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Infiltration into a Roadside Grassed Swale

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ABSTRACT

Roadside grassed swales or drainage ditches are an attractive storm water control measure because they can infiltrate water into the soil, filter sediments and associated pollutants out of the water and settle solids onto the soil surface. Measured infiltration parameters such as saturated hydraulic conductivity (K_{sat}), however, have spatial variation of up to two orders of magnitude; even in engineered soil. Thus, one infiltration measurement has great uncertainty. For this, study measurements of K_{sat} were taken at 108 locations at a selected swale located in Madison, WI to quantify their spatial variability. A storm water runoff model was developed to calculate the storm water infiltration efficiency of a swale by using field K_{sat} measurements. The water balance was conducted by calculating infiltration loss of direct rainfall and introduced storm water by using the Green-Ampt infiltration model, and routing the excess volume to the outlet of the swale using a water balance equation. A comparison between computed swale outflow and monitored swale outflow showed the accuracy of infiltration predictions with proper measurements of K_{sat}. The water quality performance through infiltration of a given swale can thus be computed from field measurements of K_{sat}.

KEYWORDS

Saturated hydraulic conductivity, grassed swale, infiltration loss, storm water runoff

INTRODUCTION

Grassed swales are shallow, open vegetated drains/channels/ditches that are designed to convey, filter and infiltrate stormwater runoff (Barrett et al. 1998a; Deletic and Fletcher 2005). They serve three purposes: removing water during rainfall-runoff events, infiltrating water into the soil, and filtering the solids and associated pollutants from the water.Vegetated cover on sloped applications slow the overland flow to allow greater opportunity for infiltration into the soil, and allow solids to settle while also providing an opportunity for nutrient uptake through the root system. Volume reduction occurs primarily through infiltration into the soil, either as the water flows over the side slope perpendicular to the roadway or down the length of the swale parallel to the roadway.For the selected swale in this study we found that a large uncertainty of greater than a factor of three is associated with 11 or less infiltration measurements. Because of high spatial variation of infiltration parameters such as saturated hydraulic conductivity (K_{sat}), it is recommended to take approximately 20 measurements in the field to obtain a representative infiltration rate of a swale. The Modified Philip Dunne(MPD) infiltrometer (Ahmed et al., 2011)is a relatively new device which can be used to take multiple measurements to calculate the saturated hydraulic conductivity (K_{sat}) and wetting front suction (ψ)of a swale. For this study, 108 measurements were taken at a swale located in Madison, WI. By using the spatially distributed K_{sat} value measured in the field along with other information, the performance of an existing swale can be quantified.A runoff-routing model has been developed using the Green-Ampt equation to calculate the performance of a swale in infiltrating stormwater runoff, applicable for different design storms, or for observed storm events. Input parameters for the Green-Ampt model are saturated hydraulic conductivity, wetting front suction, and initial soil moisture.

In this paper a verification of therunoff-routingmodel by comparing predicted infiltration loss with the actual infiltration loss of the swale located in Madison, WI will be presented.

METHOD

The swale selected for this study is located near Hwy 51 at Madison, WI, north of Hwy 12/18. The precipitation, inflow and outflow monitoring data were available for this swale. The swale is divided into two reaches,which will be termed the upstream swale and downstream swale.The swales receive surface runoff from the roadway on the east side. On the west side the swale receives water through a pipe as a concentrated flow, which discharges street runoff. There are three monitoring flumes: one to monitor concentrated flow on the west side, one to monitor discharge from the upstream swale and one to monitor flow from the downstream swale. The precipitation and flow data were monitored by the U.S. Geological Survey. There were 83 measurements of MPD parameters (K_{sat}, ψ and initial soil moisture)taken in the upstream swale and 25 were measured in the downstream swaleon 7/16/12 and 7/17/12 (Figures 1 and 2). The swale was divided into 20 cross sections, 40 to 78 *ft* apart and at each cross section 3 to 7 measurements were taken 4 *ft* apart, as in Figure 2.

Figure 1. Taking infiltration measurements using the MPD Infiltrometer in the swale located near Hwy 51, Madison, WI.

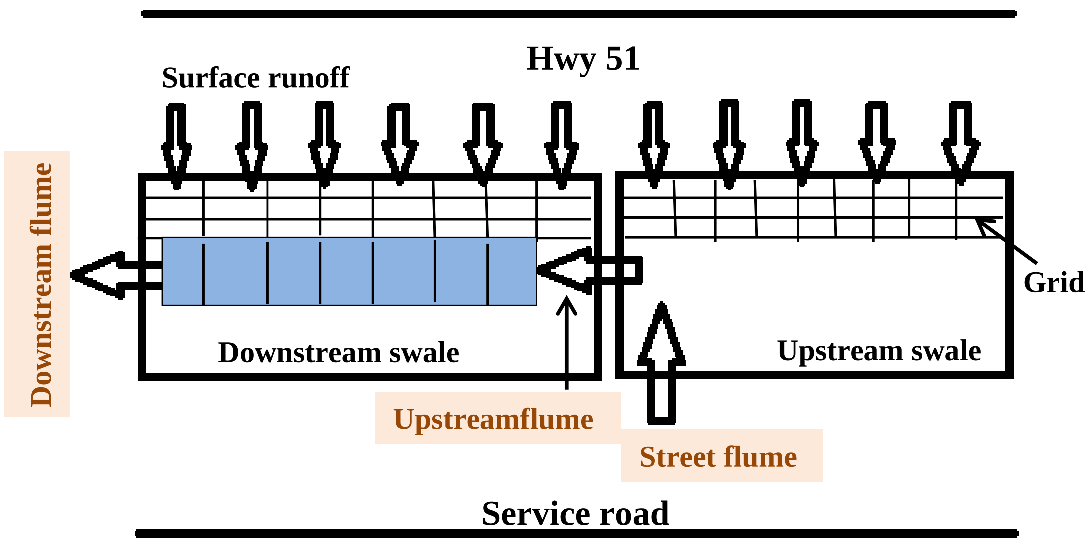

Figure 2.Plan view of the swalelocated near Hwy 51, Madison, WI.

A stormwater runoff model was developed to calculate the stormwater infiltration efficiency of a swale by using field infiltration measurements. This model is applicable for different design storms, or for observed storm events. The stormwater runoff model as applied to a swale focuses on the calculation of the water balance for rain falling directly on the swale and for stormwater introduced into the swale from the adjacent roadway and concentrated inflows by culverts or drainage pipes. The water balance is conducted by calculating infiltration loss of direct rainfall and introduced stormwater, and routing the excess volume to the outlet of the swale. The routing of the flow in the swale is accomplished by dividing the swale into cross section cells of longitudinal distance$B_j$for each time increment and then computing water surface profile, taking into account the surface area of infiltration and the water balance for each cross section. The water surface profile at the swale is developed using the dynamic equation of gradually varied flow, illustrated in Figure 3 and given in Equations 1 through 4.

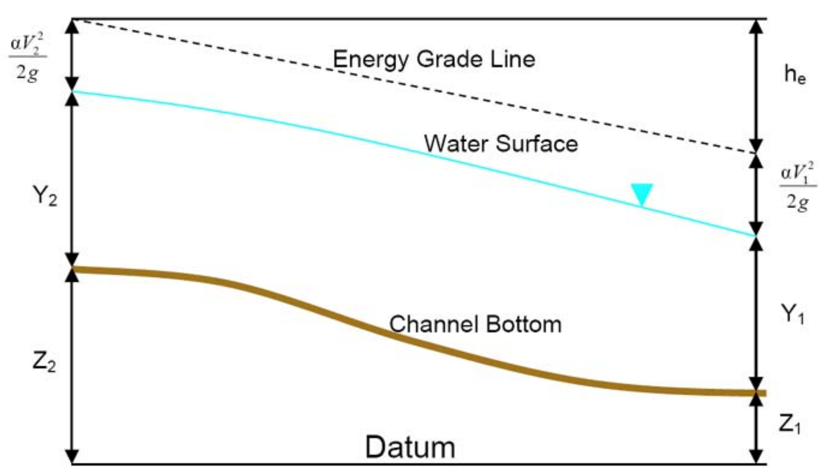

Figure 3. Gradually varied flow energy balance

$$E_1 = Y_1 + \alpha \frac{V_1^2}{2g} \tag{1}$$

$$E_2 = Y_2 + \alpha \frac{V_2^2}{2g} \tag{2}$$

$$\Delta x = \frac{E_2 - E_1}{S_0 - S_f} = \frac{\Delta E}{S_0 - S_f} \tag{3}$$

$$S_f = \left(\frac{nQ_{in_j}}{AR^{2/3}}\right)^2 \tag{4}$$

where, E = Specific energy,

Y = Depth of water in the swale (*ft*),

a = Energy co-efficient,

V = Velocity of water across the cross-section (*ft/s*),

S_0 = Average bottom slope of the swale,

S_f = Frictional slope,

n = Manning's coefficient,

Q_{in} = Inflow rate to section j (ft^3/s),

A = Cross-sectional area across the swale (ft^2),

R = Hydraulic radius (*ft*).

For a given flow rate from upstream (Q_{in_j}), the water surface profile for each cross section is quantified. The surface area for infiltration is calculated from the wetted perimeter and width of the cross section, B_j. Then the outflow rate is calculated by the water balance equation given in equation 5, which is applied at each cross section.

$$\boldsymbol{Q_{out_j}\Delta t = (Q_{in_j} + Q_{side_j} + Q_{conc_j})\Delta t - A_j * F_j/12} \tag{5}$$

where, $Q_{out\,j}$ = downstream outflow rate for section j (ft^3/s),

$Q_{in\,j}$ = inflow rate to section j (ft^3/s),

$Q_{side\,j}$ = lateral inflow to section j(ft^3/s),

$Q_{conc\,j}$ = concentrated inflow from culverts or pipes to section j (ft^3/s),

A_j = Area of the infiltrating surface for section j(ft^2),

$F_j(t)$= infiltration depth (*in*) into the swale bottom of section j during the time interval.

The outflow discharge at the section at the downstream end of the swale is the discharge from the swale. The depth of the water used in equations1 through 4 is a fitted depth to approximate the actual cross-sectional profile.The excess flow from the swale side slope $Q_{side\,j}$ is calculated by determining infiltration of direct rainfall combined with the stormwater flow from the adjacent road surface. The Green-Ampt equation (Mays 2005) employed to compute$Q_{side\,j}$ for cumulative infiltration is:

$$\boldsymbol{F(t) = K_{sat}t + \psi\Delta\theta ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right)} \tag{6}$$

where, $F(t)$ = cumulative infiltration (*in*),

K_{sat} = saturated hydraulic conductivity of soil (*in/hr*),

Ψ = wetting front suction (*in*),

$\Delta\theta$ = change in soil moisture content during the storm, or ($\theta_s - \theta_i$),

θ_s = saturated moisture content (fraction), and

θ_i = initial moisture content (fraction).

By using these equations, the infiltration loss into the soil as well as the volume of runoff that does not infiltrate in the swale, and flows down the channel, can be quantified. The unknown parameters in these equations are K_{sat}, Ψ and $\Delta\theta$. The moisture content needs to be determined prior to the rainfall event. K_{sat} and Ψ can be determined using either field measurements or estimation methods such as pedo-transfer function procedures (Schaap et al. 2001). Finally, the swale is divided into grids and infiltration measurements are taken at each cell to estimate K_{sat} and Ψ.

The model is developed so that it can receive surface runoff from one or both sides of the swale. As discussed previously, the swale is divided into multiple cross sections in the longitudinal direction. Then, each cross section is divided into multiple cells along the swale side slope down to the base of the swale. These cells are employed to calculate the progressive downslope loss of stormwater introduced at the edge of the road surface. Rain falling directly on each cell is also accounted for in the calculation of infiltration. The calculation procedure is thus as follows: For a given rainfall intensity, the amount of infiltration of direct rainfall and input road surface stormflow of the cell closest to the road is calculated for each swale cross section and the excess volume is passed along the side slope of the swale on to the next cell downslope. The rainfall and stormwater that does not infiltrate along the cross-section side slope is infiltration excess and reaches the center of the swale. This excess flow becomes the input, Q_{side_j}, for cell j in equation 5. The sum of outflow volume ($V_{out} = \sum Q_{out_j} \Delta t$) and the volume of total rainfall (V_{rain}) is calculated for each rainfall event.

Figure provides a flow chart of the steps involved in the runoff-routing model.

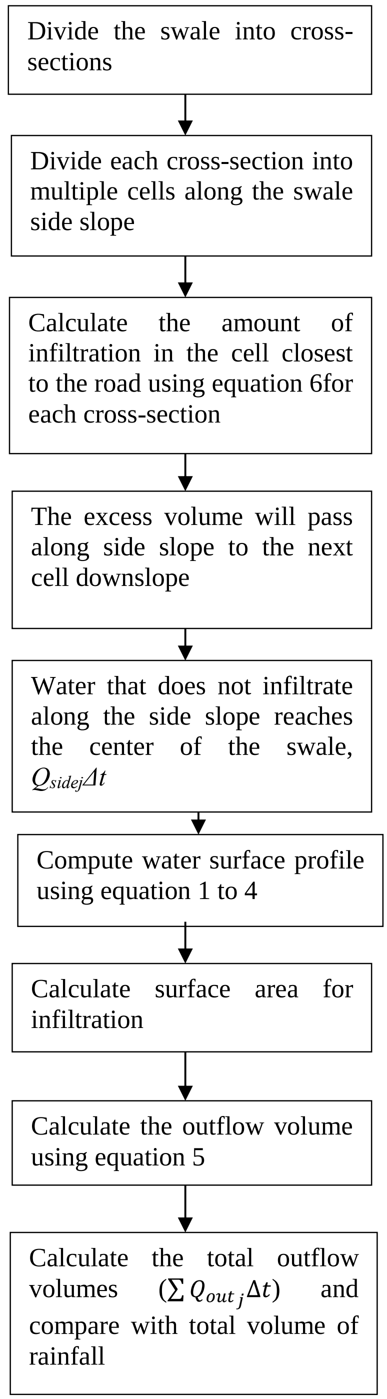

Figure 4. Flow chart of the steps involved in runoff-routing model.

RESULTS

By using the infiltration model (Equation 6) it was predicted that no water reaches at the center of the upstream swale for the monitored rainfall events because the saturated hydraulic conductivity was relatively high. However, the concentrated pipe flow on the west side did form a pool just upstream of the flume separating the upstream from the downstream swales. So, the infiltration model (Equation 6) and water balance equation (Equation 5) were used to model the downstream swale, which receives water from the upstream swale and surface runoff from Hwy 51. The geometric mean of K_{sat} of the downstream swale is 2.8 *in/hr*, and the soil suction is assumed to be 1.2 *inches*. The volume of water that flows through the effluent flume of the downstream swale was predicted with the model, and the predicted runoff-rainfall ratio V_{out}/V_{rain} was compared with the monitored runoff-rainfall ratio V_{out}/V_{rain} for several rainfall events.These comparisons are summarized in Table 1.

Table 1. Comparison of the predicted and monitored runoff-rainfall ratio.

Rainfall event	Initial Moisture content (%)	Total rainfall (*cm*)	Rainfall intensity (*cm/hr*)	Monitored data			Predicted data	
				Vol. of water through upstream flume (m^3)	Vol. of water through downstream flume (m^3)	Runoff/ Rainfall	Vol. of water downstream flume (m^3)	Runoff/ Rainfall
4/20/12	7	0.58	0.29	4	2	0.020	0.7	0.006
5/3/12	32	1.6	0.91	23	17	0.054	18	0.058
5/6/12	35	2.8	1.24	45	44	0.080	37	0.068
7/18/12	3	2.2	1.27	20	12	0.028	8	0.019
10/14/12 (morning)	-	1.8	1.19	13	0.2	0.001	4	0.012
10/14/12 (afternoon)	-	1.2	0.30	6	8	0.033	1	0.005
10/22/12	-	1.24	0.32	4	4	0.018	0.5	0.002
10/25/12	-	1.24	0.56	7	12	0.053	4	0.016

The soil moisture content data for 10/14/12, 10/22/12 and 10/25/12 was not available but the sum of the rate at which the swale received runoff from the road and the rainfall intensity is smaller than the individual K_{sat} values of that swale, which will allow the whole volume of surface runoff to infiltrate at the side slope.Thus, the moisture content of the soil does not have any effect on infiltration rate for these specific cases.

For the larger rainfall events on 5/3/12, 5/6/12 and 7/18/12, the monitored and predicted Runoff/Rainfall ratio is predicted fairly well. For the smaller events with an upstream inflow 13 m^3orless, however,the prediction does not compare as well with the monitored outflow. The reason might be that most of the water is infiltrating, and the difference between large numbers typically results in a high percentage error in the prediction.

CONCLUSIONS

The stormwater runoff model delivered a good prediction of runoff/rainfall ratio for some rainfall events, while for some low intensity storm events (below 0.22 *in/hr*) the predictions were not as accurate. The model takes into account the spatial variability of K_{sat} in the swale. However, in the application developed, the geometric mean of the measured values was used in calculating infiltration loss. There is some evidence that the proper mean shifts from arithmetic mean for low intensity storms to the geometric mean at high intensity storms. Whether or not the geometric mean is the appropriate value to use still remains to be investigated.

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