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COMPOSITE FLOW RESISTANCE

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Abstract: Composite flow resistance describes cross-section average properties of resistance to flow in rivers. A data set including 2,604 composite roughness values (Darcy-Weisbach f and Manning n) is closely examined. These field measurements show that both resistance parameters vary with flow discharge Q and friction slope S_f. The analysis of Box-Whisker plots indicates less variability in Manning n than Darcy-Weisbach f. The ratio of the upper quartile to the lower quartile for Manning n remains less than 2.3. The variability in Manning n for boulder-bed channels was higher than that of all vegetated channels. The recommended average values of Manning n for different types of channel and vegetation are generally higher than those suggested in the literature and should result in higher flood stages at a given flow discharge. These recommended values should be helpful in the practical hydraulic analysis of river flows with one-dimensional numerical models.

***Keywords*:** Composite flow; roughness coefficients; vegetated and natural channels; friction factors; field measurements

1. INTRODUCTION

Resistance to flow describes mean flow velocity as a function of surface roughness from bed material and vegetation along the wetted perimeter of open channels. This study focuses on composite flow resistance, which describes the average properties of resistance to flow in rivers. The general types of channels considered includes grain roughness for sand, gravel, cobble and boulder-bed streams and bank vegetation roughness in terms of grass, shrubs and trees (Amiri *et al.*, 2016).

A useful digest of early experimental and field investigations of Manning roughness coefficients in open channels and natural streams was presented by Chow (1959). Field evaluations of stream flow resistance coefficients are published worldwide in research reports such as Barnes (1967), for natural channels in Washington, Jarrett (1985) for streams in Colorado, Annable (1996) for watercourses in Southern Ontario, Gillen (1996) for streams in west-central Florida, and Hicks and Mason (1998) for rivers in New Zealand. Engelund (1966) studied the hydraulic resistance of alluvial streams, van Rijn (1982) considered the equivalent roughness for dunes in sand-bed channels, and Wu *et al*. (1999) examined variations in roughness coefficients for unsubmerged and submerged vegetation. Other interesting studies include Coon (1998) for the estimation of roughness coefficients in natural stream channels with vegetated banks, Phillips and Ingersoll (1998) regarding the verification of roughness coefficients for selected natural and constructed stream channels in Arizona, Lang *et al*. (2004) on an Australian handbook of stream roughness coefficients, and Soong *et al*. (2009) for estimating Manning roughness coefficients for natural and man-made streams in Illinois. Studies of the new millennium include Yen (2002) on open channel flow resistance, and Chen (2010) on theoretical analyses for the interaction between vegetation bending and flow, and Lee and Lee (2013) and Lee and Julien (2012) on numerical studies for levee protection works. Resistance to flow relationships have been proposed by Strickler (1923), Meyer-Peter and Mueller (1948), Lane and Carlson (1953), Henderson (1966), Limerinos (1970), Griffiths (1981), Jarrett (1984), Jobson and Froehlich (1988), Bray and Davar (1987), and Ab Ghani et al. (2007).

In channels with predominant vegetation, the primary form of resistance is generally the plants themselves rather than the bed. Hence, when applied to vegetated flows such coefficients become a function of flow and vegetation factors including flow depth (Wu *et al.*, 1999, Shucksmith *et al.*, 2011), velocity (Armanini *et al.*, 2005), plant density (James *et al.*, 2004) and flexibility (Jarvela, 2002). For vegetated channels, resistance coefficients vary with depth and velocity, hence the use of a single coefficient is likely to result in significant error (Dudill *et al.*, 2012). Resistance to flow relationships for vegetated channels have been proposed by Bray (1979), Jobson and Froehlich (1988), Coon (1998), Freeman et al. (1998), Lopez and Barragan (2008), and Shucksmith et al (2011). Jochen and Juha (2013) summarized current practices for the estimation of flow resistance caused by floodplain vegetation in emergent flow conditions. Nikora et al. (2004), Yang et al, (2007), and Hua et al. (2013) also looked at velocity profiles over vegetated surfaces. Ferguson (2010) also stimulated a debate as to whether Manning's roughness coefficient should be used at all. It may therefore be important to examine roughness coefficients and compare the values and variability in Manning n and Darcy-Weisbach f from field measurements.

By combining the measurements from above-cited studies, a database for vegetated channels could be compiled with data from 287 rivers. A second database describing natural channels has been collected from Lee and Julien (2006). These two databases primarily describe channels near bankfull flow conditions, which are representative of high, flow conditions (periods of return typically between 2 and 5 years), but do not reflect either very low flows or extreme flood conditions. It becomes interesting to question how vegetation resistance may compare with the roughness generated by boulders in steep mountain streams. The analysis of the variability in these two roughness parameters will be useful to find out how the Darcy-Weisbach coefficient f, and Manning coefficient n vary with flow discharge, friction slope and median grain size as well as with the type of bed material and bank vegetation.

This study of interest defines composite values of resistance to flow parameters in natural and vegetated channels. The term of natural channels is coined in contrast to man-made channels and consist primarily of grain roughness. It is also clear that vegetated channels are also natural, but these channels describe conditions for which vegetation was identified as a predominant channel feature compared with grain roughness. This article provides a comparison between Darcy-Weisbach *f* and Manning *n* for two large databases, one for vegetated channels and the other for natural channels. The first section briefly reviews some methods to determine composite roughness coefficients, followed by a description of the databases. The analysis of Manning *n* and Darcy-Weisbach *f* and their variability with respect to discharge, friction slope and relative submergence includes several Box-Whisker plots of both roughness coefficients for different types of bed material and bank vegetation. The analysis will indicate which of Manning *n* and Darcy-Weisbach *f* shows less variability and methods to reduce the variability will be explored. This will finally lead to comparisons with Chow (1959) and recommendation on average values and variability in roughness coefficients for different types of bed material and vegetation.

2. FLOW RESISTANCE RELATIONSHIPS

The primary source of channel roughness in rivers is frictional resistance associated with shear stress along the wetted perimeter. The shear stress exerted at the interface between the flow and the bed is described by $\tau_0 = \gamma R_h S_f$ where τ_0 = boundary shear stress, $R_h = A/P$ hydraulic radius which is the ratio of the cross sectional area A to the wetted perimeter P, S_f = energy slope, for uniform flow, γ = specific weight, and ρ = specific mass of water. The shear velocity $u_* = (\tau_0/\rho)^{1/2} = (gR_h S_f)^{1/2}$ is also very important in the analysis of resistance to flow.

The conventional approach to describe frictional resistance is based on the assumed proportionality between boundary shear and the square of the average velocity, with the resistance accounted for by a single coefficient of resistance (Bathurst, 1982). The most commonly used resistance coefficients are Chézy C (1769), Darcy-Weisbach f (Darcy-Weisbach equation resulted as a combination of the equation that made the formula by Darcy in 1857 and derived by Weisbach in 1845), and Manning n (1889). These equations are generally applicable to open channel flows.

$$V = C R_h^{1/2} S_f^{1/2} \tag{1a}$$

$$V = \sqrt{\frac{8}{f}} \sqrt{g R_h S_f} = \sqrt{\frac{8}{f}} u_* \tag{1b}$$

$$V = \frac{k}{n} R_h^{2/3} S_f^{1/2} \tag{1c}$$

where V = cross-sectional average velocity, $u_* = (gR_h S_f)^{1/2}$ is the shear velocity, g = gravitational acceleration, and k = unit conversion factor (1 for SI, and 1.49 for English units).

The resistance equations may be interchanged conveniently as the coefficients are interrelated owing to the following identity obtained from the three forms of Equation (1):

$$\frac{V}{u_*} \equiv \frac{C}{\sqrt{g}} \equiv \sqrt{\frac{8}{f}} \equiv \frac{k}{\sqrt{g}} \frac{R_h^{1/6}}{n} \tag{2}$$

Manning's equation has become the most widely-used resistance equation in practical river hydraulics and therefore an analysis of Manning n is essential. The evaluation of the Darcy-Weisbach roughness coefficients in rivers is also important because it is the only dimensionless roughness coefficient. Since Chézy C and Darcy-Weisbach f are interchangeable from Eq. (2), only values of Darcy-Weisbach f are further considered in this study, for comparison with Manning n.

2.1. Bed material roughness

River flows are turbulent and for bed material coarser than sand, resistance to flow in rivers without bed forms can be approximated by the following equation as a function of flow depth h and median diameter of the bed material d_{50} (Julien 2010).

$$\sqrt{\frac{8}{f}}(\equiv \frac{V}{u_*}) = 5.75 \log(\frac{2h}{d_{50}}) \tag{3}$$

Alternatively, power law equations of the type Manning-Strickler can be written as the following equation when the grain roughness coefficients is n=0.064 $d_{50}^{1/6}$ with d_{50} (m) (Julien, 2002; 2010).

$$V = 5(\frac{h}{d_{50}})^{1/6} \sqrt{ghS_f} \tag{4}$$

$$f \approx 0.3(\frac{d_{50}}{h})^{1/3} \tag{5}$$

The advantage of the Darcy-Weisbach f formulation is the simplicity offered by its dimensionless form, thus independent from the system of units.

2.2. Vegetation roughness

Vegetation is an important component of river ecosystems which contributes to aquatic habitat diversity while increasing channel stability through reduced bank erosion. Riverbank vegetation affects the composite channel roughness during floods. Various approaches have been developed to predict flow resistance in vegetated channels. Petryk and Bosmajian (1975) developed a procedure for the analysis of vegetation density and determined the roughness coefficient for a densely vegetated flood plain. Naot *et al*. (1996) carried out an investigation on the hydrodynamics of turbulent flow in partly vegetated open channels.

Freeman *et al*. (1998) developed a method for estimating Manning n for shrubs and woody vegetation with submerged flow conditions. James *et al*. (2001) developed a resistance model for flow through emergent reeds for uniform flow conditions within homogeneous arrangements of rigid, vertical stems. They also proposed an alternative form of equations for conditions where resistance arises predominantly from stem drag. Desai and Chicktay (2005) used linear superposition of the velocity defect through the experiments consisted of obtaining cross sectional velocity profiles.

Additional methods have been proposed for the analysis of composite resistance to flow including Chow (1959), ASCE (1963) and Barnes (1967). The USGS method (Arcement and Schneider, 1984) estimates the overall resistance of a channel based on Cowan (1956) and the photographic method by Phillips and Ingersoll (1998), Lang *et al.* (2004), KICT (2007), and Soong *et al.* (2009) are also cited for the reader's reference.

3. DATABASE

The sources of the data sets compiled for this analysis of channel roughness are listed in Table 1. The database includes a total of 2,604 field measurements sub-divided into 1,865 measurements for natural channels and 739 measurements for vegetated channels. Natural channels are primarily described in terms of their substrate (or bed material) and four main types are recognized: sands, gravels, cobbles and boulders. In the case of vegetated channels, the main types are classified into three categories (grasses, shrubs and trees). The range of channel parameters according to substrate and vegetation type for the data sets is also presented in Table 2. Obviously, the type of vegetation could be considered to be independent from the bed substrate such that each of the four bed material types could also be subdivided into different vegetation types. This investigation simply focuses on the primary type of roughness, either bed material roughness or vegetation. It is also important to emphasize that the roughness values under investigation are the composite values, and do not represent local roughness coefficients for each different substrate or vegetation type.

4. ANALYSIS AND RESULTS

First, the Manning-Strickler relationship is examined in terms of a plot of V/u_* vs h/d_s. The relationships between the Darcy-Weisbach f and Manning n are then explored as a function of friction slope S_f and flow discharge Q. Box-Whisker plots are used to define maximum and minimum values as well as 25th and 75th percentiles. Two centerlines inside the box represent the mean and median values, respectively.

4.1. Effects of relative submergence h/d_s

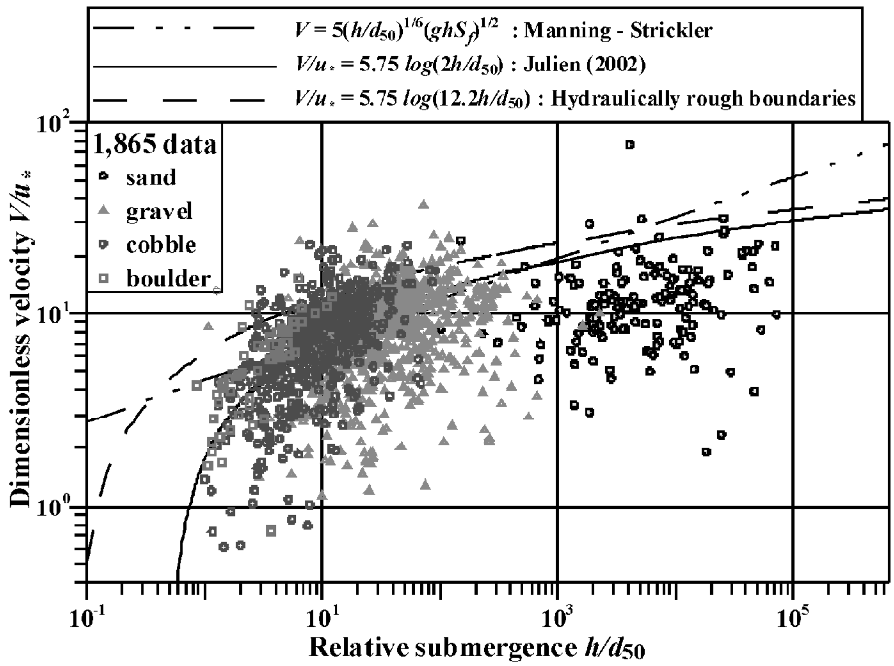
This analysis compares values of V/u_* as a function of relative submergence h/d_s. Figure 1 plots the analysis results of the dimensionless velocity (V/u_*) where u_* is the shear velocity with relative submergence (h/d_{50}). Figure 1(a) describes conditions for natural channels and Figure 1(b) applies to vegetated channels.

Table 1
Summary of the data sources and parameter variability

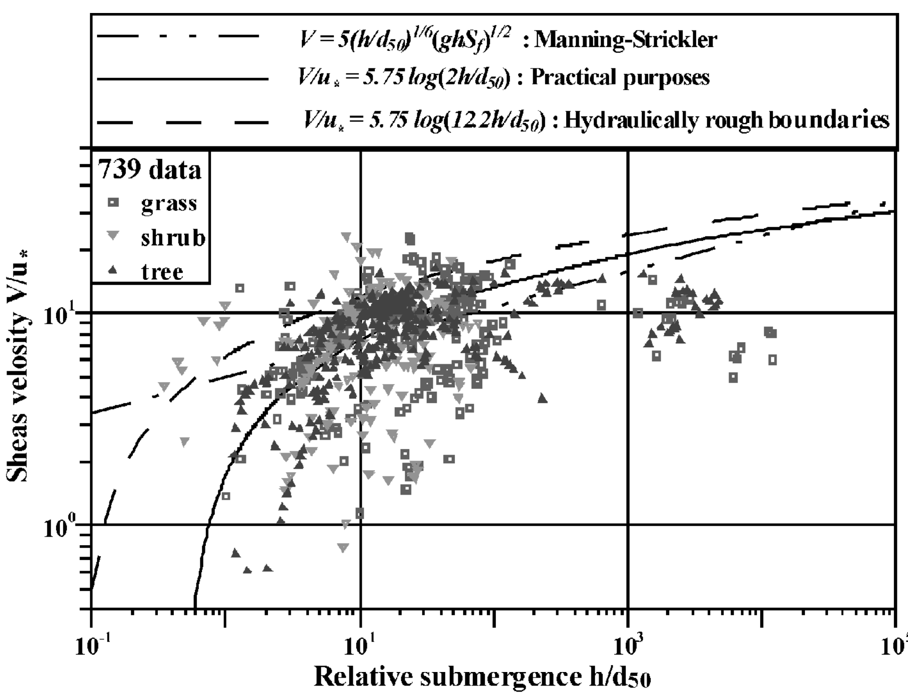
Data source	*Author*	*Number*	*Discharge* *Q (m^3/s)*	*Friction slope* *S_f (-)*	*Mean diameter* *d_{50} (mm)*	*Velocity* *V (m/s)*	*Flow depthh* *(m)*
Naturalchannels	Barnes (1967)	14	3.91-1,951	0.00070-0.04050	93-253	0.98-2.99	0.39-4.92
	Annable (1996)	34	2.27-99	0.00033-0.03600	0.17-125	0.54-2.27	0.04-2.00
	Hicks andMason (1998)	463	0.01-3,220	0.00001-0.04040	0.33-893	0.06-3.66	0.10-9.17
	Coon (1998).	219	2.18-1,464	0.00031-0.01312	15.24-365.76	0.43-5.11	0.28-4.09
	Phillips andIngersoll (1998)	22	1.10-255	0.00130-0.02500	0.042-110	0.66-3.64	0.25-1.46
	Lee andJulien (2006),Lee (2010)	1,113	0.05-26,560	0.00001-0.08100	0.01-945	0.02-4.70	0.04- 15.67
	Subtotal	1,865	0.01-26,560	0.00001-0.08100	0.01-945	0.02-5.11	0.04-15.67
Vegetatedchannels	Barnes (1967)	10	42.48-1,951	0.00070-0.04050	93-253	1.98-2.99	1.05-4.92
	Annable (1996)	34	2.27-99	0.00033-0.03600	0.17-125	0.54-2.27	0.04-2.00
	Hicks andMason (1998)	458	0.01-3,220	0.00001-0.04040	0.33-893	0.06-3.66	0.10-9.17
	Coon (1998)	219	2.18-1,464	0.00031-0.01312	15.24-365.76	0.43-5.11	0.28-4.09
	Phillips andIngersoll (1998)	18	4.76-208	0.00130-0.02500	0.42-110	0.66-3.64	0.25-1.20
	Subtotal	739	0.01-3,220	0.00001-0.04050	0.17-893	0.06-5.11	0.04-9.17
Total	2,604	0.01-	26,560	0.00001-0.08100	0.01-945	0.02-5.11	0.04-15.67

Table 2
Range of channel parameters according to substrate and vegetation type

Data type		*Name*	*Number*	*Discharge* Q *(m^3/s)*	*Friction slope* S_f *(-)*	*Mean diameter* d_{50} *(mm)*	*Velocity* V *(m/s)*	*Flow depth* h *(m)*	*Range h/d50*
Natural channels	Bed material	Sand	172	0.14-26,560	0.00010-0.02860	0.01-1.64	0.02-3.64	0.10-15.67	200-100,000
		Gravel	989	0.01-14,998	0.00009-0.08100	2-63.6	0.04-4.70	0.04-11.15	20-2,000
		Cobble	651	0.02-3,820	0.00001-0.05080	64-253	0.07-4.29	0.10-6.94	1-80
		Boulder	53	2.00-1,700	0.02060-0.03730	263-945	0.32-5.11	0.28-4.09	1-15
	Subtotal	1,865	0.01-26,560	0.00001-0.08100	0.01-945	0.02-5.11	0.04-15.67	1-100,000	
Vegetated channels	Vegetation	Grass	281	0.01-750	0.00007-0.01790	0.33-304.8	0.06-3.66	0.16-3.96	1-15,000
		Shrub	150	0.38-542	0.00001-0.03400	16-893	0.1-3.64	0.04-3.08	0.4-200
		Tree	308	0.02-3,220	0.00010-0.04050	0.17-397	0.07-5.11	0.10-9.17	1-6,000
	Subtotal		739	0.01-3,220	0.00001-0.04050	0.17-893	0.06-5.11	0.04-9.17	0.4-15,000
Total			2,604	0.01-26,560	0.00001-0.08100	0.01-945	0.02-5.11	0.04-15.67	0.4-100,000



(a) Relationships for *log* h/d_{50} *vs log* V/u_* in natural channels



(b) Relationships for *log* h/d_{50} *vs log* V/u_* in vegetated channels

Figure 1: Relationships with relative submergence for natural and vegetated channels

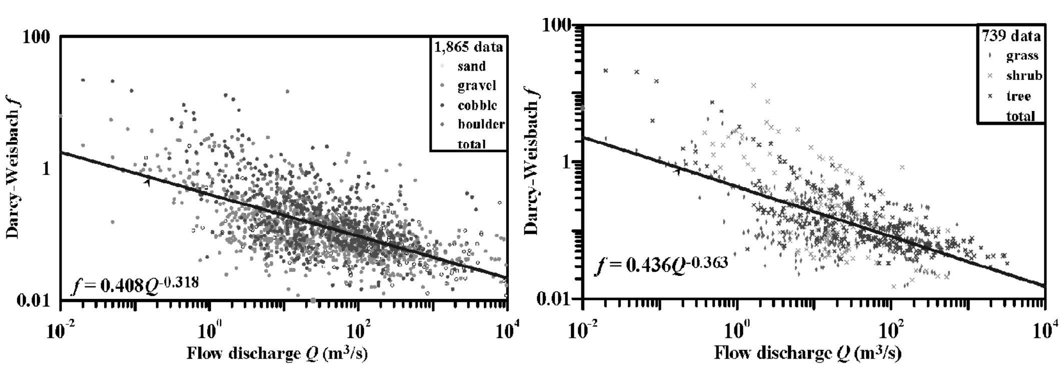
Both Figures 1(a) and 1(b) are quite similar and indicate a reasonably large variability in V/u_* as a function of h/d_s. The values of V/u_* at high h/d_{50} are typically lower than those of hydraulically rough channels. Vegetation also increases resistance to flow and correspondingly decreases the value of V/u_*. In all cases, the ratio V/u_* rarely exceeds 30.

4.2. Analysis of Darcy-Weisbach f for natural and vegetated channels

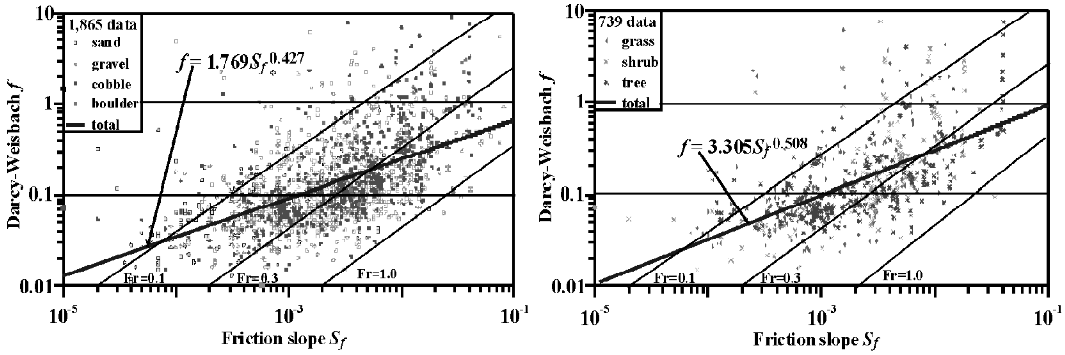
The analysis of the Darcy-Weisbach roughness coefficients is presented in Figure 2. The variability is high but definite trends in the data are clearly visible. In all cases, the friction coefficient increased as friction slope increased and flow discharge decreased. . Regression relationships could be defined between *f* and both discharge *Q* and friction slope S_f. In Figures 2(a) and (b), equations for the Darcy-Weisbach roughness coefficient *f* are obtained by regression for natural and vegetated channels. The relationships were developed by a power law regression ($f=aQ^b$, $f=aS_f^{\,b}$) and the relationships plotted in Figures 2(a) and (b) are respectively $f=0.408Q^{-0.318}$ ($R^2=0.37$), $f=0.436Q^{-0.363}$ ($R^2=0.41$), and $f=1.769S_f^{0427}$ ($R^2=0.30$), $f=3.305S_f^{0.508}$ ($R^2=0.36$). It is noticeable that very similar trends are observed for natural and vegetated channels. Overall, the roughness coefficient increased with the bed material size and the friction factor for shrubs is slightly higher than for grasses and trees. Finally, it is interesting to notice in Figure 2(b) that the flow in natural and vegetated channels is almost always subcritical ($0.1 < Fr < 1.0$).

The variability of the results around the mean is also similar both for the vegetated and natural channels. The Box-Whisker plots for *f* are shown for comparison between natural and vegetated channels. The variability around the mean is about the same regardless of the types of bed roughness or vegetation. The variability of boulders and shrubs is slightly higher than the others. The Box-Whisker plots for the Darcy-Weisbach *f* in natural and vegetated channels are shown as Figure 2(c) and summarized in Table 3.

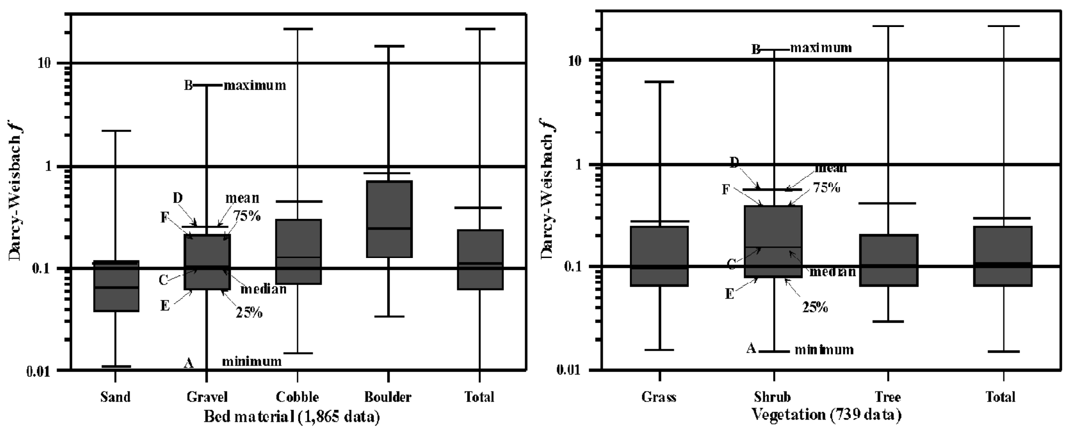
In Table 3, the distribution range of Darcy-Weisbach roughness coefficient *f* varies when considering minimum and maximum values, as shown by the ratio B/A. However,



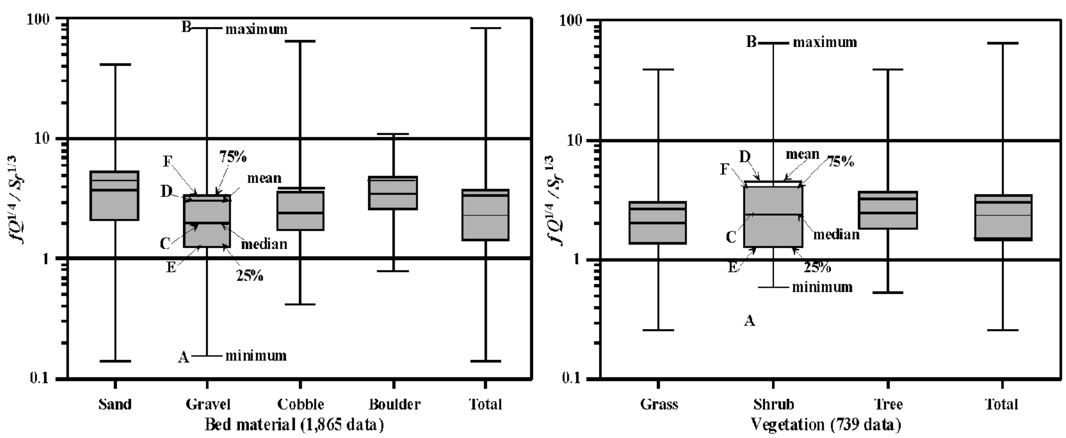
(a) Regression between *log f and log Q*



(b) Regression between *log f and log* S_f



(c) Box-Whisker plots for *f*



(d) Box-Whisker plots for $fQ^{1/4}/S_f^{1/3}$

Figure 2: Analysis of Darcy-Weisbach roughness coefficients in natural and vegetated channels

Table 3
Analysis of Box-Whisker plots for Darcy-Weisbach *f* in natural and vegetated channels

Roughness type		*Type*	*Number*	*A* *Minimum*	*B* *Maximum*	*C* *Median*	*D* *Mean*	*Quartile (percentile)* *E* *First (25th)*	*F* *Third (75th)*	*B/A*	*D/C*	*F/E*
Natural channels	Bed material	Sand	172	0.011	2.2	0.06	0.115	0.03	0.11	198	1.8	3.0
		Gravel	989	0.010	6.1	0.10	0.251	0.06	0.21	612	2.4	3.3
		Cobble	651	0.015	21.4	0.12	0.465	0.07	0.30	1,430	3.6	4.2
		Boulder	53	0.034	14.6	0.24	0.794	0.13	0.63	429	3.2	4.9
Vegetated Channels	Vegetation	Grass	281	0.016	6.1	0.10	0.271	0.06	0.24	382	2.7	3.8
		Shrub	150	0.015	12.9	0.15	0.580	0.08	0.39	860	3.7	5.0
		Tree	308	0.030	21.5	0.10	0.434	0.07	0.20	715	3.7	3.7

the ratio D/C of the mean to the median values is relatively constant in both databases with $1.8 < D/C < 3.7$. The ratio F/E of the quartiles is also relatively constant with $3.0 < F/E < 5.0$. It is interesting to note that the observations for natural and vegetated channels are very similar.

When considering the parameter $fQ^{1/4}/S_f^{1/3}$, the analysis of Box-Whisker plots is shown in Figure 2(d) and Table 4. The parameter $fQ^{1/4}/S_f^{1/3}$ was considered in an attempt to possibly reduce the variability around the mean by reducing the effects of discharge and slope. It is interesting to notice that the variability around the mean of all natural and vegetation types is indeed significantly reduced and a fairly narrow range for all values of $fQ^{1/4}/S_f^{1/3}$ can be defined for all natural and vegetated channel types. In Table 4, the main observation is that the ratios B/A, D/C and F/E are greatly reduced compared with the results in Table 3. For instance, values of $D/C < 1.8$ and $F/E < 3.1$ are obtained in all cases. The following mean values of $fQ^{1/4}/S_f^{1/3}$ could be used: 4.33 for sand, 3.23 for gravel, 3.72 for cobble, 4.44 for boulder, 2.82 for grass, 4.45 for shrubs and 3.25 for trees. In all cases, a value of $fQ^{1/4}/S_f^{1/3} \approx 3$ would fit inside all boxes for all different roughness types.

4.3. Analysis of Manning n for natural and vegetated channels

The analysis of Manning roughness coefficients and corresponding relationships with discharge Q and friction slope S_f are shown in Figure 3. In Figures 3(a) and (b), Manning roughness coefficients are shown to vary slightly with discharge Q and friction slope S_f. The trends are less pronounced than those observed for Darcy-Weisbach f in Figure 2. The power law relationships in Figures 3(a) and (b) are $n=0.059Q^{-0.101}$ ($R^2=0.18$), $n=0.061\,Q^{-0.124}$ ($R^2=0.24$), and $n=0.111S_f^{0.162}$ ($R^2=0.20$), $n=0.144S_f^{0.199}$ ($R^2=0.28$) for natural and vegetated channels, respectively. Even though the coefficients of determination, R^2 are lower than the corresponding relationships for Darcy-Weisbach f, these trends remain perceptible in Figure 3.

Box-Whisker Plots for n and $nQ^{1/8}/S_f^{1/6}$ are also shown for natural and vegetated channels, respectively. From the results compiled in Table 5, the main observations relate to the ratios B/A, D/C and F/E. The values of B/A are much lower than those found for Darcy-Weisbach f in Tables 3 and 4. Also, Manning n values in natural and vegetated channels show lower values of the ratios D/C and F/E than those of both Tables 3 and 4. The variability of Manning n is therefore lower than that of Darcy-Weisbach f values, as could be expected from Eq. (2). On the basis of reduced parameter variability, the use of Manning n becomes preferable to the use of Darcy-Weisbach f.

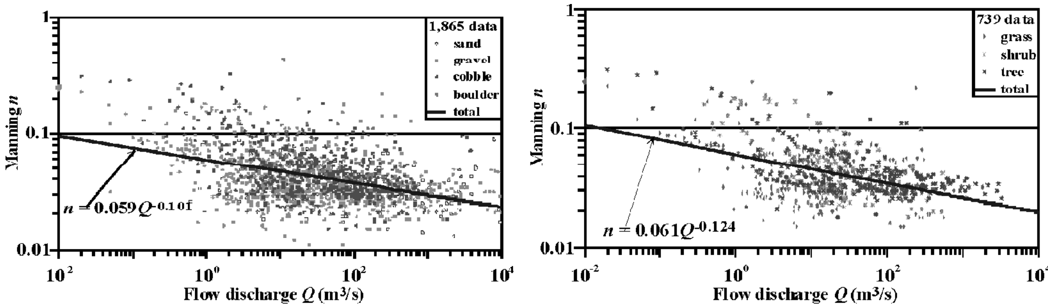
When considering $nQ^{1/8}/S_f^{1/6}$, the results of Box-Whisker Plots in natural and vegetated channels are plotted in Figure 3(d) and listed in Table 6. It is interesting to notice that the values of D/C and F/E are generally lower for $nQ^{1/8}/S_f^{1/6}$ than Manning n. The use of $nQ^{1/8}/S_f^{1/6}$ may thus lead to a modest improvement over the use of Manning n. When comparing with the results of Table 4, the parameter $nQ^{1/8}/S_f^{1/6}$ shows less variability than the parameter $fQ^{1/4}/S_f^{1/3}$.

Table 4
Analysis of Box-Whisker plots for $fQ^{1/4}/S_f^{1/3}$ in natural and vegetated channels

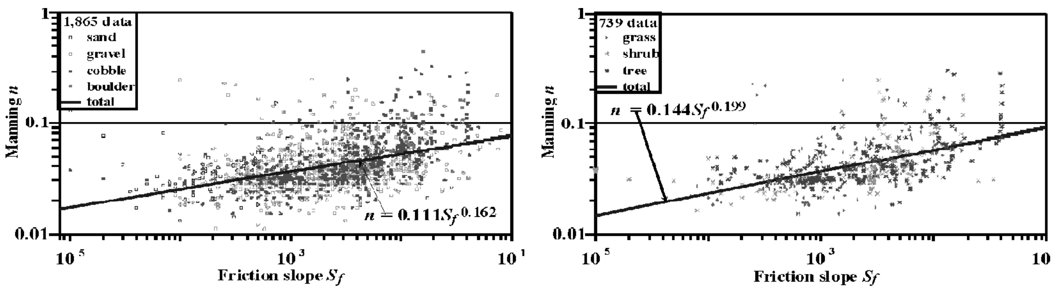
Roughness type		*Name*	*Number*	*A* *Minimum*	*B* *Maximum*	*C* *Median*	*D* *Mean*	*Quartile (percentile)* *E* *First (25th)*	*F* *Third (75th)*	*B/A*	*D/C*	*F/E*
Natural channels	Bed material	Sand	172	0.141	41.3	3.74	4.33	2.04	5.27	293	1.2	2.6
		Gravel	989	0.155	83.6	1.98	3.23	1.28	3.37	539	1.6	2.6
		Cobble	651	0.415	64.4	2.45	3.72	1.71	3.63	155	1.5	2.1
		Boulder	53	0.775	10.8	3.47	4.44	2.67	4.70	13	1.3	1.8
Vegetated channels	Vegetation	Grass	281	0.260	38.2	2.02	2.82	1.36	2.99	147	1.4	2.2
		Shrub	150	0.579	64.4	2.46	4.45	1.29	3.95	111	1.8	3.1
		Tree	308	0.520	39.3	2.46	3.25	1.81	3.63	75	1.3	2.0

Table 5
Analysis of Box-Whisker plots for Manning *n* in natural and vegetated channels

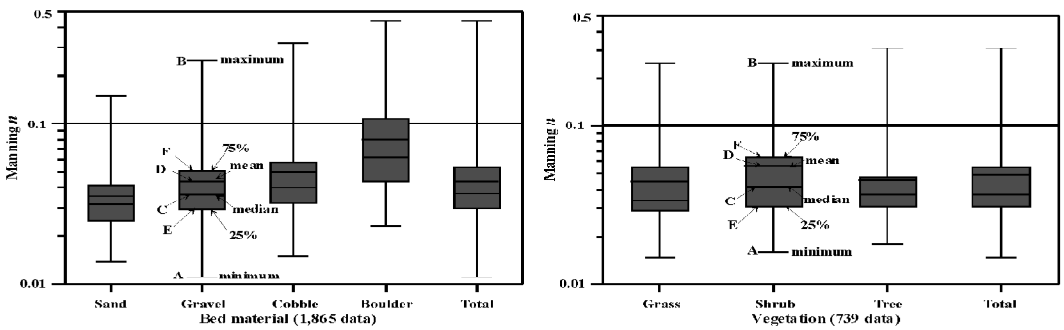
Roughness type		*Name*	*Number*	*A* *Minimum*	*B* *Maximum*	*C* *Median*	*D* *Mean*	*Quartile (percentile)* *E* *First (25th)*	*F* *Third (75th)*	*B/A*	*D/C*	*F/E*
Natural channels	Bed material	Sand	172	0.014	0.15	0.03	0.036	0.03	0.04	10	1.2	1.7
		Gravel	989	0.011	0.25	0.04	0.045	0.03	0.05	22	1.3	1.8
		Cobble	651	0.015	0.33	0.04	0.051	0.03	0.06	21	1.3	1.8
		Boulder	53	0.023	0.44	0.06	0.080	0.04	0.10	19	1.3	2.3
Vegetated channels	Vegetation	Grass	281	0.015	0.25	0.03	0.045	0.03	0.06	17	1.3	1.9
		Shrub	150	0.016	0.25	0.04	0.057	0.03	0.06	16	1.4	2.0
		Tree	308	0.018	0.31	0.04	0.047	0.03	0.05	17	1.3	1.6



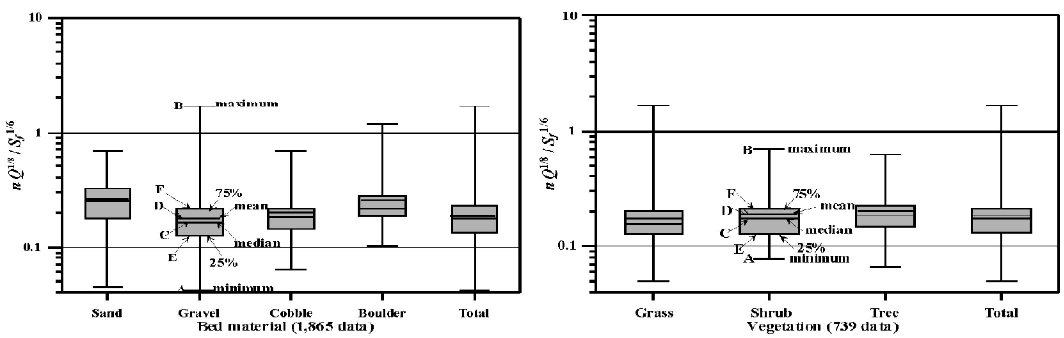
(a) Regression between *log n and log Q*



(b) Regression between *log n and log* S_f



(c) Box-Whisker plots for *n*



(d) Box-Whisker plots for $nQ^{1/8}/S_f^{1/6}$

Figure 3: Analysis of Manning roughness coefficients in natural and vegetated channels

Table 6
Analysis of Box-Whisker plots for $nQ^{1/8}/S_f^{1/6}$ in natural and vegetated channels

Roughness type		*Name*	*Number*	*A* *Minimum*	*B* *Maximum*	*C* *Median*	*D* *Mean*	*Quartile (percentile)* *E* *First (25th)*	*F* *Third (75th)*	*B/A*	*D/C*	*F/E*
Natural channels	Bed material	Sand	172	0.044	0.69	0.25	0.26	0.17	0.32	15	1.0	1.8
		Gravel	989	0.041	1.67	0.16	0.19	0.12	0.21	40	1.1	1.7
		Cobble	651	0.063	0.69	0.17	0.19	0.14	0.21	11	1.1	1.5
		Boulder	53	0.102	1.19	0.21	0.26	0.18	0.27	11	1.2	1.5
Vegetated channels	Vegetation	Grass	281	0.050	1.67	0.15	0.17	0.12	0.20	33	1.1	1.6
		Shrub	150	0.077	0.69	0.17	0.19	0.12	0.21	9	1.1	1.7
		Tree	308	0.066	0.62	0.18	0.19	0.14	0.22	9	1.0	1.5

5. SUMMARY AND DISCUSSION

This analysis of 2,604 field measurements of composite roughness in natural and vegetated channel reduces to the distribution shown in Table 7 for the Darcy-Weisbach *f* and Manning *n*. It is observed that the variability in Manning *n* is less than the variability in Darcy-Weisbach *f*. It is suggested to use the average value of Manning *n* as a first approximation. The information about the minimum and maximum values gives the widest range of values found in this data set and may be used for sensitivity analyses. Users should also compare their values of Manning *n* and Darcy-Weisbach *f* on Figures 2 and 3 (a) and (b) for comparison with the range of values at a given flow discharge and channel slope. It is also noted that there are fewer points for boulder-bed streams, hence these comparisons can be less reliable.

Table 7
Distribution range for Darcy-Weisbach *f* and Manning *n* for natural and vegetated channels

Roughness type	*Name*	*Number*	*Roughness coefficients*					
			Darcy-Weisbach f			*Manning n*		
			Minimum	*Average*	*Maximum*	*Minimum*	*Average*	*Maximum*
Natural	Sand	172	0.011	0.115	2.188	0.014	0.036	0.151
channels	Gravel	989	0.010	0.251	6.121	0.011	0.045	0.250
(1,865 data)	Cobble	651	0.015	0.465	21.462	0.015	0.051	0.327
	Boulder	53	0.034	0.794	14.592	0.023	0.080	0.444
	Subtotal	1,865	0.011	0.325	21.462	0.011	0.047	0.444
Vegetated	Grass	281	0.016	0.271	6.121	0.015	0.045	0.250
channels	Shrub	150	0.015	0.580	12.910	0.016	0.057	0.250
(739 data)	Tree	308	0.030	0.434	21.462	0.018	0.047	0.310
	Subtotal	739	0.015	0.400	21.462	0.015	0.048	0.310
Total		2,604	0.010	0.350	21.462	0.011	0.048	0.444

Table 8 also compares Manning *n* values from Table 7 with those of Chow (1959) and Julien (2002). In general, the average values of Manning *n* are fairly comparable but somewhat higher than suggested by Chow (1959) and Julien (2002). Of the four types of natural channels, Manning *n* increase with grain diameter, as expected, and *n* is the highest for boulder-bed streams. Of the three vegetation types, shrubs show higher resistance to flow.

The main findings of this study on composite resistance to flow in natural and vegetated channels include the following: (1) in general, Manning *n* values show less variability than Darcy-Weisbach *f* values; (2) mean values of Manning *n* can be obtained from Table 8 for different channel roughness and vegetation type; (3) the range of variability in values from Table 5 should then be considered for the given channel type; for instance quartile values can be considered; (4) in general, Manning *n* increases with friction slope S_f and decreases with discharge *Q* and the parameter $nQ^{1/8}/S_f^{1/6}$ can be considered in relation to Figure 3 and Table 6; (5) the Darcy-Weisbach friction coefficient varies significantly with discharge

Table 8
Comparisons with Manning *n* values from Chow (1959) and Julien (2002)

Roughness type	*Description*	*Manning n*								
		Minimum			*Average*			*Maximum*		
		Chow (1959)	*Julien (2002)*	*This study*	*Chow (1959)*	*Julien (2002)*	*This study*	*Chow (1959)*	*Julien (2002)*	*This study*
Natural channels	**Sand**	0.025	0.010	0.014	**0.030**	**0.025**	**0.036**	0.033	0.040	0.151
	Gravel	0.030	0.015	0.011	**0.035**	**0.023**	**0.045**	0.040	0.030	0.250
	Cobble	0.035	0.020	0.015	**0.045**	**0.028**	**0.051**	0.050	0.035	0.327
	Boulder	0.045	0.025	0.023	**0.050**	**0.033**	**0.080**	0.060	0.040	0.444
Vegetated channels	**Grass**	0.025-0.030	0.030	0.015	**0.030-0.035**	**0.050**	**0.045**	0.035-0.050	0.070	0.250
	Shrub	0.035-0.070		0.016	**0.050-0.100**		**0.057**	0.070-0.160		0.250
	Trees	0.030-0.110		0.018	**0.040-0.150**		**0.047**	0.050-0.200		0.310

and friction slope and the mean values of $fQ^{1/4}/S_f^{1/3}$ may be considered in conjunction with Figure 2(d) and Table 4. In all cases, the plots with the relative submergence in Figure 1 can be useful when the flow depth, mean flow velocity and median grain diameter of the bed material are available. However, the flow velocity and depths are usually the variables that needed to be estimated in hydraulic modeling investigations. Finally, the values of Manning *n* and Darcy-Weisbach *f* recommended in this study can help improve the practical determination of resistance coefficients for use in one-dimensional numerical models.

6. CONCLUSIONS

This study focuses on an analysis of a large database of field measurements of roughness coefficients in natural and vegetated channels. It is to be noted that the roughness values reported in this study are composite values representing cross-section averages of resistance coefficients. Resistance relationships are shown to vary with flow discharge and friction slope. The main conclusions from this investigation include:

1. Both Manning *n* and Darcy-Weisbach *f* friction factors vary with flow discharge *Q* and friction slope S_f. Detailed trends and relationships are found in Figures 2 and 3;
2. In general, the variability in Manning *n* is less than the Darcy-Weisbach friction factor *f*, as demonstrated in Tables 3 and 5;
3. Average Manning *n* values are proposed from this study in Table 7. The average values of Manning *n* shown in Table 8 are somewhat higher than proposed by Chow (1959) and Julien (2002);
4. The ratio D/C of the mean to the median value is best for Manning *n* with a range of 1.2-1.3 for natural channels and 1.3-1.4 for vegetated channels; and
5. The ratio F/E of the third quartile (75^{th}) to the first quartile (25^{th}) for Manning *n* ranges from 1.7-2.3 for natural channels and 1.6-2.0 for vegetated channels.

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