

**DETERMINATION OF FLOW RESISTANCE  
COEFFICIENT USING MULTIPLE LINEAR  
REGRESSION AND GENETIC EXPRESSION  
PROGRAMMING**

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PROGRAMMING**

by

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## LIST OF SYMBOLS

A	Cross-sectional area in $m^2$
B	Width of channel in m
C	Chezy's constant
$C_v$	Volumetric concentration of sediment [ppm]
$D_0$	Diameter of pipe in m
$d_s$	Diameter of sediment in m
$d_{50}$	Particle size of which 50% of the bed material by weight is finer.
$d_{75}$	Particle size at which 75% of bed material by weight is finer.
$d_{90}$	Particle size at which 90% of bed material by weight is finer.
Fr	Froude number
$f$	Darcy-Weisbach coefficient
$g$	Acceleration due to gravity [ $m/s^2$ ]
K	Relative roughness
m	Metre
$n$	Manning's roughness coefficient [ $m^{1/3}/s$ ]
$n_g$	Manning's roughness coefficient [ $m^{1/6}$ ]
N	Number of samples (observations)
$O_i$	Observed values
$\hat{O}$	Mean observed values
P	Wetted perimeter in m
$P_i$	Predicted values
$\hat{P}$	Mean of predicted values
Q	Discharge [ $m^3/s$ ]

R	Hydraulic radius
$R^2$	Coefficient of determination
$Re$	Reynolds Number
S	Slope of Energy Line
$S_o$	Slope of flow
$S_s$	Specific gravity of sediment
$T_b$	Total bed load
$T_t$	Total Suspended Load
$T_j$	Total bed load material
T	Temperature of water [ $^{\circ}C$ ]
t	Time
U	Shear velocity [m/s]
V	Flow velocity [m/s]
$W_s$	Terminal fall velocity [m/s]
$y_o$	Flow depth in m
$\nu$	Kinematic viscosity [ $m^2/s$ ]
$\tau$	Shear stress
$\mu$	Geometric mean of discrepancy
$\rho$	Density of water [ $kg/m^3$ ]
$\rho_s$	Density of sediment [ $kg/m^3$ ]

## **LIST OF ABBREVIATIONS**

DID	Department of Irrigation and Drainage
GA	Genetic Algorithm
GP	Genetic Programming
HJRS	HJRS Civil and Structural Engineering Consultant
JAKIM	Department of Islamic Development, Malaysia
JICA	Japan International Cooperation Agency
MAE	Mean Absolute Error
MSMA	Urban Storm-water Management Manual for Malaysia
REDAC	River Engineering and Urban Drainage Research Centre
RMSE	Root Mean Square Error
SPSS	Statistical Package for the Social Sciences
SSE	Error Sum of Squares
SSR	Regression Sum of Squares
SST	Total Sum of Squares
USM	University Sains Malaysia
UTP	University of Technology, Petronas

**PENENTUAN PEKALI RINTANGAN ALIRAN MENGGUNAKAN  
REGRESI LINEAR BERGANDA DAN PENGATURCARAAN GENETIK  
EKSPRESI**

**ABSTRAK**

Penggunaan nilai yang tepat bagi pekali kekasaran untuk rintangan aliran di saluran terbuka adalah keperluan dalam pengiraan. Jurutera telah menggunakan beberapa persamaan rintangan aliran yang melibatkan kekasaran butiran, bentuk kekasaran dan gabungan kedua-duanya. Walau bagaimanapun, persamaan *Manning* telah digunakan secara meluas di peringkat antarabangsa untuk meramalkan nilai kekasaran dalam saluran semula jadi. Dalam kejuruteraan sungai, pekali kekasaran Manning,  $n$ , telah digunakan secara meluas dalam model hidraulik sungai. Prosedur untuk memilih nilai  $n$  adalah subjektif dan memerlukan penilaian dan kemahiran yang dibangunkan terutamanya melalui pengalaman selain daripada mengetahui faktor-faktor yang mempengaruhi nilai  $n$ . Oleh kerana aliran dan sempadan kekasaran adalah berbeza dengan keadaan sungai yang sedia ada, maka satu model perlu dibangunkan untuk menilai nilai  $n$  bagi sungai-sungai di Malaysia. Kajian ini telah dijalankan keatas empat lembangan sungai iaitu Sungai Kinta, Sungai Langat, Sungai Muda dan Sungai Kurau. Sejumlah 501 data telah dikumpul di empat lembangan sungai tersebut. Penilaian persamaan-persamaan sedia ada iaitu Strickler, Limerinos, Bruschin, Griffith, Bray, Jarrett, Julien dan Ab. Ghani telah dijalankan. Berdasarkan penilaian persamaan yang dipilih, Persamaan Jarret (1984) dan Ab Ghani et al. (2007) adalah disarankan untuk meramal kadar aliran bagi sungai-sungai berpasir seperti Sungai Kinta dan Sungai Langat. Untuk sungai-sungai berkerikil seperti Sungai Muda dan Sungai Kurau, Jarret (1984), Bruschin (1985) dan Limerinos (1970) adalah disarankan

untuk meramal kadar aliran. Pembangunan persamaan baru telah dijalankan dalam kajian ini dengan menggunakan Regresi Linear Berganda (MLR) dan Pengaturcaraan Genetik Ekspresi (GEP). Persamaan berasaskan MLR (Persamaan 4.4) adalah disarankan manakala persamaan berasaskan GEP (Persamaan 4.6) adalah amat disarankan. Pembangunan lengkung perkadaran sungai dalam kajian ini (Rajah 4.16 hingga 4.19) mengesahkan kesesuaian Persamaan 4.4 dan 4.6 dalam mengira kadar aliran yang boleh digunakan untuk meramalkan aliran rendah dan juga tinggi bagi sungai-sungai di Malaysia.

**DETERMINATION OF FLOW RESISTANCE COEFFICIENT USING  
MULTIPLE LINEAR REGRESSION AND GENETIC EXPRESSION  
PROGRAMMING**

**ABSTRACT**

The use of the accurate value of the roughness coefficient for flow resistance in the open channel is a necessity in computation. The engineers have used a number of flow resistance equations involving grain roughness, form roughness and a combination of both. However, Manning's equation has been widely used internationally for predicting roughness values in natural channels. In river engineering, Manning's roughness coefficient,  $n$ , has been used widely in river hydraulic models. The procedure for selecting  $n$  is subjective and requires judgment and skill that is developed primarily through experience apart from knowing the factors which affect the values of  $n$ . Since flow and boundary roughness vary with existing river conditions, a model of some form must be developed to evaluate  $n$  for rivers in Malaysia. This research has been carried out on four rivers namely the river basins of Kinta River, Langat River, Muda River, and Kurau River. A total of 501 data have been collected at the four-river basin. Assessment of the existing equations i.e. Strickler, Limerinos, Bruschin, Griffith, Bray, Jarrett, Julien, and Ab. Ghani was carried out. Based on the evaluation of the selected equations, Jarret (1984) and Ab Ghani et al. (2007) equation are recommended to predict flow discharge for the sandy rivers such as Kinta River and Langat River. For gravel rivers such as Muda River and Kurau River, Jarret (1984), Bruschin (1985) and Limerinos (1970) equation are recommended to predict flow discharge. The development of new equations was carried out in the present study using Multiple Linear Regression (MLR) and Genetic

Expression Programming (GEP). The MLR-based equation (Equation 4.4) is recommended while GEP-based equation (Equation 4.6) is greatly recommended. The development of flow rating curve for the rivers in the present study (Figures 4.16 to 4.19) validate the applicability of Equations 4.4 and 4.6 in calculating the flow discharge which can be used to predict low and high flows for rivers in Malaysia.

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background

Life will exist when there is water. God initially created the barren earth. For life to exist on the earth, God then sent down water (rain) from the sky. This has been stated in many verses in the Holy Quran such as in Surah Az-Zukruf, Verse 11, God stated:-

وَالَّذِي نَزَّلَ مِنَ السَّمَاءِ مَاءً بِقَدَرٍ فَأَنشَرْنَا بِهِ بَلْدَةً مَيْتًا كَذَلِكَ تُخْرَجُونَ

Meaning “And who sends down rain from the sky in measured amounts, and We revive thereby a dead land – thus will you be brought forth”.

Meanwhile, in Surah Al-Hajj, Verse (63) God gave the following statement:-

أَلَمْ تَرَ أَنزَلَ مِنَ السَّمَاءِ مَاءً فَتُصْبِحُ الْأَرْضُ مُخْضَرَّةً إِنَّ اللَّهَ لَطِيفٌ خَبِيرٌ

Which means: “Do you not see that Allah has sent down water (rain) from the sky and the earth becomes green? Indeed, Allah is Subtle and Acquainted.”

What can be deduced from the above statements? Where there is water, there will be life. Therefore it is natural for the early development and progress of human civilization to start from small settlements located near rivers. A few examples of early civilizations located near rivers were at the Tigris and Euphrates Rivers in Iraq, Nile River in Egypt and Hwang Ho River in China. At this present time, these ancient settlements have developed into major towns and modern metropolitan cities.

Rivers, apart from where civilizations begin, are the main source of water supply for human consumption and for the irrigation of agricultural lands. Rivers also can be a source of electrical power. Other activities such as flood control, river regulation, navigation, and recreation are centre around river. With the development of land and air transport, water transportations in rivers are not much in use. Now, river ferry is only operating at places where roads are not available.

In Malaysia the major towns initially began close to the rivers, now the rivers are not only flowing near the towns but they are flowing within the towns. Examples of such towns or cities are Malacca Historical City, Kuala Lumpur City, and Ipoh City. Only at the Malacca River, a facility for a boat ride along the river for tourists still exist. In Sarawak, river transports are still much in use because there are many places which do not have access to the road. In another part of the country, boats are sometimes used to ferry passengers to cross from one side to the other side of a river.

Although rivers have given us much benefit, they also can cause hardship and catastrophe to the population. Developments which are very rapid and lacking stringent supervision by the authorities, contribute to the destructions of mankind themselves, and contribute to the adverse effect on the environment. Scour and deposition of the river bed, erosion of river banks and destruction of the structure protecting river banks, will take place. Eventually, the river will become shallow and can no longer accommodate the surface runoff during heavy rainfall. This can cause flooding and flash floods when the river can no longer convey the water fast enough but will overflow its banks instead. The flood will cause damage to properties and crops, casualties and loss of life, disease epidemics, and other intangible losses annually (Liu and Chan, 2003).

Flow in the river is related to the roughness of river bed and banks. Quite a number of studies have been carried out to examine in depth on the roughness to flow which is in the form of Manning's coefficient of resistance to flow,  $n$ . They have been carried out by the U.S. Government agencies such as United State Geological Survey (USGS), American Society of Civil Engineers (ASCE), US Army Corps of Engineers (USACE) and Federal Highway Authority (FHWA). Individual researchers are also taking part in and contributing to the study in this field.

Up to the present time, there are many equations to find the value of Manning's  $n$ , have been formulated. Due to the difference in a scenario between the location where the research has been done, the equations obtained if applied to the local location give unsatisfactory results compared to the actual values measured at the field. This has been proven by research done by Ab Ghani et al. (2007). Although the results from the equations obtained are satisfactory because they are within the discrepancy ratio of 0.5 – 2, researches are still needing to study whether other methods discovered recently can also be used locally as well. The purpose of this study is to compare the values of the results obtained using several methods. Hence the method which gives the best result is the best method to be used in finding the value of Manning's coefficient of resistance,  $n$ , for Malaysian rivers.

## **1.2 Problem Statement**

Engineers use a number of flow resistance techniques involving grain roughness, form roughness and a combination of both. The most common practice is to express the total resistance in terms of Manning's,  $n$ . As a consequence, Manning's equation has been widely used for predicting discharge in natural channels (Barnes, 1967; Chow, 1959; Julien, 2002; Karim, 1995; Raudkivi, 1993).

Southeast Asia has long experienced a monsoon climate with dry and wet seasons. With mean annual rainfall precipitation locally in excess of 5,000 mm, the very intense rainstorms in the steep mountains of Malaysia have caused frequent and devastating floods in the last five years especially in 2003 (Northern states of Kedah, Penang, and Perlis) and 2006 (Southern states of Malacca, Johor and Pahang). Urbanization also exacerbates the problem and increases river discharge due to an increase in impervious areas of the upper watershed. The protection of the communities against floods has become the primary concern of the Malaysian government. One of the methods commonly used to mitigate the floods is by constructing levees or bunds along with the lowland areas surrounding the river channel.

A recent example of the flood mitigation project involves the Muda River, Kedah (Julien et al., 2006) that highlights several important points in the design of flood remediation countermeasures against intense and regular flooding during the monsoons of South-East Asia. The study covers 41.2 km between the river mouth and Ladang Victoria which was the area that was heavily flooded in 2003. The hydraulic analysis using HEC-RAS model of the existing river system in the study area was carried out to provide information on the variations of river water levels, discharges, and velocities during flood events. Due to lack of field measurement data to determine suitable values of Manning's  $n$ , different values were tried during the calibration of the HEC-RAS model. The best results were obtained with Manning's,  $n$  of 0.030 and 0.050 for the main channel and floodplains respectively. Water level records at three locations (Ladang Victoria, Bumbong Lima and River Mouth) during the 2003 flood were used to check the predicted water level by the HEC-RAS model. The model results are considered sufficiently accurate for the determination of levee heights.

This study by Julien et al. (2006) highlights the need to determine accurately the suitable values of Manning's  $n$  for both the main channel and floodplain. Most hydraulic computations related to indirect estimates of discharge require an evaluation of the roughness characteristics. A number of empirical equations were developed and these studies have been continued by government agencies and private sectors in the developed nation such as the USA (Dooge, 1991; Yen, 2002). Natural channel morphology depends on the interaction between fluid flow and the erodible channel boundary. Velocity is strongly related to flow resistance, which is one of the most important elements in the interaction between the fluid flow and the channel boundary (Graf, 1998; Julien, 2002; Yen, 2002).

### **1.3 Significance of the Study**

The determination of Manning's roughness coefficient  $n$  has been a problem to the Engineer for a long time. This is because there is still no accurate and objective method to determine the value of  $n$ . Limerinos (1970) stated that it is unlikely the determination of  $n$  values for channels can be an exact science. Meanwhile, Barnes (1967) indicated the selection of the values of  $n$  remains chiefly an art primarily developed through experience. According to Chow (1959), veterans at selecting  $n$  values should exercise sound engineering judgment and experience. For a beginner, selection of  $n$  values can be considered as not more than a guess, because different persons will obtain different results.

Since not all engineers have the experience to determine the value of  $n$  and furthermore the difference in the conditions of sites, makes it necessary for research to determine a suitable method to be carried out with respect to the local situation. Although past studies had been carried out before this for rivers in Malaysia, new

studies are necessary to verify the new methods that had been developed recently to see whether they can be used directly and to compare which method gives the most accurate result.

#### **1.4 Objectives of the Study**

In an open channel, flows are related to the roughness of the bed and walls of the channel. Manning formula is preferably used to measure the discharge in an open channel. To get an accurate value of the discharge, the most suitable value of Manning's coefficient of resistance,  $n$ , should be used. There are many equations that can be used to calculate the value of the Manning roughness coefficient. By understudying a few of them and comparing with the results obtained, the most suitable equation can be attained.

The objectives of the present study are as follows: -

- (a) Assessment of existing equations using river data in Malaysia.
- (b) Development of new equations for estimating Manning's Roughness Coefficient,  $n$  using Multiple Linear Regression (MLR) and Genetic Expression Programming (GEP)
- (c) Development of flow rating curve using newly developed equations for Manning's,  $n$ .

#### **1.5 Scopes of Study**

The scopes of the present study involve the taking of data such as bed materials load, bed load, slope of water surface and river bed, flow velocity, depth and width of river. From the above data, the cross-section, the hydraulic radius  $R$ , the discharge and

the size of the bed material of the river can be determined. For this study, the data were gathered from the rivers in the previous studies (Abdul Ghaffar, 2003; DID, 2009). They are the rivers at the Kinta River basin, the Langat River basin in Selangor, the Kurau River basin in Perak, and the Muda River basin in Kedah.

## **1.6 Thesis Outline**

This thesis consists of five chapters. Chapter 1 starts with the introduction of water and life and rivers as a generator of human civilization, their advantages and disadvantages. This chapter also focuses on the objectives, the scope, the necessity and the methods of the study.

While Chapter 2, presents the literature review on the development of roughness coefficients and resistance to flow. The factors which influence the values of Manning's Coefficient of Roughness and the results of the researches that have been done locally and at the international level are presented.

Chapter 3 gives a brief description of the study sites and how to choose a suitable study site, the study sites, and the methodology to collect samples.

Chapter 4 gives the method to obtain Manning's Roughness Coefficient using existing equations and how to derive the new equations.

Whilst in the last chapter, Chapter 5 will give conclusions on the study done and other proposals for future study.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 Introduction

A flow is uniform when its depths, its cross-sections, and its velocities remain constant at any point along the channel. Thus, uniform flow can be characterized by the water surface to be parallel with the bed of the channel. Uniform flow usually refers to uniform, steady flow. Uniform flow conditions require driving and resisting forces to be balanced. Hence, the flow is neither accelerating nor decelerating. So, the average channel cross-section, slope, and velocity are assumed constant under constant discharge conditions. Uniform flow rarely happens in a natural channel but also in a man-made channel. Although uniform flow seldom exists, this type of flow is used as a standard for theoretical and experimental research for other types of flow apart from understanding the resistance to flow.

Morphology in a natural open channel depends on the interaction between fluid flow and the materials that can be eroded from the boundary of the said channel. There are several forces which are responsible to change the form and function of a channel. The main forces are as follows: -

- i) The weight of the water or the fluid itself which is caused by the effect of acceleration due to gravity,  $g$ , and the slope of the channel.
- ii) Resistance which oppose the flow of the water down the slope of the channel. These two forces can be classified as forces which oppose each other.

Hence, the relationship between these forces will determine the ability of the flowing water to erode the boundary of the channel and to transport the eroded

materials. There are many parameters which influence the flow in an open channel such as bed materials, bed forms, cross-sectional and planform variability, vegetation, etc, which result in a complex situation. Average velocity in river engineering applications is commonly calculated using one of the three equations: Chezy, Darcy-Weisbach or Manning (Yen, 2002). This can also be solved by using models or by doing detailed experiments.

## **2.2 Development in Open Channel Flow Resistance**

Studies on resistance to flow in the open channel had been carried out by several researchers since 1769. The equations had been categorized under three types. They are the basic equations for hydraulic roughness, channel roughness and vegetation resistance. The basic equations for hydraulic roughness are Chezy, Darcy-Weisbach and Manning.

### **2.2.1 Chezy Equation**

The first person to develop equation for hydraulic roughness was Antoine Chezy in 1769. The equation is known as Chezy Equation and is usually expressed as Chow (1959).

$$V = C\sqrt{RS_f} \quad (2.1)$$

where  $V$  is the flow velocity in m/s,  $C$  is the factor of flow resistance or Chezy's  $C$ ,  $R$  is the hydraulic radius in m and  $S_f$  is the slope of the energy line. Chezy's  $C$  can be determined using equations by Ganguillet Kutter (G.K.), Bazin and Powell equations (Chow, 1959).

### 2.2.2 Darcy-Weisbach Equation

Darcy-Weisbach developed this equation in 1845 primarily to describe flow resistance in a pipe which is given as:

$$h_f = f \frac{L}{d_0} \frac{V^2}{2g} \quad (2.2)$$

where:

$h_f$  = the frictional loss for flow in pipe, in m,

$f$  = the friction factor,

$L$  = the length of pipe, in m,

$d_0$  = the diameter of pipe, in m,

$g$  = the acceleration due to gravity, in m/s<sup>2</sup>

Equation 2.2 can be written for flow in an open channel as:

$$h_f = f \frac{L}{4R} \frac{V^2}{2g} \quad (2.3)$$

Rearranging above with  $V$  as the subject of the equation:

$$V = \sqrt{\frac{8g}{f}} \sqrt{R} \sqrt{\frac{h_f}{L}} \quad (2.4)$$

For uniform flow in an open channel,  $h_f/L$  equals the slope of energy line,  $S_f$ , hence equation (2.4) is the same as equation (2.1), that is the Chezy equation, with

$$C = \sqrt{\frac{8g}{f}} \quad (2.5)$$

### 2.2.3 The Manning Equation

Another resistance equation was proposed by Robert Manning, an Irish engineer, in 1889, for uniform flow in an open channel as:

$$V = \frac{K}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} \quad (2.6)$$

where  $V$  = flow velocity in m/s,

$n$  = roughness coefficient known as Manning's  $n$ ,

$R$  = hydraulic radius in m, and

$S_f$  = the slope of energy line.

The value of  $K$  in the British unit is 1.486. According to White (1999), if the dimensions of the equation are to be considered, they are found to be non-homogeneous. It will become homogeneous if  $1.486/n$  has a dimension of  $\{L^{1/3}/T\}$ . If  $n$  is dimensionless, then 1.486 will have the dimension of  $\{L^{1/3}/T\}$ . So in the British unit,  $K$  equals  $1.486 \text{ ft}^{1/3}/\text{s}$ . Converting the value of  $K$  to metric, then  $(1.486 \text{ ft}^{1/3}/\text{s})(0.3048 \text{ m/ft})^{1/3}$  equals to  $1.49 \text{ m}^{1/3}/\text{s}$ . So, in the metric system,

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (2.7)$$

$$\text{or} \quad n = \frac{1}{V} R^{2/3} S^{1/2} \quad (2.8)$$

By checking on the dimensions of the RHS of equation 2.7, the dimension of  $n$  is found to be  $TL^{-1/3}$ . To get rid of the dimension of time,  $T$ ,  $n$  should be multiplied by  $g^{1/2}$ . Thus, the dimension of  $ng^{1/2}$  will become  $L^{1/6}$ . To make  $ng^{1/2}$  dimensionless,  $ng^{1/2}$  is to be divided by  $R^{1/6}$ .

The roughness factor from Chezy, Darcy-Weisbach and Manning equation can be related as follows:

$$\sqrt{\frac{f}{8}} = \frac{n}{R^{\frac{1}{6}}} \frac{\sqrt{g}}{K} = \frac{\sqrt{g}}{C} = \frac{\sqrt{gRS}}{V} \quad (2.9)$$

If the value of one coefficient is known, then the value of the other coefficients can be computed.

#### 2.2.4 Roughness Coefficient and Sediment Size

There are many equations which have been formulated by researchers considering the roughness of the particles and channel. The first researcher was Strickler (1923), with an equation as:

$$n = \frac{1}{21.1} d_{50}^{\frac{1}{6}} \quad (2.10)$$

where  $d_{50}$  = sediment diameter of uniform sand in m and represent the particle size in which 50 percent of the bed material is finer.

For coarse bed material, Meyer-Peter and Müller (1948) modified Strickler equation as:

$$n = \frac{1}{26} d_{90}^{\frac{1}{6}} \quad (2.11)$$

where  $d_{90}$  = sediment diameter and represent particle size in which 90 percent are finer than  $d_{50}$ .

Other researchers are Lane and Carlson (1953),

$$n = \frac{1}{21.14} d_{75}^{\frac{1}{6}} \quad (2.12)$$

Henderson (1966),

$$n = 0.031d_{75}^{\frac{1}{6}} \quad (2.13)$$

and Julien (2002),

$$n = 0.062d_{50}^{\frac{1}{6}} \quad (2.14)$$

$$n = 0.046d_{75}^{\frac{1}{6}} \quad (2.15)$$

$$n = 0.038d_{90}^{\frac{1}{6}} \quad (2.16)$$

Apart from  $d$  – the sediment diameter, researchers also used other properties of the channel such a water level,  $y_0$ , hydraulic radius,  $R$ , and the slope of the channel,  $S_0$ .

Limerinos (1970) formulated the roughness coefficient as:

$$n = \frac{0.113R^{\frac{1}{6}}}{0.35 + 2.0 \log_{10}\left[\frac{R}{d_{50}}\right]} \quad (2.17)$$

and Froehlich (1978) formulated the equation as:

$$n = 0.245 R^{0.14} \left(\frac{R}{d_{50}}\right)^{-0.44} R \left(\frac{R}{T}\right)^{0.30} \quad (2.18)$$

while Bray (1979) give an equation as:

$$n = \frac{0.113y_0^{\frac{1}{6}}}{1.09 + 2.2 \log_{10}\left(\frac{y_0}{d_{50}}\right)} \quad (2.19)$$

Griffiths (1981)

$$n = \frac{0.113R^{\frac{1}{6}}}{0.76 + 1.98 \log_{10}\left(\frac{y_0}{d_{50}}\right)} \quad (2.20)$$

Brownlie (1983)

$$n = \left[ 1.893 \left\{ \frac{R}{d_{50}} \right\}^{0.1374} S^{0.112} \right] 0.034 d_{50}^{0.167} \quad (2.21)$$

Bruschin (1985)

$$n = \frac{d_{50}^{\frac{1}{6}}}{(12.38) \left( R \frac{S_o}{d_{50}} \right)^{\frac{1}{7.3}}} \quad (2.22)$$

Jarret (1984)

$$n = 0.32 R^{0.16} S^{0.38} \quad (2.23)$$

Ab. Ghani et al. (2007)

$$n = 4 \times 10^{-8} \left( \frac{y_0}{d_{50}} \right)^2 - 5 \times 10^{-5} \left( \frac{y_0}{d_{50}} \right) + 0.0582 \quad (2.24)$$

Azamathulla et al. (2013)

$$n = \frac{S_o}{\left[ \left( \frac{-2.5 + \frac{k_s}{R}}{\left( \frac{b}{y} \right) \times Re} \right) - \left\{ \left( \frac{Fr}{8} \right) - \left( \frac{b}{y} \right) \right\} \right]} + \frac{\frac{k_s}{R}}{\left[ \left\{ (Re - 9.9) + \left( \frac{k_s}{R} \right)^2 \right\} - \left\{ \frac{9.9}{Fr} - \frac{b}{y} \right\} \right]} + \frac{S_o}{\left[ \left( \frac{Fr + 0.98}{-9.8 + \frac{k_s}{R}} \right) - \{ (-9.8 S_o) - Fr \} \right]} \quad (2.25)$$

where  $S_o$  is bed slope of channel,  $Re$  is Reynold Number,  $Fr$  is Froude Number,  $k_s$  is wall surface roughness,  $R$  is hydraulic radius,  $b$  is channel width and  $y$  is flow depth.

Pradhan and Khatua (2018)

$$n = \left[ \frac{-1.86 \sqrt{S_o} (\beta - S_o - 8.89)}{Fr} \right] + \left[ \frac{\left( \frac{-7}{s} \gamma^2 \right) - 11.64 (2\beta)}{Re} \right] + \left[ -2.54 \sqrt{S_o} \ln(\alpha) S_o \right] \quad (2.26)$$

where  $\beta$  is relative depth,  $s$  is sinuosity,  $\gamma$  is relative roughness and  $\alpha$  is width ratio.

Other researchers who formulated roughness coefficient,  $n$ , are Bray and Davar (1987), Chang et al. (2010), Einstein and Barbarossa (1952), Lacey (1930), Simons and Richardson (1966), Engelund (1966), Garde and Raju (1966), Senturk (1967), Sugio (1974), Yang (1976), Froehlich (1978), Karim and Kennedy (1981), Jarret (1984), Jarrett (1987) and Jarret (1992).

### **2.2.5 Vegetation Resistance**

According to Chow (1959), vegetation can also be regarded as a kind of surface roughness depending on the height, density, distribution, and type of vegetation. Prediction of vegetative roughness is highly problematic and uncertain due to the wide array of quantitative and qualitative parameters that must be included to accurately account for vegetative flow disturbances (Fischenich, 1997). These parameters may include but are not limited to: vegetation type; plant size, shape, and rigidity; stand density; composition of mixed vegetative assemblages (e.g., riparian communities with grasses, sedges, willows, and cottonwoods); and seasonality issues (e.g., summer leaf-on vs. winter leaf-off resistances). A variety of roughness calculation methods have been presented to overcome this difficulty. Although there is a significant body of literature on the subject, a knowledge gap remains in the consistent, robust prediction of vegetative roughness. However, the literature abounds with observations of critical system processes. One of the most important considerations in vegetative roughness prediction is the relative influence of plant height on flow depth. Emergent vegetation is herein defined as vegetation that is greater in height than the flow depth; submerged vegetation height is less than flow depth. From the immense body of vegetative roughness literature, two studies have emerged with generic applicability (Fischenich, 2000; Freeman et al., 2000).

Fischenich (2000) presented a method of estimating roughness based purely on the theories of conservation of linear momentum and drag. For steady, uniform flow, his approach can be summarized as:-

$$n = \frac{k_n R^{\frac{1}{6}}}{\left(\frac{U}{u_*}\right)\sqrt{g}} \quad \text{where } \frac{U}{u_*} = \sqrt{\frac{2}{A_d C_d R}} \text{ for Emergent} \quad (2.27)$$

$$\frac{U}{u_*} = \frac{2.5}{H}(X + Y) \text{ for Submerged} \quad (2.28)$$

$$X = 1.26 h_p^2 \frac{2h_p}{11C_d A_d} [1 - e^{-5.5C_d A_d}] \quad (2.29)$$

$$Y = (H - 0.95h_p) \left[ \ln\left(\frac{H}{Kh_p} - \frac{0.95}{K}\right) - 1 \right] - (0.05h_p) \left[ \ln\left(\frac{0.05}{K}\right) - 1 \right] \quad (2.30)$$

$$K = 0.13e^{-((C_d A_d - 0.4)^2)} \quad (2.31)$$

where  $h_p$  is vegetation height,  $A_d$  is vegetation density per unit channel length,  $C_d$  is an empirical dimensionless drag coefficient,  $z$  is distance from the bed,  $k_n$  is roughness coefficient,  $R$  is hydraulic radius,  $H$  is water depth,  $U$  is flow velocity and  $u_*$  is shear velocity.

Freeman et al., (2000) method was developed through dimensional analysis and calibrated with data from laboratory testing of live vegetation as shown in Figure 2.1.

Two equations were developed for prediction of Manning's  $n$ .

For Submerged Vegetation:

$$n = 0.183 k^n \left(\frac{E_s A_s}{\rho A_i u_*^2}\right)^{0.183} \left(\frac{h_p}{H}\right)^{0.243} (MA_i)^{0.273} \left(\frac{v}{Ru_*}\right)^{0.115} \left(\frac{R^{\frac{2}{3}} S_o^{\frac{1}{2}}}{u_*}\right) \quad (2.32)$$

For Emergent Vegetation:

$$n = (3.487 \times 10^{-5}) k_n \left( \frac{E_s A_s}{\rho A_i^* u_*^2} \right)^{0.150} (M A_i^*)^{0.166} \left( \frac{R u_*}{\nu} \right)^{0.622} \left( \frac{\frac{2}{R^3 S_o^{\frac{1}{2}}}}{u_*} \right) \quad (2.33)$$

where  $E_s$  is modulus of plant stiffness ( $E_s = \frac{F_{45} H^2}{3I}$ ),  $F_{45}$  is horizontal force necessary to bend a plant stem 45 degrees,  $I$  is second moment of inertia of plant stem cross-section,  $D_s$  is stem diameter,  $A_s$  is total cross-sectional area of all plant stem measured at a height of  $h_p/4$ ,  $h_p$  is total plant height,  $\rho$  is density of water,  $A_i$  is frontal area of plant blocking flow ( $A_i = h_p' W_e$ ),  $h_p'$  is leaf mass height,  $W_e$  is leaf mass width,  $u_*$  is shear velocity,  $H$  is water depth,  $M$  is plant density (plants/m<sup>2</sup>),  $\nu$  is kinematic viscosity (m<sup>2</sup>/s),  $R$  is hydraulic radius,  $S_o$  is slope of bed,  $k_n$  is roughness factor and  $A_i^*$  is effective blockage area of emergent vegetation ( $A_i^* = [H - (h_p - h_p')] W_e$ ) (McKay and Fischenich, 2011)

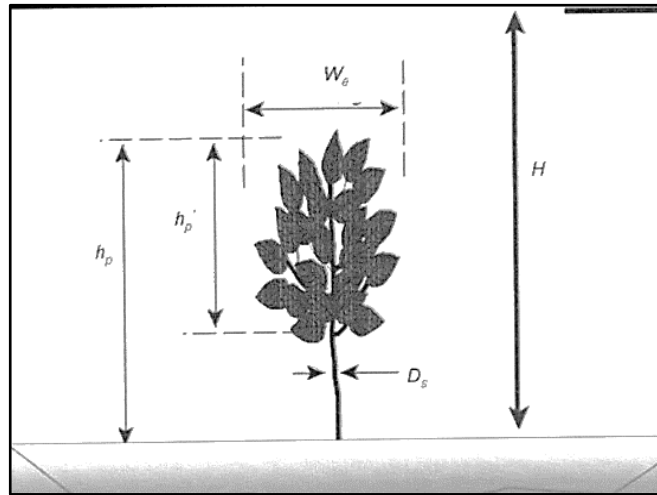


Figure 2.1 Schematic of idealized plant dimensions (Freeman et al., 2000)

The equations on vegetation resistance were formulated by Bray (1979), Freeman et al. (1998), Petryk and Bosmajian (1975), Strickler (1923) and Froehlich (1978).

Petryk and Bosmajian (1975) developed a method of analysis of the vegetation density to determine the roughness coefficient for a densely vegetated flood plain. By summing the forces in the longitudinal direction of a reach and substituting in the Manning's formula, they developed the following equation.

$$n = n_o \sqrt{1.0 + \left(\frac{C_D \Sigma A_i}{2gAL}\right) \left(\frac{K_n}{n_o}\right)^2 \left(\frac{A}{P}\right)^{\frac{4}{3}}} \quad (2.34)$$

Bray (1979) gave the following equations.

$$n = 0.104 S_o^{0.177} \quad (2.35)$$

$$n = 0.104 d_{50}^{0.179} \quad (2.36)$$

$$n = \frac{0.0927R^{\frac{1}{6}}}{0.248 + 2.36 \log\left(\frac{R}{d_{50}}\right)} \quad (2.37)$$

The roughness equation of Sauer (1989) is :-

$$n = 0.115S_o^{0.18}R^{0.08} \quad (2.38)$$

There are several factors which affect the value of Manning's Roughness,  $n$ . They are the surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstruction, size, and shape of channel, stage and discharge, seasonal change and suspended load and bed load materials. To cater for the above factors, Cowan, (1956) has developed a procedure to compute the value of  $n$  as follows:

$$n = (n_o + n_1 + n_2 + n_3 + n_4)m_5 \quad (2.39)$$

where  $n_o$  is the basic value of  $n$  for a straight, uniform, smooth channel in the natural material involved,  $n_1$  is the added value to correct the effect of surface irregularities,  $n_2$  is the added value for variations in the shape and size of the channel,  $n_3$  for

obstruction to flow,  $n_4$  the value for vegetation and flow condition, whilst  $m_5$  is a correction factor for channel meandering. The values of  $n_0$  to  $n_4$  and  $m_5$  can be obtained from Chow (1959).

### **2.2.6 Other Methods of Determining Roughness Coefficient**

Apart from using the equations above, the selection of a value for  $n$  is subjective, based on one's own experience and engineering judgement. However, there are a few aids which are available to help the experienced engineer to select an appropriate value of  $n$ . Tables giving the values of roughness coefficient can be found in most hydraulics text books as given by Chow (1959) and additional tables by Barnes (1967). Tables are also produced by US Government Agencies such United State Geological Survey (USGS), and United State Army Corps of Engineers (USACE). Table 2.1 gives the values of Manning's roughness coefficient,  $n$ , extracted from Chow (1959).

Other than the tables, photos of the channels whose values of  $n$  have been determined and compiled by Barnes (1967) and by the U.S. Government agencies stated above are also available. By using the photographs, an experience engineer can determine the Manning Roughness coefficient,  $n$ , of another river which has similar characteristics as the river whose Manning Roughness Coefficient,  $n$  is known. A few illustrations are shown in Figure 2.2.

At present, there are many results obtained from empirical or graphical analysis of laboratory data but they cannot be applied to the field conditions with confidence. This is because the field conditions are more complex compared to conditions that exist in the laboratory flumes. The resistance to flow in an open channel varies with changes

in water depth, slope, fluid density, fine material concentration, bed material size, bed material gradation, fall velocity of sediment particles, cross-sectional shape and seepage force (Simon and Senturk, 1992). The hydrologists will have to continue doing more researches and hopefully some day they will obtain an objective method to compute the roughness and loss in energy in an alluvium channel with confidence.

Table 2.1 Values of Manning's roughness,  $n$  (Chow, 1959)

Type of channel and description	MINIMUM	NORMAL	MAXIMUM
<b>D. NATURAL STREAM</b>			
<b>D.1. Minor Streams (top width at flood stage &lt; 100 ft)</b>			
(a) Stream on plain			
1. Clean, straight, full stage, no rift or deep pool.	0.025	0.030	0.033
2. Same as above, but more stones and weeds.	0.030	0.035	0.040
3. Clean, winding, some pools and shoals.	0.033	0.040	0.045
4. Same as above, but some weeds and stones.	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections.	0.040	0.048	0.055
6. Same as 4, but more stones.	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools.	0.050	0.070	0.080
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush.	0.075	0.100	0.150
(b) Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages.			
1. Bottom : gravels, cobbles, and few boulders.	0.030	0.040	0.050
2. Bottom : cobbles with large boulders.	0.040	0.050	0.070
(a) Pasture, no brush.			
<b>D.2. Flood Plains</b>			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
(b) Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
(c) Brush			
1. Scattered brush, heavy weeds.	0.035	0.050	0.070
2. Light brush and trees, in winter.	0.035	0.050	0.060
3. Light brush and trees in summer.	0.040	0.060	0.080

Table 2.1 Values of Manning's roughness,  $n$  (Chow, 1959) (*continued*)

Type of channel and description	MINIMUM	NORMAL	MAXIMUM
4. Medium to dense brush , in winter.	0.045	0.070	0.110
5. Medium to dense brush, in summer.	0.070	0.100	0.160
(d) Trees			
1. Dense willows, summer, straight.	0.110	0.150	0.200
2. Cleared land with tree stumps, no sprouts.	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts.	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches.	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches.	0.100	0.120	0.160
D.3. Major Stream (top width at flood stage > 100 ft). The $n$ value is less than that for minor streams of similar description, because banks offer less effective resistance			
a. Regular section with no boulders or brush.	0.025		0.060
b. Irregular and rough section.	0.035		0.100

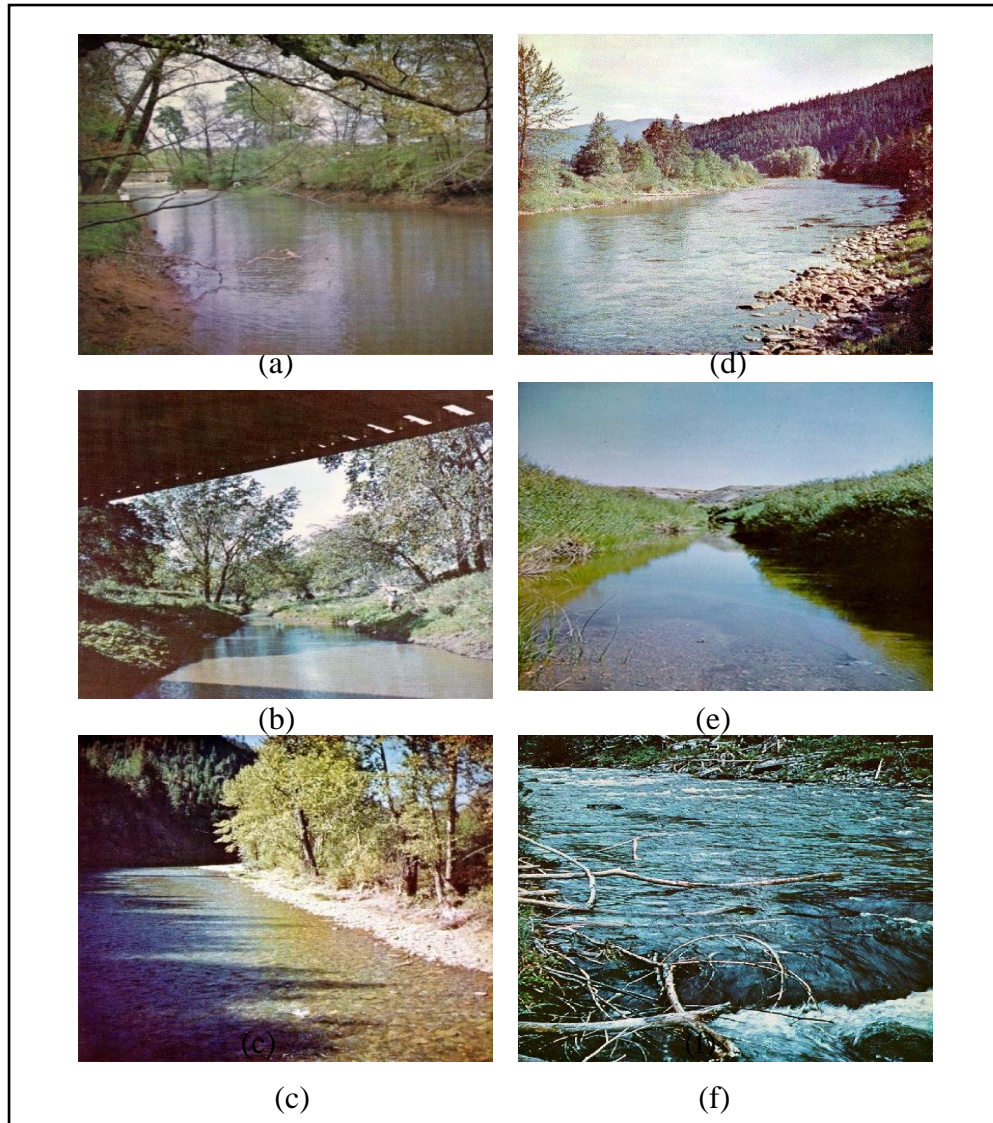


Figure 2.2 Photographs of U.S. River Reaches with Values of Manning's  $n$ .  
 (a) Indian Fork below Atwood Dam near New Cumberland, Ohio  $n = 0.026$   
 (b) Salt Creek @ Roca, Nebr.,  $n = 0.030$   
 (c) Coeur d'Alene River near Prichard, Idaho,  $n = 0.032$   
 (d) Moyle River at Eastport, Idaho,  $n = 0.038$   
 (e) Beaver Creek near Newcastle, Wyo.  $n = 0.043$   
 (f) North Fork Cedar River near Lester, Wash.,  $n = 0.059$  (Barnes, 1967).

## 2.3 Multiple Linear Regression (MLR)

### 2.3.1 Introduction

Scientists and engineers usually collect data and then will determine the nature of the relationship between two quantities. This relationship can be obtained using the method of correlation and simple linear regression. Generally, a regression equation is in the form of  $y = A + Bx + \varepsilon$ , where  $y$  is the dependent variable that the equation tries to predict while  $x$  is the independent variable that is being used to predict  $y$ .  $A$  is the intercept of the least squares (regression) line at the  $y$ -axis and  $\varepsilon$  is known as the random error term or residual. However, there are many situations where there is one dependent variable (criterion variable) and many independent variables (predictor variables) exist. If the relationship between one dependent variable and more than one independent variables is linear, the technique of multiple regression can be used.

Multiple linear regression (MLR) is an extension of the simple linear regression which involves one dependent variable  $Y$  and two or more independent variables,  $X_1, X_2, \dots, X_n$ . It is a statistical tool which is used to evaluate the relationship between two or more independent variables to a single dependent variable (Kleinbaum and Kupper, 1978).

There are two general forms of the multiple regression models. The first is in the form of linear regression model as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots + \beta_p X_p + \varepsilon \quad (2.40)$$

Where  $Y$  is the dependent variable,  $X_1, X_2, X_3, \dots, X_p$ , are the independent variables,