Infiltration Capacity of Roadside Filter Strips with Non-Uniform Overland Flow

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Abstract

The side slope to a roadside swale (drainage ditch) constitutes a filter strip that has potential for infiltration of road runoff, thereby serving as a stormwater quantity and quality control mechanism. A total of thirty-two tests were performed during three seasons in four different highways located in the Minneapolis-St. Paul metropolitan area, MN to analyze the infiltration performance of roadside filter strips and the effect of fractional coverage of water on infiltration. Three different application rates were used in the experiments. All the tests showed that water flow on the lateral slope of a roadside swale is concentrated in fingers, instead of sheet flow, at the typical [road](#) runoff intensities for which infiltration practices are utilized to improve surface water quality. A linear relationship between flux of water from the road and fraction of wetted surface was observed, for the intensities tested.

The average percentage infiltration of the medium road runoff rate ($1.55 \times 10^{-4} \text{ m}^2/\text{s}$, without direct rainfall) experiments performed in fall was 85% and in spring 70%. For the high road runoff rate ($3.1 \times 10^{-4} \text{ m}^2/\text{s}$, without direct rainfall) tests the average amount of water infiltrated was 47% and for the low road runoff rate ($7.76 \times 10^{-5} \text{ m}^2/\text{s}$, without direct rainfall) tests it was 69%, both set of tests performed in spring and summer. The saturated hydraulic conductivity of swale soil was high, relative to the values typical of laboratory permeameter measurements for these types of soils. This is believed to be due to the macropores generated by vegetation roots, activity of macrofauna (e.g. earthworms), and construction/maintenance procedures. The trend was to have more infiltration when the saturated hydraulic conductivity was higher and for a greater side slope length, as expected. The vegetation, type of soil and length of the side slope are important to consider for constructing and maintaining roadside swales that will be efficient as stormwater control measures. These measurements indicate that the filter strip portion of a roadside swale typically infiltrates a substantial fraction of road runoff. However, the measurements do not incorporate the influence of direct rainfall upon the infiltration into filter strips.

Keywords: Filter strip; infiltration; overland flow; saturated hydraulic conductivity; roadside drainage ditch, stormwater control measure.

1. Introduction

A growing trend in stormwater management is to include techniques that reduce runoff volumes and improve runoff water quality in addition to reducing the peak flow rate. Such techniques are called low impact development (LID) practices or Green Infrastructure (GI) and are typically designed to reduce runoff and to mimic a site's predevelopment hydrology. These practices include filter strips and vegetated drainage ditches (grassed swales), among others. They improve water quality by infiltration, filtration, and sedimentation. For roadway runoff flowing into a grassed swale, volume reduction occurs primarily through infiltration into the soil, either as the water flows over the side-slope in a direction perpendicular to the roadway into the swale or down the length of the swale channel parallel to the roadway. Most of the prior research on swales was on the channel portion, not the side slope. According to Barrett *et al.* (1998), as long as the road runoff is allowed to flow directly down the side slope into the swale, the side slope acts as a filter strip. Pollutant removal can occur by sedimentation of solid particles onto the soil surface, filtration of solid particles by vegetation, or infiltration and adsorption/degradation of pollutants dissolved in the runoff (Abida and Sabourin, 2006). The infiltration capacity of each swale will depend on many variables and each swale should be examined individually (Ahmed *et al.*, 2015).

Using synthetic runoff, Deletic and Fletcher (2006) studied a 5m long grass strip with a 7.8% average longitudinal slope and found 33% of average infiltration rates (as a percentage of the inflow) for the tests where the inflow water was mixed with sediment and 56% where the inflow was clean. A study by Liu *et al.* (2016) analyzed the synthetic runoff from 5m long loamy hillslopes (15° and 30° slopes) with different vegetation treatments on a newly built unpaved

road. The mean runoff coefficient for the grassed side slopes was less than 0.1. The runoff coefficient was found to be correlated with the saturated hydraulic conductivity, vegetation cover, root weight density, and root length density.

Multiple studies have monitored volume reduction with swales subject to natural storm events. For example, Lancaster (2005) monitored infiltration along roadside swales in Washington, and reported 100% infiltration within the first two meters from the edge of pavement in one site (36 precipitation events). At another site, 67% of the events (18 precipitation events) had no observed runoff. Ahearn and Tveten (2008) investigated the performance of four 41 year-old, unimproved roadside swales. The results from the monitoring station located at 4 meters from the edge of pavement showed 66% to 94% runoff volume reduction.

The main difference between the side slope to a roadside grassed swale and traditional filter strips is the slope, the former having much greater incline. Hunt *et al.* (2010) investigated the volume reduction capability of a 44.8 m (147 ft) vegetative filter strip with a 1.25% slope over a 16-month period and 23 rainfall events. Total volume reduction over the monitoring period was 85% and the 3 events that produced runoff at the base of the swale had total rainfall depths greater than 40 mm (1.6 inches). Knight *et al.* (2013) monitored different vegetative filter strips with a level spreader. The strips had 1% slope, sandy loam/clay loam soils, and an estimated 0.1 cm/h hydraulic conductivity. The 8m long strip had an average runoff reduction of 36% while the 20 m long strip had a 59% average volume reduction.

Barrett (1998) indicated that in practice, flow in swales tends to concentrate in small, incised channels that reduce their effectiveness in removing constituents dissolved in highway runoff. Le Bissonnais *et al.* (2004) reported a reduction in the efficiency of grassed strips when the runoff was concentrated in rills and the surface was not completely covered by sheet flow. Poletika *et*

al. (2009) investigated the effect of upper boundary application flow rate and flow concentration on percentage volume reduction of a vegetative filter strip. An application flow rate of approximately $2.09 \times 10^{-4} \text{ m}^2/\text{s}$ had a mean volume reduction of 41% and an application flow rate of $4.78 \times 10^{-4} \text{ m}^2/\text{s}$ had a 34% volume reduction. The plot with concentrated flow (covering 10% of the surface width) had a volume reduction of 16%.

Results from previous research on infiltration performance of swales and filter strips have great variability on percentage of water infiltrated, probably because they have a wide range of inputs, use different methods to apply the water, and have different extents of concentrated flow. They generally vary in location, swale characteristics and type of soil, precipitation intensity and duration, drainage area, and whether the water is input as natural or artificial rain, or concentrated runoff. Based on previous studies, it is believed that the infiltration performance of swales is linked to infiltration capacity of the soil, initial soil moisture content, ratio of impervious drainage area-swale area, length and width of the vegetated area, slope, type of flow down the side slope of the swale (sheet or concentrated flow), and total depth and intensity of precipitation. Consequently, the experiments presented in this research take into account the most important factors for typical roadside swales side slopes. According to Asleson *et al.* (2009), monitoring the performance of full-scale stormwater treatment devices during real storm events is difficult to do with accuracy; alternatively performance tests of field installation using simulated rainfall events is a more reliable approach. In this research, the effect of non-uniform overland flow under a range of generated runoff fluxes on infiltration rates is tested. The goal is to analyze the volume reduction achieved by roadside filter strips (side slope of the swale) under different rainfall regimes using simulated runoff.

2. Method

2.1 Site Selection and Preparation

The four highways selected for this study were analyzed previously in field infiltration measurements study by Ahmed *et al.* (2015): Hwy 13 (Hwy 13 and Oakland Beach Ave. SE, Savage, MN), Hwy 47 (University Ave. NE and 83rd Ave. NE, Fridley MN), Hwy 55 (Snelling Ave. and County Rd. E, Arden Hills, MN), and Hwy 77 (Cedar Ave. and E 74th St. North of Hwy 494, Bloomington, MN). These swales are between 30 and 50 years-old, constructed by the Minnesota Department of Transportation. Two locations were tested in each highway, 6-10 m apart, chosen to assure safety and ease of access. All of the side slopes had 90% or more vegetation cover, which is sufficient to consider these vegetated. For water quality purposes, for example, CALTRANS (2003) found that “a minimum vegetative cover of about 65% is required for pollutant concentration reduction to occur, and a rapid decline in performance occurs below about 80%.” The soil types studied (loam, loamy sand, sandy loam, and sandy clay loam) correspond to hydrologic soil groups A, B and C (NRCS, 2009).

For the field tests, the grass was mowed with a lawn mower and shears were used to finish cutting the surface vegetation to a height of approximately 1 cm. The grass clippings were collected in the lawn mower bag and the remainder was cleared with a bamboo rake (Figure 1). The water depths during the tests were lower than the height of the remaining vegetation. The roots of the vegetation were not modified, leaving the existing soil matrix and soil macroporosity in the original state. Surface roughness data was collected using a pin meter operated on a fixed frame. Cross-sectional pin meter measurements were documented with a camera, collecting the relief every 10.2 cm (4 in) along the entire length of the swale side slope.

2.2 Experimental Procedure

Three different boundary flux rates (q_b) were used (Table 1), equivalent to a uniform rainfall intensity of 2.8 cm/h, 5.6 cm/h, and 11.2 cm/h intensity over a 10 m wide road and shoulder, assumed typical for a road with 2 lanes. Water equivalent to the road runoff intensity from each of these events was applied to a strip width of 0.9 m at the top of the slope along the edge of the shoulder of the road. The water was pumped with a hose from a reservoir with a submersible pump. Discharges were adjusted with a valve, volumetrically calibrated before every experiment to 4.3, 8.5, and 17 L/min. The water was pumped to a plastic box with a rectangular weir (Figure 1). To enable visualization of the flow patterns, the water was mixed with industrial kaolin (median particle size 0.5 μm), a clay mineral, using a paint mixer to achieve a 13 g/L uniform concentration. The total volume of water for each experiment was 255 L. The water patterns were recorded by installing a camera with a mounting pole set in the channel of the swale; the pole had an adjustable height and the average height at which the camera was set was 2.5 - 3 m. The camera was programmed to take one picture every five seconds. A 1x1m mesh frame was installed on the swale to facilitate corrections of angle distortions in the pictures taken (Figure 2 a).

Table 1 Boundary flux (q_b), intensity (I), assumed width of the road (W_r), and duration of the test corresponding to the low, medium and high flux experiments.

	q_b (m^2/s)	I (cm/h)	W_r (m)	Duration (min)
Low flux	7.76×10^{-5}	2.79	10	60
Medium flux	1.55×10^{-4}	5.59	10	30
High Flux	3.10×10^{-4}	11.18	10	15

108 The water not infiltrated by the swale was collected from a clay lined trench dug at the bottom of
109 the side slope connected to a receiving bucket. The total volume of water that was not infiltrated
110 (runoff) was recorded, as well as the runoff rate when the system reached steady state, or when
111 the volume collected over 30 second intervals was constant by the end of the tests. The following
112 data were collected:

- 113 • Micro-topography of the surface,
- 114 • Total volume of runoff water (water not infiltrated in the side slope of swale),
- 115 • Intensity of runoff flow,
- 116 • Wetted surface area over time,
- 117 • Soil texture and bulk density,
- 118 • Initial soil moisture content, and
- 119 • Saturated hydraulic conductivity and effective wetting front suction.

120 For each highway, two soil cores of 13 cm length from the surface were collected during fall
121 2014, using a cylindrical core sampler to examine bulk density and porosity (ASTM D2937-10).
122 Those cores were used to investigate soil texture; the soil samples were processed using the wet
123 sieving analysis (ASTM D6913) and hydrometer analysis (ASTM D422) to determine % clay, %
124 silt and % sand in each sample. Before each test, three soil samples were collected to determine
125 initial soil moisture content (ASTM D2216). The Green Ampt (1911) parameters, saturated
126 hydraulic conductivity and wetting-front suction (ψ) in the upper 25 cm were estimated at the
127 end of the field tests using the MPD infiltrometer method (Asleson *et al.* 2009; Olson *et al.*,
128 2013; Ahmed *et al.* 2014). For this, twenty measurements of falling head were taken per highway
129 and utilized in the MPD spreadsheet to compute the saturated hydraulic conductivity and the
130 capillary suction of the soil ahead of the wetting front.

To evaluate the wetted area, images were processed following a five step procedure using the software ImageJ, an image processing and analysis software. First, based on the frame positioned in the field, the image (Figure 2a) was orthogonally projected (Figure 2b), using the ImageJ plugin Projective_Mapping with a bilinear approximation. Second, the picture was transformed into an 8-bit grey scale. Afterwards, a study area was selected and cropped based on the spread of the water along the slope. Then, a Fuzzy Contrast Enhancement (Figure 2c) plugin (Alestra and Battiatto, 2008) was used to differentiate the wetted from the dry area. Finally, a thresholding method that binarises 8-bit images was implemented to select the wetted area. The preferred technique was the “Intermodes” method (Prewitt *et al.*, 1966), which assumes a bimodal histogram (Figure 2d). Verification of the images was made by visually observing the locations of the water on the slope and comparing them to the information taken from the photographs; the results were similar.

3. Results and Analysis

The analysis is based on a total of 32 tests performed during fall 2014, spring 2015, and summer 2015 on highways: 51, 77, 47, and 13 in the Minneapolis-St. Paul, USA metropolitan area. The duration of the low, medium, and high application rates was 60, 30 and 15 minutes, respectively.

3.1 Dimensionless Infiltration Parameters

Infiltration measurements were made at two strips in each of four sites. Representative dimensionless parameters will be used to generalize the results. These were chosen from knowledge of the physical processes. The first parameter is a relative volume of infiltration:

$$V_i^* = \frac{V_{inf}}{V_{in}} \quad (1)$$

; where V_{inf} is the volume infiltrated and V_{in} is the input volume. When V_i^* is equal to one, all of the runoff from the road has infiltrated in the side slope of the swale. The second parameter is a relative saturated hydraulic conductivity:

$$K_s^* = \frac{K_{sat} W_S}{I W_R} \quad (2)$$

; where K_{sat} is a representative saturated hydraulic conductivity for the side slope, I is average rainfall intensity, W_S is the width of the swale perpendicular to the road, and W_R is the width of the road draining into the swale. Infiltration fraction will typically increase with K_s^* . In a sheet flow, K_s^* equal to one will result in complete infiltration of the water. This factor does not take into account concentrated flow, which would reduce V_i^* , or soil moisture deficit, which would increase V_i^* . The field experiments results presented show the relationship between K_s^* and V_i^* , taking into account concentrated flow and initial soil moisture content.

3.2 Characteristics of the Roadside Filter Strips

Table 2 provides information about the sections of the roadside filter strips examined during the field experiments. Using the percentages of clay, silt and sand in a textural triangle (USDA, 2014) the soil texture class in the upper 13 cm was determined. Rows with two soil textures (Hwy 51, 47, and 13) indicate that among the eight soil cores samples, there were both textural classes of soil. The slope and length of the side slope perpendicular to the road were measured at each site. The values of K_{sat} were adjusted to 20°C by multiplying the measured K_{sat} at a given temperature (T) by the viscosity correction factor $\eta_T / \eta_{20^\circ C}$; where η_T is the viscosity of water at a certain temperature.

The representative saturated hydraulic conductivity for infiltration given in Table 2 is computed as:

$$K_{sat} = \beta K_{sat \text{ Arithmean}} + (1-\beta) K_{sat \text{ Geomean}} \quad (3)$$

,where the arithmetic ($K_{sat \text{ Arithmean}}$) and geometric ($K_{sat \text{ Geomean}}$) mean values were calculated from 20 measurements of saturated hydraulic conductivity using the MPD infiltrometer (Ahmed *et al.*, 2015) performed on the strips tested. Equation 3, with $\beta = 0.32$, was derived by fitting to a simulation that used 268 K_{sat} measurements at 12 sites by Weiss and Gulliver (2015). They found that a linear combination of K_{sat} arithmetic and geometric mean values more accurately represented the observed aggregated infiltration in the soil of stormwater treatment practices, including swales.

Table 2 Characteristics of the swales studied based on soil cores samples, estimations of saturated hydraulic conductivity (at 20°C), and length and slope of the sections used in the experiments.

*Coefficient of variation in parenthesis.

	Soil Texture	Arithmetic mean of Ksat (cm/h) (at 20°C)	Geometric mean of Ksat (cm/h) (at 20°C)	Ksat (cm/h) (based on Eq. 3)	HSG (based on Eq. 3)	Bulk Density (g/cm ³)	Porosity (%)	Average Initial Soil Moisture Content (Fall) (%)	Average Initial Soil Moisture Content (Spring) (%)	Slope	Length studied (cm)
Hwy 51	Loam /sandy loam	5.1 (1.44)*	2.8	3.5	B	1.1	0.56	0.15	0.30	5:1	406
Hwy 77	loamy sand	7.5 (0.94)*	4.9	5.7	A	1.2	0.56	0.15	0.20	5:1	407
Hwy 47	loamy sand /sandy loam	4.9 (1.29)*	2.8	3.5	B	1.2	0.54	0.12	0.27	5:1	779
Hwy 13	Loam /sandy clay loam	6.1 (1.87)*	3.2	4.1	A	1.1	0.58	0.13	0.29	4:1	422

3.3 Infiltration Volume

Table 3 summarizes the results of the different experiments performed at the highway 51, 77, 47, and 13 sites during fall 2014, and spring and summer 2015, with percentage of volume infiltrated, start time of runoff (flow not infiltrated entering the channel) and approximate runoff

190 rate (at the bottom of the side slope) after steady state in runoff was approached for the different
191 cases studied. The field tests were performed in this order: medium flux (fall 2014), medium flux,
192 low flux, and high flux (spring and summer 2015).

Table 3 Results of the field experiments in chronological order at the four highways selected during the three different seasons using three different intensities of boundary flux. The fall experiments were performed in 2014 and the spring and summer tests in 2015. The (-) indicates no runoff generation, *Tests affected by construction and**Site with plains pocket gopher holes.

	Season	Boundary Fluxes	Site	Runoff start time (min)	Rate runoff (steady state) (L/min)	% Wetted Area	% Infiltrated
Hwy 51	Fall	Medium Flux	Site 1	17	2.75	84%	86.5%
			Site 2	9	3.1	69%	74.1%
	Spring	Medium Flux	Site 1	11.6	5.5	61%	61.4%
			Site 2	12	4.2	69%	72.4%
		Low Flux	Site 1*	8.8	3.1	67%	59.2%
			Site 2*	5.6	3	77%	62.1%
		High Flux	Site 1*	1.7	16.25	79%	32.2%
			Site 2*	1.4	16.5	90%	32.7%
Hwy 77	Fall	Medium Flux	Site 1	6.3	3.75	64%	64.8%
			Site 2	15	4.2	70%	76.6%
	Spring	Medium Flux	Site 1	9	4.85	66%	61.8%
			Site 2	8.8	4.75	54%	65.9%
		Low Flux	Site 1	17.6	2.5	85%	68.9%
			Site 2	28.8	2.5	66%	72.9%
		High Flux	Site 1	2	16.25	82%	20.6%
			Site 2	3.3	15	88%	37.5%
Hwy 47	Fall	Medium Flux	Site 1**	-	-	75%	100%
			Site 2	27.6	0.04	83%	100%
	Spring	Medium Flux	Site 1**	25	1	70%	98.0%
			Site 2	9.8	4.4	77%	72.7%
	Summer	Low Flux	Site 1**	-	-	70%	100%
			Site 2	14.8	2.5	57%	65.0%
	Summer	High Flux	Site 1**	10	2.8	80%	95.0%
			Site 2	5.9	8	81%	74.9%
Hwy 13	Fall	Medium Flux	Site 1	18.5	2.5	77%	88.4%
			Site 2	18.25	2.6	72%	87.0%
	Spring	Medium Flux	Site 1	10.9	4.5	75%	68.4%
			Site 2	9.2	6.9	70%	59.1%
	Summer	Low Flux	Site 1	11.8	2.82	58%	60.7%
			Site 2	13	2.8	57%	60.7%
	Summer	High Flux	Site 1	1.5	13	85%	41.8%
			Site 2	1.6	13.2	80%	42.2%

During spring 2015, before the low flux tests, the roadside swale of Hwy 51 (both sites) was impacted by the placement of fiber optic cable across the ditch and the nearby construction of County Road E bridge. The surface of the swale had vegetation losses and compaction due to truck and excavation operations, however these factors did not noticeably affect the results. At highway 47, plains pocket gopher (*Geomys bursarius*) holes were observed at site 1, and the infiltration rates at this site were high, with almost 100% infiltration for all intensities. This is presumed to be a special case due to the plains pocket gopher holes, and will not be included in the analysis. Figure 3 displays the average infiltration percentage for the different intensities. The total equivalent simulated rainfall depth (assumed to be applied over the road) was 2.8 cm in all tests. The average percentage of water infiltrated during the medium flux experiments performed in fall (8 tests) was 85%, or 2.4 cm of rain on the road with a 13% standard deviation. This value is higher than the results observed during spring, with 70%, or 1.95 cm of rain on the road with a 12% standard deviation. During the high flux experiments (8 tests) the average of water infiltrated was 47%, or 1.3 cm of rain on the road with a 25% standard deviation. The average water infiltrated during the low flux experiments was 69%, or 1.93 cm of rain on the road with a 14% standard deviation.

Figure 4 provides the mean and standard deviation of the runoff coefficient (ROC) at the end of the experiment, or the rate of runoff at the end of the experiment divided by the boundary flux rate, for each set of tests. The medium flux fall tests had a lower ROC than in the spring, probably because of the low initial soil moisture content for those tests. The infiltration data collected from the medium flux experiments (spring tests) was similar to the low flux tests. These results imply that either there was a reduction in the saturated hydraulic conductivity or an increase of the soil moisture content in the experiments carried out after the first tests (medium

flux) in spring. The similar start time of runoff (Figure 5) and greater ROC (Figure 4) confirm this observation. In the spring tests at highway 13 (Figure 5), the ROC of the low flux test was 0.66, higher than the medium flux test 0.53; both had similar start times of runoff generation. The possible causes of the relative infiltration reduction are addressed in the Discussion, section 4.2.

3.4 Roughness and Wetted Area

The surface of the swales studied neither showed signs of previous erosion nor experienced erosion during the experiments. The measurements taken with the pin meter were translated into a random roughness factor (RR) (Allmaras *et al.*, 1966), which is the standard deviation of surface elevations. The RR reveals the vertical variability in surface elevations (Yang *et al.*, 2013) and was found to be close to the same value for all sites. The average RR (perpendicular to the flow) for all the swales was 4 mm with a standard deviation of 1mm. The average RR (parallel to the flow), corrected for slope, was 5 mm, with a standard deviation of 3 mm. For these swales, the variation in RR was minor, and a correlation of RR and wetted area was not attempted.

The wetted area appears to be related to the rainfall intensity over the road (Figure 6). A greater intensity, results in more area covered by water. The mean value of percentage wetted area was 72%, with a 9% standard deviation for the selected intensities among the four sites. The maximum percentage wetted area was 90% and minimum 54%. An empirical relationship between fraction of wetted area and intensity is given in the following equation, fitted to the field data:

$$\text{Fraction of Wetted Area} = 0.00225 \times \text{Intensity [mm/h]} + 0.581 \quad (4)$$

Roughness measurements showed that there were minimal preferential pathways in the micro-topography. We hypothesize that the sensitivity of wetted area to intensity is due to the absence of preferential flow features. We also hypothesize that if there were structured micro-topography, oriented in the downslope direction, there would be smaller sensitivity to intensity. The side slopes of the swales were relatively smooth, indicating that the Minnesota Department of Transportation's maintenance procedures were effective.

3.5 Saturated Hydraulic Conductivity and Infiltration

As expected, the saturated hydraulic conductivity of the soil is observed to be an important factor for infiltration rates. Figure 7 displays the relationship between the percentage infiltrated (V_i^*) and dimensionless parameter K_s^* , which is a function of the saturated hydraulic conductivity, rainfall intensity, width of the swale perpendicular to the road, and width of the road. The soil moisture deficit was higher in Test 1 than in the three other tests. The results indicate that V_i^* rises sharply below a K_s^* of 0.3. For K_s^* greater than 0.3, other factors seem to influence the percent infiltrated in the tests. The influence of soil moisture content, for example, can be seen in the high percent of V_i^* values measured in Test 1. This influence is discussed in the next subsection.

3.6 Initial Soil Moisture Content Effect on Infiltration

The initial soil moisture content during the spring experiments was higher than the previous fall, for the same boundary flux. Subsequently, the volume of water infiltrated during the spring experiments was lower than during the fall tests. Figure 8 shows the relationship between the percentage of water infiltrated and the soil moisture deficit (computed as the difference between the porosity of the soil and initial soil moisture content). The trend is to see a lower volume

infiltrated for initially wetter conditions. Figure 8 indicates there is lower sensitivity of infiltration capacity to soil moisture deficit reduction, which is also linked to a decrease in sorptivity. The data seemed to be relatively constant until a soil moisture deficit of 0.35, then it rises rapidly at higher soil moisture deficits. For a soil moisture deficit above $\Delta\theta = 0.35$ the percentage of water infiltrated appears to follow a linear relationship.

To relate the dimensionless parameter K_s^* and soil moisture deficit to percentage infiltration (V_i^*) a log-log multiple regression equation has been developed using the field data, excluding the data from for Site 1 at Hwy 47, where pocket gopher holes were observed:

$$V_i^* = \beta_0 K_s^{*\beta_1} \Delta\theta^{\beta_2} \quad (5)$$

where $\beta_0 = 1.79$, $\beta_1 = 0.25$, and $\beta_2 = 0.68$, $\Delta\theta$ is the fraction soil moisture deficit, and $V_i^* \leq 1$. Figure 9 shows the goodness of fit of the equation. A correlation coefficient of 0.47 ($n = 28$) and a slope significantly different from zero ($\alpha = 0.05$) were observed.

4. Discussion

4.1 Analysis of the Experimental Design Parameters

The three different boundary flux rates used (Table 1), were based on the correspondent return periods (T) of 1-year, 2-year and 10-year in the Minneapolis-St. Paul metropolitan area, Minnesota, USA (Perica *et al.*, 2013). Additionally, the field tests were designed to investigate the processes that are believed to be the most significant in infiltration and runoff. There are differences in conditions between what could occur during a real storm event and what occurred in the controlled field tests. A list of those differences is given below.

- The rainfall that would be occurring on the side slope in a real event was not considered in the

field tests. The initial soil moisture deficit is overestimated because of the lack of pre-wetting of the soil by rainfall incident directly on the side slope surface. Additionally, the added volume due to direct rainfall could spread the fingers and consequently reduce the concentration of flow on the side slope, increasing the fraction of wetted area over time. This effect would be greater downslope and for high flows. Overall, the direct rainfall would be expected to decrease the volume of road runoff infiltrated.

- The water supply container was placed downslope of the shoulder. However, many shoulders consist of gravel and compacted soil, and some water will infiltrate into the shoulder material. This effect will reduce the actual intensity of flow entering the side slope to a value below the intensities associated with the given event return periods, and will increase the fraction of infiltrated road runoff.
- The initial abstraction of water that would be retained on the surface of the road is not taken into account. Again, this effect will reduce the actual intensity of flow entering the side slope below the intensities associated with the given event return periods and will increase the fraction of infiltrated road runoff.
- Natural decaying organic matter on the side slope surface will absorb some fraction of the direct precipitation and road discharge. The presence of organic matter would decrease the amount of road runoff that reaches the bottom of the filter strip.
- The rainfall intensity over the road surface and runoff from the road was assumed to be constant and to flow directly to the side slope without a lag time (the time of concentration was assumed to be zero). Incorporating a lag time would increase the fraction of infiltrated road runoff.
- The road discharge was imposed as a uniform sheet flow at the location where it entered the

side slope. In the actual field situation it is likely that runoff from the road will not enter uniformly onto the side slope. This will have a variable impact on runoff. These effects are not being considered because the focus of this research was on infiltration of road runoff into the slope. Based on our results, we believe that this infiltration is a significant portion of the infiltration into most roadside swales.

4.2 Importance of Soil Moisture and K_{sat} Measurements

The soil textures (Table 2) of the roadside filter strips soils correspond to hydrologic soils groups (HSGs) A, B and C; however, the K_{sat} values estimated correspond to values close to or above the lower end of HSG A, 3.6 cm/h (NRCS, 2009) with a small variance. Lee, *et al.* (2016) have found that soil texture is a “poor” predictor of infiltration performance. It is particularly interesting that at Hwy 13, with a loam/sandy clay loam soil texture type corresponding to an HGA B/C soil, measured K_{sat} corresponds to a HSG A soil. In the field, it was observed that the clay did not exist as a layer within the soil profile, but was heterogeneously distributed in aggregates, allowing infiltration around the clay. Furthermore, it is important to highlight that after 30 years receiving road runoff these roadside filter strips were not clogged with sediment. The high K_{sat} of the soil was probably high due to the macropores generated by vegetation roots, activity of macrofauna (e.g. earthworms), and roadside construction/maintenance procedures.

The behavior in Figure 8, where percentage infiltration rises rapidly at higher soil moisture deficits, is not consistent with a sorptivity-based infiltration model from infiltration theory. That theory shows that as the moisture deficit increases, the infiltration capacity approaches a maximum value asymptotically. Instead, the plot shows the infiltration capacity increasing without apparent bound as the moisture deficit increases. The high soil moisture deficit values

occurred in fall 2014, and the percentage infiltration difference between seasons (fall and spring), for the same boundary flux, might be explained by a series of factors related to soil structure, changes in macropores and temperature, and surface sealing. Each of these factors has been analyzed taking into account the measured and observed characteristics of the sites studied. Soil cracking due to aggregate formation during wet-dry cycles takes place in soils containing high percentage of clay (Beven and German, 1982; Preston *et al.*, 1997). Soils with more than 15% of clay content exhibit aggregate structure (Horn *et al.*, 1994, Jarvis, 2007), however the soils in this study had 5% or less percentage of clay content. In addition, no surface cracks were observed in the field. Freeze-thaw cycles would not explain the observed decreased percentage infiltration during spring since these would likely increase the hydraulic conductivity after winter (Chamberlain and Gow, 1979; Zimmie and LaPlante, 1990). The temperature during the spring tests was higher (an average of 13.5F higher) than in the fall tests. Therefore the viscosity of water was lower in spring, which would result in higher infiltration rates; this effect does not justify the trends seen on Figure 8. There are two phenomena that might explain the decrease in infiltration percentage during spring: seasonal changes in roots and surface sealing. During fall with drier weather conditions roots are dying, leaving voids in the soil (Fisher *et al.*, 2015); therefore, infiltration capacity could have been increased (Gish and Jury, 1983; Mitchel *et al.*, 1995; Beven and German, 2013) during the fall tests. On the other hand, during spring, the new fine growing roots can clog soil pores and decrease infiltration capacity (Fisher *et al.*, 2014; Barley, 1954). Finally, the reduction of infiltration capacity after the fall tests may be due to surface sealing (Moore, 1981; Singer and Le Bissonnais, 1998; Gomez and Nearing, 2005). There are two types of rainfall-induced surface seals: structural seals (related to raindrop impact and sudden wetting), and sedimentary seals (result from settling of fine particles carried by

runoff). Dense vegetation protects the surface of the swales from structural seals, since raindrop energy is mitigated before impacting the soil surface. However, during the fall experiments the vegetation was cut, and the slope surface was exposed to rain drop impact afterwards, increasing the possibility of surface sealing development.

The lack of a substantial percentage infiltration difference between the medium flux and low flux experiments in the spring implies a change in the soil condition in the latter of the two experiments. There are two hypotheses to explain this outcome. First, the kaolinite particles suspended in the water could have precipitated and clogged soil pores. The latter tests would have started with an initially partially sealed surface, causing the infiltration rates to be lower than in the first experiment. A similar situation was previously observed in filter strip field tests by Deletic and Fletcher (2006) with sediment with a median diameter of 50 μm . However the particle size of 0.5 μm in the present study is likely too small to clog the larger and more influential pores.

Second, an incomplete drainage could have occurred between experiments. Typically, two days of drainage occurred between the tests at each site. On swale side slopes the soil is compacted at a depth of 20-30 cm during construction so that the saturated hydraulic conductivity is significantly smaller than at the surface. Water draining from a given infiltration experiment will be impeded by the lower permeability layers, with an increase soil moisture and thereby increase the wetting front potential (decrease the wetting front suction) at depth. Per infiltration theory, such as with the Green and Ampt model, this will then reduce the infiltration capacity of the soil for subsequent infiltration tests. In the experiments conducted we measured the initial water content of only the surface layer of soil and therefore do not have evidence for this reduction in wetting front suction. Although the saturated hydraulic conductivity would be unchanged, the

soil moisture would have needed further characterization at depth due to the two-layer impact on soil moisture content. We believe that the second hypothesis is the more likely explanation for the reduction on infiltration.

4.3 Comparison to Previous Research

The results of this study are best compared with filter strip studies. The differences would be the higher slope of the side slopes in a roadside swale and the attention to the measurement of K_{sat} in this study, without the need for calibration. Deletic and Fletcher (2006) used synthetic runoff applied upslope of a grass strip that was 5m long, (comparable to the 4 m side slopes considered in this study) with a 7.8% average longitudinal slope, and 0.3 m width. The initial soil moisture content was not measured and the tests were classified as initially wet or dry. A simplified double-ring infiltrometer test was used to get an estimation of the saturated hydraulic conductivity (0.72-3.6 cm/h). However, after calibration to match the measured infiltration at the plot scale, the K_{sat} values were assumed to be in the range of: 3.6-27 cm/h. The range and magnitude of K_{sat} values were greater than the ones observed in the roadside swales of this study (3.47-5.74 cm/h). The boundary fluxes utilized by Deletic and Fletcher were 3.3×10^{-4} , 6.7×10^{-4} , and $1 \times 10^{-3} \text{ m}^2/\text{s}$, the first being similar to the high flux in this study ($3.1 \times 10^{-4} \text{ m}^2/\text{s}$), corresponding to a 10-year storm; the other two fluxes were two and three times greater, possibly because they were designed to simulate a more concentrated flow. The runoff coefficients (ROCs) obtained in the cases where the inflow water was mixed with sediment were 0.38 (dry conditions) and 0.67 (wet conditions); these results are lower than the 0.88 ROC values observed in the field experiments presented here for a similar flux. The difference in K_{sat} is the main reason for the dissimilar results obtained.

In the experiments by Liu *et al.* (2016) two newly constructed sloped grassed field scale plots with 17% and 33% slopes, 5m long were studied applying water from an upstream water distributor. The soil moisture content was not reported. K_{sat} values were measured using the constant head method (16.1 and 17.7 cm/h for each slope, respectively). The boundary fluxes applied were 1.3×10^{-4} and 1.7×10^{-4} m²/s, similar to the medium flux used in this study (1.55×10^{-4} m²/s). These parameters correspond to a K_s^* in the range of 1.34-1.97, which is approximately 2 to 13 times greater than the K_s^* observed in this study (Figure 7). In addition, they found saturated hydraulic conductivity and the ROC had a -0.97 correlation coefficient, which indicates the importance of K_s^* . The average ROC for both side slopes was 0.07, five to nine times lower than the ROC values of 0.37 (fall) and 0.6 (spring) observed in the field tests presented in this study. These results are not surprising since the K_{sat} values estimated by Liu *et al.* were approximately three times greater than the ones estimated in the highways studied in this research.

In contrast to the other studies presented using synthetic runoff, the field tests reported in this study show the response to a wide range of boundary fluxes, including both high and low flows, representing typical intensities for which roadside filter strips in swales are designed and utilized to improve surface water quality. Measurement of the initial soil moisture has been found to be important to compare the soil's infiltration performance. In addition, the percentage of wetted area was estimated in all tests, providing information about flow concentration in grassed roadside swales under different runoff fluxes. Furthermore, measuring K_{sat} in the field is essential since the soil texture is not a good proxy (Lee *et al.*, 2016). Multiple measurements of K_{sat} are necessary due to its spatial variability (Asleson *et al.*, 2009; Olson *et al.*, 2013; Ahmed *et al.*, 2015); and 10 measurements per site were taken in these field tests. Finally, these

experiments were performed in roadside swales that are 30-50 years-old, therefore the infiltration capacity estimated corresponds to the long-term infiltration of these stormwater control measures.

5. Conclusions

A total of thirty-two tests were performed during three seasons on four different highways located in the Minneapolis-St. Paul metropolitan area, Minnesota, USA to analyze the infiltration performance of roadside filter strips and the effect of fractional coverage of water on infiltration. This study assists the evaluation of vegetated roadside filter strips located on the side slope of swales as stormwater control measures. The channel portion of a roadside swale has typically been the main element believed to control and reduce stormwater runoff, however the side slope shows great potential for runoff infiltration.

All the tests indicated that water flow on the lateral slope of a roadside swale is concentrated in fingers, instead of sheet flow, at the typical rainfall/runoff intensities for which infiltration practices are utilized to improve surface water quality. The minimum fraction wetted detected was 54% and maximum 88%, with an average of 72% and standard deviation of 9%. A linear relationship between flux of water from the road and fraction wetted was observed, for the intensities tested. Due to the maintenance procedures followed by the Minnesota Department of Transportation, the surface of the side slopes was relatively smooth with no prominent topographical features or signs of erosion; this was supported by low random roughness (RR) measurements.

Despite the initial compaction during construction, the saturated hydraulic conductivity of the swales soil was high, relative to the values typical of laboratory permeameter measurements for

the type of soil. This is believed to be due to the macropores generated by vegetation roots, activity of macrofauna (e.g. earthworms), and construction/maintenance procedures. An average of 1.9 cm of runoff from a typical two-lane highway was infiltrated during the experiments, indicating a high potential for side slope infiltration in these swales.

The trend was to have more infiltration when the saturated hydraulic conductivity was higher and for a greater side slope length, as expected. The vegetation cover, type of soil and length of the side slope would be important to consider for constructing roadside swales that will be efficient in stormwater management. The volume infiltrated during spring for the same intensity (medium flux) was on average 12% lower than in fall due to the larger initial soil moisture content in the spring. Finally, a log-log regression equation has been developed that relates percentage of water influx infiltrated with a dimensionless saturated hydraulic conductivity parameter (K_s^*) and soil moisture deficit. This equation can provide an estimate of percentage infiltration in the side slopes of roadside swales, which is often the most important means of infiltration because of their area relative to the channel of the swales.

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