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Methods for Predicting the Values of Manning's Roughness Coefficient: State of the Art

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ABSTRACT

Manning's roughness coefficient (n) is crucial for reliable hydraulic analysis of natural and artificial open channels. This paper presents a state-of-the-art work on principles of flow resistance mechanisms of natural channels and n estimation approaches. Furthermore, it reviews classical empirically driven approaches, such as Strickler, Cowan, Meyer–Peter and Müller, Limerinos, and Henderson, as well as tabulated, photographic, and storage-based techniques. The latter is a consideration in terms of formulations that factor into vegetation effects, bed material characteristics, bedform-induced resistance, and composite channel roughness. Newer advances in entropy theory, statistical approaches, and data-driven methods are also introduced. The study describes both the advantages and disadvantages of specific methods and shows that no way to predict Manning's n can be applied universally under different flow conditions and channel types. Instead, the precise estimation has to be based on empirical field observations, analytical construction, and engineering judgment. The observations support the use of an integrated and hybrid approach and can be supplemented with high-resolution measurements and standardized databases for the purpose of minimizing prediction uncertainty for the roughness estimation. This review contributes to enhancing the knowledge and application base of researchers and practitioners in river hydraulics, channel design, and flood modeling.

Keywords: Manning's roughness, Natural rivers, Resistance mechanisms, River hydraulics.

1. INTRODUCTION

In any engineering studies dealing with rivers and river intersections, such as barrages, bridges, intakes, regulators, and diversion weirs, knowing the flow velocity and depth is essential. The majority of hydraulic computations for flow in channels and overbank areas require evaluating flow resistance, typically described by Manning's roughness coefficient (n). While some books in the field of open channel hydraulics, river morphology, and river engineering include chapters on river bed and bank roughness coefficients, and empirical

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investigations in this field have been conducted for over a century **(Melese, 2018)**, this topic continues to be researched by scholars and government practitioners worldwide. The hydraulic roughness coefficients of rivers are affected by many factors since rivers flow under various and complex conditions. Hence, many studies have been conducted on different environments, and a broad array of relationships has been proposed. This is why experts who perform engineering studies of rivers must possess knowledge not only of the effective factors influencing rivers but also of the diverse environments involved within them. For n, there is a series of equations to resolve (or at least make predictions about) the values, but none of these can, by itself, make clear the discharge of the river being studied **(Isma et al., 2025)**.

The morphology of natural channels and rivers depends on the collision, friction, and momentum change of the flowing water with the bed material **(Chang, 2008)**. Flow velocity is strongly affected by flow resistance, which is an essential feature in this collision. Drawdown resistance equations often rely on the roughness of particles and the combination of it with flow conditions, but Manning's roughness coefficient is used in the real world to predict the extent of roughness in natural channels. It is a fascinating issue to determine roughness coefficients in hydraulics **(Shen et al., 2026).**

The Manning equation, which combines measurements of channel geometry and slope with an estimate of resistance to flow (Manning's n or roughness) to estimate stream velocity. This estimated velocity is multiplied by the cross-sectional area of the channel to calculate discharge. There can be, however, substantial error in discharge estimates based on the Manning equation. These poor estimates of discharge often occur because the estimates of flow resistance are incorrect **(Marcus et al., 1992)**.

However, (**Chow, 1959)** indicated that the value of n is highly variable and depends on surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstruction, size and shape of channel, and stage and discharge. Selecting Manning n values is a judgment and skill-driven procedure. It can only be trained through experience. For rivers in developed societies, government bodies and private sectors will continue to investigate ways of predicting their n values **(Afzal et al., 2022; Nama et al., 2025).**

This review paper aims to summarize, analyze and evaluate the latest methods used to estimate Manning's n roughness modulus in open channels and natural rivers, comparing traditional and modern methods, including those based on remote sensing and artificial intelligence, and outlining their advantages, limitations and areas of application, to guide researchers and engineers to choose the most appropriate method according to the channel characteristics and flow conditions.

2. PRINCIPLE OF ROUGHNESS COEFFICIENT OF NATURAL RIVER BED

The river beds, such as mountain and lowland tributaries and streams, have varied geometry (sinuous paths, irregular cross sections, and varied longitudinal slopes). Furthermore, the changes in hydraulic characteristics of flow throughout the length, width, and depth of rivers are very frequent; see **Fig. 1**. Moreover, the construction of hydraulic structures in river beds abruptly changed the natural regime of the river **(Jovanović, 1994).**

In natural beds, the most significant factors affecting the roughness coefficient are the cross-section irregularity, river bed gullies, and scouring of alluvium. Also, the roughness coefficient changes along the river bed when the water depth is changed see **Fig. 2 (Gurnell and Midgley, 1994; Anderson et al., 2006).**

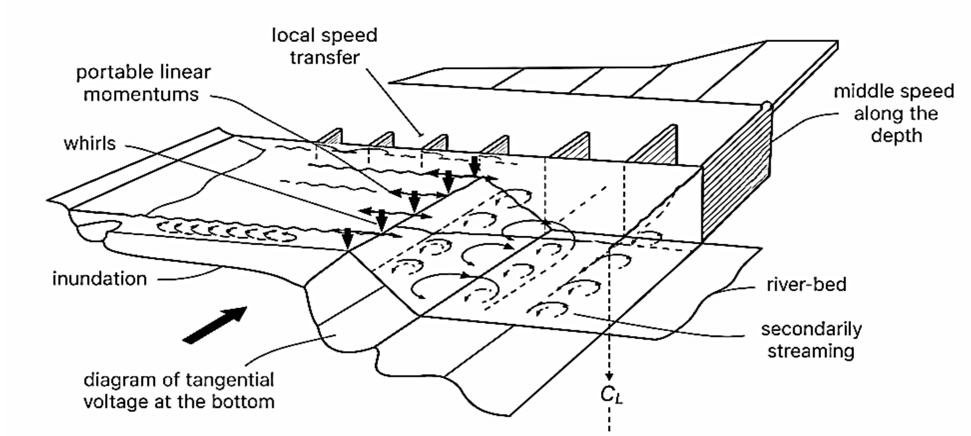

Figure 1. Conceptual model of changes in hydraulic characteristics of flow throughout a river reach **(Elvis et al., 2009).**

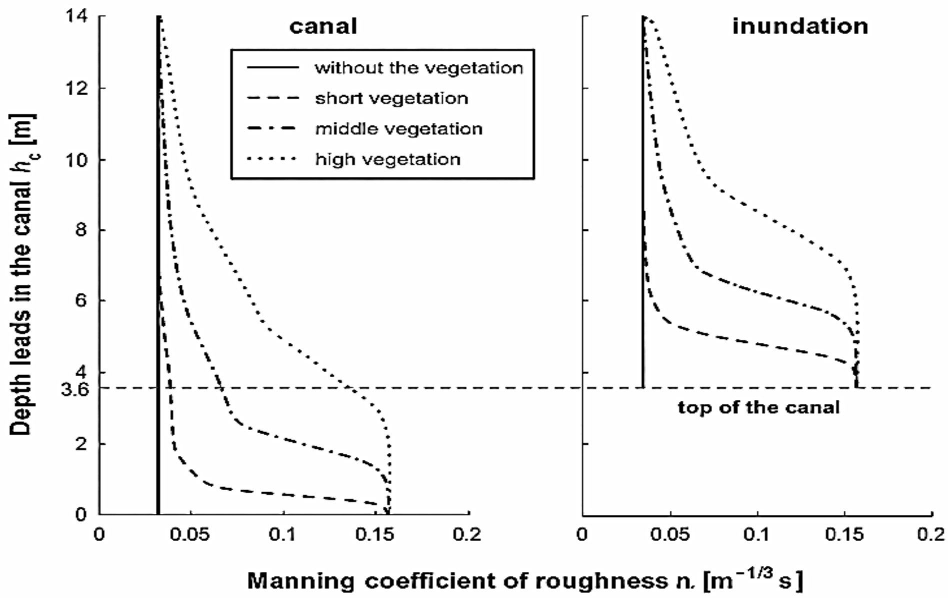

Figure 2. Variation of roughness coefficient with water depth in the main canal and inundation banks **(Elvis et al., 2009).**

With the same river bed, the roughness coefficient varied with the status of vegetation that covers the bed. However, the river bed of tall vegetation has an approximately constant roughness coefficient **(Chen et al., 2023)**, while this coefficient changes with time in case of short and middle vegetation, as shown in **Fig. 3**.

The flow patterns and channel roughness are significantly estimated by the flood wave speed **(Fisher and Reeve, 1994; Kouwen and Fathi-Moghadam, 2000).** Higher flood waves are subjected to a smaller influence of roughness compared to lower flood waves. The roughness coefficient at many water currents decreases with increasing water depth. However, as soon as the flood banks are inundated, the roughness coefficient is sharply increased, see **Fig. 2 (Barnes, 1967; Anderson et al., 2006).**

In open channel flow with a complete roughness, the vertical velocity profile is represented by the logarithmic law. The Prandtl logarithmic law modified by **(Nikuradse, 1933)** can be used to describe this profile mathematically **(Stephan and Gutknecht, 2002).** Different equations for determining the velocity profile for the submerged vegetation, which is based on the modified Prandtl logarithmic law, are shown in **Table 1 (Stephan and Gutknecht, 2002).**

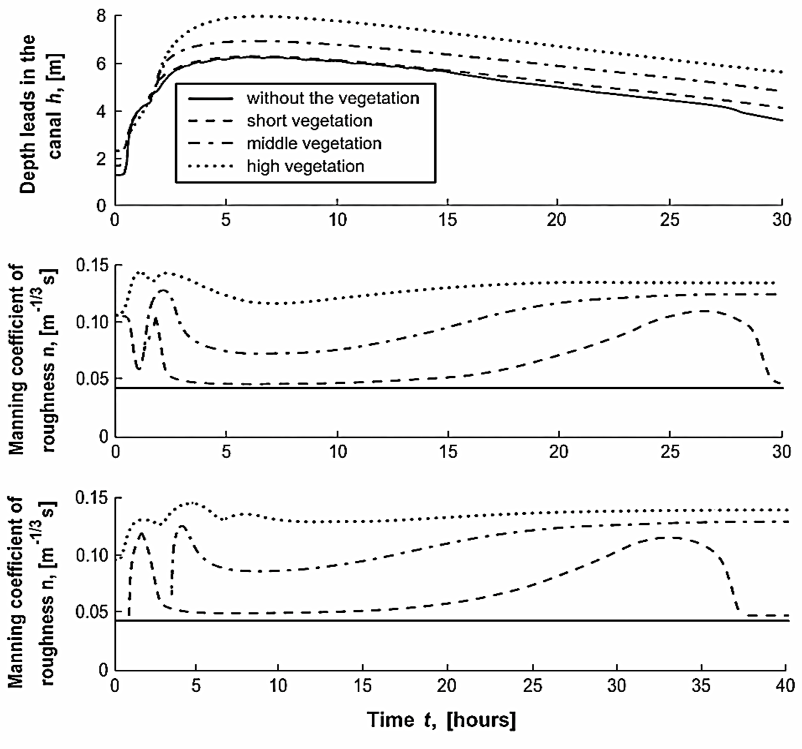

Figure 3. Change of Roughness coefficient with time for different vegetation heights **(Elvis et al., 2009).**

3. METHODS FOR DETERMINING MANNING'S ROUGHNESS COEFFICIENT

The Manning equation is an empirical equation used to determine the average flow velocity in a uniform open channel. In Europe, it is also known as Manning's formula, the Gauckler-Manning-Strickler formula, Gauckler-Manning-Strickler, or Gauckler-Manning formula. It was presented in 1867 by Philippe Gauckler. In 1890, Robert Manning developed this equation **(Chow, 1959; Bahramifar et al., 2013).**

Table 1. Velocity profile determination methods over the vegetation **(Stephan and Gutknecht, 2002).**

Author	Velocity distribution across the vegetation
(Plate and Quraishi, 1965)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \frac{y - h_p}{n_{ras}}$
(Kouwen and Coworkers, 1969)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \frac{y}{n_{ras}} + c$
(Nnaji and Wu, 1973)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \frac{R}{n_{ras}}$
(Haber, 1982)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \frac{y}{n_{ras}} + \frac{v_{yP}}{v_o}$
(Murota and Coworkers, 1984)	Slow s way: $\frac{v}{v_o} = \frac{1}{\kappa_o} ln \left(y - \left(h_p - h^{'}\right) + c\right.$
	Rapid sway: $\frac{v}{v_o} = \frac{1}{\kappa_o} ln\, y + c$

(Christensen, 1985)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \left\{ \frac{y - (h_p - \varepsilon/29.7)}{\varepsilon} \right\} + 8.5$
(Temple, 1986)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \ (y - \ \alpha_{yp}) + c$
(Watanabe and Kondo, 1990)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \ \left\{ \frac{y - (h_p - h^{'})}{n_{ras}} \right\}$
(El-Hakim and Salama, 1992)	$\frac{v}{v_o} = A + \frac{1}{B} ln \left\{ \frac{y}{h_p} \right\}$
(Klopstra and Coworkers, 1997)	$\frac{v}{v_o} = \frac{1}{\kappa} ln \left\{ \frac{y - (h_p - h^{'})}{n_{ras}} \right\}$

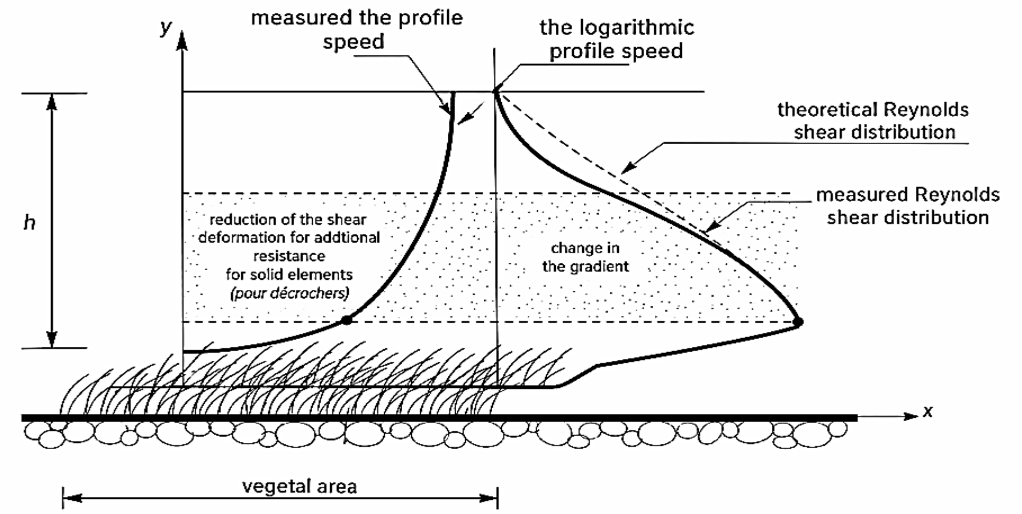

Figure 4. Spreading of the predominant vegetation boundary layer **(Stephan and Gutknecht, 2002).**

$$v = \frac{1}{n} R^{2/3} S^{1/2} \quad (1)$$

where v is the flow velocity (m/s), S is the energy gradient, n is the roughness coefficient or resistance to flow ($m^{-1/3}$ s), and R is the hydraulic radius (m).

Comparing Eq. (1) with the Chezy formula, ($v = C\sqrt{RS}$), where $C = \sqrt{8g/f}$ (C is known as the Chezy coefficient, f is the Darcy–Weisbach friction factor, g is gravity acceleration), resulting that $C = \frac{1}{n} R^{1/6}$ and $f = \left(\frac{n^2}{R^{1/3}}\right)(8g)$. Various investigators propose varieties of expressions for the Chezy coefficient. Most of these are archaic and relevant only to the past (**Subramanya, 2009; Imed et al., 2018**). These expressions are considered in this paper. Because most of the river flow is in a rough turbulent region, Manning's formula Eq. (1) is considered, for practical purposes, the most convenient one. It has a simple form and is also subsidized by considerable experience. Therefore, it is the most suitable choice in open channel flow hydraulics **(Sanz-Ramos et al., 2021)**. The Manning equation assumes uniform flow. However, it fails to account for resistance in cases where the Reynolds number effect is predominant. In addition, limitations of the Manning equation and hydraulic calculations include streams subject to debris flow, very high-gradient streams, and modification of the channel during a flood **(Subramanya, 2009; Barnes, 1967)**.

Numerous studies were conducted to investigate and predict Manning's roughness coefficient (n). Considering the principles of the roughness coefficient and the factors that influence the estimated value of this coefficient, various approaches and methods were developed and used for estimating Manning's roughness coefficients (n). Most of these methods are described below.

3.1 Storage Methods (SCS Method)

The Soil Conservation Service (SCS) method (storage method) is used to estimate n value through the division of base n values for a regulated bed, a straight and uniform channel. This value is modified by multiplying it by a correction factor estimated by critical observation. In this method, the flow turbulence is used as an indicator or measure of the hindrance degree **(USACE, 1994)**.

3.2 Ven Te Chow Method

The Ven Te Chow method (1959) is utilized for determining the n in natural beds of open channels by using tabulated values presented based on measured n values in specific channel beds **(Chow, 1983)**. In these tables, the maximum, normal, and minimum rates of n for each type of channel bed are illustrated. Usually, such tables are available in most literature that deals with the determination of natural open channels, as shown in **Table 2 (George and Verne, 1989).**

Table 2. Manning's coefficients (n) of different channel types **(George and Verne, 1989).**

Natural Channels	**Minimum**	**Normal**	**Maximum**
Minor Streams (top Width at flood stage<30 meters)			
Streams on plain:			
Clean, straight, full stage, no refit or deep pools	0.025	0.030	0.033
Same as above, but with more stones and weeds	0.030	0.035	0.040
Clean, winding, same pools and shoals	0.033	0.040	0.045
Same as above, but some stones and weeds	0.035	0.045	0.050
Same as above, but lower stages, more ineffective slopes and sections.	0.040	0.048	0.055
Clean, winding, same pools and shoals, some weeds, and many stones	0.045	0.050	0.060
Sluggish reaches, Weedy, deep pools	0.05	0.070	0.080
Very weedy reaches, deep pools, or floodways with a heavy stand of timber and underbrush.	0.075	0.100	0.15
Mountain streams, no vegetations in channels, banks usually steep, trees and brush along banks submerged at high stages:			
Bottom gravel, cobbles, and a few boulders	0.030	0.040	0.050
Bottom cobbles with large boulders	0.040	0.050	0.070
Flood Plains			
Pasture, no brush:			
Short grass	0.025	0.030	0.035
High grass	0.030	0.035	0.050
Cultivated areas:			
No crop	0.020	0.030	0.040
Mature row crops	0.025	0.035	0.045
Mature field crops	0.030	0.040	0.050

Brush:			
Scattered brush, heavy weeds	0.035	0.050	0.070
Light brush and trees, in winter	0.035	0.050	0.060
Light brush and trees, in summer	0.040	0.060	0.080
Medium to dense brush, in winter	0.045	0.070	0.110
Medium to dense brush, in summer	0.070	0.100	0.160
Trees:			
Dense willows, summer, straight	0.110	0.150	0.200
Cleaned land with tree stumps, no sprouts	0.030	0.040	0.050
Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
Same as above, but the flood stage reaches the branches	0.100	0.120	0.160
Major Streams (top Width at flood stage>30 meters)			
Regular section with no boulders or brush	0.025	---	0.060
Irregular, regular, and rough section	0.035	---	0.100
Lined channels			
Concrete-lined	0.012	---	0.018
Concrete rubble	0.017	---	0.030
Unlined channels			
Earth is straight and uniform	0.017	---	0.025
Winding and sluggish	0.022	---	0.030
Rocky beds, weeds on banks	0.025	---	0.040
Earth bottom, rubble sides	0.028	---	0.035
Rock cuts	0.025	---	0.045

3.3 Photographic Method

The hydraulic parameters describing flow can be combined with the geometry of riverbeds to calculate the surface resistance coefficient. The American Geophysical Union (AGU) uses a program to provide hydrotechnicians with an accuracy of about ±15% to determine this resistance coefficient for flow through a canal under varying flow conditions. The approach comprises a series of photographs that reveal every required kinematic and geometric characteristic of the bed section studied **(Elvis et al., 2009; Antonino et al., 2021)**. Based on the above photos, some parameters are visible:

- The location where the flood line is visible on the bed,
- Peak flow in the canal, collected by a specialized hydrometric wing,
- High water level marks that help to provide surface profile information at maximum flow,
- Peak flow boundaries relative to the canal's shores.

Using an estimate of the calculated flow rate, water surface shapes, and observations made in more than two cross sections of the bed, the value of n is also estimated **(Gurnell and Midgley, 1994)**.

3.4 Slope-Area Back-Calculation Method

The slope-area back-calculation method is an indirect hydraulic technique used to estimate hydraulic roughness or discharge parameters in open waterways based on measured field data **(Guardiola-Albert et al., 2021)**. This method relies on the concept of quasi-uniform flow and the application of Manning's equation, Eq. (1), to a selected section or group of sections of the waterway. It is widely used in hydraulic studies and numerical model calibration, particularly when field measurements of discharges or water levels during floods are available **(Xinyue et al., 2026)**. In this method, when the field-measured discharge value, cross-sectional characteristics, and water surface slope are available, Manning's equation, Eq. (1), can be rearranged to extract the roughness coefficient value **(Takata et al., 2024)**.

3.5 HEC-RAS Inverse Calibration Method

The HEC-RAS inverse calibration method is a modern technique used to estimate Manning's n through the inverse calibration of hydraulic models. This method relies on using the HEC-RAS model to simulate flow in canals and rivers, then iteratively adjusting the Manning coefficient values until the best match is achieved between the calculated water levels and the measured water levels in the field **(Ameer, 2016; Xiaofeng and Yalan, 2025)**. This methodology is widely used in hydraulic studies and numerical model calibration due to its ability to represent spatial variations in roughness along the watercourse.

The theoretical basis of the method relies on the gradually varied flow equations solved by the HEC-RAS software, where the water surface level is calculated based on the energy equation between successive sections **(Sarmad et al., 2020)**. The calibration process begins by inputting the measured cross-sections, discharges, and observed water surface levels. The n values are then adjusted using differential optimization techniques to minimize the discrepancy between the calculated and measured levels **(Serrano-Núñez et al., 2022)**. Calibration performance is typically measured using an error function such as root mean square error, coefficient of determination, Nash–Sutcliffe Efficiency, and percent bias **(Attari et al., 2021; Abouelsaad et al., 2024)**.

3.6 LiDAR and Land Cover Mapping

LiDAR and Land Cover Mapping is a modern method for estimating n using remote sensing techniques and high-resolution spatial data **(Hossain et al., 2009)**. This method integrates satellite land cover classification data with airborne laser scanning data, providing accurate models of the land surface, elevations, vegetation cover, and natural and man-made obstructions **(Ahmed and Nagwa, 2012)**. This integration allows for a more accurate characterization of the physical properties of river channels and floodplains than traditional methods that rely solely on field observations.

The theoretical basis of the method rests on the principle that the value of n is directly related to the degree of surface roughness, which is influenced by the type of land cover, vegetation density, surface shape, and the presence of obstructions within and along the river channel **(Chaojie et al., 2025).** By classifying land cover into different categories (such as water bodies, agricultural land, forests, urban areas, and bare land), initial n values are assigned based on reference tables published in engineering and hydraulics literature, such as **(George and Verne, 1989; Papaioannou et al., 2022).** LiDAR data are also used to extract additional indicators, such as vegetation height and density, surface slope, and terrain roughness, allowing for spatial adjustments to the n values and improving their accuracy.

This method is advantageous because it can produce continuous spatial maps of the n values covering large areas, while reducing the effort and time required for field surveys. This makes it suitable for runoff and flood modeling and hydraulic simulation applications, particularly in large river basins and hard-to-reach areas **(Zhang and Li, 2022; Wang et al., 2023)**.

3.7 Neural Networks and AI Regression Method

The Neural Networks and AI Regression method is one of the most advanced approaches for estimating n. It utilizes machine learning and deep learning techniques to analyze large amounts of data from multiple sources and extract nonlinear relationships between the physical properties of a river channel and n values **(Abinash and Jahnvi, 2025)**. The data used includes satellite imagery, LiDAR data, digital elevation models (DEMs), hydrological and hydraulic data, soil and land cover properties, and field measurements of Manning's coefficient.

The theoretical foundation of this method rests on training an AI model using a dataset containing input variables (features) and measured or estimated values of n (target variables) **(Mohammad et al., 2023; Liu et al., 2026)**. During the training process, the neural networks or intelligent regression models learn the complex patterns and relationships between river channel properties and surface roughness without requiring any predefined mathematical assumptions. After validating the model's performance using independent data, it becomes capable of predicting n values at new locations based on their spatial and environmental characteristics.

This method is distinguished by its ability to integrate large and diverse datasets and address the interplay of factors affecting watercourse roughness, resulting in higher accuracy compared to traditional methods, especially in areas with significant spatial variability (**Irzooki and Najem, 2022**). Furthermore, the models can be continuously updated as new data becomes available, making them an effective tool for producing spatial maps of the n and supporting hydraulic modeling, flood analysis, and water resource management applications, particularly in light of ongoing advancements in artificial intelligence and remote sensing technologies **(Kuras et al., 2021; Khodnevych and Stefanyshyn, 2023)**.

3.8 Empirical Methods and Formulas for Determining Manning Coefficient

3.8.1 Strickler

Nowadays, several empirical equations are utilized for determining the n value. One of the oldest methods is that presented by Strickler in 1923 **(French, 1986; Behzad and Behreza, 2015).** Also, **(Samer et al., 2019; Binh et al., 2024)** used this old equation:

$$n = 0.047 \times d_{50}^{1/6} \quad (2)$$

where d_{50} represents the particle size (m) of a slope revetment and channel bed where 50% of the bed material is finer.

3.8.2 Meyer – Peter, Muller

For mixtures of bed materials with considerable coarse-grained sizes, **(Meyer et al., 1948)** presented a modified expression:

$$n = 0.0384 \times d_{90}^{1/6} \quad (3)$$

Where d_{90} is the particle diameter (mm) of the grains that compose 90% of the bed material. This equation is reported to be useful in predicting n in mountain streams paved with coarse gravel and cobbles **(Subramanya, 2009; Ji-Sung et al., 2010).**

3.8.3 Cowan

(Cowan, 1956) developed a procedure for estimating the n value based on the hydraulic and geometric characteristics of the channel **(Čubanova et al., 2025)**.

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m \quad (4)$$

where n_o is the basic value of n, which is constant for the smooth uniform and natural component, n_1, n_2, n_3, n_4, and m are additional values for comprising the effect of surface irregularities, variations in the size and shape of the channel cross section, barriers, flow and vegetation conditions and meandering, see **Table 3**, as cited by **(Chow, 1959**).

Table 3. Estimated n value by Cowan **(Chow, 1959**).

Variable	Description Channel	Recommended Value
Basic, n_0	Earth	0.020
	Rock	0.025
	Fine Gravel	0.024
	Coarse Gravel	0.028
Irregularity, n_1	Smooth	0.000
	Minor	0.005
	Moderate	0.010
	Severe	0.020
Cross section, n_2	Gradual	0.000
	Occasional	0.005
	Alternating	0.010-0.015
Obstructions, n_3	Negligible	0.000
	Minor	0.010-0.015
	Appreciable	0.020-0.030
	Severe	0.040-0.060
Vegetation, n_4	Low	0.005-0.010
	Medium	0.010-0.020
	High	0.025-0.050
	Very High	0.050-0.100
Meandering, m	Minor	1.000
	Appreciable	1.150
	Severe	1.300

3.8.4 Henderson

(Henderson, 1966) indicated that these experiments were based on current flow in a channel of a pebbly bed, and d was the mean particle diameter of the bed material. However, **(Henderson, 1966)** presented Eq.(5) for determining n **(French, 1986; Hooman and Mohsen, 2010)**:

$$n = 0.034 \times d_{50}^{1/6} \quad (5)$$

3.8.5 Limerinos

(Limerinos, 1970) presented the empirical equation for calculating the n value based on determining the R and d_{84} (within a range of 1.5 to 250 mm) **(Anonym, 1994; Clancy, 2021).** This equation was developed based on experimental measurements of eleven water fluxes with a range of bed material textures from small gravel to medium-sized pebbles **(Aizhong et al., 2018**).

$$n = \frac{0.8204R^{1/6}}{1.16+2.0log\left(\frac{R}{d_{84}}\right)} \tag{6}$$

3.8.6 Petryk and Bosmajian

In 1975, Petryk and Bosmajian presented a new approach for evaluating the vegetation density to determine the n value for very small depths of inundation **(Chow, 1983; Gurnell and Midgley, 1994)**. Based on the longitudinal forces that can be determined by substituting the Manning equation, Eq. (7) was obtained to calculate the n value. However, **(Simons and Senturk, 1976)** showed that, according to experimental findings of Stickler, equation (2) cannot be used in movable bed channels **(French, 1986).**

$$n = n_0\sqrt{1+\left(\frac{C^*\times\sum A_i}{2gAL}\right)\left(\frac{1}{n_0}\right)^2}\,R^{4/3} \tag{7}$$

where no is the n of channel boundary ($m^{-1/3}s$) (vegetation impact is included), C* is the real friction coefficient of vegetation in the current direction, ΣAi is the total frontal surface of the vegetation which impedes the current (m^2), g is the gravity acceleration constant (m/s^2), A is the area of the bed cross section (m^2), L is the channel length (m), and R is channel hydraulic radius in (m).

3.8.7 Raudkivi

Raudkivi modified computations of the Strickler method in 1976 and presented Eq. (8) evaluation of n computations **(Raudkivi, 1990**):

$$n = 0.042 \times d^{1/6} \tag{8}$$

Where d is the average particle size in (m). Then Eq. (9) was developed to be:

$$n = 0.013 \times d_{65}^{1/6} \tag{9}$$

where d_{65} is the particle diameter (mm) of the grains that compose 65% of the bed material. Then, Raudkivi indicated that Eqs. (8) and (9) can be utilized for specifying the roughness height in the stabilized river bed in hydraulic models.

3.8.8 Burkham and Dawdy

In 1976, Burkham and Dawdy pointed out that Limerinos' formula for calculating the n value applies to the upper flow regime in sandy bed channels. In Strickler's equation for solid beds, the absolute surface roughness depth (ε) is related to the d_{50} size of the bed sediment **(Chow, 1983).**

$$n = C\varepsilon^{1/6} \quad (10)$$

At $\varepsilon=d_{90}$ for riprap rampart and discharge capacity of channel riprap, the Chezy coefficient (C) equals 0.034 and 0.038, respectively. Whereas for natural sediment, C has a value of 0.034 at $\varepsilon=d_{50}$.

3.8.9 Garde and Raju

In 1978, Garde and Raju noted that Strickler's analysis focused on various natural channels in Switzerland. These channels featured rough bed materials and were free of waves **(French, 1986).** Based on the work of these authors, the roughness coefficient is calculated using the following formula:

$$n = 0.039 \times d_{50}^{1/6} \quad (11)$$

where d_{50} is the particle diameter (mm) of the grains that composes 50% of the bed material.

3.8.10 Subramanya

(Subramanya, 1982) developed Eq. (12) for calculating the n value.

$$n = 0.047 \times d_{50}^{1/6} \quad (12)$$

3.8.11 Arcement and Schneider

In 1989, Arcement and Schneider refined the equation of **(Cowan, 1956)** and introduced the term stream power. They included a correction factor which adjusts the sinusoidal element (m) to 1 in this case by considering the variations in channel size and channel shape. In this equation, the value of n_2 was assumed to be zero, then the equation became:

$$n = (n_b + n_1 + n_3 + n_4)\text{m} \quad (13)$$

which n_b is the basic value of n in the open-land surface.

n_b selection for floodplains is the same as for channels. To aid in this process, they issued a guide to estimating n values. The guide offers an approach that assigns reliable n values to channels and floodplains. It starts with a base value for the channel and then makes adjustments according to various roughness factors. The final estimate of n is arrived at through a series of decisions reflecting how those elements interact.

3.8.12 Brownlie

(Brownlie, 1983) established a relationship to estimate n, Eqs. (14) and (15), in lower regime flow conditions based on hydraulic conditions and bed material properties through large amounts of field and flume experimental data **(Aminuddin et al., 2007)**.

$$n = \left[1.6940\left(\frac{R}{d_{50}}\right)^{0.1374} S^{0.1112} G^{0.1605}\right] 0.034{d_{50}}^{0.167} \quad (14)$$

In conditions of upper regime

$$n = \left[1.0123\left(\frac{R}{d_{50}}\right)^{0.0662} S^{0.0.0395} G^{0.1282}\right] 0.034 {d_{50}}^{0.167} \quad (15)$$

where d_{50} is the median particle size of the bed material (ft), G is the coefficient of gradation on the base material, S is the slope of the line (ft/ft), and R is the hydraulic radius (ft).

$$G = \frac{1}{2}\left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}}\right) \quad (16)$$

3.8.13 Karim and Kennedy

(Karim and Kennedy, 1990) presented a relationship to calculate the value of n, Eq. (17). This relationship can be applied to the data field and flume.

$$n = 0.037 {d_{50}}^{0.126} \left(\frac{f}{f_0}\right)^{0.465} \quad (17)$$

d_{50} in (m), f is total friction factor, f_o is grain friction factor and $\frac{f}{f_0} = 1.20 + 8.92\frac{\Delta}{h}$
Where Δ is the dune height and h is the flow depth.

3.8.14 Rickenmann

The total Manning roughness coefficient is derived by **(Rickenmann, 1994)** equation.

$$\frac{1}{n_{tot}} = \frac{0.56 g^{0.44} Q^{0.11}}{S^{0.33} d_{90}^{0.45}} \quad (18)$$

n_{tot} is the total Manning's roughness coefficient in $T/L^{1/3}$. Q is the flow discharge in L^3/T.

3.8.15 Rickenmann Depth-Relative Flow

(Rickenmann, 2005) developed a simple relationship with loss calculation through relating the flow resistance, depth of relative flow, and drag as a function of the slope.

$$\frac{n'}{n_{tot}} = 0.083 S^{-0.35} \left(\frac{h}{d_{90}}\right)^{0.33} \quad (19)$$

$n' is$ grain roughness.

3.8.16 Chiari and Rickenmann

(Chiari and Rickenmann, 2007) suggested a rate of n on the surface to that of as a function of flow rate, d90, bottom slope, as well as gravitational acceleration, Eq. (20).

$$\frac{n'}{n_{tot}} = \frac{0.0756 Q^{0.11}}{g^{0.06} d_{90}^{0.45} S^{0.33}} \quad (20)$$

3.8.17 Moramarco and Singh

(Moramarco and Singh, 2010) investigated n in open channel parameters based on entropy leading, and developing Eq. (21).

$$n = \frac{R_h{}^{1/6}/\sqrt{g}}{\emptyset(M)\frac{1}{k}\left[ln\left(\frac{y_{max}}{y_0}\right)-0.4621\right]} \quad (21)$$

$\emptyset(M)$ is the shape parameter, y_{max} is maximum flow depth. and y_0 is zero-velocity level.

3.9 Formulation n based on Linear Separation

Further, **(Bajorunas, 1952)** proposed the linear separation of the Manning roughness coefficient, consisting of the surface-related friction (skin friction) associated to the basic channel resistance granules, which is referred to as grain roughness (n'), while for the bedform, the basic flow resistance, and roughness changes, referred to as n". This formulation is shown in Eq. (22).

$$n = n' + n'' \quad (22)$$

in which $n' = \frac{d_s^{1/6}}{29.3}$ and $n'' = \emptyset\left(\frac{R'S_f}{168d_{35}}\right)$

3.10 Formulation n Based on Linear Separation Based on Bed Configuration (Wibowo-Manning)

(Wibowo, 2015) showed that the linear separation of the n based on the flow resistance in the field of bed moves, Eq. (12), where n' and n" can be calculated using Eqs. (23) and (24).

$$n' = \frac{R^{1/6}}{\left[6.0+5.75log\left(\frac{R'}{k_S}\right)\right]\sqrt{g}} \quad (23)$$

$$n'' = \frac{\tau_*''\left(\frac{1}{k}ln\left(\frac{R'}{k_S}\right)\right)^2 n'^2 k_f^2}{2\rho\lambda d(S_r-1)(cos\alpha tan\phi - sin\alpha)k_3} \quad (24)$$

Where τ_*'' is the shear stress relative due to the basic form ($\tau_*'' = \tau_* - \tau_*'$, $\tau_* = hS/(\rho s - \rho)ds$, kf is shape form (=1); k_3 is the correction factor (0,20 to 0,90), λ is the length of bedform; d is grain diameter; tan Ø is the dynamic friction coefficient, and α is the angle of the bed channel.

3.11 Methods of Determining Equivalent n

The bed of a natural channel is usually composed of different materials. Accordingly, the wetted perimeter can be divided into several distinct parts. Thus, these different parts are represented by different n. For example, different materials can be used for lining the bottom and sides of the irrigation and drainage channels. Likewise, glass sidewalls and a metal bottom can be used to build a laboratory flume. Typical examples include natural rivers with sandy beds and vegetated banks, as well as floodplains featuring various types of land use. Such channels are called composite channels. **(Akan, 2006)**. For this type of channel, an equivalent roughness, composite roughness (ne), must be calculated to represent the roughness of the entire perimeter of each cross-section in the channel. In the literature, there are many equations proposed for estimating the equivalent roughness of composite channels. Illustrated below are some of the commonly used equations.

3.11.1 Method 1

For a channel perimeter of N distinct segments, each has a different n value. If the length Manning roughness factor of the i-th segment is represented by P_i and n_i, respectively. Based on the condition that the mean velocities corresponding to the different segments are equal, Eq. (25) was obtained **(Chow, 1983; Raudkivi, 1990)**:

$$n_e = \left(\frac{\sum_{i=1}^{N} P_i n_i^{1.5}}{\sum_{i=1}^{N} P_i}\right)^{2/3} \quad (25)$$

3.11.2 Method 2

As explained by **(Krishnamurthy and Christense, 1972; Chow, 1983)**, based on the condition that the total force resisting flow is equal to the sum of forces resisting flow over the different segments of the perimeter, the hydraulic radius of each sub-section is equal to the radius of the whole cross-section. It was obtained as follows:

$$n_e = \left(\frac{\sum_{i=1}^{N} P_i n_i^{2}}{\sum_{i=1}^{N} P_i}\right)^{1/2} \quad (26)$$

3.11.3 Method 3

In 1932, Lotter illustrated that, based on the condition that the total discharge is the sum of subarea discharges, Eq. (27) was established, which is cited by (**Herman et al., 2015**):

$$n_e = \frac{P R^{5/3}}{\sum_{i=1}^{N} \frac{P_i R^{5/3}}{n_i}} \quad (27)$$

3.11.4 Method 4

In 1960, Felkel showed that, based on the condition that the total discharge is the sum of subarea discharges, Eq. (28) was established, which is cited by (**Herman et al., 2015**):

$$n_e = \frac{P}{\sum_{i=1}^{N} \frac{P_i}{n_i}} \quad (28)$$

3.11.5 Method 5

(Krishnamurthy and Christensen, 1972) illustrated that based on the condition of the logarithmic velocity distribution over depth h for a wide channel, Eq. (29) was established as follows **(Krishnamurthy and Christensen, 1972)**.

$$n_e = exp\left(\frac{\sum_{i=1}^{N} P_i .\ h_i^{3/2} .\ ln(n_i)}{\sum_{i=1}^{N} P_i .\ h_i^{3/2}}\right) \quad (29)$$

3.11.6 Method 6

(Yen, 1991) demonstrated that, based on the condition that the total shear velocity is a weighted sum of subarea shear velocity, Eq. (28) was established, which is cited by (**Herman et al., 2015**).

$$n_e = \frac{\sum_{i=1}^{N} n_i P_i}{P} \quad (30)$$

3.12 Methods of Estimating n Based on Measurement Data

In addition to the empirical equations for calculating the n value, which are reported above, there are some efficient and practical approximate equations. Such equations enable easy, rapid, and reliable determination of n. These equations are developed based on the geometric and kinematic features of the channel bed **(Žic, 2008).**

The first method of n calculation requires calculating the mean value of the hydraulic gradient ($\underline{I_E}$). This gradient is calculated based on the average total loss (ΔH) along the specified bed section with a ΔL length. Also, it must be indicated that C is determined based on the Manning equation and that the n for two cross sections (i) and (i-1) is approximately the same value ($n_1 \cong n_2 \cong n$).

$$\underline{I_E} = \frac{\Delta H}{\Delta L} = \frac{\underline{I_E}\Delta L}{\Delta L} = \frac{I_{E,i} + I_{E,i-1}}{2} \quad (31)$$

$$n = 2^{1/2} \frac{(R_i . R_{i-1})^{2/3}}{\left(v_i R_{i-1}^{4/3} + v_{i-1} R_i^{4/3}\right)^{1/2}} \underline{I_E}^{-1/2} \quad (32)$$

where: Ri, R_{i-1} is the hydraulic radius (m) in cross section (i) and (i-1), while ν_i, ν_{i-1} are the mean velocities of flow (m/s) in cross section (i) and (i-1). The other method of approximately determining the n value is based on estimating the mean flow velocity v and mean R along the bed section of ΔL length (m):

$$\underline{I_E} = \frac{\Delta H}{\Delta L} = \frac{n^2 \underline{v}^2}{\underline{R}^{4/3}} = \frac{n^2 \left(\frac{v_i + v_{i-1}}{2}\right)^4}{\left(\frac{R_i + R_{i-1}}{2}\right)^{4/3}} \quad (33)$$

$$n = 2^{1/3} \frac{(R_i + R_{i-1})^{2/3}}{v_i + v_{i-1}} I_E^{1/2} \quad (34)$$

The third method of calculating the n value is based on determining the n_1 and n_2 along a defined channel length (ΔL), whereby moderating the n_1 and n_2 values, the n value of this reach is determined:

$$n = \frac{n_i + n_{i-1}}{2} = \frac{\left(\frac{R_i^{2/3}}{v_i} I_E^{1/2}\right) + \left(\frac{R_{i-1}^{2/3}}{v_{i-1}} I_E^{1/2}\right)}{2} \quad (35)$$

For a channel reach of the same kinematic and geometric characteristics of the bed sections, considerably, using the first method gives a different n value from that of using the second method. While the second and third methods approximately give the same result (see **Fig. 5**, as an example) **(Žic, 2008).**

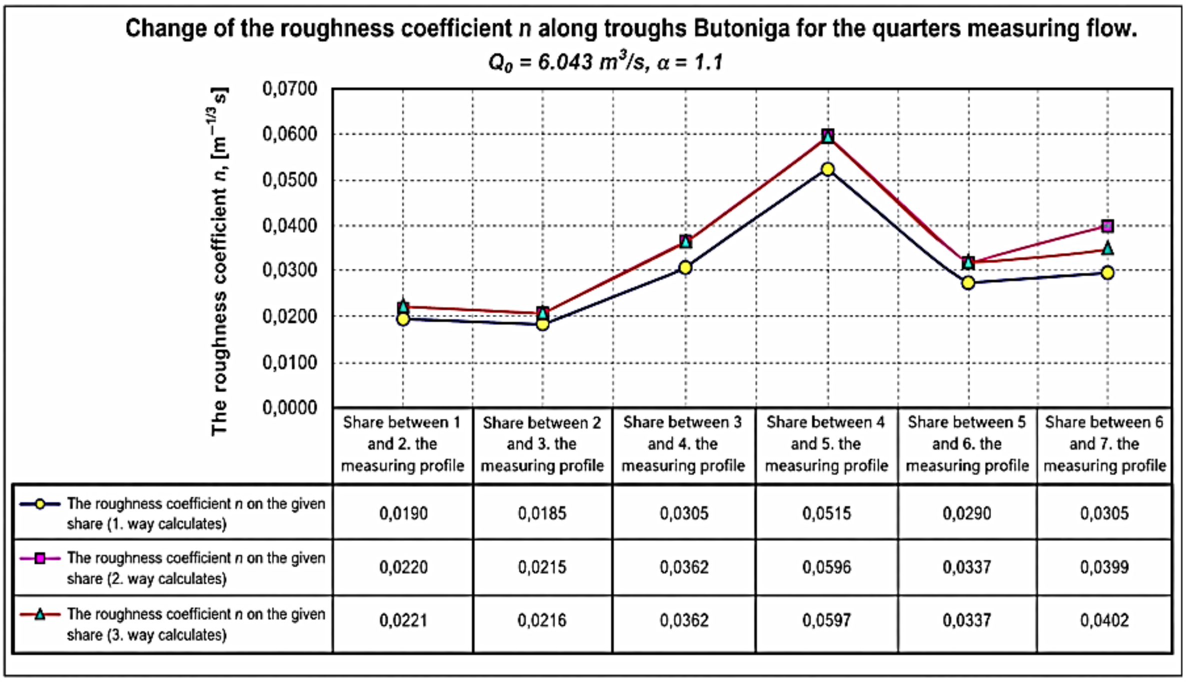

Figure 5. Change of n in a specific section of Butoniga bed using the three methods of n determination **(Žic, 2008).**

4. SUMMARY AND COMPARISON OF MANNING COEFFICIENT DETERMINATION METHODS

In order to give a summary of the methods for finding the value of the Manning coefficient and to facilitate comparison between them and to identify the most suitable application for each method, Table 4, summarizes all methods used to calculate the value of n, which includes the method name, its equation, the author who established the method, the best location and case for its use, and the accuracy of the method.

Table 4. Summary and comparison of Manning coefficient determination methods

Method	Equation / Formulation	Established by	Best location / case of use	Accuracy / limitations
Manning equation (back calculation)	$n = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{v}$	Robert Manning, based on Gauckler (**Chow, 1959**).	Uniform open channels where discharge, velocity, slope and geometry are measured	Depends strongly on measured hydraulic data; errors occur if flow is non-uniform or assumptions are violated.
SCS Storage Method	$n = n_0 \times$correction factors	Soil Conservation Service (SCS), **(USACE, 1994**).	Natural channels with vegetation, irregularity and obstruction effects	Simple but subjective because correction factors depend on visual judgment.

Ven Te Chow Table Method	Tabulated values of n based on channel type	**(Chow, 1959; Chow, 1983)**	Quick estimation for rivers, canals and floodplains	Accuracy depends on engineer experience; typical uncertainty is relatively high.
Photographic Method	Based on photographic comparison of channel characteristics	AGU method reported by **(Elvis et al., 2009)**	Natural rivers where field photographs and hydraulic observations are available	Accuracy about **±15%** according to the paper.
Slope–Area Back Calculation Method	Rearranged Manning equation using measured Q, geometry and slope	**(Takata et al., 2024)**	River reaches with measured flood discharge and water surface slope	High reliability if field measurements are accurate; sensitive to uncertainty in slope and discharge.
HEC-RAS Inverse Calibration	Optimization of n to minimize difference between simulated and observed water levels	HEC-RAS modeling approach, **(Sarmad et al., 2020)**	Rivers where cross sections and observed stages are available	Often highly accurate after calibration; depends on quality of observations and calibration data.
LiDAR + Land Cover Mapping	Spatial assignment of n based on land cover, vegetation and terrain roughness	Remote sensing-based methods, **(Chaojie et al., 2025)**	Large basins, inaccessible areas, flood modeling	Provides continuous n maps; accuracy depends on land-cover classification quality.
Neural Networks / AI Regression	$n=f(X_1, X_2,...,X_n)$ learned from training data	AI-based methods **(Kuras et al., 2021; Khodnevych and Stefanyshyn, 2023)**	Complex rivers with many interacting variables	Potentially highest accuracy when sufficient training data exist; requires large datasets.
Strickler Method	$n=f(d_{50})$	Strickler, **(French, 1986)**	Gravel-bed rivers with known sediment size	Simple and widely used; limited when vegetation and bedforms dominate.
Meyer–Peter & Müller Method	$n=f(d_{90})$	**(Meyer–Peter and Müller, 1948)**	Mountain streams with coarse gravel/cobbles	Suitable for coarse beds; not suitable for vegetated channels.
Cowan Method	$n=(n_0+n_1+n_2+n_3+n_4)m$	**(Cowan, 1956)**	Natural rivers considering bed, irregularity, vegetation and meandering	Better than single-factor methods; still depends on subjective classification.
Henderson Method	$n=f(d)$	**(Henderson, 1966)**	Pebble-bed channels	Developed from experimental data; limited to similar bed conditions.

Limerinos Method	$n=f(R,d_{84})$	**(Limerinos, 1970)**	Gravel-bed natural channels	Based on measured roughness; applicable for gravel to pebble beds.
Petryk & Bosmajian Method	Vegetation drag-based formulation	Petryk & Bosmajian, **(Chow, 1983)**	Shallow flows with vegetation	Good for vegetated channels; requires vegetation parameters.
Raudkivi Method	Modified Strickler relationship using sediment size	**(Raudkivi, 1990)**	Stabilized river beds	Useful for sediment-controlled roughness.
Burkham & Dawdy Method	Based on equivalent roughness height	Burkham & Dawdy, **(Chow, 1983).**	Sandy-bed channels	Limited to sediment-controlled channels.
Garde & Raju Method	$n=f(d_{50})$	Garde & Raju, **(French, 1986)**	Natural rough channels without waves	Suitable for coarse natural channels.
Brownlie Method	$n=f(d_{50},R,S,G)$	**(Brownlie, 1983)**	Sand-bed channels under lower/upper flow regimes	More physically based; needs sediment and hydraulic parameters.
Karim & Kennedy Method	Based on friction factors and sediment characteristics	**(Karim and Kennedy, 1990)**	Sediment transport channels	Useful where sediment transport data exist.
Rickenmann Methods	Resistance related to slope, depth and discharge	**(Rickenmann, 1994; Rickenmann, 2005)**	Steep mountain torrents and gravel rivers	Developed for steep slopes; not general for lowland rivers.
Entropy Method	n related to entropy parameter and cross-section characteristics	**(Moramarco and Singh, 2010)**	Natural rivers with available hydraulic geometry	Promising but requires additional calibration.
Composite Roughness Methods	Equivalent (n_e) from multiple subsection roughness values	Horton, Einstein, Chow, Lotter, Felkel, etc. **(Chow, 1983)**	Compound channels, floodplains, rivers with mixed materials	More realistic for heterogeneous channels, but uncertainty increases due to subdivision assumptions.
Measurement-based Methods (Žic)	Derived from measured velocity, hydraulic radius and losses	**(Žic, 2008)**	Gauged river reaches	Reliable when field hydraulic measurements are available.

5. CONCLUSIONS

Estimation of Manning's roughness coefficient (n) is still a necessary but frustrating aspect of open channel hydraulics. More than a century of empirical and theoretical refinement, estimation of n for natural rivers is a challenging task because of the spatial and temporal variation of hydraulic, geomorphic, and biological factors. This overview brought together the principal approaches and empirical formulas developed to estimate n values, from the original semi-empirical equations of Strickler and Cowan in 1923 and 1956, respectively,

through equations developed more recently, incorporating sediment characteristics, plant influences, and entropy analysis. The overview demonstrates that it is impossible to use any one approach to precisely compute Manning's n for all types of channels and flow conditions. Empirical relations such as those of Meyer-Peter and Müller, Strickler, and Limerinos are still widely utilized because they are simple and based on calibration, but neglect the dynamic impacts of bedform variability, vegetation thickness, and unsteady flow. Composite roughness formulas, such as Horton, Einstein, and Chow, are a more representative characterization of natural channels by incorporating spatial heterogeneity but are subject to limited accuracy due to subjective estimation of parameters and measurement uncertainty. Recent advancements with statistical, remote sensing, and entropy-based methods show promising avenues towards improving prediction quality through data-driven calibration and multi-scale characterization of the roughness effect. In summary, the literature indicates that Manning's n cannot be estimated from a single empirical relation but from a combination of field observation, analytical calculation, and professional judgment. Future studies will entail the development of hybrid and machine-learning-based models to assimilate high-resolution hydraulic and geomorphological data to reduce roughness prediction uncertainty. Moreover, standardized measurement databases of measured n values under controlled and natural conditions would enhance the comparability and reproducibility of results between different studies.
In conclusion, while Manning's roughness coefficient continues to be a valuable and indispensable tool in hydraulic engineering, precise prediction calls for an interdisciplinary approach integrating theory, measurement, and modeling to better reflect the complex nature of flow resistance in natural rivers and constructed channels.

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Credit Authorship Contribution Statement

Ala Hassan Nama and Sabah Jassim Mohammed conceived the study. Sura Sabah and Mahmoud S. Al-Khafaji performed the data collection and analysis, interpreted the results, and wrote the draft of the manuscript. Mahmoud S. Al-Khafaji reviewed the manuscript and put it in the final version. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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طرق التنبؤ بقيم معامل مانينغ للخشونة: أحدث ما توصلت إليه الدراسات

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الخلاصة

يُعدّ معامل خشونة مانينغ (n) عاملاً حاسماً في التحليل الهيدروليكي الموثوق للقنوات المفتوحة الطبيعية والاصطناعية. تُقدّم هذه الورقة البحثية أحدث ما توصل إليه العلم في مبادئ آليات مقاومة التدفق في القنوات الطبيعية، بالإضافة إلى مناهج تقدير معامل n. كما تستعرض الدراسة الأساليب الكلاسيكية المعتمدة على العلاقات التجريبية مثل طرائق ستريكلر وكوان وماير–بيتر ومولر وليميرينوس وهندرسون، إضافةً إلى الأساليب المعتمدة على الجداول والصور والطرائق القائمة على تخزين البيانات. وتشمل هذه الطرائق صيغاً تأخذ في الحسبان تأثيرات الغطاء النباتي، وخصائص مواد قاع النهر، والمقاومة الناتجة عن أشكال القاع، وكذلك الخشونة المركبة للقناة. كما تعرض الدراسة تطورات أحدث، مثل نظرية الإنتروبي، والأساليب الإحصائية، والطرائق المعتمدة على البيانات. وتناقش الدراسة مزايا وعيوب كل طريقة، وتبيّن أنه لا توجد طريقة واحدة يمكن تطبيقها بشكل عام للتنبؤ بقيمة معامل مانينغ تحت مختلف ظروف الجريان وأنواع القنوات. بل إن التقدير الدقيق لهذا المعامل يجب أن يعتمد على الملاحظات الميدانية والعلاقات التجريبية والتحليل الهندسي إضافةً إلى الخبرة الهندسية. وتشير النتائج إلى أهمية استخدام نهج متكامل وهجين يمكن دعمه بقياسات عالية الدقة وقواعد بيانات معيارية بهدف تقليل عدم اليقين في تقدير الخشونة. هذهِ المراجعة تسهم في تحسين القاعدة المعرفية والتطبيقية للباحثين والممارسين في مجالات هيدروليكا الأنهار، وتصميم القنوات، ونمذجة الفيضانات.

الكلمات المفتاحية: خشونة مانينغ؛ الأنهار الطبيعية؛ آليات المقاومة؛ هيدروليكا الأنهار.