31.63 (-6.39~-156.5)	$8.3*10^{-6}$

A positive capillary pressure (*C*) indicates that the soil is hydrophobic (repels water) and a negative *C* value indicates the soil is hydrophilic (attracts water). Most soil is hydrophilic. In addition, positive *C* values have been shown to occur when a high conductivity layer is surrounded by a low conductivity region, even though the soil is hydrophilic. The optimized results for saturated hydraulic conductivity are not highly sensitive to the value of *C*, so small deviations in the data resulting in the spline fit and optimization can result in a positive value of *C*.

XII. Maintenance:

Inside the collar needs to be kept clean.

XIII. Safety:

One needs to wear safety glasses when using a hammer on the driver to pound the bottom part of the MPD infiltrometer into the soil.

XIV. References:

Asleson, B.C., R.S. Nestingen, J.S. Gulliver, R.M. Hozalski, and J.L. Nieber, "Assessment of Rain Gardens by Visual Inspection and Controlled Testing," *Journal of the American Water Resources Association,* 45(4), 1019-1031, 2009.

A.S.T.M. D 2937-04, 2004. Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method. ASTM international Ed.

Eugene R.Weiner 2008, Applications of Environmental Aquatic Chemestry, A Practicle Guide, Second Edition.

Klute, A. 1986. Methods of Soil Ananlysis, Part I. Physical and Mineralogical Methods, 2nd edition. Soil Science Society of America, Inc. Publisher, Madison, WI.

Nestingen, R.S., 2007, A comparison of Infiltration Devices and Modification of the Philip Dunne Permeameter for the Assessment of the Rain Gardens

Philip, J. R. 1993. Approximate Analysis of Falling-Head Lined Borehole Permeameter. Water Resources Research 29:3763-3768.

Rawls, W.J., D.L. Brakensiek and N. Miller 1983, Green-Ampt Infiltration Parameters from Soils Data, J. Hydraulic Div., ASCE, vol 109, no. 1, pp. 62-70.

Regalado C. M., et al.(2005) "Simplified Method to Estimate the Green-Ampt Wetting Front Suction and Soil Sorptivity with the Philip-Dunne Falling Head Permeameter", Vedose Zone Journal, 4.2, 291-299.

Warrick, A.W., and D. R. Nielsen. 1980. Spatial variability of soil physical properties in the field. *In:* Applications of Soil Physics. D. Hillel (ed.). Academic Press, New York,pp.319–344.