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Field infiltration measurements in grassed roadside drainage ditches: Spatial and temporal variability

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SUMMARY

Roadside drainage ditches (grassed swales) are an attractive stormwater control measure (SCM) since they can reduce runoff volume by infiltrating water into the soil, filter sediments and associated pollutants out of the water, and settle solids onto the soil surface. In this study a total of 722 infiltration measurements were collected in five swales located in Twin-Cities, MN and one swale located in Madison, WI to characterize the field-saturated hydraulic conductivity (K_{fs}) derived from the infiltration measurements of these swales. Measurements were taken with a falling head device, the Modified Philip Dunne (MPD) infiltrometer, which allows the collection of simultaneous infiltration measurements at multiple locations with several infiltrometers. Field-saturated hydraulic conductivity was higher than expected for different soil texture classes. We hypothesize that this is due to plant roots creating macropores that break up the soil for infiltration. Statistical analysis was performed on the K_{fs} values to analyze the effect of initial soil moisture content, season, soil texture class and distance in downstream direction on the geometric mean K_{fs} value of a swale. Because of the high spatial variation of K_{fs} in the same swale no effect of initial soil moisture content, season and soil texture class was observed on the geometric mean K_{fs} value. But the distance in downstream direction may have positive or negative effect on the K_{fs} value. An uncertainty analysis on the K_{fs} value indicated that approximately twenty infiltration measurements is the minimum number to obtain a representative geometric mean K_{fs} value of a swale that is less than 350 m long within an acceptable level of uncertainty.

1. Introduction

Impervious surfaces such as roads, parking lots and rooftops, lead to increased runoff volume which will increase the mass of pollutants that reach receiving water bodies (Field, 1975; Booth and Jackson, 1997; Kayhanian et al., 2007, 2012). Stormwater control measures (SCMs) are designed to reduce the runoff volume and to treat runoff to improve water quality before reaching surface water resources (National Research Council, 2008). Many conventional SCMs, such as catch basins, wetlands and retention ponds, are efficient in capturing suspended solids (e.g., Howard et al., 2011, 2012) but are not designed to treat for dissolved pollutants (Erickson et al., 2007, 2012; O'Neill and Davis, 2012a, 2012b). Infiltration practices are believed to reduce runoff generation in a watershed and to remove most pollutants, with the exception of chloride and nitrate, through filtering and adsorption processes of the soil matrix. (National Research Council, 2008; Davis et al., 2012). These practices include permeable pavement, bioinfiltration, infiltration basins and grassed swales (Erickson et al., 2013).

Grassed roadside drainage ditches are shallow, open vegetated channels that are designed to convey stormwater runoff to storm sewers or receiving water bodies. They are often employed along highways, where highway medians and roadside drainage ditches may essentially act as grassed swales because they filter and settle solids and infiltrate water (Barrett et al., 1998a, 1998b; Deletic and Fletcher, 2005). Fig. 1 shows a grassed roadside drainage ditch on Hwy 212 in Chaska, Minnesota that has the capability to reduce runoff volume (Ahmed et al., 2014b). Volume reduction occurs primarily through infiltration into the soil, either as the water flows over the slide slope perpendicular to the roadway into the swale or along the bottom of the swale parallel to the roadway. Pollutant removal can occur by sedimentation of solid particles onto the soil surface, filtration of solid particles by vegetation, or infiltration of dissolved pollutants (with stormwater) into the soil (Abida and Sabourin, 2006).

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Fig. 1. The Roadside drainage ditch on Hwy 212 near Chaska, has been shown to infiltrate stormwater and act as a grassed swale.

As with infiltration trenches and basins, grassed swales can become clogged with particles and debris in the absence of proper maintenance. Several studies have shown that a majority of stormwater pollutants are trapped in the upper soil layers (Wigington et al., 1986; Mikkelsen et al., 1997; Dierkes and Geiger, 1999; Kwiatkowski et al., 2007; Komlos and Traver, 2012). In some cases the sediment deposits can begin to choke out the vegetative cover and create an erodible surface capable of contributing sediment and other pollutants directly downstream (Erickson et al., 2010, 2013).

The fraction of stormwater runoff that can be infiltrated by a grassed swale depends on many variables including rainfall intensity and total runoff volume, swale soil type, the maintenance history of the swale, vegetative cover in the swale, swale slope, and other factors. Using simulated runoff, Yousef et al. (1987) found that swales infiltrated between 9% (input rate of 0.079 m/h) and 100% of the runoff (input rate of 0.036 m/h) with significant variability. Due to the wide range of performance Yousef et al. (1987) stated that to determine the performance of individual swales, each swale should be tested separately. Also because of this wide variability of infiltration rates, even within a single swale, multiple measurements should be made. The Modified Philip-Dunne infiltrometer, a new method of measuring infiltration capacity of the soil surface has recently been developed (Asleson et al., 2009; Olson et al., 2013; Paus et al., 2013; Ahmed et al., 2014b). The infiltrometer allows multiple measurements to be taken over a relatively large area. This falling head type of infiltrometer has an advantage over the commonly employed constant head infiltrometers in that they require less time and water volume to conduct field tests (Ahmed et al., 2011a,b).

Despite the prevalence of grassed roadside drainage ditches within roadway right-of-ways, there has been very limited gathering of data to test the effect of soil textural differences, prevailing vegetation, season, and sedimentation on the spatial and temporal variability of infiltration properties. This research documents the infiltration parameters of six grassed roadside drainage ditches (this term will be used interchangeably with grassed swales) located in the Twin Cities, MN and Madison, WI, providing a large data set for estimation of soil infiltration properties, with consideration for spatial and temporal variability. With this data the effects of soil texture, antecedent soil moisture, season, and location (swale side slope versus swale bottom) are examined. In addition, an uncertainty analysis was also performed on four sets of measurements to determine the required number of infiltration measurement that balances effort and accuracy in deriving a representative mean infiltration capacity of grassed roadside drainage ditches (grassed roadside swales).

2. Methods

2.1. Site Selection

Sixteen highways were selected around the Twin-Cities metropolitan area in Minnesota within a reasonable commute where swales are located either within the median or along the side of the highways. These swales are essentially the drainage ditches constructed by the Minnesota Department of Transportation, and are typically 30–50 years old. For each highway, three soil cores were collected, using a soil corer between the soil surface and 0.6 m of depth to investigate the soil profile. Subdivisions of each soil sample were based on a visual change in soil color. These soil samples were brought into the lab for wet sieving analysis (ASTM D6913) and hydrometer analysis (ASTM D422) to determine% clay, % silt and% sand in each sample. Using these percentages in a textural triangle (USDA, 2014), the soil texture class was identified. The lists of soil texture class for different swales are given in Table 1. The soil textural class of the top 25 cm was taken into consideration because the falling head infiltrometer can capture infiltration properties of this region. If the same highway is addressed in two or more rows in the table it indicates that the swale located in that highway contains all corresponding textural classes of soil (i.e. Hwy 35E, Hwy 35W near TH 10).

Five highways were selected for further study, given in bold in Table 1, to represent the soil combinations found in the region. In addition to the measurements taken at the Minnesota swale sites, infiltration measurements were taken in a swale located at Hwy 51 in Madison, WI, north of Hwy 12/18. The Madison site was chosen because the precipitation, inflow, and outflow monitoring data for the swale were available via the USGS National Water Information System (U.S. Geological Survey, 2014). A comparison with this monitoring data is reported by Ahmed et al. (2014b).

2.2. Infiltrometer operation

At each swale, infiltration measurements were made using Modified Philip Dunne (MPD) infiltrometer, as illustrated in Fig. 2 (Ahmed et al., 2014a), which was used to estimate the field-saturated hydraulic conductivity (K_{fs}) and capillary soil suction

Table 1
Soil texture class[a] up to 25 cm depth from soil surface of different swales located in Minnesota.

Swale locations[b]	Soil texture class
Hwy 10, Hwy 35E, Hwy 35 W near TH 10	Sand (>86% sand)
Hwy 5, **Hwy 47**, Hwy 65, Hwy 96, Hwy 97, **Hwy 77**, Hwy 7, Hwy 35 W Burnsville, Hwy 35E, Hwy 35 W near TH 10	Loamy sand (70–86% sand, 30% > silt, 10–15% clay) and Sandy loam (50–70% sand, 50% > silt, 15–20% clay)
Hwy 51, Hwy 36	Loam (50–72% sand, 28–50% silt, 20–28% clay) and Sandy loam (50–70% sand, 50% > silt, 15–20% clay)
Hwy 212	Silt loam (20–50% sand, 50–80% silt, 28% > clay) and Loam (50–72% sand, 28–50% silt, 20–28% clay)
Hwy 13	Loam (50–72% sand, 28–50% silt, 20–28% clay), Sandy clay loam (72% < sand, 30% > silt, 20–35% clay) and Silt (92% < silt)

[a] Sand (>0.02 mm diameter), silt (0.002–0.02 mm), clay (<0.002 mm).

[b] Number of soil cores at each site is three. Infiltration measurements were collected in swales with Bold letters.

(ψ) of the soil at that location. A total of ten soil samples from the soil surface were collected at each site on the test day by a coring method (ASTM D 2937-04, 2004) to determine the soil bulk density, porosity and initial gravimetric soil moisture content (Klute, 1986; A.S.T.M., 2000, 2005) of the soil samples. The MPD infiltrometer can capture the infiltration process up to a certain depth from the soil surface depending on the water storage characteristics of the soil. From previous studies it was found that this depth can vary from 10 to 25 cm. So the mean initial volumetric soil moisture content was assumed to be uniform for the whole test area up to the depth of wetting front. The mean porosity of the soil samples was measured and used as the saturated volumetric soil moisture content. The MPD infiltrometer was inserted 5 cm into the surface of the soil and then filled to a certain height (usually between 30 and 40 cm) of water. The head of water over time during the test was recorded. At each cross-section 6–7 infiltration measurements were taken. Typically, 18–21 infiltration measurements were made simultaneously with a crew of two to three people.

The collected data from each infiltrometer measurement were analyzed via a spreadsheet utilizing visual basic programming to best fit the water elevation versus time data by optimizing K_{fs} and ψ estimates, according to specifications given in Ahmed et al. (2014a). Required inputs are initial soil moisture content, final soil moisture content (assumed to be the porosity at saturation), the penetration depth of the infiltrometer and the water elevation (relative to the soil surface) versus time data. The temperature of the water was generally between 7 and 21 °C. The assumptions made for the MPD infiltrometer analysis are isotropic media, a Green–Ampt sharp wetting front and a spherical geometry for the wetting front. Detailed development of the equations used in the analysis is given in Ahmed et al. (2014a).

3. Results and discussion

3.1. Summary of infiltration measurements

Table 2 gives the soil texture class, number of measurements, porosity of soil and the mean initial soil moisture content on the day of measurement for the six swales. Three cross-sections were chosen for each swale, and for each cross-section 5–7 infiltrometer measurements were conducted. The number of infiltration measurements varied from 17 to 21 per day, with the exception of the Madison swale where 105 measurements were taken by a crew of five people in two days. A total of 722 infiltration measurements were made for this study.

Fig. 2. Modified Philip Dunne (MPD) Infiltrometer.

3.2. Distribution of field-saturated hydraulic conductivity

The K_{fs} values of swales located both in the Twin-Cities area and in Madison were observed to be log-normally distributed. As an example, the K_{fs} values of the Hwy 51, Madison swale are plotted in a histogram, showing the frequencies of occurrence in given intervals for the values of K_{fs} (Fig. 3). To obtain a distribution that better fits a normal distribution, a logarithmic transformation was performed for all of the derived field-saturated hydraulic conductivity values. The histogram of $log_{10}(K_{fs})$ for the Madison swale (Fig. 4) indicates that the data is closer to a normal distribution in log space (a log-normal distribution). The statistical analyses on the derived K_{fs} values were therefore performed log-transformed data for all swales. The mean of a distribution in log space is the geometric mean, which will be reported for all K_{fs} values derived herein.

3.3. Measurement uncertainty analysis

An uncertainty analysis was performed on the 83, 42, 52 and 63 infiltration measurements on the WI-Hwy 51 (Madison, WI) swale, MN-Hwy 47 swale, MN-Hwy 51 (Arden Hills, MN) swale and MN-Hwy 212 swale, respectively. These locations were selected because a large number of infiltration measurements were collected on these sites, allowing for a more complete uncertainty analysis. The bootstrap nonparametric method (Moore et al., 2009; Carpenter and Bithell, 2000) was used to develop confidence intervals around the geometric mean of each data set mentioned above. In the implementation of the bootstrap method, sampling was done with replacement and the process was repeated 1000 times, as recommended for the 95% confidence interval by Carpenter and Bithell (2000). Fig. 5 shows the 95% confidence interval around the geometric mean.

From Fig. 5 we can conclude that:

- Uncertainty in the geometric mean of a factor of 4–7 is associated with five spatially distributed measurements of K_{fs} over the site.
- With 10 measurements the uncertainty decreases to a factor of 2.5–3.25.
- With 20 measurements the uncertainty decreases to a factor of 1.8–2.2.
- With 40 measurements uncertainty decreases to a factor of 1.5–1.7.

We consider these uncertainties of the geometric mean to be large, indicating that more measurements of K_{fs} are required to reduce this uncertainty than are normally considered. The uncertainty of the geometric mean in Fig. 5 has a maximum curvature at approximately 10 measurements, and the benefits of at least 10 measurements to reduce uncertainty are substantial. This would seem to be a reasonable minimum number of measurements at the sites. Beyond that, however, the number of measurements would depend upon the level of uncertainty desired. We consider 20 infiltration measurements to be a balance between effort and accuracy of K_{fs} measurements. The length of each of these tested swales is roughly 350 m, so our recommendation is 20 measurements be collected for swales that are up to 350 m long.

Table 2
Summary of infiltration measurements in Fall 2011, Spring 2012 and Summer 2012.

Season	Swale location	Soil texture class	# of measurement	Initial soil moisture content (%)	Porosity
Fall 2011	Hwy 77	Loamy sand	17	18	45
	Hwy 47	Loamy sand/sandy loam	20	32	56
	Hwy 51(Chaska)	Loam/sandy loam	20	26	64
	Hwy 212	Silt loam/loam	20	29	49
	Hwy 13	Loam/sandy clay loam/silt	19	24	53
Spring 2012	Hwy 47	Loamy sand/sandy loam	20	28	52
	Hwy 51(Chaska)	Loam/sandy loam	20	15	50
	Hwy 212	Silt loam/loam	20	20	40
Summer 2012	Hwy 47 (upstream)	Loamy sand/sandy loam	21	22	48
			21	23	48
	Hwy 47 (middle)		21	31	50
			21	37	50
			19	43	50
	Hwy 47 (downstream)		21	23	43
			21	10	45
	Hwy 51 (Chaska) (upstream)	Loam/sandy loam	18	27	56
			18	30	56
			18	32	56
	Hwy 51 (Chaska) (middle)		21	33	48
			21	30	48
			18	15	48
	Hwy 51 (Chaska) (downstream)		21	29	52
			21	38	52
	Hwy 212 (upstream)	Silt loam/loam	21	24	38
			21	26	38
			21	25	38
	Hwy 212 (middle)		21	18	43
			12	39	43
			21	19	43
	Hwy 212 (downstream)		21	12	42
			21	29	42
	Hwy 51 (Madison)	–	108	4	52

Measurement should spread out along the swale with 2–4 equal spacing cross sections and each cross-section should have 5–9 equal spacing measurements. However, swales longer than 350 m may require more than 20 measurements.

3.4. Sensitivity analysis on field saturated hydraulic conductivity

The impact of initial soil moisture content, soil texture class, location of the measurement (side slope/center of the channel), season, and distance from outflow pipe downstream upon K_{fs} were investigated for the swales. The Tukey–Kramer method was used to perform the significance test. A summary of the analyses is provided in this section.

3.4.1. Effect of initial moisture content

According to the mathematical formulation, the initial moisture content should not affect the estimated K_{fs}. To test this it was determined that repeated and intensive infiltration measurements should be taken at three sites to test for any possible relationship between initial moisture content and K_{fs}. Among the five swales the sites that had the closest commute and wide soil texture variation were chosen, where infiltration measurements were conducted at each cross-section (upstream, middle and downstream) of MN-Hwy 47, MN-Hwy 51 and MN-Hwy 212. This provided a reasonable amount of variability of initial moisture content. A schematic diagram of location of infiltration measurements and soil cores is shown in Fig. 6. The results of this investigation, shown in Table 3, are mixed. At MN-Hwy 51 (downstream), K_{fs} increased with an increase in initial moisture content. At MN-Hwy 47(downstream) and MN-Hwy 212 (downstream), K_{fs} decreased with an increase in initial moisture content. At MN-Hwy 47 (middle), MN-Hwy 51 (upstream), MN-Hwy 51 (middle) and MN-Hwy 212 (middle), K_{fs} went both up and down with an increase in initial

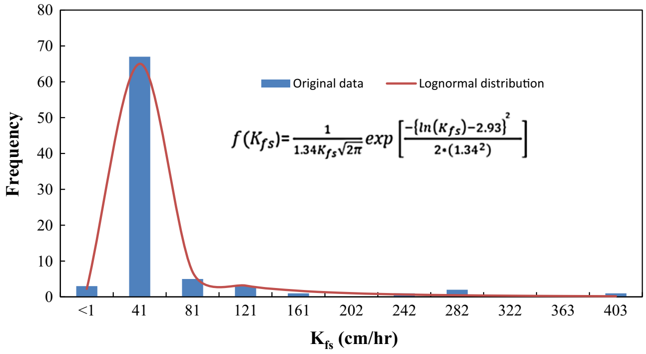

Fig. 3. Histogram of actual K_{fs} values of Madison swale.

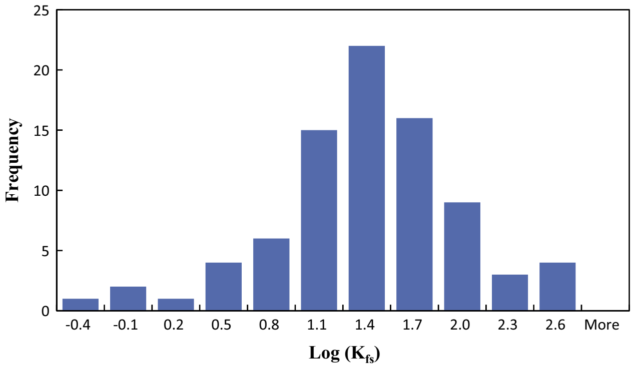

Fig. 4. Histogram of log transformed K_{fs} values of Madison swale.

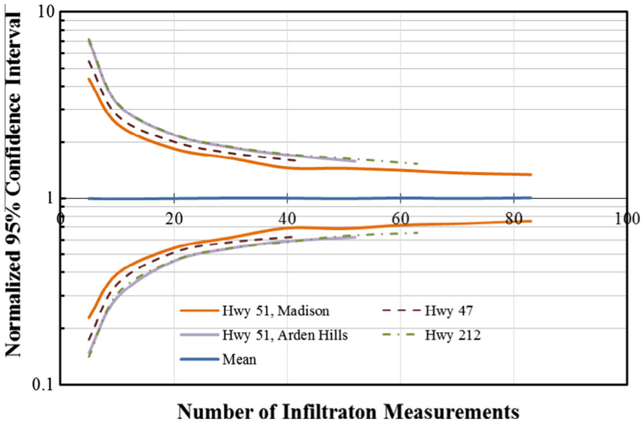

Fig. 5. 95% confidence interval normalized by geometric mean. *X* axis represents the number of infiltration measurement collected at each site.

moisture content. However, from these results it appears that initial moisture content does not substantially affect estimated K_{fs} in any consistent manner, as expected.

The Tukey–Kramer test (Kleinbaum et al., 2007) for significant differences confirms this statement. The test resulted in no significant difference among geometric mean K_{fs} value in the same swale for different moisture content within 90%, 95% and 99% confidence interval, with the exception of one swale (MN-Hwy 47, middle). In this swale the geometric mean K_{fs} for moisture content of 37% was significantly different than the geometric mean K_{fs} for moisture content of 43% at the 90%, 95% and 99% confidence interval. The Tukey–Kramer test takes mean and standard deviation of each pair of data set into account and since for MN-Hwy 47, middle cross-section, the difference in mean and standard deviation between K_{fs} for the moisture contents of 37% and 43% was high, they were significantly different. So except for one site in Hwy 47, these statistical tests confirm that field-saturated hydraulic conductivity is a soil property that, with the Green–Ampt analysis, is relatively unchanged with the change of initial moisture content.

One phenomenon that could lead to a dependence of estimated K_{fs} on initial moisture content would be the dependence of air entrapment on initial moisture content. The amount of entrapped air in the soil at field saturated conditions will affect the field saturated hydraulic conductivity. However, since we did not measure the final water content of the soil after and infiltration test, but only assumed the final water content to be equal to the porosity, it is not possible for our data to quantify the effect of air entrapment and the relation between it and initial moisture content.

3.4.2. Effect of soil texture classes

Measurements were taken at five swales with different soil texture classes in Fall 2011, as summarized in Table 4. Data were collected on the sites where the soil cores were taken so that the K_{fs} values represent the soil textural classifications. The soil texture classes in Table 4 represents the soil of the top 25 cm. The geometric mean value of K_{fs} varied from 0.75 to 3.9 cm/h, a fairly small range given the variation in soil textures. For each soil texture class the geometric mean K_{fs} value was either higher than the typical K_{fs} value or at the higher end within the typical range. These swales are up to 50 years old, and it is possible that the macropores created by the grass in the swale provides them with a higher K_{fs} than would normally be expected. Macropore impacts include the rapid flow of water along certain pathways, bypassing a large part of the porous medium (Schaik et al., 2010). A 0.002% increase in pore space by a single macropore can increase the infiltration capacity by 65% (Beven and Germann, 1982). Since the number of measurements was not the same, the Tukey–Kramer method was used to determine differences in geometric mean K_{fs} value for different soil textural classification. No significant difference was observed among geometric mean K_{fs} values within the 90%, 95% and 99% confidence interval. The reason for this might be the high coefficient of variation (COV), which is the ratio between the standard deviation and arithmetic mean of log transformed K_{fs} data, between 1.09 and 14.4. A high COV value represents higher spatial variability of K_{fs}, which is substantial in this case, thus masking out any difference that might exist between soil textural classes. However, the factor of 5 variation in geometric mean K_{fs} is well below the expected variation of a factor of 20 reported by Rawls et al. (1983). It indicates that though the spatial variation of K_{fs} at each

Table 3
Summary of the analysis using infiltration measurements with different moisture content.

Location	Initial moisture content (%)	Number of measurements	Geometric mean of K_{fs} (cm/h)	COV* of K_{fs}
Hwy 47 (middle)	31	21	1.70	4.16
	37	21	3.85	1.49
	43	19	0.85	15.21
Hwy 47 (downstream)	10	21	17	0.24
	23	21	11.50	0.58
Hwy 51, Arden Hills (upstream)	27	18	6.50	0.78
	30	18	5.70	0.87
	32	18	2.10	2.58
Hwy 51, Arden Hills (middle)	15	18	2.80	1.87
	30	21	4.45	0.80
	33	21	1.75	3.36
Hwy 51, Arden Hills (downstream)	29	21	2	2.85
	38	21	4	1.23
Hwy 212 (middle)	18	21	0.45	2.39
	19	21	1.05	32.41
	39	12	0.30	0.93
Hwy 212 (downstream)	12	21	6.53	1.06
	29	21	2.03	2.80

* COV = Co-efficient of variance.

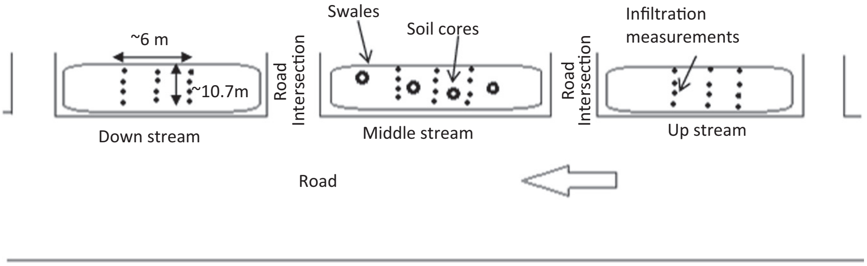

Fig. 6. A schematic diagram of the reaches of grassed swale located next to road.

Table 4
Geometric mean K_{fs} values in swales for different soil texture classes taken in Fall 2011.

Location	Soil texture class	Number of measurements	Geometric mean of K_{fs}, (cm/h)	Coefficient of variation (COV) of K_{fs}	Typical K_{fs} (Rawls et al., 1983), (cm/h)
Hwy 47	Loamy sand & Sandy loam	20	2	3.55	1–3
Hwy 51, Arden Hills	Loam & Sandy loam	20	2	3.34	0.34–3
Hwy 212	Silt loam & Loam	20	0.75	14.38	0.34–0.65
Hwy 13	Loam, Sandy clay loam & Silt loam	19	3.9	5.6	0.15–0.65
Hwy 77	Loamy sand	17	2	1.09	1

site is wide, the variation of mean K_{fs} within soil texture is narrow. This could be caused by plant root macropores in these swales or may be that variable soil compaction was such a dominant factor in these swales that it overcomes the soil texture effect on the K_{fs}.

3.4.3. Derived K_{fs} values in side slope vs in center of the swale

A Tukey–Kramer test was performed between K_{fs} values of the side slopes and K_{fs} values of center of all the swales. A significant difference between geometric mean K_{fs} values of the side slopes and the center of the swale was observed for swales located in Minnesota and Madison, WI, at a 95% confidence interval with the exception of one swale at MN-Hwy 212. This indicates that care should be taken to separately conduct measurements for K_{fs} on the side slope and center of the swale. The geometric mean of K_{fs} from the side slopes and the center of the swales, shown in Table 5, indicate that there is no strong trend in terms of which value is higher or lower. At MN-Hwy 212 and MN-Hwy 47, the side slopes had a higher K_{fs} than the center of the swale, and at MN-Hwy 51 in Minnesota and Madison, the side slopes had a lower K_{fs} than the center of the swale. Thus, while the side slopes are different than the center of the swale, there is no indication that either will have a higher K_{fs}. There is, therefore, no observed evidence that sedimentation in the center of the swale causes a reduction in infiltration. This is a different result than postulated by Barrett et al. (1998a). One reason could be that the growth of plant roots in the center of the swale creates macropores that alleviate sedimentation-induced reduction of infiltration rates.

3.4.4. Effect of season

A summary of the analysis using the infiltration measurements that were taken at three swales (MN-Hwy 212, MN-Hwy 47 and MN-Hwy 51) of different soil texture classes for the two seasons are given in Table 6. The geometric mean of K_{fs} was higher in spring than summer for MN-Hwy 51 and lower for MN-Hwys 47 and 212. The differences, however, were not great compared to the COV of each data set. Since the number of measurements is the same for each treatment, two factor ANOVA tests were performed on season. No significant difference was observed between the geometric mean K_{fs} values of fall and spring with 50–95% confidence intervals, partially due to the high COV (1.92–14.38). The COV values were high because of high standard deviation of log-transformed K_{fs} values, where K_{fs} varied up to two orders of magnitude in the same site. These results are different than what was observed by Emerson and Traver (2008). They reported that the infiltration rate of the stormwater BMP is strongly dependent on the temperature. But in the present study the measured K_{fs} value is associated with the temperature of the water used in the MPD infiltrometer test which did not change significantly over the test days.

3.4.5. Effect of distance from downstream outflow pipe

For each of the three swales three reaches were selected where 41–61 infiltration measurements were taken at various distances upstream from the outflow pipe. The hypothesis underlying this test was that sediment transported into the swale could deposit more heavily near the outflow pipe, and this would then produce a trend of increasing K_{fs} with distance upstream from the outflow point of the swale. The geometric mean value of estimated K_{fs} values for each reach was calculated and a Tukey–Kramer test was performed to see if there are significant differences among geometric mean K_{fs} for three different reaches of the same swale for 90%, 95% and 99% confidence intervals. From this test it was observed that in some cases there is a significant difference among the

Table 5
Comparison between geometric mean K_{fs} at the center and side slope of the swales. K_{fs} = Geo-mean × $10^{\pm w}$.

Location	Center of the swale			Side slope of the swale		
	# of meas.	Geo-mean K_{fs} (cm/h)	95% C.I. of Log K_{fs} (w)	# of meas.	Geo-mean K_{fs} (cm/h)	95% C.I. of Log K_{fs} (w)
Hwy 212, Chaska, MN	78	0.8	0.2	90	1.31	0.16
Hwy 47, Fridley, MN	63	2.9	0.2	87	6.5	0.2
Hwy 51, Arden Hills, MN	78	4.8	0.16	81	2.2	0.16
Hwy 51, Madison, WI	13	45.7	0.25	70	16	0.14

Table 6
Summary of the analysis using infiltration measurements in Fall 2011 and Spring 2012.

Location	Fall 2011			Spring 2012		
	Number of measurements	Geometric mean of K_{fs}, (cm/h)	COV* of K_{fs}	Number of measurements	Geometric mean of K_{fs}, (cm/h)	COV* of K_{fs}
Hwy 47	20	2	3.55	20	1.5	4.94
Hwy 51, Arden Hills	20	2	3.34	20	2.8	1.92
Hwy 212	20	0.75	14.38	20	0.45	2.66

* COV = Co-efficient of variance.

geometric mean K_{fs} of the same swale and in some cases there is no significant difference. For further investigation, regression analysis was performed on these data. For each swale it was found that the geometric mean K_{fs} value of at least one reach among three reaches was significantly different. The regression equations for all three swales are as follows:

$$\text{Hwy 47}: \; K_{fs} = 10^{1.82-0.96x} \tag{1}$$

$$\text{Hwy 212}: \; K_{fs} = 10^{1.52-1.16x} \tag{2}$$

$$\text{Hwy 51}: \; K_{fs} = 10^{-0.57+0.85x} \tag{3}$$

where x is the distance from upstream (km), and K_{fs} is the field-saturated hydraulic conductivity (cm/h). Over the length of each swale in the downstream direction (approximately a quarter km), the geometric mean K_{fs} of MN-Hwy 47 decreased by a factor of 1.73, the geometric mean K_{fs} of MN-Hwy 212 decreased by a factor of 2.0 and the geometric mean K_{fs} of MN-Hwy 51 increased by a factor of 1.6.

Based on the regression Eqs. (1)–(3) we can conclude that in some cases geometric mean K_{fs} will increase and in some cases geometric mean K_{fs} will decrease with distance downstream. In general, one might expect to have lower K_{fs} value downstream because of increased sedimentation as the pipe is approached. However, many other factors affect the distribution of K_{fs}, including vegetation density, erosion, the presence of macropores, and soil compaction, and these may have a dominating effect over any possible effect from sedimentation.

Other studies that support this finding are Yonge (2000) reported no significant difference in solid retention between the tested vegetated highway shoulders. Barrett (2004a,b) found a substantial reduction in TSS concentration at the side slope but for many events the change in TSS concentration along the length of the swale was small. This would mean that the deposition of the sediment in the swale channel is not dependent on the location along the channel.

4. Conclusions

Six roadside swales were selected for analysis of infiltration rates, chosen to represent the range of soil samples found in Minnesota and Wisconsin, USA. The near-surface (upper 25 cm) K_{fs} values of the six swales varied from 0.75 cm/h to 15.5 cm/h, and were roughly a factor of 2.8 (mean) or 1.5 (median) greater than the published mean values (Rawls et al., 1983) for the same soil texture classes. This may be due to roots creating macropores in the near-surface soil, which is normally not taken into consideration in laboratory soil permeability tests.

For these measurements we found that there is no statistically significant evidence that soil texture class has an effect on the mean field-saturated hydraulic conductivity of a swale. One reason for this might be the high coefficient of variation (COV), but the variation in K_{fs} were lower than those expected for these soil textural classes as reported in the literature (Rawls et al., 1983). In addition soil moisture content and season was found to have no statistically significant effect on the mean field-saturated hydraulic conductivity of these swales. This is expected, because theoretically K_{fs} values should not be dependent upon soil moisture. Finally the required number of measurements of K_{fs} required to provide a specified level of uncertainty in the representative geometric mean of K_{fs} has been derived and given in Fig. 5 which indicates that 20 measurements should be collected for swales that are up to 350 m long for a 95% confidence interval of a factor of between 1.8 and 2.2.

The K_{fs} values at the side slope are observed to be different than in the center of the swale, but not necessarily higher. This could be attributed to sedimentation in the center of the swale causing a reduction in K_{fs} values, but also result of roots in the vegetated swale creating macropores which will help to increase K_{fs}. The distance from the downstream end in a swale was found to not have a consistent effect on the geometric mean K_{fs}. The swale located in Madison, WI did not show any evidence of the effect of the distance from downstream on geometric mean K_{fs} of the swale. On the other hand, the swales located in Minnesota showed evidence that the distances from downstream can have a positive or negative effect on the cross-sectional geometric mean K_{fs}. This result implies that infiltration measurements should be spread over the swales of interest to obtain accurate results. Deposition at the lower reaches of the swale did not appear to cause a lower K_{fs} in that region, possibly because the grass roots broke up the sedimentation and created macropores in the near-surface soil or because sedimentation did not favor the lower reaches of the swale.

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