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Using two-point velocity measurements to estimate roughness in streams

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Abstract

An accurate estimation of Manning's roughness coefficient is of vital importance in any hydraulic study including open channel flows. There are many empirical methods to estimate the values of roughness however these methods are often applicable only to a narrow range of river conditions. In many rivers, the velocities at two-tenths and eight-tenths of the depth at stations across the stream are available to estimate Manning's roughness *n* based on a logarithmic velocity distribution. The two-point velocity method has been used for wide channels in some studies reported in the literature. This paper re-investigates and extends the method to real streams of finite width. A sensitivity analysis is also considered. The two-point velocity method is applied to three streams: Acheron River (at Taggerty), the Merrimans Creek (at Stradbroke West) and Tambo River (at Ramrod Creek). The results are compared with some other applicable methods. Although velocity measurement errors were unavoidable and/or the assumption of logarithmic velocity distribution may have been violated, the results are still better than using some other empirical formulae. It is suggested that this two-point velocity method can be used as a means to estimate roughness coefficients for streams where two-point velocity data are available, which is often the case from routine gaugings.

Key Words: streams, roughness, two-point velocity method, and logarithm distribution.

Introduction

An accurate estimation of Manning's roughness coefficient *n* is of vital importance in any hydraulic study including open channel flows. This also has an economic significance. If estimated roughnesses are too low, this could result in over-estimated discharge, under-estimated flood levels and over-design and unnecessary expense of erosion control works and *vice versa* (Ladson et al., 2002).

The direct method to determine the value of roughness (Barnes, 1967, Hicks and Mason, 1991) is time consuming and expensive because friction slopes, discharges and some cross sections must be measured. Therefore, in current practice many indirect methods have been used to estimate roughness in streams from experience or some empirical relationship. Most textbooks and many other publications on open channel hydraulics present tables or photographs of channel reaches of known *n* values which can be used to estimate *n* for a different reach having recognisably similar characteristics (Chow, 1959, French 1985, Barnes, 1967, Hicks and Mason, 1991). Many empirical formulas have been developed to estimate the values of roughness based on the particle size distribution curve of surface bed material (French, 1985, Henderson, 1966). Some of them come indirectly from slope-area empirical formulas combined with Manning's equation to obtain the roughness (Dingman and Sharma, 1997). However these methods are often applicable only to a narrow range of river conditions and the accuracy is still questionable.

In many rivers, although the discharges are measured at one cross-section, if the slope is not known one cannot directly calculate the roughness value. However, a simple method to measure stream flow is to measure velocity in several verticals at 0.2 and 0.8 times the depth. With reference to the logarithmic law of velocity distribution it can be seen that the velocity distribution depends on the roughness height, which may be related to Manning's *n*. If the distribution is known then the value of *n* can be determined. Chow (1959) and French (1985) applied this method to wide rough channels. In this paper, the two-point velocity method is re-investigated and extended to real streams of finite width by using hydraulic radius and average equivalent roughness, to estimate the value of the roughness coefficient.

Methods

The proposed two-point velocity method is applied to three rivers: the Acheron River at Taggerty, Merrimans Creek at Stradbroke West and the Tambo River at Ramrod Creek, with the ratios between width and depth ranging from 7 to 20. These sites correspond to gauging stations of the Victorian streamflow measurement network where at least three cross-sections have been surveyed and the stages have been measured manually from the gauge boards. This data can be used to calculate the roughness by using the same method described in Barnes (1967) and Hicks and Mason (1991) (and below) that are considered as the measured roughness values of the channels. The results computed from the proposed two-point velocity method are compared with the measured roughness values and the roughness values estimated from some other applicable empirical methods, which can use streamgauging data (cross-sections, stages and slopes) to calculate the roughness (see Table 1). The three rivers were selected because the discharge values of the available velocity measurement data are the same as the discharge values in Lang *et al.* (2004b) so that it is possible to make a comparison of the methods.

Direct method to calculate Manning's n

The roughness values are calculated by using the same method described in Barnes (1967) and Hicks and Mason (1991) which is considered to give the most accurate roughness values of the channels:

$$n=\frac{1}{Q}\left(\frac{(h_m-h_1)+(h_{vm}-h_{v1})-\sum_{i=2}^{m}\left(k_{(i-1),i}\Delta h_{v_{i-1,i}}\right)}{\sum_{i=2}^{m}\frac{L_{i-1,i}}{Z_{i-1}Z_i}}\right)^{1/2} \tag{1}$$

where Q is the water discharge (in m^3/s), m is the number of cross-sections (with the m^{th} cross-section being furthest upstream), $Z = AR^{2/3}$, A is the wetted channel cross-sectional area (in m^2), R is the hydraulic radius (in m), L is the reach length, h_i is the water surface elevation at i cross section, h_v is the velocity head at i cross section, Δh_v is the change in velocity head between the upstream and downstream cross-sections and $k(\Delta h_v)$ approximates the energy loss due to acceleration or deceleration in a contracting or expanding reach, k is assumed equal to zero for contracting reaches and 0.5 for expanding reaches.

Some applicable empirical equations for the three rivers

Some applicable equations to estimate roughness for the three river using stream gauging data are chosen to compare with the proposed method (see Table 1). The applicable conditions of these equations are discussed in Lang *et al.* (2004a).

Table 1. Some applicable empirical equations to calculate roughness applied for the 3 rivers

Method	Equation
Lacey (1946)	$n = 0.0928S^{1/6}$
Riggs (1976)	$n = \frac{1}{1.55}A^{-0.33}R^{2/3}S_w^{\;0.45+0.056\log S_w}$
Bray (1982) (Equation 6.16)	$n = 0.104S_w^{\;0.177}$
Sauer (in Coon, 1998)	$n = 0.11S_w^{\;0.18}\left(\frac{R}{0.3048}\right)^{0.08}$
Dingman and Sharma (1997)	$n = \frac{1}{1.564}A^{-0.173}R^{0.267}S_w^{\;0.5+0.0543\log S_w}$

Note: S is friction slope and S_w is water surface slope.

Estimation of roughness by using the two-point velocity method

The logarithmic velocity distribution for a rough channel can be expressed as follows:

$$u=\frac{u_*}{\kappa}\ln\frac{30z}{k_s} \tag{2}$$

where u is point velocity (m), u_* is shear velocity (m/s), κ is the von Kármán coefficient$=0.4$, z is distance from the bottom (m), k_s is equivalent roughness (m).

Substituting the velocity at two-tenths the depth $u_{0.2}$ and the velocity at eight-tenths the depth $u_{0.8}$, at a distance 0.8d and 0.2d respectively from the bottom of a channel, where d is the depth of water at a measurement vertical, then eliminating u_* from those equations, gives:

$$\ln\frac{d}{k_s}=\frac{3.178-1.792x}{x-1} \tag{3}$$

where $x=u_{0.2}/u_{0.8}$.

Rearranging equation (3) gives:

$$k_s=\frac{d}{\exp\left(\dfrac{3.178-1.792x}{1-x}\right)} \tag{4}$$

Then the average equivalent roughness for the whole cross-section is:

$$\overline{k_s}=\frac{\sum k_{si}P_i}{\sum P_i} \tag{5}$$

where k_{si}, P_i are equivalent roughness and perimeter respectively at vertical measurement *i*.

For a rough channel, from Keulegan's study (Chow, 1959):

$$\frac{V}{V_*}=6.25+2.5\ln\frac{R}{\overline{k_s}} \tag{6}$$

where V is mean velocity, V_* is friction velocity, $R=A/P$ is hydraulic radius, where P is the wetted perimeter of the whole section.

Combining the Manning formula $V=1/n\times R^{2/3}\sqrt{S}$ and friction velocity $V_*=\sqrt{gRS}$ gives:

$$\frac{V}{V_*}=\frac{R^{1/6}}{\sqrt{g}n} \tag{7}$$

where *g* is acceleration due to gravity.

Equating the right-hand sides of Eqs. (6) and (7) and solving for roughness *n*,

$$n=\frac{R^{1/6}}{\sqrt{g}\left(6.25+2.5\ln\dfrac{R}{\overline{k_s}}\right)} \tag{8}$$

Sensitivity analysis

For an analysis of sensitivity and to simplify the problem a wide rough channel is considered where $R=d$, $k_s=\overline{k_s}$, and from Equations (3), (6) and (7) *n* can be obtained as follows:

$$n=\frac{(x-1)d^{1/6}}{5.57(x+0.95)} \tag{9}$$

Furthermore, considering errors Δn, Δd, and Δx in the three quantities, to first order:

$$\Delta n=\frac{\partial n}{\partial d}\Delta d+\frac{\partial n}{\partial x}\Delta x \tag{10}$$

From Equation (9) and (10), the relationship between relative error in *n* and relative errors in *d* and *x* can be obtained:

$$\frac{\Delta n}{n}=\frac{1}{6}\frac{\Delta d}{d}+\frac{1.95x}{(x+0.95)(x-1)}\frac{\Delta x}{x} \tag{11}$$

It can be seen that the relative error in *n* is 1/6 of the relative error in depth *d*, while the results are sensitive to the velocity ratio *x* because of the term $x-1$ in the denominator.

Results

Figure 1 shows the relationship between relative errors in *x* and relative error in Manning's roughness *n* in order to see the effect of error on *x* on errors on *n* with difference of river depth and roughness. The depth ranges from 0.5 m to 4 m and the roughness coefficient ranges from 0.02 to 0.05. These are the common ranges of roughness and depth in natural streams.

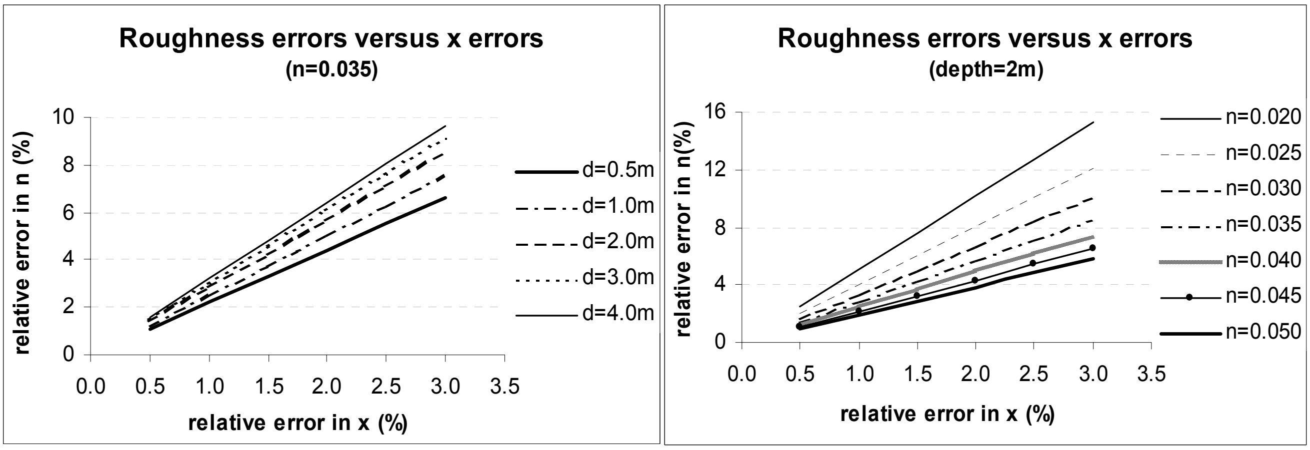

Figure 1. Relationship between relative errors in roughness *n* and relative errors in *x* (the ratio of velocity at 0.2 the depth to that at 0.8 the depth)

The two-point velocity method was applied to three rivers in Victoria: the Acheron River at Taggerty, the Merrimans Creek at Stradbroke West and the Tambo River at Ramrod Creek with the ratios between width and depth ranging from 7 to 20. These rivers were chosen because the available velocity data have the same discharges as the data in Lang *et. al* (2004a,b) in order to make a comparison. The velocity measurement data at these gauges were supplied by Thiess Environmental Services Pty Ltd. The results are compared with some other applicable methods for all three rivers (see Table 1). Figure 2 illustrates the estimated roughness using different methods for the three rivers against the values calculated from the Hicks and Mason method (considered to be the measured roughness values, Lang *et. al*, 2004a,b).

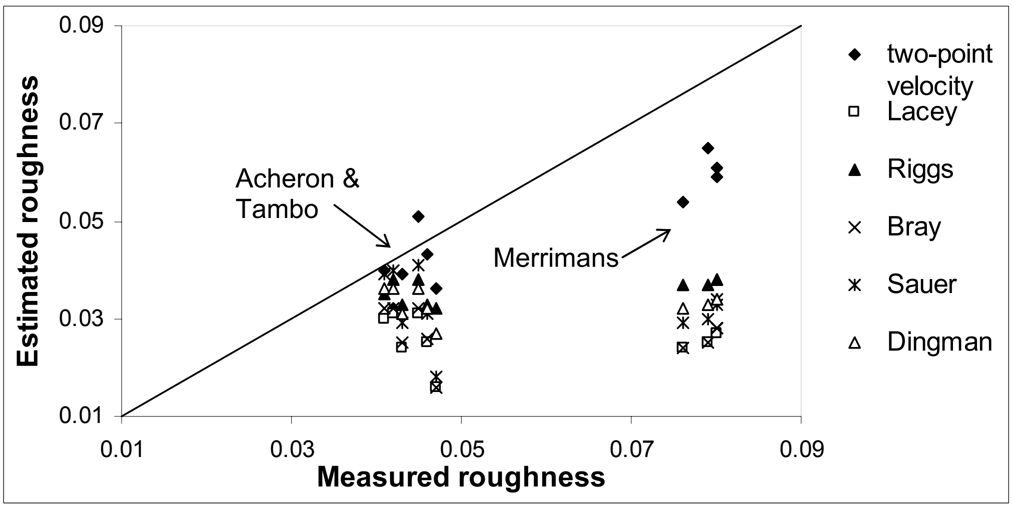

Figure 2: Correlation between measured values of roughness and values computed by various methods including the two-point velocity method.

Discussion

From Figure 1 it can be seen that relationship of the relative errors in *n* and relative errors in *x* (the ratio of velocity at 0.2 the depth to that at 0.8 the depth) depend on the depth and the roughness of streams. The smoother and deeper a stream is, the more sensitive the relative error in *n* is to relative error in *x*. It indicates that the application of the proposed two-point velocity method should be with caution in relatively smooth deep rivers.

From Figure 2 it can be seen that the computed roughness values for the Merrimans Creek (at Stradbroke West) using all the empirical equations are considerably underestimated. Using the two-point velocity method the computed values are much closer to the measured values in comparison with the results computed from the other methods. For the other two rivers, the Acheron River (at Taggerty), the Tambo River (at Ramrod Creek), it also gives similar or better results than using the empirical methods. The results indicate that this method can be used as a means to estimate roughness coefficients for the streams where two-point velocity data are available, as they often are.

Conclusions

This paper has re-investigated and extended the two-point velocity method of estimating the roughness for streams based on a logarithmic velocity distribution. The advantage of the method is that it can estimate the roughness value using two-point velocity data at a gauge section without any information about friction slope or water surface slope. A sensitivity analysis also has been undertaken. It indicates that the smoother and the deeper the river is, the more sensitive the error in n is to the error in the ratio of velocity at two-tenths the depth to that at eight-tenths the depth. The two-point velocity method has been applied to three rivers: the Acheron River (at Taggerty), the Merrimans Creek (at Stradbroke West), and the Tambo River (at Ramrod Creek) in Victoria. The results have been compared with some other applicable empirical formulae. Although velocity measurement errors were unavoidable and/or the assumption of logarithm velocity distribution may have been violated the results from the proposed method are still better than using some other empirical formulae. It is suggested that this method can be used as a means to estimate roughness coefficients for any streams where two-point velocity data are available, which is the case for many existing and future stream-gaugings. Some further verification studies will be made.

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