Hydraulic Resistance in Grass Swales Designed for Small Flow Conveyance

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Abstract: Grass swales, originally used for erosion control in agricultural settings, are now widely employed in urban environments as an effective best management practice for controlling pollutants in stormwater runoff. In particular, vegetated swales are quite successful in removing heavy metal concentrations when the depth of flow is small relative to grass height. However, guidance materials currently available for design of vegetated channels focus on larger depths of flow (large flow conveyance/erosion control), and for such conditions the hydraulic resistance exerted by the vegetation can be significantly different than that observed when the depth of flow is small (remediation). Utilizing a series of laboratory channels, small-flow retardance curves have been developed in the present work for Bluegrass, Centipede, and Zoysia grass species. These "small-flow" curves extend the well-known Stillwater n versus VR diagram by approximately 1 order of magnitude, to smaller values of VR. Experimental results should provide valuable design guidance to those faced with the need to hydraulically design a swale intended for shallow depths of flow.

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Introduction

A vegetated channel (or grassed swale) is generally a wide, shallow open channel having a dense stand of vegetation covering its side slopes and bottom. Guidelines for the hydraulic design of vegetated channels are available from a number of sources (USDA 1940, 1954, 1987; Ree 1949; Ree and Palmer 1949; Doll and Fredenhagan 1954; Chow 1959; Kouwen and Li 1980; Temple 1982, 1991; Kouwen 1992; Wu et al. 1999), but these documents address channels where the depth of flow is relatively large in comparison to the height of vegetation; they are particularly useful for erosion control designs. Alternative swale installations for pollution control require shallow depths of flow relative to the height of vegetation, and for such conditions the hydraulic resistance exerted by the vegetation can be significantly different than that observed when the depth of flow is larger (WERF 2003).

Hydraulic resistance within an open channel arises from viscous and drag forces, which are exerted on the wetted perimeter. Vegetal characteristics, such as density and grass length, dominate the flow resistance in a majority of vegetated waterways (USDA 1987). This resistance is commonly represented by parameters such as Manning's roughness coefficient n, Chezy's resistance factor C, or the Darcy–Weisbach friction factor f. Among these, Manning's n is most frequently used in the computation of open channel flows (Wu et al. 1999).

The U.S. Department of Agriculture (USDA)-sponsored research efforts (1940, 1954) found that n varies systematically with the product of mean flow velocity and the hydraulic radius (VR) for a given type of vegetation, and that the relationship is practically independent of channel slope/shape. Further experimentation revealed that vegetal species with similar characteristics/levels of density, rigidity, height, and submergence would produce similar n versus VR curves. Based on their observations, the USDA categorized comparable species into five classes of retardance: very high (**A**), high (**B**), moderate (**C**), low (**D**), and very low (**E**). The composite n versus VR relationships (herein, the "Stillwater" curves) for each retardance class may be seen on the right-hand side of Fig. 1.

Some observations regarding these retardance curves are noteworthy. First, the product VR is proportional to the Reynolds number R, which for open channel flow can be expressed as (Chow 1959)

$$\mathsf{R}=\frac{VR}{\nu} \tag{1}$$

The kinematic viscosity ν of water is known to be stable under normal conditions. With this recognition, a graph of n versus VR (Fig. 1) may be viewed as having a likeness to the Moody diagram (Moody 1944). That is to say, the retardance curves illustrate the functional dependence of a hydraulic resistance coefficient on the Reynolds number and the relative roughness of the conveyance.

The Stillwater retardance curves illustrated on the right-hand side of Fig. 1 terminate at lower bounds of VR approximately

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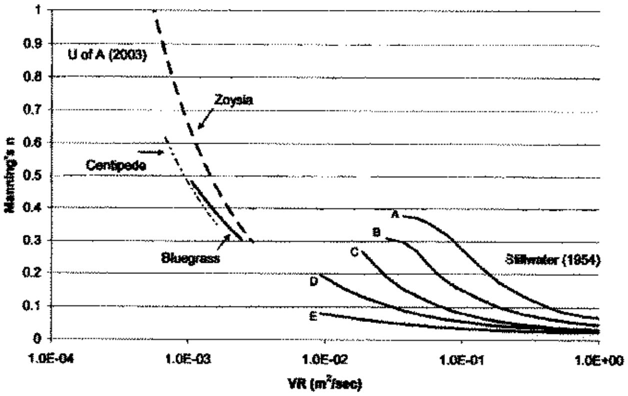

Fig. 1. Indoor laboratory and Stillwater (U.S. Department of Agriculture) retardance curves

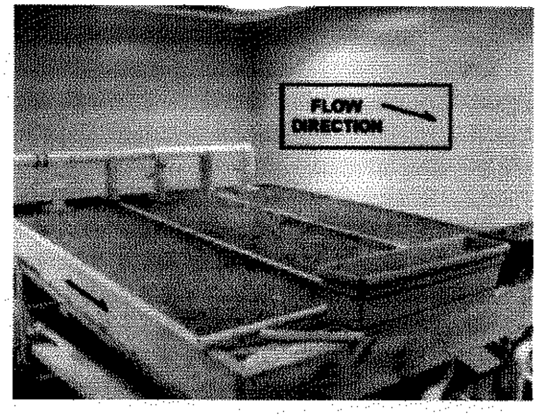

Fig. 2. Indoor experimental swales

equal to 0.01 m^2/s. Dividing this value by the kinematic viscosity ($\upsilon = 10^{-6}$ m^2/s, water at 20°C) yields a Reynolds number of R = 10,000, a value representing a marginally turbulent flow regime. In our experiments, presented later, we have sought to extend the range of the Stillwater curves in response to the need for information on hydraulic resistance when R < 10,000, where the flow regime is likely transitional.

Experimental Methodology

Experiments for the quantification of hydraulic resistance in grass swales have been conducted in three indoor (laboratory) swales. The indoor swales (Fig. 2) were constructed from lumber as an array of three identical rectangular trays. These channels were sealed with a watertight epoxy (resulting in nearly frictionless sidewalls), partially filled with a loamy sand soil, and seeded/sodded with commonly used grass species. The indoor swales were assembled in a greenhouse facility where the photoperiod of synthetic sunlight (ambient ultraviolet and visible) and the temperature (~25°C) could be effectively monitored/controlled. Table 1 provides information regarding the established vegetal species, cover densities, and experimental grass heights. Reference stem densities for the three grasses were determined to represent good to very good cover (Temple 1982). Furthermore, the vegetal blade length was maintained to a height consistent with a mowed urban swale.

Each indoor swale was 0.6 m in width, 2.4 m in length, and 80 mm in depth (from the top edge of the sides to the soil surface). Longitudinal slopes could be set to any of seven predefined values, ranging from 0.01 to 10.0%. Swales, neglecting minor variations in the soil surface, had a rectangular cross-sectional area of flow. Furthermore, because the depths of flow introduced were kept shallow (depth <10% of width), each swale could be treated as a "wide" open channel where the hydraulic radius can be taken as equal to the depth of flow (Chow 1959).

Water was delivered via a pump and polyvinyl chloride piping network consisting of multiple valves and an inline flow meter. Gravel filters were constructed at the swale entrances to dissipate excess energy and to establish a uniform distribution of flow over the channel width.

Determination of hydraulic characteristics in the swales was accomplished through a detailed examination of experimental flow profiles at a series of cross sections along each swale. The cross-sectional area A was calculated as the average flow depth multiplied by cross-sectional width. The wetted perimeter P and the hydraulic radius R were evaluated similarly. The discharge Q was evaluated utilizing a weir located at the terminal end of each channel. Finally, the cross-sectional velocity V was determined as Q/A.

Data Analysis

With information obtained during laboratory experiments (flow depths, cross-sectional areas, wetted perimeters, and hydraulic radii) and knowledge of the discharge Q, an "apparent" (or "equivalent") value of Manning's n was determined for each swale reach between adjacent cross sections as (Kirby 2003):

$$n = \left\{ \frac{\overline{R}^{4/3}}{\overline{V}^2 \Delta x} \left[h_1 + \frac{V_1^2}{2g} - \left(h_2 + \frac{V_2^2}{2g} \right) \right] \right\}^{1/2} \tag{2}$$

Here, h and V=water surface elevation and average velocity of flow at a cross section; g=the acceleration of gravity; $\overline{R} = (R_1 + R_2)/2$=average hydraulic radius for the reach; $\overline{V}$=similarly defined as the average flow velocity for the reach; subscripts 1 and 2 refer to upstream and downstream cross sections (respectively); and Δx=length of the reach (20 cm). Manning's n values so determined for each of nine reaches were arithmetically averaged to obtain a final representative value for each experimental run.

Table 1. Experimental Vegetation Characteristics

Common name	Scientific name	Average density (stems/m^2)	Blade length (mm)
Centipede	Eremochloa ophiuroides	6,253	50–80
Kentucky Bluegrass	Poa pratensis	5,019	35–80
Zoysia	Zoysia x 'Emerald'	4,772	40–80

Table 2. Range of Experimental Conditions

	Centipede	Bluegrass	Zoysia
Slope (%)	0.1–10.0	0.1–10.0	0.1–10.0
Flow depth (mm)	27–50	24–60	24–60
Velocity (m/)	0.047–0.075	0.065–0.100	0.048–0.103
Discharge (L/s)	25–62	39–91	17–111
Manning's n	0.27–0.95	0.26–0.56	0.28–1.35

Table 2 contains a summary of the indoor experimental conditions. Unfortunately, the sheer volume of information collected prohibits a complete parameterization of individual experimental runs within the limited confines of a technical note. A comprehensive data set is available in Kirby (2003) and WERF (2003).

Observations after each test indicated that while a majority (>75%), of the grass stems had been bent or partially bent over as a result of the flow, damage to the vegetation/underlying soils was imperceptible.

Experimental Results and Discussion

The Manning equation strictly should be applied only to fully turbulent flow. However, because the data gathered from our experiments are representative of a more transitional flow regime, we attempted to convert our "apparent" n values into Darcy–Weisbach f values using the expression

$$f=\frac{8gn^2}{KR^{1/3}} \tag{3}$$

where K=factor depending on the system of units utilized (K=1 for the SI system of units, and is equal to 1.49^2 for the United States customary system of units). It was hypothesized that if one were to plot data values of f versus R on a Moody-type diagram, the scatter could be explained by variations in the relative roughness of the channel. An attempt was made to describe relative roughness as the ratio of grass height to flow depth (or hydraulic radius, since the channels were wide). This effort proved to be a failure. Ultimately, it was concluded that scatter in the data was due to unexplainable influences (spatial/temporal variations in flow velocity, grass rigidity, etc.). Further, in view of the relationship between f and n, expressed by Eq. (3), the data presented essentially the same information whether they were summarized in terms of f or in terms of an "equivalent" Manning's n. We chose the latter in the interest of promoting consistency with the well-known and widely utilized Stillwater retardance curves.

Data from our experiments on Bluegrass, Centipede, and Zoysia are illustrated in Fig. 3, along with fitted trend lines.

Fig. 1 is a combination of the historical Stillwater curves (right hand) and the trend lines (Fig. 3) representing our data. A clear conclusion from the data presented in Fig. 1 is that the equivalent Manning's n increases sharply as the Reynolds number of the flow (VR) decreases into the transitional range, and is much more sensitive to variations in VR than it is in the turbulent flow regime represented by the Stillwater curves.

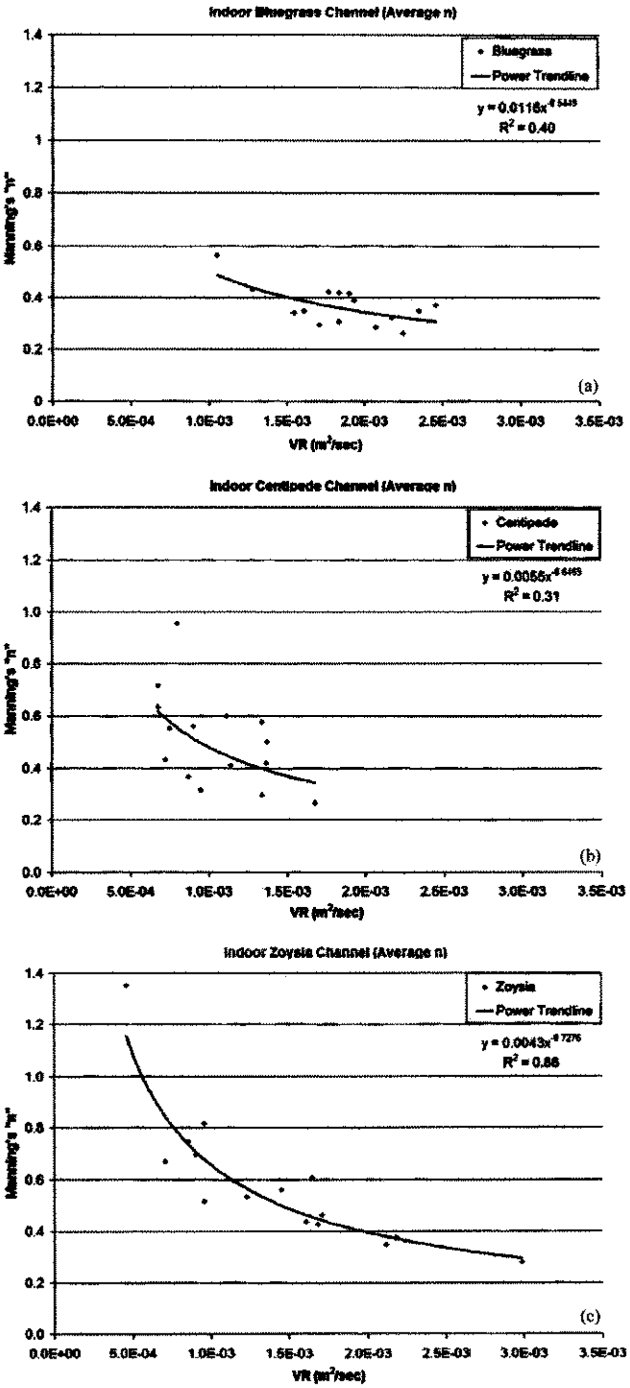

Fig. 3. Experimental data/fitted trend lines from indoor laboratory swales for (a) Bluegrass, (b) Centipede, and (c) Zoysia

Conclusions

The research reported in this paper has extended the USDA retardance curves to be applicable to a transitional flow regime for three commonly cultivated grass species: Bluegrass, Centipede, and Zoysia. While further experimentation is needed to fill the void between our retardance curves and the historical Stillwater diagram, similarities in vegetal characteristics (namely grass height and species) support this conclusion. Future work should also examine the suitability of alternative types of constitutive relationships, as applications of the Manning formula strictly should be limited to turbulent flows. Despite the fact that this consideration has been violated here, it is believed that our "equivalent" Manning's n values are practically useful. The research conducted should provide valuable design guidance to those faced with the need to hydraulically design a swale intended for shallow depths of flow.

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Notation

The following symbols are used in this paper:

- **A** = very high retardance class;
- A = cross sectional area;
- **B** = high retardance class;
- **C** = moderate retardance class;
- C = Chezy's resistance factor;
- **D** = low retardance class;
- D = diameter;
- **E** = very low retardance class;
- f = Darcy–Weisbach friction factor;
- g = gravitational acceleration;
- h = water surface elevation;
- K = unit conversion constant (SI=1; United States=1.49^2);
- n = Manning's roughness coefficent;
- P = wetted perimeter;
- Q = discharge;
- R = Reynolds number;
- R = hydraulic radius;
- $\bar{R}$ = average hydraulic radius within given reach;
- V = average flow velocity;
- $\bar{V}$ = average flow velocity within given reach;
- VR = product of flow velocity and hydraulic radius;
- ν = kinematic viscosity of water;
- Δx = length of reach.

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