



Roughness coefficient and its uncertainty in gravel-bed river

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Abstract: Manning's roughness coefficient was estimated for a gravel-bed river reach using field measurements of water level and discharge, and the applicability of various methods used for estimation of the roughness coefficient was evaluated. Results show that the roughness coefficient tends to decrease with increasing discharge and water depth, and over a certain range it appears to remain constant. Comparison of roughness coefficients calculated by field measurement data with those estimated by other methods shows that, although the field-measured values provide approximate roughness coefficients for relatively large discharge, there seems to be rather high uncertainty due to the difference in resultant values. For this reason, uncertainty related to the roughness coefficient was analyzed in terms of change in computed variables. On average, a 20% increase of the roughness coefficient causes a 7% increase in the water depth and an 8% decrease in velocity, but there may be about a 15% increase in the water depth and an equivalent decrease in velocity for certain cross-sections in the study reach. Finally, the validity of estimated roughness coefficient based on field measurements was examined. A 10% error in discharge measurement may lead to more than 10% uncertainty in roughness coefficient estimation, but corresponding uncertainty in computed water depth and velocity is reduced to approximately 5%. Conversely, the necessity for roughness coefficient estimation by field measurement is confirmed.

Key words: roughness coefficient estimation; field measurement; gravel-bed river; uncertainty

1 Introduction

The main physical forces controlling flow in a river are inertia, pressure, gravity, and friction. These are directly influenced by the geometry and roughness of a river. For a gravel-bed river composed of relatively immobile, coarse bed material, the geometry can easily be determined, whereas estimation of the roughness is much more difficult because it is a lumped parameter that mostly reflects the flow resistance of the river. Since the roughness coefficient has an extensive effect on flow analysis of a river, including computation of the water level and velocity, its accurate estimation is important for prediction of the water level during flooding, design of hydraulic structures, and stability assessment of revetments. In addition, considering ecological aspects of a river, the roughness coefficient is also significant

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in simulation of flow conditions associated with habitat suitability.

Because of its importance, various efforts have been made to quantify the roughness coefficients of gravel-bed rivers in an objective manner. Among them, an element-based method (Cowan 1956) and empirical equations that relate the roughness coefficient either to bed material (Strickler 1923; Meyer-Peter and Muller 1948; Keulegan 1938; Bray 1979) or to relative depth (Charlton et al. 1978; Bray 1979; Griffiths 1981; Limerinos 1970) are representative. However, owing to the diversity and irregularity of natural rivers, prediction of the roughness coefficient for a specific river reach using these methods is not simple. Thus, until now, field measurements have been made either to directly estimate the roughness coefficient (Coon 1995) or to provide references (Barnes 1967; Hicks and Mason 1991).

However, there remain uncertainties whether using the methods referred to above or using field measurements. From a practical viewpoint, water level and discharge as variables computed by numerical modeling are influenced by uncertainty in estimating the roughness coefficient. Conducting simulation of dam breakage flow for the Teton Dam, Fread (1988) showed that variation in calculated flood flow water depth was less than 5% with a 20% change in the roughness coefficient. He therefore argued that even if uncertainty in Manning's roughness coefficient is large, its effect on the water depth might be reduced considerably in the process of computation. However, Kim et al. (1995) showed that a 20% change in the roughness coefficient in several reaches of the Han River can cause the calculated flood peak to vary by up to 10%. These two rather opposite results show that the effect of uncertainty of the roughness coefficient on calculated variation in the flood water level may be different according to the discharge and conditions of each flood event. Wohl (1998) calculated discharges of past flood events of five rivers with flood marks using four different roughness estimation methods. According to his study, when the channel gradient is less than 0.01, a 25% change in the roughness coefficient may give rise to up to a 20% variation in computed discharge. Small and steep-gradient rivers with low width-depth ratios show higher sensitivity to changes in the roughness coefficient than large rivers. This means that a slight variation in the roughness coefficient may have a relatively large effect when discharge is calculated for small-size and medium-size rivers. Therefore, careful attention should be paid when estimating the roughness coefficient, and the relevant uncertainties should be considered.

With this background, estimation of the roughness coefficient was conducted for a typical, medium-size gravel-bed river reach based on field measurements of water level and discharge. It was compared with the roughness coefficient estimated by other methods, so that their applicability to the study reach could be evaluated. Furthermore, in order to examine uncertainties related to the roughness coefficient, the effects of inaccurate estimation of the roughness coefficient on water depth and discharge computation were analyzed for different discharge values. Finally, uncertainty in the roughness coefficient estimated by field measurement was also investigated.

2 Study river reach

This study was conducted in a gravel-bed river reach located in the middle reaches of the Dalcheon River in South Korea (Fig. 1). The average width of the channel is 110 m. The width-depth ratio for bankfull flow ranges from 20 to 30. The riverbed is mainly composed of coarse gravels with abundant cobbles, and the bed topography is undulating and characterized by alternating riffles and pools. The study reach is a regulated river channel located downstream of the Goesan Dam, and its downstream end is the confluence with the Ssangcheon River. The average channel gradient is approximately 1/650. The drainage area of the reach at its upstream end, the Goesan Dam, is 675.2 km². The 50-year design flood discharge amounts to 1750 m³/s.

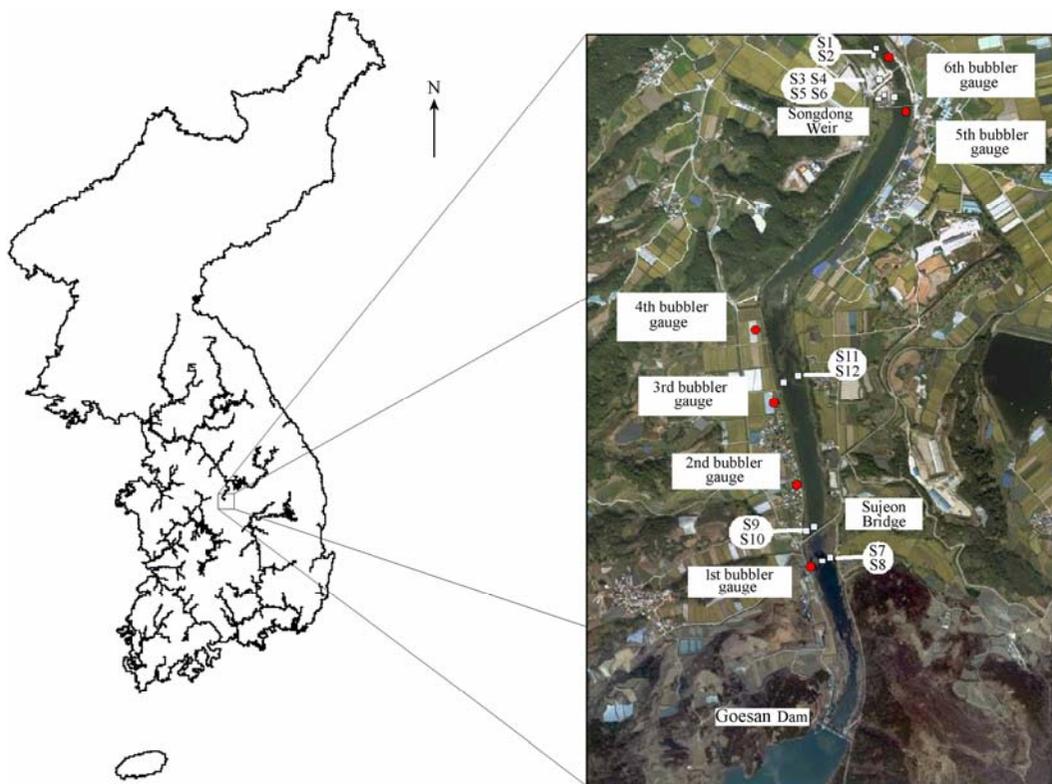


Fig. 1 Study site in Korean Peninsula

The Goesan Dam, with its hydroelectric power station, controls streamflow either with a generator during the low flow season or with a spillway gate during the summer rainy season. Usually, it releases discharges ranging from 6 m³/s to 16 m³/s during the low flow season, and discharges of up to 1200 m³/s for flood control during the flood season through gate operation. Thus, discharges of various magnitudes can be provided while maintaining a quasi-steady state, which is a good condition for field measurement for estimation of the roughness coefficient.

As a part of an experimental river, the study reach has fifteen water level sensors of seven

types equipped with automatic loggers (Fig. 2). The distances of the sensors from the Goesan Dam are in parentheses in Fig. 2. Continuously recorded data from five bubbler gauges (1st through 5th) installed along the study reach were used together with those near the official gauging station located at the Sujeon Bridge. Data used for analysis were mainly obtained during several flood events in July 2005 and July 2006.

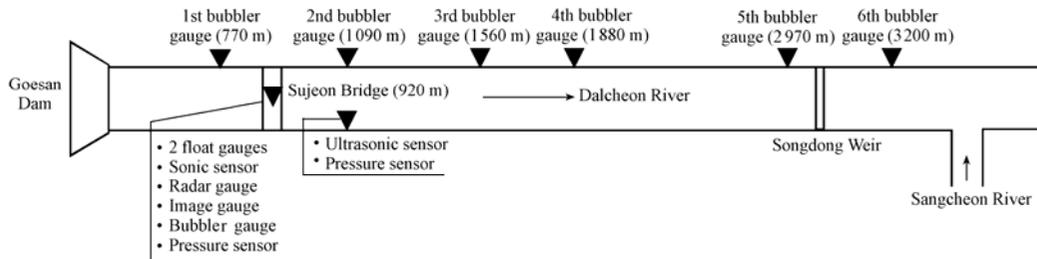


Fig. 2 Location of water level measurement instruments

Cross-sections, including the six gauged ones (Fig. 3), were surveyed every 50 m along the study reach. They were used both to calculate the roughness coefficient and to compute the water depth and velocity with the one-dimensional flow analysis software.

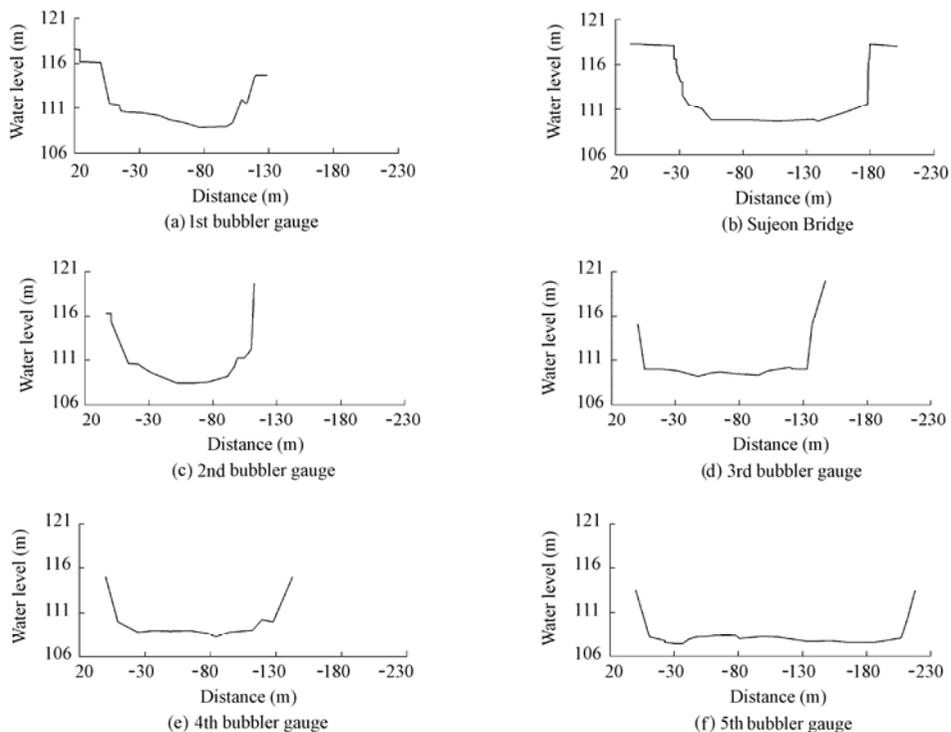


Fig. 3 Cross-sections for water level measurements

In a coarse gravel-bed river, there is a close relationship between roughness and riverbed

surface material because roughness is mainly related to surface friction. Thus, characteristics of bed material need to be investigated. For this reason, bed material sampling was conducted at 12 points (S1 - S12) located at either bars or riffles according to the grid-by-number method (ISO 1992), in the spring of 2007. This was justified by the fact that temporal change in bed material is considered to be negligible because the riverbed along the study reach is armored and most of the bed load transport is intercepted by the dam.

Fig. 4 is a plot of cumulative grain size distributions both for the individual (thin lines) and whole (thick line) samples. Representative particle sizes were determined by the graphical method (Table 1). The d_m values are grain size of the m th percentile, while d_w indicates weighted representative grain size as defined by Limerinos (1970). Though there is a slight size difference between samples collected from riffles and bars, arithmetic mean values of the 12 samples were adopted for this study.

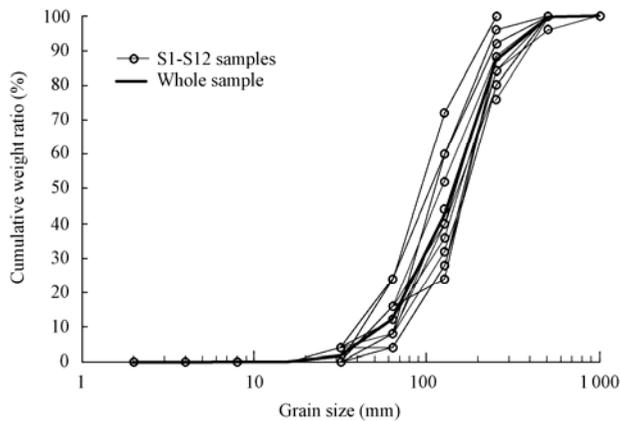


Fig. 4 Cumulative curves of bed material

Table 1 Representative bed material sizes for all sampling locations

Location	d_{16} (mm)	d_{50} (mm)	d_{86} (mm)	d_{90} (mm)	d_w (mm)	Remarks
S1	70.79	109.65	194.98	218.78	156.96	Gravel bar
S2	48.98	89.13	165.96	190.55	131.21	Gravel bar
S3	47.86	102.33	208.93	239.88	160.84	Gravel bar
S4	64.57	151.36	295.12	354.81	228.94	Riffle
S5	74.13	141.25	234.42	281.84	190.44	Riffle
S6	85.11	158.49	239.88	281.84	199.99	Riffle
S7	64.57	162.18	239.88	281.84	199.04	Riffle
S8	79.43	162.18	309.03	371.54	242.02	Riffle
S9	74.13	138.04	245.47	363.08	196.11	Riffle
S10	85.11	165.96	288.40	363.08	231.34	Riffle
S11	63.10	120.23	229.09	281.84	179.83	Riffle
S12	70.79	151.36	257.04	316.23	206.71	Riffle
Average	69.05	137.68	242.35	295.44	193.62	

3 Estimation of roughness coefficient

3.1 Estimation using measured data

The NCALC model (Jarrett and Petsch 1985), developed by the United States Geological Survey (USGS), is used for direct calculation of the roughness coefficient from the measured water level and discharge data. Governing equations and basic theories are as follows:

Discharge in a uniform steady state is computed with Manning's formula (Eq. (1)). This equation can also be applied to non-uniform flow through modification reflecting head loss due to bed friction (Jarrett and Petsch 1985):

$$Q = \frac{1}{n} AR^{2/3} S_f^{1/2} \quad (1)$$

where Q is the discharge (m^3/s), n is Manning's roughness coefficient, A is the flow area (m^2), R is the hydraulic radius (m), and S_f is the friction slope. S_f is calculated from Eq. (2):

$$S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta h_v - k \Delta h_v}{L} \quad (2)$$

where h_f is the friction head loss, Δh is the water level difference, Δh_v is the difference in velocity head, L is length, and k is a constant reflecting contraction and expansion of sections. If flow is contracted, k becomes 0; for expansion it becomes 0.5.

If there are multiple sections, the roughness coefficient is calculated from Eq. (3) (Barnes 1967; Hicks and Mason 1991):

$$n = \frac{1}{Q} \sqrt{\frac{(h_1 + h_{v_1}) - (h_m + h_{v_m}) - \sum_{i=2}^m (k_{i-1,i} \Delta h_{v_{i-1,i}})}{\sum_{i=2}^m \frac{L_{i-1,i}}{Z_{i-1} Z_i}}} \quad (3)$$

where Z equals $AR^{2/3}$, and m is the number of sections.

The NCALC model also provides another method for estimating the mean roughness coefficient by adding extra weight to the friction head loss. The weighted value of n is computed by Eq. (4):

$$n = \frac{n_{1,2} h_{f_{1,2}} + \dots + n_{N-1,N} h_{f_{N-1,N}}}{h_{f_{1,2}} + \dots + h_{f_{N-1,N}}} \quad (4)$$

Except for the case in which the friction head loss for the specific sub-reach is relatively large, roughness coefficients computed with Eq. (3) and Eq. (4) are almost the same. The water surface slope can be input into Eq. (1) as a substitute for the friction slope to compute the roughness coefficient of each cross-section, but this neglects the effect of friction head loss. Thus, the roughness coefficient calculated with this method is used for comparison with results obtained using Eq. (3) and Eq. (4) (Fig. 7).

From the record of observed dam-released discharge and water level data, 32 cases were

selected for analysis. Roughness coefficients were computed for a wide range of discharge, from $37 \text{ m}^3/\text{s}$ to $1237 \text{ m}^3/\text{s}$.

Though roughness coefficients associated with certain discharges can be calculated from water level data measured at six cross-sections (Fig. 3), the water surface slope should be provided for direct application of Manning’s formula. However, determination of the water surface slope is difficult for a natural coarse gravel-bed river that has a nonlinear water surface profile, especially at low flow. In this study, the water surface slope at each cross-section was determined from measured water levels in both upstream and downstream sections (Fig. 5). Consequent spatial and temporal variations of the roughness coefficient computed by Eq. (1) are displayed in Fig. 6.

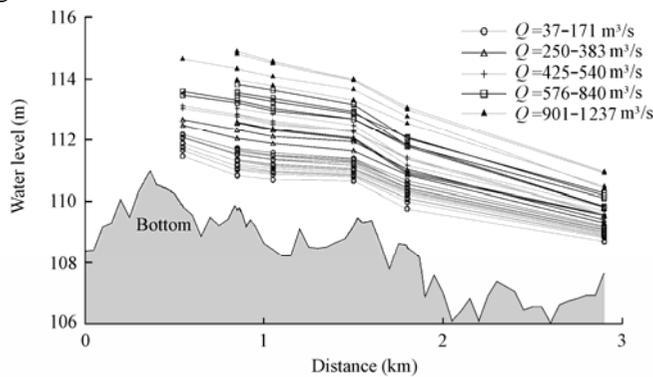


Fig. 5 Longitudinal water surface profile for different discharges

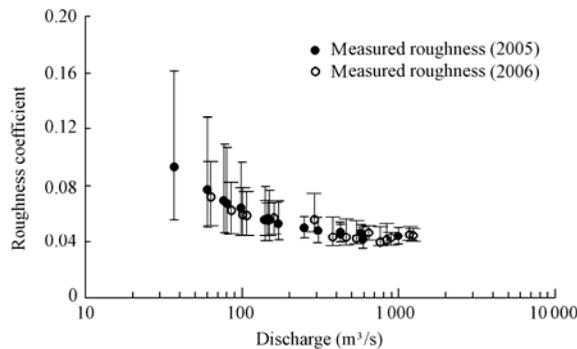


Fig. 6 Variation of Manning’s roughness coefficient with discharge

Error bars in Fig. 6 represent spatial variation of roughness coefficients due to different conditions at the six water level gauging sections. As discharge increases, the spatial variation of the roughness coefficient tends to decrease. This means there are large differences in estimated roughness coefficients at low flow, but spatial variation diminishes with increasing discharge for flood flow. In the same plot, dots of different color stand for roughness coefficients of different years (black for 2005 and white for 2006), which together show temporal variation. This shows that flow resistance of rivers in an unsteady state may change even at the same discharge. Thus, there is still a limitation to estimating spatial and temporal

change in roughness coefficients using Manning's formula.

Roughness coefficients calculated using the NCALC model for years 2005 and 2006 are plotted in Fig. 7 (R^2 is the coefficient of determination). According to the results, weighted mean roughness coefficients with friction head loss taken into account are larger than those calculated by other equations at a relatively small discharge. This is because the difference in friction head loss between sections changes drastically for discharges less than about $600 \text{ m}^3/\text{s}$. However, for discharges over $600 \text{ m}^3/\text{s}$, there appears to be no significant difference in roughness coefficients computed by Eq. (3) and Eq. (4).

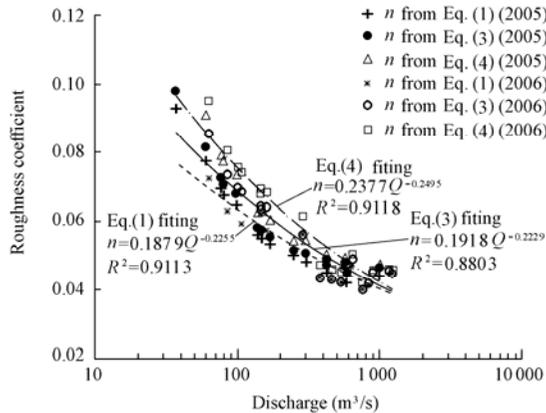


Fig. 7 Manning's roughness coefficients calculated using NCALC model

Regression analysis of discharge and roughness coefficients based on a power function for roughness coefficient data computed by Eq. (1), Eq. (3), and Eq. (4) shows nearly identical tendencies. In this study, the roughness coefficient was finally determined by Eq. (3). Its calculated mean value is 0.044 for discharges over $600 \text{ m}^3/\text{s}$. This value was used for comparison with values calculated by other empirical methods.

3.2 Estimation of roughness coefficient based on previous studies

There are two sorts of methods for estimation of roughness coefficients without any field measurement. One is based on roughness elements. The other uses empirical formulae.

The USGS uses an element-based method developed by Cowan (1956) to estimate roughness coefficients for rivers. In this method, six roughness elements affecting flow resistance are individually considered and then integrated into the final roughness coefficient for a specified river reach (Table 2). In practice, some expertise is required to choose proper values for each element. This study referred to the guidelines suggested by Arcement and Schneider (1989), and the roughness coefficient of the study reach was estimated to be 0.039.

After reviewing literature concerning Manning's roughness coefficient, Yen (1992) arranged various formulae in terms of their historical and theoretical backgrounds, various field conditions, and practical application. These empirical formulae can be categorized in three types: Strickler-type, power-based, and semi-logarithmic-based formulae. They were

used to estimate the roughness coefficient of the study reach (Table 3).

Table 2 Application of Cowan’s method

Item	Parameter	Guidelines	Results	Remarks
n_b	Basic coefficient	0.030-0.050	0.030	Gravel and cobble
n_1	Irregularity	0.001-0.005	0.002	Slight
n_2	Changes in section	0.001-0.005	0.001	Slight
n_3	Obstructions	0.000-0.004	0.004	A few bridges
n_4	Vegetation	0.002-0.010	0.002	Insignificant
m	Meandering	minor	1.000	$L_m/L_s = 1.07$
n			0.039	

Note: L_m is the meander length, and L_s is the straight length: $m = 1.0$ for $L_m/L_s = 1.0-1.2$, and $n = (n_b + n_1 + n_2 + n_3 + n_4) m$.

Table 3 Values computed from empirical formulae

Type	Investigator	Formula	n
Strickler	Strickler (1923)	$n = 0.047d_{50}^{1/6}$	0.034
	Meyer-Peter and Muller (1948)	$n = 0.038d_{50}^{1/6}$	0.031
	Keulegan (1938)	$n = 0.039d_{50}^{1/6}$	0.028
	Bray (1979)	$n = 0.0593d_{50}^{0.179}$	0.042
	Bray (1979)	$n = 0.0495d_{50}^{0.16}$	0.041
Power	Charlton et al. (1978)	$\sqrt{1/f} = 1.27(h/d_{50})^{0.23}$	Eq. (5)
	Bray (1979)	$\sqrt{1/f} = 1.36(h/d_{50})^{0.281}$	Eq. (6)
	Griffiths (1981)	$\sqrt{1/f} = 1.33(R/d_{50})^{0.287}$	Eq. (7)
Semi-logarithmic	Limerinos (1970)	$\sqrt{1/f} = 2.031g(R/d_{50}) + 0.35$	Eq. (8)
	Bray (1979)	$\sqrt{1/f} = 2.361g(h/d_{50}) + 0.248$	Eq. (9)
	Griffiths (1981)	$\sqrt{1/f} = 1.981g(R/d_{50}) + 0.76$	Eq. (10)

Roughness coefficients estimated by Strickler-type formulae range from 0.028 to 0.042. The values are considerably different from one another, reflecting the different conditions from which these formulae are derived.

Roughness coefficients estimated by six power-based and semi-logarithmic-based equations were compared by examining the relationship between the roughness coefficient (n) and the friction factor (f), which is established by combining Darcy-Weisbach and Manning’s formulae to form Eq. (11):

$$\frac{1}{\sqrt{f}} = \frac{K_n/\sqrt{8g}}{n/R^{1/6}} = \frac{0.11288}{n/R^{1/6}} \quad (11)$$

where K_n is a coefficient depending on the unit system and equivalent to 1.0 in SI units, and g is gravitational acceleration. Geometric means of roughness coefficients computed for the study reach using six depth-dependent empirical formulae were compared with roughness coefficients computed by Eq. (3) in association with discharge (Fig. 8).

Roughness coefficients estimated using power-based and semi-logarithmic-based formulae tend to decrease with increasing discharge. They are also plotted in Fig. 8 for

comparison with the roughness coefficients obtained by field measurements for both 2005 and 2006 (black dots in Fig. 8). Roughness coefficients calculated by six different equations also cover a wide range. Of the six equations, Limerinos's formula is the best fit for the data of this study for discharges over 400 m³/s. Standard deviations of roughness coefficients calculated by each equation are also shown in Fig. 8.

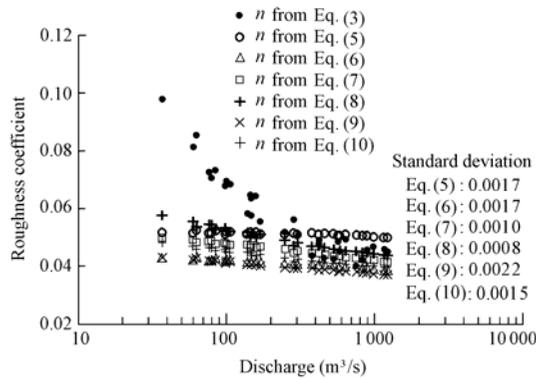


Fig. 8 Comparison of computed n and n obtained by measured data

For relatively small discharges, below 400 m³/s, roughness coefficients calculated by Limerinos's formula are much smaller than those derived from the measured data, and deviate from them. This phenomenon is thought to be related to characteristics of flow over the non-uniform, undulating riverbed of a gravel-bed river. In a river with a simply shaped cross-section, like the study reach, as water depth becomes larger and velocity faster during flood flow, spatial variation is also reduced. In contrast, as water depth and velocity decrease during low and medium discharges, flow is controlled by the spatial irregularity of a riverbed.

4 Uncertainty related to roughness coefficient

4.1 Uncertainty of hydraulic variables due to change in roughness coefficient

When the roughness coefficient is estimated based on field-measured data, it is necessary to extrapolate for use within unmeasured ranges of flow. From both Fig. 8 and Limerinos's formula (Eq. (8)), the roughness coefficient for a discharge of 1750 m³/s, which is equivalent to a 50-year design flood, can be estimated to be 0.043. The Basic River Plan's (BRP) officially assigned value in Chungcheongbukdo Province of Korea for the same discharge is 0.033, which is approximately 23% less than the value estimated by this study. Because the two proposed roughness coefficients may give rise to different velocity and flood water level computations, which are important to engineering practice, it is necessary to analyze the uncertainty related with computed hydraulic variables caused by differences in the roughness coefficient. Under the assumption that the value of the roughness coefficient of the BRP is true, the effect of a 20% increase in the roughness coefficient on calculated water depth and

velocity was analyzed using HEC-RAS, a one-dimensional flow analysis software, for seven different discharge conditions ranging from 37 m³/s to 1 750 m³/s (Fig. 9). Downstream boundary conditions for the simulation were the design flood water level of 113.31 m for the 1 750 m³/s case and the measured water level at the 5th bubbler gauge for the remaining six cases of lesser discharge. The maximum and mean difference and rate of change are shown together in Fig. 9.

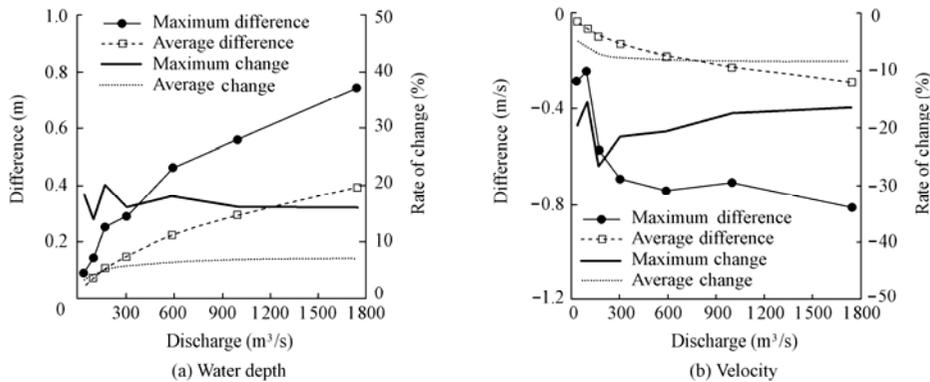


Fig. 9 Variation of hydraulic parameters with discharge

In the study reach, a 20% increase in the roughness coefficient leads to a 7% increase in water depth and an 8% decrease in velocity on average, but at a particular cross-section it gives rise to a 15% increase in water depth and a decrease in velocity of the same degree at maximum, equivalent to a 0.7 m rise and a 0.8 m/s slowing, respectively. However, as discharge decreases, the maximum change in water depth and velocity caused by a 20% increase in the roughness coefficient is likely to be limited to particular cross-sections because computation results depend on riverbed conditions such as non-uniformity in a longitudinal profile, in addition to the roughness coefficient. Nevertheless, absolute change in water depth and velocity tends to diminish with decreasing discharge. Therefore, uncertainty in estimation of roughness coefficients may have a significant influence on computed water depth and velocity in a medium- or small-size river like the Dalcheon River. This contrasts with results of previous studies by Fread (1988) and Kim et al. (1995), which focused on larger rivers with higher discharge.

4.2 Uncertainty in estimating roughness coefficient due to measurement errors

As indicated in the previous paragraph, roughness coefficients estimated using measured water level and discharge data are quite different from those of the BRP. Some uncertainty is implied in the roughness coefficient value designated by the BRP, resulting in other uncertainties related with computed results such as water depth and velocity. The average effect of uncertainty in the roughness coefficient on uncertainty in estimation of water depth and velocity tends to decrease with the increase of discharge. Nevertheless, as the estimated

value of the roughness coefficient for low flow often exceeds double the value for flood flow, as shown in the results of this study, it is still useful to estimate the roughness coefficient directly from measurements of water level. Moreover, at low flow, considering spatial variation in water depth over an irregular riverbed profile, which is common in a gravel-bed river, a detailed division of a target river reach into hydraulically homogeneous sub-reaches is necessary for more accurate estimation of the roughness coefficient.

Estimation of the roughness coefficient based on measured data mainly includes two kinds of uncertainties related with measurement errors. One comes from error in water level measurement. Lee (2001) conducted statistical analysis on error in water level measurement by ordinary gauging stations considering two major error elements: instrumental error and error due to waves caused by wind. Assuming that errors have standard normal distribution with a mean value of zero, he estimated standard deviation of the distribution to be 15.7 mm. This equals an error of ± 40.5 mm at a 99% confidence level. The other uncertainty comes from error in discharge measurement. In general, uncertainty in discharge measured by the standard velocity-area method is known to fall within 10% for streams wider than 10 m with at least 20 measurement verticals. This uncertainty may be reduced to 5% with precise measurement. In this study, maximum and minimum errors in roughness coefficients were estimated at the two different uncertainty levels of 5% and 10% for measured discharge, and uniform distribution was assumed. Fig. 10 shows uncertainty in the roughness coefficients estimated using Monte Carlo simulation, considering the uncertainty range of two input variables for the two discharge cases of $37 \text{ m}^3/\text{s}$ and $1000 \text{ m}^3/\text{s}$.

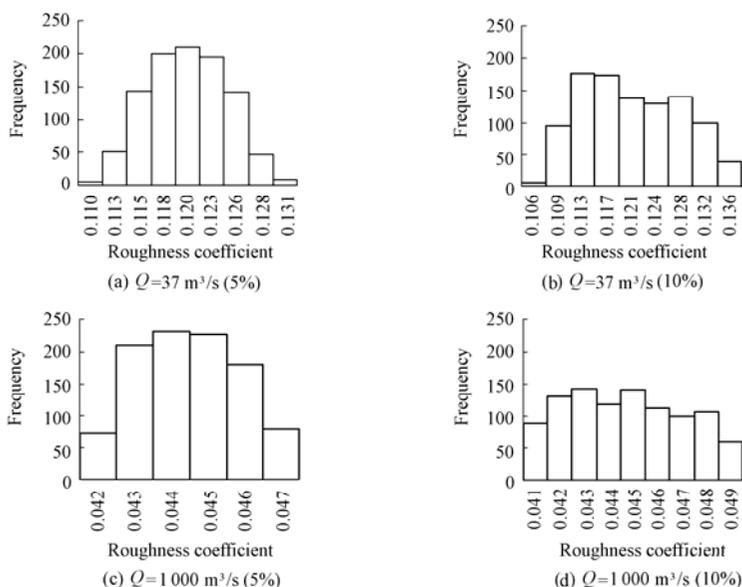


Fig. 10 Uncertainty of calculated Manning's n due to error in measurement

Non-uniform flow computation using the standard step method was performed with

roughness coefficients calculated from Monte Carlo simulation, shown in Fig. 10, in order to examine changes in hydraulic variables along the study reach (Fig. 11). Variation in water depth and velocity with application of the designated roughness coefficient of the BRP for the two discharge cases is also shown in Fig. 11.

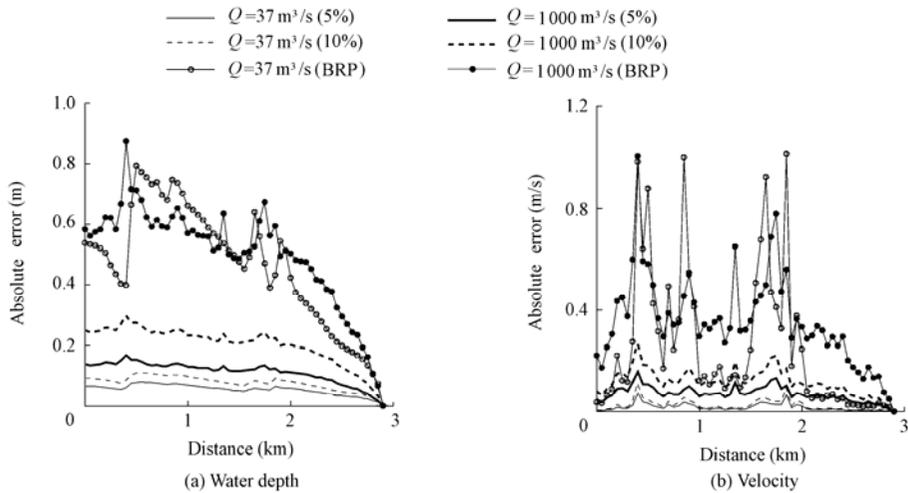


Fig. 11 Absolute error in computed hydraulic variables

The roughness coefficient value designated in the BRP (0.033) is approximately 72.5% and 25% smaller than those estimated in this study for discharges of 37 m³/s and 1000 m³/s, respectively. Such a small value may give rise to relatively large errors when used for calculation of water depth and velocity. When the BRP roughness coefficient is used, the relative errors in the water depth are 61.3% at maximum and 24.7% on average for a discharge of 37 m³/s, and 20.2% at maximum and 10.3% on average for a discharge of 1000 m³/s. The relative errors in velocity are 233% at maximum and 68% on average for a discharge of 37 m³/s, and 33% at maximum and 15% on average for a discharge of 1000 m³/s, respectively. These results suggest that careful attention should be paid when using the designated roughness coefficient of the BRP for low flow calculation. Numerical simulation has often been used for calculation of flow characteristics of medium-size and small-size streams to evaluate ecological habitat suitability, but due to a lack of studies dealing with roughness characteristics at medium and low flow in coarse gravel-bed rivers with irregular riverbed configuration, the designated roughness coefficients originally intended for use in computation of the flood water level are often used without enough verification. If the roughness coefficient value chosen for low flow deviates significantly from that for flood flow, like the designated value in the BRP, the reliability of simulation results is obviously in doubt.

Uncertainty in roughness coefficients arising from measurement error propagates to cause uncertainty in computed hydraulic variables. Table 4 summarizes calculated results for discharges of 37 m³/s and 1000 m³/s with errors of 5% and 10%. The error in water level

measurement is considered equal for all cases. Errors in estimating roughness coefficients are likely to be mainly influenced by errors in discharge measurement regardless of discharge magnitude. For a discharge of 37 m³/s, 5% and 10% errors in discharge measurement contribute to errors of 9.9% and 14.0% in roughness coefficients, while at 1000 m³/s discharge measurement errors of the same magnitude cause roughness coefficient errors of 6.2% and 11.3%, respectively. This implies that the estimated roughness coefficient for low flow is apt to be more affected than that for flood flow by the same degree of uncertainty in measurement.

Table 4 Statistics of hydraulic variables associated with error of roughness coefficient

Discharge (m ³ /s)	Error of discharge (%)	<i>n</i>			Standard deviation	Uncertainty of <i>n</i> (%)	Relative error of water depth (%)		Relative error of velocity (%)	
		Min.	Mean	Max.			Max.	Mean	Max.	Mean
37	5	0.109	0.120	0.132	0.004	9.9	6.1	2.9	11.8	4.7
	10	0.104	0.121	0.137	0.007	14.0	8.5	4.1	17.7	7.0
1000	5	0.042	0.044	0.047	0.001	6.2	3.9	2.3	5.1	3.1
	10	0.040	0.044	0.049	0.002	11.3	6.9	4.2	8.7	5.1

The effect of uncertainty of the roughness coefficient on calculation of water depth and velocity was analyzed using Monte Carlo simulation and is presented in Table 4. As shown in Table 4, large uncertainty of roughness coefficient at low flow has less effect on water depth and velocity calculation than it does at flood flow. When discharge is 37 m³/s, the uncertainty in the roughness coefficient estimated by field measurement, expressed as a percentage variation (9.9% and 14.0%), is large itself, but the corresponding resultant mean relative depth error is relatively small (2.9% and 4.1%). These values are nearly equivalent to those for the 1000 m³/s conditions (2.3% and 4.2%). The same is also true for the velocity error. For a discharge of 37 m³/s, the mean relative errors of velocity corresponding to 5% and 10% uncertainty in discharge measurement are 4.7% and 7.0%, while for 1000 m³/s they are 3.1% and 5.1%, respectively. This means that the roughness coefficient estimated by field measurement is sufficient for accurate calculation of hydraulic variables in spite of its uncertainty. The necessity for roughness coefficient estimation by field measurement is confirmed as well.

5 Conclusions

In this study, the roughness coefficient was estimated by field measurement and compared with values determined using existing empirical methods. In addition, the validity of estimation of the roughness coefficient based on field measurement was investigated by analyzing its uncertainty. The main results are the following:

(1) The roughness coefficient calculated by the NCALC model using Manning's formula modified to deal with multiple sections tends to decrease with increasing discharge, and remain constant at a value of 0.044 in the study reach above a discharge of 600 m³/s. Although the estimated roughness coefficients show spatial variation, they also decrease with increasing discharge.

(2) Though the USGS method can provide approximate values for the roughness coefficient, it requires expertise or subjective judgment. Roughness coefficients for the study reach were individually estimated using several empirical formulae, including Strickler-type, power-based, and semi-logarithmic-based equations. Of these, Limerinos's formula gives the closest values to the roughness coefficients based on field measurement of the study reach for discharge over 400 m³/s.

(3) Roughness coefficients estimated in this study deviate by about +20% from the value officially designated by the BRP. Because of this, the effect of a 20% increase in the roughness coefficient on hydraulic variables computed with the simulation model was analyzed. A 20% increase leads to a 7% increase in water depth and an 8% decrease in velocity on average. It may also cause a 0.7 m increase in water depth and a 0.8 m/s decrease in velocity at a particular cross-section, relatively large changes considering the dimensions of the study reach.

(4) Uncertainty in the roughness coefficient caused by errors in water level and discharge measurement was examined for both low and flood flow. Though a 10% error in discharge may lead to 14.0% and 11.3% uncertainties in estimated roughness coefficients for low and flood flow, respectively, the corresponding uncertainty in computed water depth and velocity is reduced to almost 5% in both cases (except for a velocity error of 7% for low flow). This means that the roughness coefficient estimated by field measurement may be used to accurately estimate hydraulic variables. The necessity for roughness coefficient estimation by field measurement is confirmed.

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