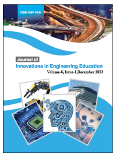

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Estimation of hydraulic parameter (Manning's roughness coefficient) in mountainous river at middle stage of Hindu Kush Himalaya region

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Abstract

Manning's roughness coefficient (n) holds significant importance within a hydrodynamic model, yet its value is notably subject to variation, influenced by both time and specific site conditions. Determining the appropriate value for 'n' is a challenging endeavour, particularly in natural watercourses, given the multitude of factors that impact this coefficient. The research unveils findings from a hydraulic model, examining the fluctuation of Manning's roughness coefficient concerning discharge, thereby influencing the flow depth in the mountainous areas of Nepal situated within the middle stage of the Hindu Kush Himalaya region. This study applied the unsteady flow model HEC-RAS to three comparable reaches in Nepal—the Bagmati River, Kamala River, and Kankai River—to determine the Manning's coefficient. Through the calibration method, which involves aligning the value to accurately replicate observed data, a suitable Manning's roughness coefficient "n" was identified. The findings indicate that this coefficient varies notably with reduced discharge and flow depth.

1. Introduction

Hydrodynamic models find extensive use in various practical applications like water resource management, project planning, and impact assessment [1, 2, 3]. The precision, stability, and robustness of a hydrodynamic model rely not only on the comprehensive foundational data employed in its construction but also on the appropriate selection of model parameters. Manning's roughness coefficient (referred to as 'n'), an essential dimensionless figure, significantly influences flow discharge and water level [4, 5]. It signifies the impact of flow resistance with genuine physical significance [6, 7]. Determining the value of 'n' in open channel flow hydraulics presents a challenging and innovative issue. The assessment of the 'n' coefficient becomes notably intricate due to its variations in both temporal and spatial dimensions. These variations in 'n' are dictated by the geometric, geomorphological, and hydraulic characteristics of the water flow and the beds of rivers or channels.

Numerous resources, comprising visuals like photos, tables, and various guides, have offered insights into the selection of Manning's roughness coefficient [8, 9, 6, 10]. However, the applicability of this empirical metric is influenced by fluctuations as well as a multitude of factors, including irregularities in rivers, alterations in cross-sections, meandering, presence of vegetation, obstacles, and variations in bed material [4, 6, 11, 12]. Additionally, these components of resistance exhibit changes across the river, leading to challenges in quantifying the 'n' values. Consequently, numerous studies have highlighted the crucial role of model calibration in determining these 'n' values [13, 14, 15]. The calibration of most mathematical models is necessary before practical implementation [16, 17]. Employing detailed measurement data in calibrating a hydrodynamic model

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facilitates the identification of the distribution of 'n' values [18]. Over the past decades, many researchers have turned to modeling approaches to analyze and estimate Manning's 'n' value, noting significantly improved outcomes compared to traditional statistical methods [19, 20, 21, 22, 23, 24, 25, 26, 27].

In the central region of the Hindu Kush Himalayas, the majority of river basins experience peak flows during the monsoon, driven by approximately 75% of the annual rainfall, significantly impacting flow dynamics and consequently altering Manning's roughness. Researchers have recently shown interest in employing various modeling techniques to predict hydraulic characteristics. This study endeavors to utilize the HEC-RAS hydraulic model to assess the fluctuations in Manning's roughness coefficient concerning discharge and resultant flow depth in the alluvial stretches of Nepal. Determining the Manning's coefficient is challenging due to its perpetual variability influenced by factors such as channel bed formations, obstructions, alterations in channel geometry, and the presence of vegetation within the channel. Particularly, Nepal's mountainous rivers exhibit diverse characteristics in terms of slope, discharge, channel structure, sediment composition, bed formations, and sediment deposition. Hence, this study adopts a calibration method to select an appropriate value for Manning's roughness coefficient ('n'), ensuring it accurately replicates observed data.

2. Model description

The software package of Hydrological Engineering Centre's River Analysis System (HEC-RAS) was developed by the United States Army Corp of Engineers which allows to perform one-dimensional and two-dimensional flow simulation both in steady flow as well as unsteady flow conditions. It is commonly used to compute water surface profiles and energy grade lines for different flow condition. The link between the river discharge, hydraulic resistance, river shape, and friction energy loss was provided by the model using empirical Manning's equation in the form of an equation (1). When channel geometry changed, energy losses were calculated by dividing the change in velocity head by the coefficients of contraction or expansion.

$$Q = K \cdot S_f^{1/2} \tag{1}$$

$$K = \frac{1}{n} A R^{2/3} \tag{2}$$

$$h_e = L S_f + C\left(\frac{\alpha_1 v_1^2}{2g} + \frac{\alpha_2 v_2^2}{2g}\right) \tag{3}$$

Where,
Q = discharge; K = conveyance of channel; S_f = energy slope; L = discharge weighted reach length; g = acceleration due to gravity; h_e = energy head loss; C = expansion or contraction coefficient; α_1 and α_2 = velocity weighting coefficient; v_1 and v_2 = average velocities; n = Manning's roughness coefficient; A = area of channel; R = Hydraulic radius.

3. Study reaches

For estimation of Manning's n, three different alluvium reach of three rivers (Bagmati River, Kamala River and Kankai River) was selected with in almost same elevation range. For each river reach, 2km river stretch was surveyed for further computation. Figure 1 shows the location of three reaches.

4. Methods

4.1. Geometric and hydrologic information

While simulating in HEC-RAS, the shape of the river reaches and the boundary conditions in upstream and downstream are essential inputs. Cross-sectional survey was employed to obtain the geometry of river reach. Each river reaches of 2 km with 100m spacing was survey used DGPD-RTK. Similarly, the measurement of flow and the survey of the water level were done concurrently. In each reach, the flow is measured three times, the water level is surveyed twice, and the third calculation is based on gauge readings.

4.2. HEC-RAS model set-up

The fundamental inputs for HEC-RAS simulation encompass geometric and flow data. Geometric data, crucial for the simulation, were established by outlining the river's path along with the flow direction. This process involved utilizing the 'River Reach' button in the HEC-RAS main menu, a procedure comprehensively detailed in the software manual. To input specific details for cross sections, the 'Cross-Section Data Editor' button within the same interface was utilized. This allowed for the entry of essential cross-section information including coordinates, downstream reach length, Manning's 'n' values, main channel specifics, and contraction or expansion coefficients. Determining the positions of river stations and their corresponding elevations on both the left and right banks played a pivotal role in ascertaining the cross-section coordinates as in Figure 2. For the purposes of this study's one-dimensional steady flow simulation, HEC-RAS offered multiple options for boundary conditions. The approach employed in this study involved utilizing the 'normal depth' method, where bed

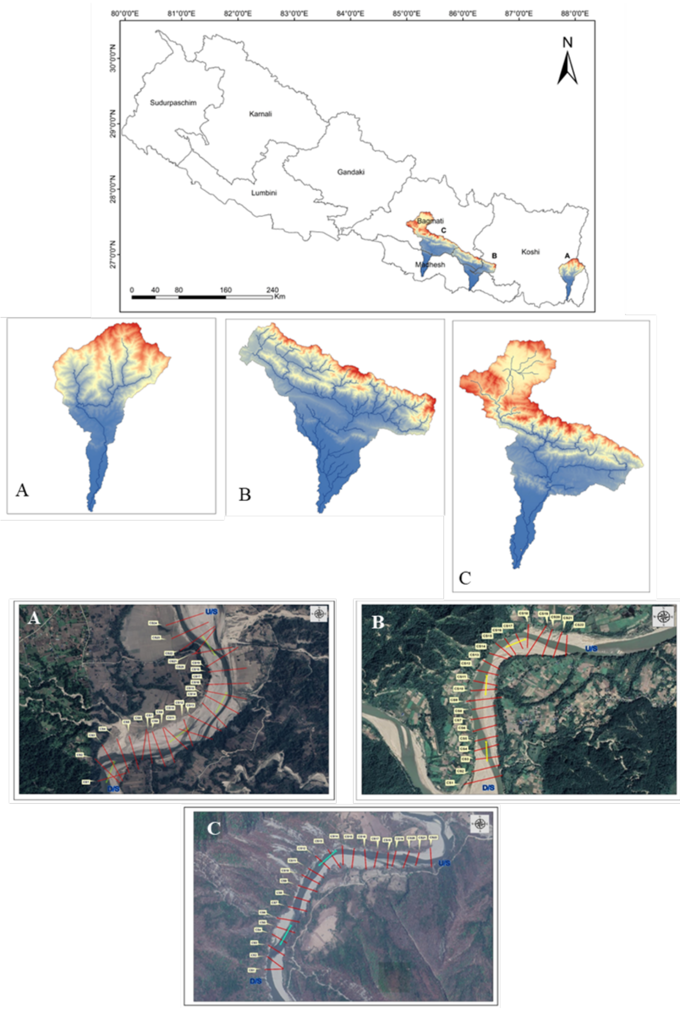


Figure 1: (A)Location of Kankai River reach, (B)Location of Kamala River reach and (C)Location of Bagmati River reach

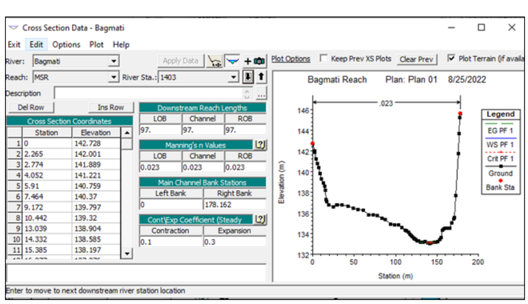


Figure 2: A sample cross-section in HEC-RAS of Bagmati River Reach

slopes in the upstream and downstream sections were specified as boundary conditions.

4.3. Estimation of Manning's Roughness Coefficient

The estimation of Manning's roughness coefficient is done by comparing known (measured) water level with simulated water level with model. To quantify the consistency in relation between observed and simulated value, four basic statistical method are used. The estimation of n-value follows the steps as shown in flowchart in Figure 3.

For estimation, the value of the Manning's roughness was increase by 0.005. The estimated value of the Manning's roughness coefficient was undertaken when the simulated water level is near to the observed water level.

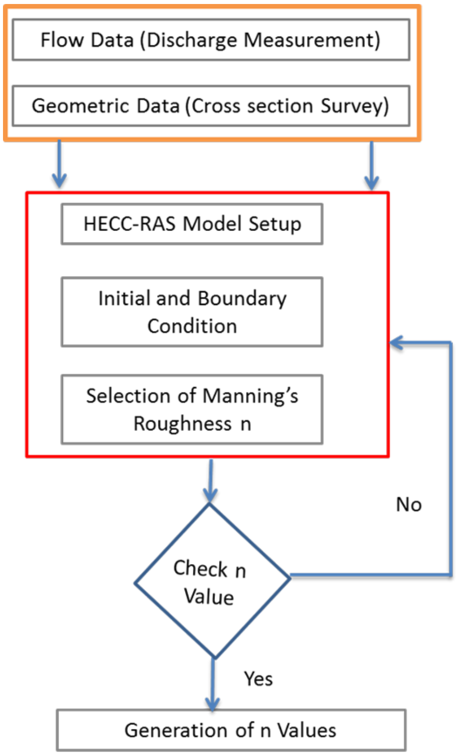


Figure 3: Flowchart for estimation of n-value

5. Results

5.1. Model calibration

During the calibration process, the Manning's coefficient "n" was systematically adjusted until the disparities between the observed and simulated water levels fell within acceptable margins. The step-by-step methodology employed in this calibration is visually detailed in the flowchart depicted in Figure 3. Following this calibration process led to the identification of the appropriate Manning's coefficient for the river stretch under examination. This calibration involved the use of three observed flows within each of the rivers: Bagmati, Kamala, and Kankai. Comparisons were made by assessing the outcomes of water level simulations in each cross-section against the observed water levels.

For Bagmati River, the Manning's roughness values that provided the closest match between the calculated water surface profile obtained through HEC-RAS and the measured profile were identified as 0.055, 0.03, and 0.02 for discharge rates of 11.29 m^3/sec, 83.201 m^3/sec, and 212.725 m^3/sec, respectively. In case of Kamala River, for the flow value of 2.63 m^3/sec, 85.748m^3/sec and 132.376 m^3/sec, the observed water surface profile is nearly matched with the simulated profile for n value of 0.09, 0.03 and 0.024 respectively. Similarly, in the case of the Kankai River, the Manning's roughness values that yielded the closest match between the calculated water surface profile generated by HEC-RAS and the measured profile were found to be 0.045, 0.025, and 0.021 for discharge rates of 7.965 m^3/sec, 130.37 m^3/sec, and 173.653 m^3/sec, respectively. Figure 4 to Figure 6 and Table 1 represent the water surface profile for different value of manning's n in three different respective rivers and three different flow conditions. Since the first measurement is done in low flow and second and third measurement is done in high flow, the variation of n along with the depth can be clearly seen.

A correlation between HEC-RAS n-values and river discharge for various flow conditions in the three distinct rivers was evident when plotted on a graph, displaying a polynomial relationship (refer to Figure 7). Thus, the relationship between Manning's n and discharge (Q) for three river Bagmati, Kamala and Kankai is represented by single polynomial equation as shown in 4,5, and 6 respectively:

$$0.1102Q^{-0.293} \tag{4}$$

$$n = 0.125Q^{-0.328} \tag{5}$$

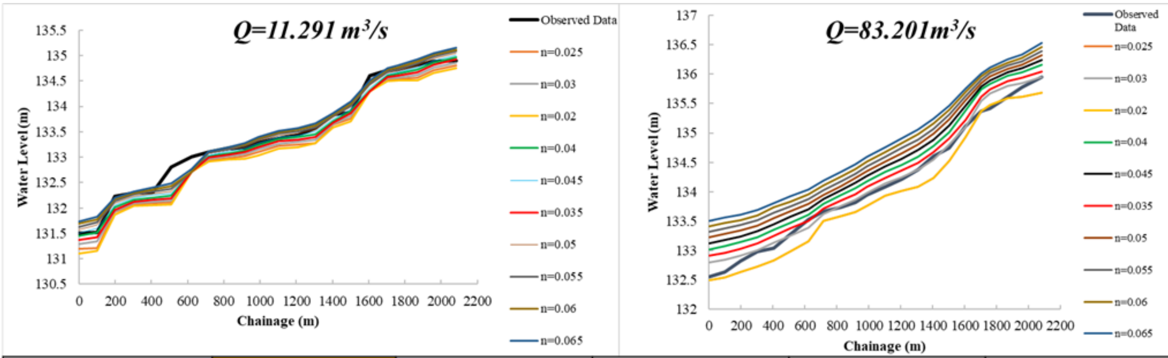
$$n = 0.0704Q^{-0.226} \tag{6}$$

The calculation of Manning's roughness coefficient on basis of empirical equation of the river reach is also calculated as Table 2:

The results mentioned above illustrate the association between 'n' values and flow depth alongside corresponding discharge, a concept elaborated by Jarrett (1989). Jarrett's work aims to elucidate how 'n' varies concerning flow depth and bed slope. Utilizing empirical formulas to derive 'n' values often yields higher values for increased discharge and flow depth. However, employing these formulas for calculating 'n' in cases of low flow may result in underestimation discrepancies.

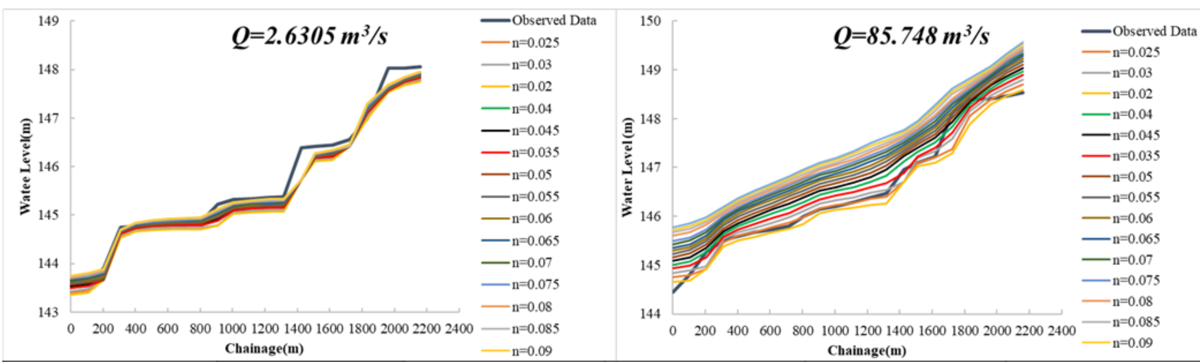
The alteration in flow discharge and channel geomorphology parameters, including local slope and cross-sectional shape, complicates the estimation of Manning's roughness coefficient in natural channels. Factors such as seasonal high flow discharge and extensive vegetation in the main channel exacerbate the challenges in estimation techniques. As a consequence, accurately estimating the Manning's roughness coefficient becomes more challenging.

Despite these difficulties, various publications highlight HEC-RAS as a powerful tool capable of providing dependable outcomes for estimating Manning's 'n' value.



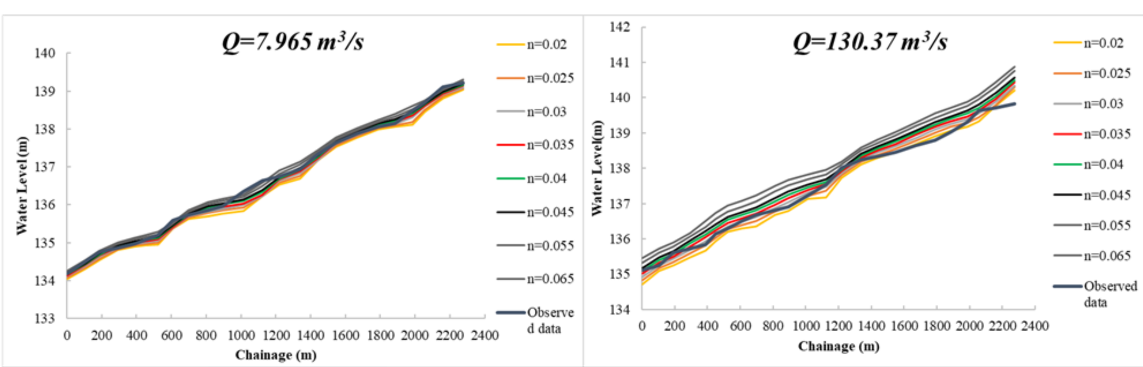
At Q=*11.291 m³/s*	n= 0.055	R-square = 0.98	PBIAS= -0.00085	NSE= 0.98	RMSD= 0.1413
At Q=*83.201 m³/s*	n= 0.03	R-square = 0.99	PBIAS= -0.04428	NSE= 0.99	RMSD= 0.1143

Figure 4: Comparison of HEC-RAS model results using different 'n' values with observed water surface profiles for varied flow conditions in the Bagmati River.



At Q=*2.6305 m³/s*	n= 0.09	R-square = 0.98	PBIAS= 0.0236	NSE= 0.98	RMSD= 0.198
At Q=*85.748 m³/s*	n= 0.03	R-square = 0.97	PBIAS= -0.03143	NSE= 0.97	RMSD= 0.2062

Figure 5: Comparative results of HEC-RAS model for various 'n' values against observed water surface profiles for different flow conditions in the Kamala River



At Q=*7.965 m³/s*	n= 0.045	R-square = 1	PBIAS= 0.008	NSE= 0.996	RMSD= 0.092
At Q=*130.37 m³/s*	n= 0.025	R-square = 0.99	PBIAS= 0.021	NSE= 0.99	RMSD= 0.169

Figure 6: Comparative results of HEC-RAS model for various 'n' values against observed water surface profiles for different flow conditions in the Kankai River.

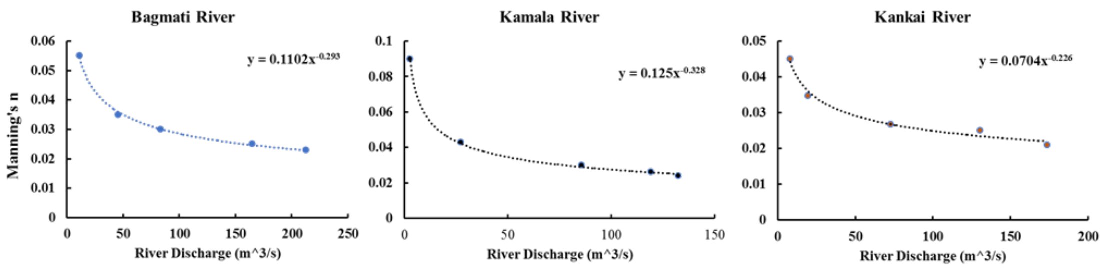


Figure 7: Polynomial relation between manning's n and river discharge for three different rivers; Bagmati, Kamala and Kankai.

Table 1: Comparative results of HEC-RAS model for various 'n' values against observed water surface profiles for different flow conditions in three different Rivers. (Bagmati River 3rd Measurement (Q=212.725 m^3/sec))

Description	Bagmati River		Kamala River		Kankai River	
Measured discharge m^3/sec	212.725		132.376		173.653	
Observed water level at gauging station (m)	136.302		146.251		137.318	
Manning's Roughness Coefficient (n)	Simulated water level (m)for					
n	0.03	136.48	0.03	146.4	0.025	137.41
n	0.025	136.35	0.025	146.27	0.023	137.36
n	0.022	136.28	0.022	146.18	0.022	137.34
n	0.023	136.3	0.024	146.24	0.021	137.32
n					0.02	137.18
Adopted Manning's Roughness Coefficient (n)	0.023		0.024		0.021	

Notably, while literature regarding the estimation of the Manning's 'n' roughness coefficient in intermittent rivers is scarce, this study presents rational results in this domain. The methodology applied and the results obtained here offer practical insights that could aid water managers and hydraulic modelers in estimating Manning's 'n' values in intermittent rivers, regardless of diverse climate conditions. This, in turn, allows for more

Table 2: Investigator Formulas and Values

Type	Investigator	Formula	Bagmati	Kamala	Kankai
Strickler	Strickler (1923)	$n = 0.047d_{50}^{1/6}$	0.026162	0.025154	0.024687
	Meyer-Peter and Muller (1948)	$n = 0.038d_{90}^{1/6}$	0.024395	0.02451	0.024538
	Keulegan (1938)	$n = 0.039d_{50}^{1/6}$	0.021709	0.020873	0.020485
	Bray (1979)	$n = 0.0593d_{50}^{1/6}$	0.033009	0.031737	0.031148
	Bray (1979)	$n = 0.0495d_{90}^{1/6}$	0.031778	0.031927	0.031964

accurate predictions, particularly in assessing flood inundation hazards and similar scenarios.

6. Conclusion

Comprehensive comprehension of fluvial processes is crucial, particularly in highly variable alluvial rivers, as water stands as a primary driver behind various phenomena occurring within the river's stretch. In recent time, hydraulic modelling is considered as a most important tool for water management. In prediction of flood, inundation mapping and other various hydrodynamic modelling, Manning's roughness coefficient plays important role. Since n-value depends upon various physical parameter, it is complex to estimate for a reach. In Nepal, river at southern part of Hindu Kush Himalaya comprises of alluvium channel and exhibits complex nature. In order to overcome the complexity of river nature and resultant hazardous situation, river modelling is an important aspect for analysing risk. Manning's roughness coefficient is fundamental parameter for any kind of modelling, so it is important to estimate the n-value in alluvium channel.

The study tends to estimate Manning's roughness coefficient within an alluvium reach where three reach from different river are taken into consideration. To fulfil the objective, three discharge measurement and corresponding water level survey in each reach is carried out. In the measured discharge, first measurement represents low flow whereas second and third measurement represents high flow. The estimation of Manning's roughness coefficient was done on basis of each measured data which results systematic decrease of n value on increasing discharge (i.e., increase in flow depth and velocity). The result resembles theory proposed by Jarrett which explains the explicit relation of n value with hydraulic radius and bed slope.

This study exhibits the HEC-RAS model's capacity to analyse the flow regime in three distinct rivers in Nepal: The Bagmati, Kamala, and Kankai Rivers. Distributed data from several cross-sections upstream and downstream of the reference station were used in this study. So, understanding the parameters needed by a model and how to interpret the analysis findings that the model produces is important, independent of the type of model that we selected to do the analysis. It is important to note that there are several uncertainties that might impact the estimated results, such as the cross-simplified section's geometry, the precision of the velocity measurement, the representativeness of the water surface slope, and others. Moreover, due to the curvature of the channel, localized changes in geometry and 2D impacts may also have an impact on the actual water surface profile. In terms of future studies, it would be fascinating to investigate the economic effects of accurately estimating the Manning's n roughness coefficient when creating comprehensive maps of flood hazards or when designing infrastructure (e.g., culvert, bridges).

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