Flow Resistance Coefficient Selection in Natural Channels: A Spreadsheet Tool

Steven E. Yochum, PhD, PE
Hydrologist, National Stream and Aquatic Ecology Center

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INTRODUCTION

A spreadsheet tool has been developed by the U.S. Forest Service National Stream and Aquatic Ecology Center to assist practitioners with selecting flow resistance coefficients for stream channels. Such coefficients are needed to quantify roughness for hydraulic modeling, stream assessments, stream restoration design, geomorphic analyses, and ecological studies. This Excel spreadsheet is available for download from the National Stream and Aquatic Ecology Center's tools webpage.

Roughness in channels and floodplains is a fundamental characteristic of stream corridors. Roughness induces the flow resistance to dissipate energy, as quantified by stream power. Flow resistance in stream channels is generally due to (1) viscous and pressure drag on grains of the bed surface (grain roughness); (2) pressure drag on bed and bank undulations (form roughness), and (3) pressure and viscous drag on sediment in transport above the bed surface (Griffiths 1987). Additionally, spill resistance associated with hydraulic jumps and wave drag on elements protruding above the water surface can be the dominant flow resistance mechanism in high-gradient channels (Curran and Wohl 2003, Comiti et al. 2009, David et al. 2011). Hence, resistance is due to roughness induced by bed and bank grain material, bedforms (such as dunes and step pools), streambank and cross section variability, sinuosity, vegetation, large instream wood, and other obstructions (Figure 1).

Flow resistance is quantified using the Manning's coefficient (n) or the Darcy-Weisbach friction factor (f). Using average flow velocity, these coefficients are defined using

$$V = \frac{R^{2/3} S_f^{1/2}}{n} = \sqrt{\frac{8gRS_f}{f}} \qquad (1)$$

where V is the average velocity (m/s), g is acceleration due to gravity (m/s^2), S_f is the friction slope (m/m), and R is the hydraulic radius (m). The hydraulic radius is

$$R = \frac{A}{P_w} \qquad (2)$$

where A is the cross section flow area (m^2 or ft^2) and P_w is the wetted perimeter (m or ft). In the English unit system, the Manning's equation is:

$$V = \frac{1.49 R^{2/3} S_f^{1/2}}{n} \qquad (3)$$

where V is in ft/s and R is in ft. Manning's n is typically preferred by practitioners while f is most often preferred by researchers. Either can be used for estimating mean channel velocity or flow resistance (friction slope).

Figure 1: Milk Creek on the White River National Forest (7/1/2015). Flow resistance is due to roughness from bed material (gravel dominated), streambank variability and vegetation, riffle-pool bedforms, large instream wood, and sinuosity.

Flow resistance coefficients tend to change by flow stage, as the submergence of roughness elements changes and dominant roughness sources shift. Hence, coefficients should be computed at the discharge magnitude of interest for the objectives of the analysis. Analyses are generally for high, bankfull, or low flow.

TOOL DEVELOPMENT and USE

Flow resistance coefficient estimation is approximate, requiring redundancy for confidence in the implemented values. This tool helps provide this redundancy, for more reliable flow resistance estimation. Generally, it is recommended that coefficient selection be multiple stepped, specifically:

1. Consult tabular guidance
2. Consult photographic guidance
3. Apply a quantitative prediction methodology

Links to tabular guidance (Aldridge and Garrett 1973, Arcement and Schneider 1989, Brunner 2016) and photographic guidance (Barnes 1967, Aldridge and Garrett 1973, Hicks and Mason 1991, Yochum et al. 2014) are provided within the references, with the permitted pdf files also included in the spreadsheet package.

Quantitative prediction methods generally come in two forms: quasi-quantitative and fully quantitative. Fully quantitative methods estimate flow resistance coefficients based upon relative submergence, using depth and a characteristic bed material size or bedform variability. However, these methods can have a substantial amount of associated error; further, they only include flow resistance due to grain roughness or bedforms, excluding other sources of resistance including obstructions, bank irregularity, vegetation, and sinuosity. In contrast, a quasi-quantitative method, such as Arcement and Schneider 1989 (based on Cowan 1956) numerically increases flow resistance due to multiple factors. However, this approach is subjective.

Instructions

To use this spreadsheet, follow these instructions:

1. Grey cells indicate fields that should be populated by users. Results are provided in the salmon colored cells.
2. Enter background information (cells D4, D5, I4 to I6), sediment size data (cells D8, E8, H8), and hydraulic information (cells D9 to D13). Computation of the quantitative methods, as well as translation between *n* and *f*, is dependent upon this information.
3. Consult tabular guidance and enter the best estimate in the grey box (cell I43; do not use in average if not confident of estimate). Tabular values are often typically substantially underestimated for channels > ~3% slope. Enter a “y” in cell K43 if you wish to include this value in the overall average.
4. Consult photographic guidance and enter an estimate in the grey box (cell I44). Enter a “y” in cell K44 if you wish to include this value in the overall average.
5. Applicable quantitative procedures (see Applicable Range) will be automatically computed. Enter a “y” next the specific results you wish to include in the averages (cells Z26 to Z42).
6. Implement the Arcement and Schneider (1989) procedure, if desired, by populating cells T20 to Y20. Results of the quantitative procedures can be utilized for n_b, though this can result in overestimated flow resistance. Enter a “y” in cell AA19 if you wish to include this estimate in the overall average.

The variables utilized in the computations are:

- S: stream channel slope (m/m). This slope is typically the friction slope (S_f) and frequently assumed to be the water surface slope. Average bed slope (as computed on the “S>0.03, Sigma z” sheet) can also be a reasonable assumption.
- D_{50}: median bed material size
- D_{84}: bed material size where 84% of the material is finer
- Step D_{84}: bed material size of step-pool bedform steps where 84% of the material is finer
- R: hydraulic radius, computed as A/P_w
- d: mean flow depth = hydraulic depth = cross section flow area / flow width
- σ_z: bedform variation, standard deviation of residuals of bed profile regression
- h_m: median thalweg depth
- Large wood in steps (y/n): “n” allows computation of the Lee and Ferguson (2002) method in channels with S ≥ 3%.

Quantitative Equations

Nine quantitative methods are included within this spreadsheet (Table 1), with the applicable methods for a particular site computed if the equation is valid and sufficient characteristics are provided. The applicable range for each method is set by the slope, relative submergence and, in one case, the presence of large wood in steps (for steeper channels). The Limerinos (1970) and Jarrett (1984) methods are in the English unit system while the remaining methods are in the SI unit system.

With the exception of Jarrett (1984), Aberle and Smart (2003) and Yochum et al. (2012), these methods rely primarily on a characteristic grain material size for prediction. Additionally, these prediction equations were typically developed using reaches intentionally selected to have little influence from sinuosity, instream large wood, streambank vegetation, bank irregularities, obstructions, and other types of roughness not due to bed material. Use thoughtful professional judgement to include in the averages only results that are deemed reasonable and appropriate.

For example, Rickenmann and Recking (2011) appears to frequently under predict flow resistance for streams with slopes > 2 or 3%. For steeper channels, using the results of prediction equations that utilize a characteristic roughness element that better represents the spill resistance than can dominate in these streams (Aberle and Smart 2003, Yochum et al. 2012) can result in more accurate predictions.

Steep Streams: Relative Bedform Submergence

For steeper streams (Figure 2), the dominant longitudinal bedforms shift from riffle pool and plane bed to step-pool and cascade (Montgomery and Buffington 1997), which can dramatically increase flow resistance. This shift occurs at S = ~3%. For such step pool and cascade channels, Manning's n for bankfull flow typically ranges from 0.1 to 0.3 (Yochum et al. 2012), with flow resistance decreasing with increasing stage and discharge. Step pool channels are characterized by a regular series of channel-spanning steps formed by clasts alone or in combination with large wood. Cascade channels are continuously tumbling, with jets and wakes over and around large clasts and wood. Spill resistance over steps as well as enhanced form resistance around clasts and wood account for much of the enhanced flow resistance in these stream types.

Table 1: Equations and applicable ranges for the quantitative methods.

		Applicable Range	
		Slope (m/m)	Relative Submergence
Yochum et al. (2012)	$n = 0.41\left(\frac{h_m}{\sigma_z}\right)^{-0.69}$ $\quad f = 29\left(\frac{h_m}{\sigma_z}\right)^{-1.56}$	0.02 to 0.20	h_m/σ_z = 0.25 to 12
Rickenmann and Recking (2011)	$\sqrt{\frac{8}{f}} = 4.416\left(\frac{d}{D_{84}}\right)^{1.904}\left[1+\left(\frac{d}{1.283D_{84}}\right)^{1.618}\right]^{-1.083}$	0.00004 to 0.03	d/D_{84} = 0.18 to ~100
Aberle and Smart (2003)	$\sqrt{\frac{8}{f}} = 0.91\frac{d}{\sigma_z}$	0.02 to 0.10	d/σ_z = 1.2 to 12
Lee and Ferguson (2002)	$\sqrt{\frac{1}{f}} = 1.48\left(\frac{R}{D_{84,,step}}\right)^{1.80}$	0.027 to 0.184	R/D_{84} (step) = 0.1 to 1.4
Bathurst (1985)	$\sqrt{\frac{8}{f}} = 5.62log\left(\frac{d}{D_{84}}\right)+4$	0.00429 to 0.0373	d/D_{84} = 0.71 to 11.4
Jarrett (1984)	$n = 0.39S^{0.38}R^{-0.16}$	0.002 to 0.039	n/a
Griffiths (1981)	$\frac{1}{\sqrt{f}} = 1.33\left(\frac{R}{D_{50}}\right)^{0.287}$	0.000085 to 0.011	R/D_{50} = 1.8 to 181
Hey (1979)	$\frac{1}{\sqrt{f}} = 2.03log\left(\frac{12.72R}{3.5D_{84}}\right)$	0.00049 to ~0.01	R/D_{84} = 0.8 to 25
Limerinos (1970)	$\frac{n}{R^{1/6}} = \frac{0.0926}{1.16+2.0log\left(\frac{R}{D_{84}}\right)}$	0.00038 to 0.039	R/D_{84} = 1.1 to 69

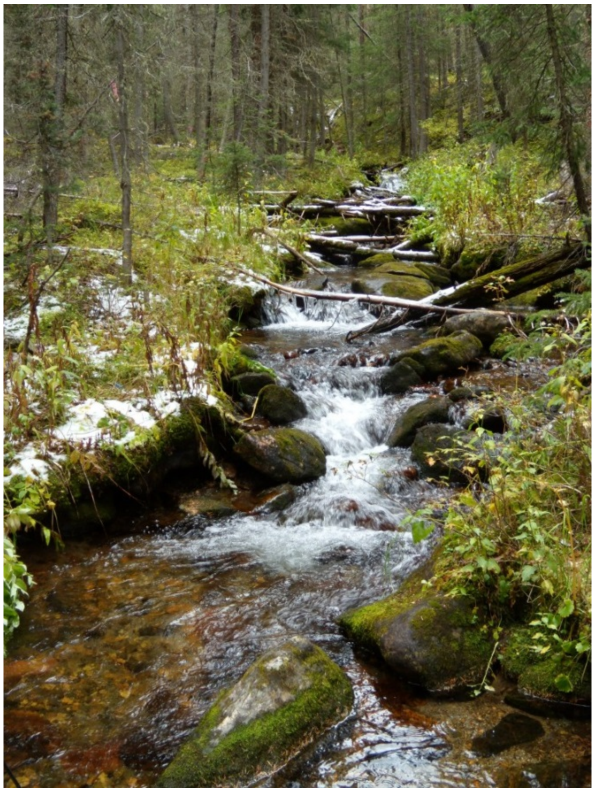

Figure 2: Low flow in East St. Louis Creek, a step pool stream on the Arapaho National Forest in the Fraser Experimental Forest (9/25/2009). Water surface slope (S) = 0.095. Bankfull flow n = 0.19.

To properly account for increased roughness in steeper streams, a bedform variation variable (σ_z) has been found to be more effective than bed material size for predicting flow resistance (Aberle and Smart 2003, Yochum et al 2012). This can be especially important in channels where large instream wood is present in steps, increasing step heights and flow resistance, and making a characteristic grain size (D_{84}) of the reach or steps less valuable for prediction. Bedform variation in the form of the standard deviation of the residuals of a thalweg longitudinal profile regression (σ_z), combined with flow depth as relative bedform submergence, is utilized for prediction. Analogous to relative grain submergence in lower-gradient streams, relative bedform submergence has been found to effectively predict flow resistance in steeper streams.

The "S>0.03, Sigma z" sheet is provided to assist practitioners with σ_z computations. To utilize these quantitative methods, a thalweg longitudinal profile survey is required. This survey should be at least 5 to 10 bankfull widths in length and should be of sufficient resolution to fully characterize all the primary facets that define the step pool or cascade bed morphology. Copy the surveyed longitudinal locations and elevations of this thalweg survey into the spreadsheet (≤ 200 points); σ_z and the average bed slope will be computed.

Arcement and Schneider Method

The Arcement and Schneider (1989) method is a semi-quantitative procedure to account for flow resistance in streams due to channel irregularity, obstructions, vegetation, and meandering (Equation 4). Numerical factors are added to a base Manning's n to account for these other forms of flow resistance, with the result multiplied by a sinuosity adjustment. The selection criteria for these factors (Table 2 and Table 3) is qualitative.

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \qquad (4)$$

If using the resulting n in such a program as HEC-RAS, take care to not double account for flow resistance due to expansions and contractions (n_2, this energy loss is addressed separately from n in HEC-RAS modeling).

Considering that the prediction equations included in this spreadsheet (Table 1) were developed using reaches that typically excluded flow resistance due to sinuosity, instream large wood, streambank vegetation, bank irregularities, and obstructions, it can be appropriate in some cases to use the average quantitative results as n_b. This should be done with caution, to avoid overestimating Manning's n, and may be inappropriate for higher gradients streams (S > 3%).

Table 2: Base values for Manning's n (n_b; adapted from Arcement and Schneider 1989).

Bed Material	Median Bed Material Size (mm)	Base n (n_b)
Sand	0.2	0.012
	0.3	0.017
	0.4	0.020
	0.5	0.022
	0.6	0.023
	0.8	0.025
	1.0	0.026
Concrete	----	0.011-0.018
Rock cut	----	0.025
Firm soil	----	0.020-0.032
Coarse sand	1-2	0.026-0.035
Gravel	2-64	0.028-0.035
Cobble	64-256	0.030-0.050
Boulder	>256	0.040-0.070

Table 3: Adjustment values for roughness (adapted from Arcement and Schneider 1989).

Channel conditions		n-value adjustment	Description
Degree of irregularity (n_1)	Smooth	0	Smoothest channel possible given the bed material
	Minor	0.001 - 0.005	Slightly eroded or scoured streambanks
	Moderate	0.006 - 0.010	Moderate to considerable bed roughness due to such features as bedforms; moderately sloughed or eroded streambanks
	Severe	0.011 - 0.020	Severely sloughed or scalloped streambanks; unshaped, jagged, and irregular surfaces in rock channels
Variation in channel cross section (n_2)	Gradual	0	Size and shape of channel changes gradually
	Alternating occasionally	0.001 - 0.005	Cross section size and shape alternate occasionally. Alternatively, channel thalweg shifts occasionionally from one side to the other (excluding planform/sinuosity related shifts that are addressed with *m*).
	Alternating frequently	0.010 - 0.015	Cross section size and shape alternate frequently. Alternatively, channel thalweg shifts frequently from one side to the other (excluding planform/sinuosity related shifts that are addressed with *m*).
Effect of obstructions (n_3)	Negligible	0 - 0.004	A few scattered obstructions are present (< 5% X-S area), including such features as debris deposits, stumps, exposed roots, logs, piers or isolated boulders.
	Minor	0.005 - 0.015	Obstruction occupy < 15% of X-S area, with spacing wide enough so that spheres of influence do not overlap. Smaller adjustments recommended for smooth versus angular objects.
	Appreciable	0.020 - 0.030	Obstructions occupy 15 to 50% of X-S area, or spacing between obstructions are small enough for spheres of influence to overlap, with the obstructions additive and blocking an equivalent portion of X-S.
	Severe	0.040 - 0.050	Obstructions occupy >50% of the X-S area, or the spaces between the obstructions are small enough to cause turbulence across most of the X-S.
Amount of vegetation (n_4)	Small	0.002 - 0.010	Tree and shrub seedlings are present (such as willow, cottonwood, alder, tamarisk), with a flow depth of at least 3 times the vegetation height at the flow of interest.
	Medium	0.010 - 0.025	Tree and shub seedlings are present, with a flow depth of 2 to 3 times the vegetation height at the flow of interest. Alternatively, brushy and moderately-dense streambank woody vegetation present.
	Large	0.025 - 0.050	~10-year old trees and shrubs present in shallow portions of the channel and lining the streambanks.
	Very large	0.050 - 0.100	Bushy willows and other shrubs and trees are prevelant in substantial portions of the channel and inundated less than their canopy heights at the flow of interest, with brushy and dense woody vegetation on streambanks.
Degree of meandering and sinuosity (m)	Minor	1.0	Sinuosity (ratio of channel length to valley length) = 1.0 to 1.2
	Appreciable	1.15	Sinuosity = 1.2 to 1.5
	Severe	1.3	Sinuosity > 1.5

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