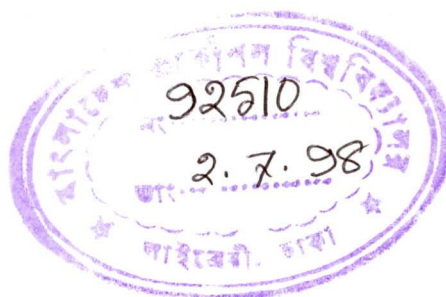


APPLICABILITY OF ALLUVIAL ROUGHNESS PREDICTORS FOR GANGES RIVER

Submitted by

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In partial fulfillment of the requirement for the degree of
Master of Science in Engineering (Water Resources)

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CERTIFICATE

This is to certify that this thesis work has been done by me and neither this thesis nor any part thereof has been submitted elsewhere for the award of any degree or diploma.



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We hereby recommend that the thesis work prepared by Md. Shafiul Alam entitled **"Applicability of Alluvial Roughness Predictors for Ganges River"** be accepted as fulfilling this part of the requirements for the degree of Master of Science in Engineering (Water Resources).

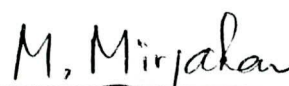
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ABSTRACT

A study has been conducted to investigate the applicability of some alluvial roughness predictors for the river Ganges utilizing data for the stations Hardinge Bridge and Baruria. Five methods based on overall roughness and eight methods based on division of roughnesses have been selected. The selected overall roughness predictors are: Simons and Richardson (1966), Garde and Ranga Raju (1970), Brownlie (1983), White et al. (1987) and Karim (1995). The selected predictors based on division of roughness are Einstein and Barbarossa (1952), Shen (1962), Engelund and Hansen (1967), Vanoni and Hwang (1967), Alam and Kennedy (1969), Haque and Mahmood (1983), Shen et al. (1990) and Van Rijn (1993). Some of the selected methods predict depth, some methods predict velocity and some methods predict both depth and velocity. However, there are some methods which predict roughness parameters directly, without predicting depth or velocity. The methods have been evaluated on the basis of depth and/or velocity, where possible, and all the methods have been evaluated on the basis of Manning's n , Chezy's C and Darcy-Weisbach friction factor f .

Assuming the flow of the river Ganges quasi-steady and quasi-uniform, the Manning, Chezy and Darcy-Weisbach formulas have been applied to compute the values of n , C and f , respectively. The roughness parameters n , C and f have also been predicted by using the roughness predictors. The roughness parameters predicted by the roughness predictors have then been compared with those computed by the Manning, Chezy and Darcy-Weisbach formulas. The grain roughness and the form roughness have also been separately predicted by using different roughness predictors. The predicted grain roughness has been compared with the grain roughness calculated by using the Strickler formula.

Almost all the roughness predictors seem to predict Manning's n satisfactorily in the moderate range of discharges. A few of them, however, predicts Manning's n reasonably in the moderate as well as high discharges. But at low discharges only the Shen (1962) method seems to predict roughness parameters satisfactorily. In fact, only the Shen method shows a good agreement with the computed values of Manning's n , Chezy's C and friction factor f at low discharges when the roughness parameters change sharply. The predicted grain roughness by the Shen method also shows a very good agreement with the grain roughness computed by the Strickler formula. It seems that only the Shen method can be used for predicting the grain roughness, the form roughness and the total roughness for the river Ganges satisfactorily.

For the river Ganges, the bed form normally remain throughout the year except at very high discharges. During flood flow the bed form is due to erosion and during low flow the bed form is due to siltation or non-erosion of the existing bed form. At Hardinge Bridge the discharge ranges from $261 \text{ m}^3/\text{s}$ to $76000 \text{ m}^3/\text{s}$, the Froude number ranges from 0.021 to 0.322 and the Reynolds number ranges from 0.66×10^6 to 45.74×10^6 . At Baruria the discharge ranges from $2860 \text{ m}^3/\text{s}$ to $130000 \text{ m}^3/\text{s}$, the Froude number ranges from 0.029 to 0.315 and the Reynolds number ranges from 0.83×10^6 to 33.33×10^6 . Considering Froude number as classification parameter, the bed form of the river Ganges is mostly in the lower flow regime i.e., ripple and dune as standing waves normally develops when Froude number is greater than or equal to 0.6 (Yalin, 1992) and anti-dunes develop when Froude number is more than 0.8 (Van Rijn, 1993).

At Hardinge Bridge the value of Manning's n ranges from 0.0109 to 0.1589 for discharge ranging from $1200 \text{ m}^3/\text{s}$ to $76000 \text{ m}^3/\text{s}$. The Darcy-Weisbach friction factor f and Chezy's C ranges from 0.0042 to 0.9960 and from 8.88 to 136.02, respectively. At Baruria the value of Manning's n ranges from 0.0092 to 0.0907 for discharges ranging from 2860 to $130000 \text{ m}^3/\text{s}$. The Darcy-Weisbach friction factor f and Chezy's C ranges from 0.0032 to 0.3794 and from 14.38 to 156.10, respectively. The Manning's n for the river Ganges increases with decreasing discharge. At low discharges the n -value is maximum and decreases rapidly with increasing discharge. With further increase of discharge the decrease of the value of n becomes gradual and at high discharges, the Manning's n becomes almost constant. The grain roughness is relatively less responsive to discharge than the form roughness. The variation of grain roughness with discharge is reverse to that of the total roughness. The variation of form roughness is similar to the total roughness, i.e. it increases with decreasing discharge.

The Manning's n for the river Ganges attains its maximum value during March and attains its minimum value during the months of August and September. The Darcy-Weisbach friction factor f also shows a similar variation like Manning's n over the year. However, the variation of Chezy's C is reverse to that of Manning's n and Darcy-Weisbach friction factor f . The Chezy's C increases with increasing discharge and decreases with decreasing discharge.

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SYMBOLS AND ABBREVIATIONS

Symbols:

A	=	Cross-sectional area
B	=	Top width
C	=	Overall Chezy coefficient
C_D	=	Drag coefficient
C_s	=	Concentration of sediment
d	=	Depth of water
d_c	=	Depth of flow above the crest
D	=	Diameter of sediment particle
D_*	=	Dimensionless particle diameter
f	=	Darcy - Weisbach friction factor
Fr	=	Froude number
F_s	=	Force due to skin shear
F_p	=	Pressure drag force
F_g	=	Grain Froude number
g	=	Acceleration due to gravity
H	=	Bed form height
L	=	Bed form length
K_s	=	Nikuradse roughness height
n	=	Manning roughness coefficient
Q	=	Total discharge
q	=	Discharge per unit width
q_*	=	$q / \sqrt{gD_{50}^3}$ = dimensionless unit discharge
Re	=	Reynolds number
Re_*	=	$U_* D / \nu$ = Boundary Reynolds number
R	=	Overall hydraulic radius
S	=	Slope of energy line
s	=	Specific gravity of sediment
T	=	Transport stage parameter
T_*	=	$(\tau_* - \tau_{*c}) / \tau_{*c}$ = excess shear
U	=	Mean velocity of flow
U_*	=	Shear velocity
U_{*cr}	=	Critical shear velocity
w_s	=	Particle fall velocity
τ_b	=	Bed shear stress
$\tau_{b,cr}$	=	Critical bed shear stress
τ_*	=	Dimensionless shear stress
δ	=	Thickness of laminar sublayer
ρ_s	=	Density of sediment particle
ρ	=	Density of water
γ_m	=	Unit weight of sediment-water mixture
γ_s	=	Unit weight of sediment
γ	=	Unit weight of water
σ_g	=	Geometric standard deviation of grain particles
ν	=	Kinematic viscosity of water
μ	=	Dynamic viscosity of water

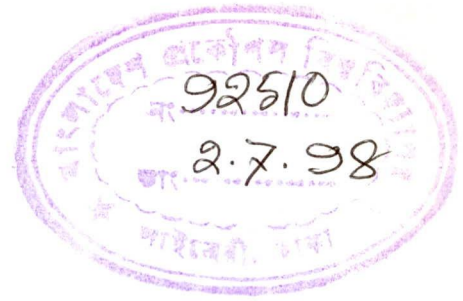
η	=	Relative depth
θ	=	Shields value
θ_{cr}	=	Critical Shields value
δ_d	=	Dune steepness value
δ_r	=	Ripple steepness value

Abbreviations:

FAP	=	Flood Action Plan
MNE	=	Mean Normalized Error
RSP	=	River Survey Project
BWDB	=	Bangladesh Water Development Board

CHAPTER 1

INTRODUCTION



1.1 General

Phenomena in rivers may vary considerably in magnitude, both in time and space. In most cases, however, they have two elements in common: the movement of water and of sediment. Flows in rivers are generally variable in time: it is unsteady. For practical applications, however, the variation may be considered so slow that a quasi-steady flow situation can be assumed.

The term "alluvial river" is usually applied to rivers in which the moving sediment and the sediment in the underlying bed is of the same character. An alluvial channel has a mobile bed, composed of non-cohesive granular materials. Such materials are unconsolidated silts, sands and gravels.

The problem of predicting flow resistance in alluvial channels with sufficient accuracy is of great interest to the hydraulic engineers. The flow boundary of an alluvial river is not fixed, but undergoes changes in its characteristic geometry and dimensions through mutual interaction between the flow and bed. When the discharge in an alluvial channel is low, the velocity as well as the shear stresses are small, the sediment particles remain at rest and the flow is similar to that over a rigid boundary. If the discharge is gradually increased, the velocity and shear stresses also increase and a critical stage (called the threshold condition) is reached when the particles on the bed begins to move. At still higher values of shear stress, the particles comprising the channel bed are set in motion and the bed deforms from its initial plane condition.

In rigid boundary open channels, the resistance to flow can be considered to be mainly caused by grain roughness, i.e. the roughness of the material forming the channel boundary. It is common for engineers to think of a rigid boundary open channel as having a single roughness value for all discharges. However, the problem of predicting the resistance to flow in alluvial rivers with mobile boundary is complicated by the fact that the configuration of the bed changes with change in flow conditions. This changing bed condition makes it

impossible to describe the resistance to flow in an alluvial channel by a single-valued resistance coefficient to a particular stream.

In dealing with natural rivers with movable beds, the engineer is confronted with the problem of evaluating frictional losses. Unless adequate and complete data are available for calculating roughness coefficients, evaluation of frictional effects is based almost upon the predictor applied. The element of doubt inevitably present forces the engineer to be conservative. The degree of conservatism exercised is reflected in project costs. If the element of doubt and confusion concerning frictional losses in natural streams could be reduced to lowest practicable limit, substantial savings in the costs of many hydraulic projects undoubtedly would result.

1.2 Background of the Study

Interest in the resistance problem in the past five or six decades has been stimulated by both laboratory and field studies of the sediment problem. Attempts to determine resistance factors for alluvial channels have been based on modification of existing fixed bed equations. Mayer-Peter and Muller (1948) divided the shear stress acting on the bed into two parts: (i) the shear stress that would be present without sand waves, and (ii) the shear stress due to bed form. This is a division into skin roughness and form roughness. Einstein (1950) and Einstein and Barbarossa (1952), using either the logarithmic velocity equations of Keulegan or the Manning-Strickler equation, separated the total resistance of the flow into that resulting from grain friction and that resulting from the form roughness such as bank irregularities and ripples and dunes.

Starting from Einstein and Barbarossa (1952), a lot of empirical formulae have been developed for predicting roughness of an alluvial river. In principle they are of two kinds, viz:

- (i) Separate estimate of grain roughness and form drag on basis of grain size distribution of the bed material and the anticipated bed forms. The total roughness is found by adding both roughnesses together.
- (ii) Integral methods in which simultaneously the continuity and the Chezy's or Manning equations are solved and the total roughness is found. These methods are based on

overall flow parameters such as depth of water and depth-averaged flow velocity. Another integral method of predicting alluvial roughness utilizing is the principles of dimensional analysis.

The prediction of flow resistance in alluvial channels is needed for two major purposes:

- i) The estimation of stage-discharge relationship.
- ii) The estimation of sediment transport from the hydraulic characteristics of the channel by means of transport formula.

Moreover, knowledge of the roughness characteristics of alluvial streams is of great value when dealing with the location of bridges, training works, flood control works, navigation and channel improvement, backwater computation due to confluences and barrages, mathematical and physical modelling of flow, prediction of aggradation and degradation due to presence of hydraulic structures and so on. In all cases the prediction is concerned either with a channel for which, under a given hydraulic conditions, no observations are available or with a channel that does not yet exist. For river studies it is desired to select a predictor on the basis of available observations and to use the predictor to extrapolate to circumstances for which no data are or will be available.

In Bangladesh most of the river courses are of alluvial nature. The three mighty rivers and their tributaries and distributaries are characterized by variability of flow, the sediment transport as well as channel configuration. Stage, discharge and sediment transport change daily, seasonally and annually. Changes in stage continuously influence scour and fill patterns along the channel bed as well as the magnitude of hydraulic roughness.

The roughness coefficient of some rivers of Bangladesh was determined by Khan (1975). Later on Khan (1979) developed the relationship between discharge, mean velocity of flow and depth of scour for 1966-67 flood period of Brahmaputra river. Stage-discharge relationship for the river Jamuna at Bahadurabad was studied by Chowdhury (1996). The River Survey Project (FAP-24) reported that bed form roughness is the main component of the overall resistance in the river Jamuna. The validity of Soil Conservation Service (SCS)

method (French, 1986) for estimating roughness coefficients were also investigated by the River Survey Project (FAP-24).

Since Einstein and Barbarossa (1952), a large number of roughness predictors has been published. Some of them predict overall roughnesses and others are based on method of division of roughness. Every method claims a quite good accuracy of its own. The applicability of these predictors for rivers of Bangladesh is of great importance from engineering point of view.

In this study, an attempt has been made to investigate the applicability of some roughness predictors for the river Ganges. At Hardinge Bridge the water level slope is 5.5×10^{-5} and the median grain size is 0.15 mm. At Baruria the water level slope is 4.0×10^{-5} and the median grain size is 0.14 mm. For that, the roughness predictors those could be applied to channels of mild slope and fine sand bed material have to be selected. To do so, 13 (thirteen) roughness predictors have been selected, 5 (five) based on overall roughness and 8 (eight) based on methods of division of roughness. They are applied to predict roughnesses of the river Ganges at the stations Hardinge Bridge and Baruria. The selected methods based on overall roughnesses are Simons and Richardson (1966), Garde and Ranga Raju (1970), Brownlie (1983), White et al. (1987) and Karim (1995) methods. The methods based on divided roughnesses are Einstein and Barbarossa (1952), Shen (1962), Engelund and Hansen (1967), Vanoni and Hwang (1967), Alam and Kennedy (1969), Haque and Mahmood (1983), Shen et al. (1990) and Van Rijn (1993) methods.

1.3 Objective of the Study

The specific objectives of the proposed study are:

1. To determine the applicability and limitations of 13 different methods for predicting the roughness characteristics of the river Ganges at the Hardinge bridge and Baruria.
2. To determine the roughness characteristics of the Ganges.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

A brief review of various earlier studies that took place during last three or four decades regarding hydraulic and roughness characteristics of the river Ganges and Padma will be made in this chapter. In addition, the roughness coefficients, shear stress, shear velocity, initiation of motion of bed material, bed configurations etc. related to roughness characteristics of alluvial channels utilized in this study will also be briefly discussed here.

2.2 Review of Previous Studies in Bangladesh

Bangladesh consists of large rivers that enter into the Bay of Bengal via Bangladesh. Most of the rivers are alluvial in nature. The main rivers in Bangladesh are the Brahmaputra (Jamuna), the Ganges (Padma) and the Meghna. These rivers are considered to belong to the main river system in Bangladesh.

The paper that first gave a comprehensive overview of the geology of the basin of the main rivers in Bangladesh was published by Morgan and McIntyre (1959). The papers by Coleman (1968, 1969) on "Brahmaputra River: Channel processes and sedimentation" is the bench- mark paper for the sedimentology of the main rivers of Bangladesh. Khan (1975) determined the roughness coefficients of some rivers of Bangladesh. Later on Khan (1979) developed the relationship between discharge, mean velocity of flow, depth of scour and maximum deposition for 1966-1967 flood period of the Brahmaputra river. Hossain (1989) studied the geomorphological characteristics of the Ganges up to the Ganges-Jamuna confluence. The study was mainly on the shifting of river, dominant discharge and the variation of the width to depth ratio. Hossain (1992) also computed dominant discharge for the Ganges utilizing data at the Hardinge Bridge station.

Within the framework of consultancy service, quite a large number of studies had been carried out regarding the Ganges and the Padma rivers. NEDECO (1968) submitted its report on 'survey of inland water-ways and ports'. NEDECO studied the variations in the elevation

of river bed and sediment transport of the rivers Ganges and Padma. Later on, NEDECO surveyed the river Ganges and submitted their report on "Rehabilitation of Ganges - Kobodak Project" during 1983. Under the Flood Action Plan - 9B, NEDECO surveyed from Haimchar to Mawa along the Padma river. Bed samples were collected from the Padma river. The analysis of the morphological data yields an insight into the morphological characteristics of the Padma river. The River Survey Project (FAP-24) conducted jointly by the Delft Hydraulics and the Danish Hydraulic Institute was initiated in June 1992 and completed in 1997. Along with other relevant activities carried out, it surveyed the bed material composition, mineralogical properties of bed material and sediment transport rate for the Ganges-Padma and the Lower Meghna river systems. The River Survey Project (FAP-24) produced the sediment rating curve for both fine and suspended sediment transports for Hardinge Bridge and Baruria for the Ganges and Goalunda for the Padma. Overall water surface slope and grain size distribution at the stations Harding Bridge and Baruria were also determined by it.

2.3 Roughness Characteristics

The roughness characteristics of a river includes the resistance coefficients, shear stress, shear velocity, roughness height, etc.

2.3.1 Chezy's C

In 1769 the French engineer Antoine Chezy developed the first uniform-flow formula known as the Chezy formula which is usually expressed as

$$U = C\sqrt{RS} \quad (2.1)$$

where, U = mean velocity of flow
 R = hydraulic radius
 S = slope of the energy line
 C = factor of flow resistance, called Chezy's C

Rearrangement of Eq. (2.1) gives

$$C = \frac{U}{\sqrt{RS}} \quad (2.2)$$

2.3.2 Manning's n

In 1889 the Irish engineer Robert Manning presented a formula, which was later modified to its present form (Chow, 1959)

$$U = \frac{1}{n} R^{2/3} S^{1/2} \quad (2.3)$$

where, U = mean velocity of flow
 R = hydraulic radius
 S = slope of the energy line
 n = co-efficient of roughness, specifically known as Manning's n.

Rearranging Eq. (2.3), we obtain

$$n = \frac{1}{U} R^{2/3} S^{1/2} \quad (2.4)$$

2.3.3 Darcy - Wiesbach friction factor f

The Darcy-Wiesbach formula, developed primarily for flow in pipes, is given by

$$h_f = f \frac{L}{d} \frac{U^2}{2g} \quad (2.5)$$

where, h_f = frictional loss
 f = friction factor
 d = diameter of pipe
 g = acceleration due to gravity

The above equation can also be applied to flow in an open channel using $d = 4R$ and the energy gradient, $S = h_f/L$. Then Eq. (2.5) can be rewritten for the friction factor as

$$f = \frac{8gRS}{U^2} \quad (2.6)$$

2.3.4 Relation between n, C and f

The relationships between Chezy's C and Darcy-Weisbach friction factor f and Chezy's C and Manning's n are given, respectively, by

$$C = \sqrt{\frac{8g}{f}} \quad (2.7)$$

and

$$C = \frac{1}{n} R^{1/6} \quad (2.8)$$

2.3.5 Strickler formula

The Strickler formula is valid for hydraulically rough surfaces only. The Chezy's roughness coefficient C according to Strickler is given by (French, 1986)

$$C = 25 \left[\frac{R}{K_s} \right]^{1/6} \quad (2.9)$$

The Strickler formula which relates grain roughness to Manning's n is (Chang, 1988)

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

in which K_s = the Nikuradse equivalent sand grain roughness.

2.3.6 White-Colebrook formula

White and Colebrook derived an expression for Chezy's roughness coefficient by integrating the velocity distribution over an entire water depth. According to White and Colebrook, the Chezy's coefficient for a hydraulic rough boundary is given by

$$C = 18 \log \left(\frac{12R}{K_s} \right) \quad (2.11)$$

2.3.7 Roughness height K_s

When the surface profile of a channel is enlarged, it can be seen that the surface is composed of irregular peaks. The effective height of the irregularities forming the roughness elements is called the roughness height K_s . This is a parameter which characterises not only the vertical size of the roughness elements but also their orientation, geometric arrangement and spacing. For this reason, the roughness height rarely corresponds to the height of the roughness elements.

Nikuradse introduced the concept of an equivalent sand grain roughness e.g. the size of uniform sand grains pasted on a surface for classifying the roughness of different surfaces to the flow. This concept of equivalent sand roughness was named after Nikuradse and is referred to as the Nikuradse equivalent sand grain roughness (K_s). Various researchers carried out experiments or analyzed data in order to determine the roughness height (K_s). An overview of grain roughness values found in literature is given below:

Einstein and Barbarossa	(1952)	:	$K_s = D_{65}$
Engelund and Hansen	(1967)	:	$K_s = 2D_{65}$
Ackers - White	(1973)	:	$K_s = 1.25D_{35}$
Hey	(1973)	:	$K_s = 3.5D_{84}$
Mahmood	(1971)	:	$K_s = 5.1D_{84}$
Van Rijn	(1984)	:	$K_s = 3D_{90}$

2.3.8 Shear stress τ_0

When water flows in an open channel, a force is developed that acts in the direction of flow on the channel bed. This force, which is simply the pull of water on the wetted area, is known as the tractive force or shear force or drag force. The average value of the tractive force per unit wetted area is called the shear stress and is represented by (Chaudhury, 1994)

$$\tau_0 = \gamma RS \quad (2.12)$$

2.3.9 Shear velocity U_*

In hydraulics the shear in the direction of motion is important. The shear velocity is a parameter having dimensions of velocity and defined as

$$U_* = \sqrt{\tau / \rho} \quad (2.13)$$

Since $\tau = \rho gRS$, the friction velocity can also be expressed as

$$U_* = \sqrt{gRS} \quad (2.14)$$

2.4 State of Flow

The state of open channel flow is governed to a large degree by viscosity, gravity and inertial forces.

2.4.1 Effect of viscosity

The flow may be laminar, turbulent, or transitional depending on the effect of viscosity relative to inertia. The flow is laminar if the viscous forces are so strong relative to the inertia forces that viscosity plays a significant role in determining the flow behavior. The flow is turbulent if the viscous forces are weak relative to the inertia forces. With turbulent flow the fluid particles moves in irregular paths which are neither smooth nor fixed but still represent the forward motion of the fluid. Between laminar and turbulent flow there is a mixed or transitional state.

The effect of viscosity relative to inertia may be represented by the Reynolds number Re which is the ratio of the inertia force to viscous force, i.e.

$$Re = \frac{UL}{\nu} \quad (2.15)$$

where L = a characteristic length, taken to be equal to the hydraulic radius R .

ν = kinematic viscosity of water

When $Re < 500$, the flow is laminar, when $500 < Re < 12500$ the flow is transitional and when $Re > 12500$, the flow is turbulent.

2.4.2 Effect of gravity

The effect of gravity upon the state of flow is represented by the Froude number expressed as

$$Fr = \sqrt{\frac{\text{Inertia force}}{\text{Gravity force}}} = \frac{U}{\sqrt{gL}} \quad (2.16)$$

where, L = a characteristic length, taken to be equal to the hydraulic depth, d
 g = acceleration due to gravity

when $Fr = 1$, the flow is in a critical state with the inertial and gravitational forces in equilibrium, when $Fr < 1$, the flow is in a subcritical state and the gravitational forces are dominant, and when $Fr > 1$, the flow is in a supercritical state and the inertial forces are dominant.

2.5 Sediment Characteristics

2.5.1 Cohesive and non-cohesive sediments

Both cohesive and non-cohesive sediments take part in morphological processes. For the non-cohesive sediments there is no physical-chemical interaction between individual particles. For cohesive sediments the physical-chemical interaction between particles plays a significant role. This is important for initiation of motion and also for transportation of sediment. Alluvial rivers are non-cohesive in character.

2.5.2 Grain size

A first measure with which to characterize non-cohesive sediments is the particle size or diameter. For fine sediments ($D < 70\mu\text{m}$) the size is usually determined by measuring the fall velocity. For coarser sediments ($D > 70\mu\text{m}$) the size is frequently determined by sieving, meaning that size is expressed using the definition of the sieve diameter and the results are presented as cumulative. The fraction or percentage by weight of a sediment that is smaller than a given size is known as sediment size.

2.5.3 Geometric standard deviation

The geometric standard deviation σ_g is defined as

$$\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}} = \frac{1}{2} \left[\frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}} \right] \quad (2.17)$$

in which, D_{16} = particle size at which 16 percent by weight is smaller
 D_{50} = particle size at which 50 percent by weight is smaller
 D_{84} = particle size at which 84 percent by weight is smaller.

2.5.4 Particle fall velocity

The term fall velocity w_s of a sphere is the fall velocity when the fluid drag force on the particle is in equilibrium with the gravity force. It is given by (Van Rijn, 1993)

$$w_s = \left[\frac{4(s-1)gD}{3C_D} \right]^{0.5} \quad (2.18)$$

where D = sphere diameter

s = specific gravity of falling particle

C_D = drag coefficient

g = acceleration of gravity

The drag coefficient C_D is a function of the Reynolds number $Re = \frac{w_s D}{\nu}$ and shape factor.

The terminal fall velocity of non-spherical sediment particles can be determined from the following formulas:

$$w_s = \frac{(s-1)gD^2}{18\nu} \quad \text{for } 1 < D \leq 100 \mu m \quad (2.19)$$

$$w_s = \frac{10\nu}{D} \left[\left(1 + \frac{0.01(s-1)gD^3}{\nu^2} \right)^{0.5} - 1 \right] \quad \text{for } 100 < D < 1000 \mu m \quad (2.20)$$

$$w_s = 1.1[(s-1)gD]^{0.5} \quad \text{for } D > 1000 \mu m \quad (2.21)$$

2.5.5 Angle of repose

This parameter appears to be a function of size, shape and porosity of the material. The angle of repose increases with decreasing roundness and size of particles. For sand the angle of repose lies in the range of 30° to 40° . Observations in nature on the avalanche lee slope of the desert dunes and river dunes also show values in the range of 30° to 40° for sand.

2.6 Initiation of Motion

The stability of a non-cohesive particle on the bed of a channel depends on the forces acting on it, such as the submerged weight, drag forces and lift forces. The two latter forces are due to flow around the particle causing pressure differences and shear stress on the particle surface. Their magnitude depends on particle dimensions and shape, roughness of the bed, local mean velocities and velocity fluctuations. In turbulent flow conditions, the velocities fluctuate in space and time and that the initiation of motion is not merely a deterministic phenomenon but a stochastic process as well.

2.6.1 Threshold value

When the hydrodynamic force acting on a grain of sediment or an aggregate of cohesive particles has reached a value that, if increased slightly, will put the grain or aggregate into motion, critical or threshold conditions are said to have been reached. When critical condition is obtained, values of such quantities as the bed shear stress, the stage of a stream or its mean velocity are said to have their threshold values. Under threshold conditions, a stream is also said to be competent to move its sediment, i.e., it has reached its competent shear stress, stage and velocity. Three different threshold values are often used in literature. They are the critical shear stress, the critical Shields value and the critical shear velocity.

2.6.1.1 Critical shear stress

The critical shear stress for the initiation of motion was introduced by Dubuat (1786). The fluid forces acting on a sediment particle resting on a horizontal bed consists of skin friction forces and pressure forces. The skin friction force acts on the surface of the particles by viscous shear. The pressure force consisting of a drag and a lift force is generated by

pressure differences along the surface of this particle. The threshold value according to the critical shear stress ($\tau_{b,cr}$) is defined as follows:

- i. In case the bed shear stress, τ_b , is smaller than the critical bed shear stress ($\tau_{b,cr}$), the sediment particle on the bed will be in equilibrium.
- ii. In case the bed shear stress, τ_b , is greater than or equal to the critical bed shear stress ($\tau_{b,cr}$), the sediment particle will be set in motion.

The critical shear stress can be obtained from Fig. 2.1 (Shields, 1936). For the particle diameter of non-uniform bed material, the median particle size D_{50} should be used.

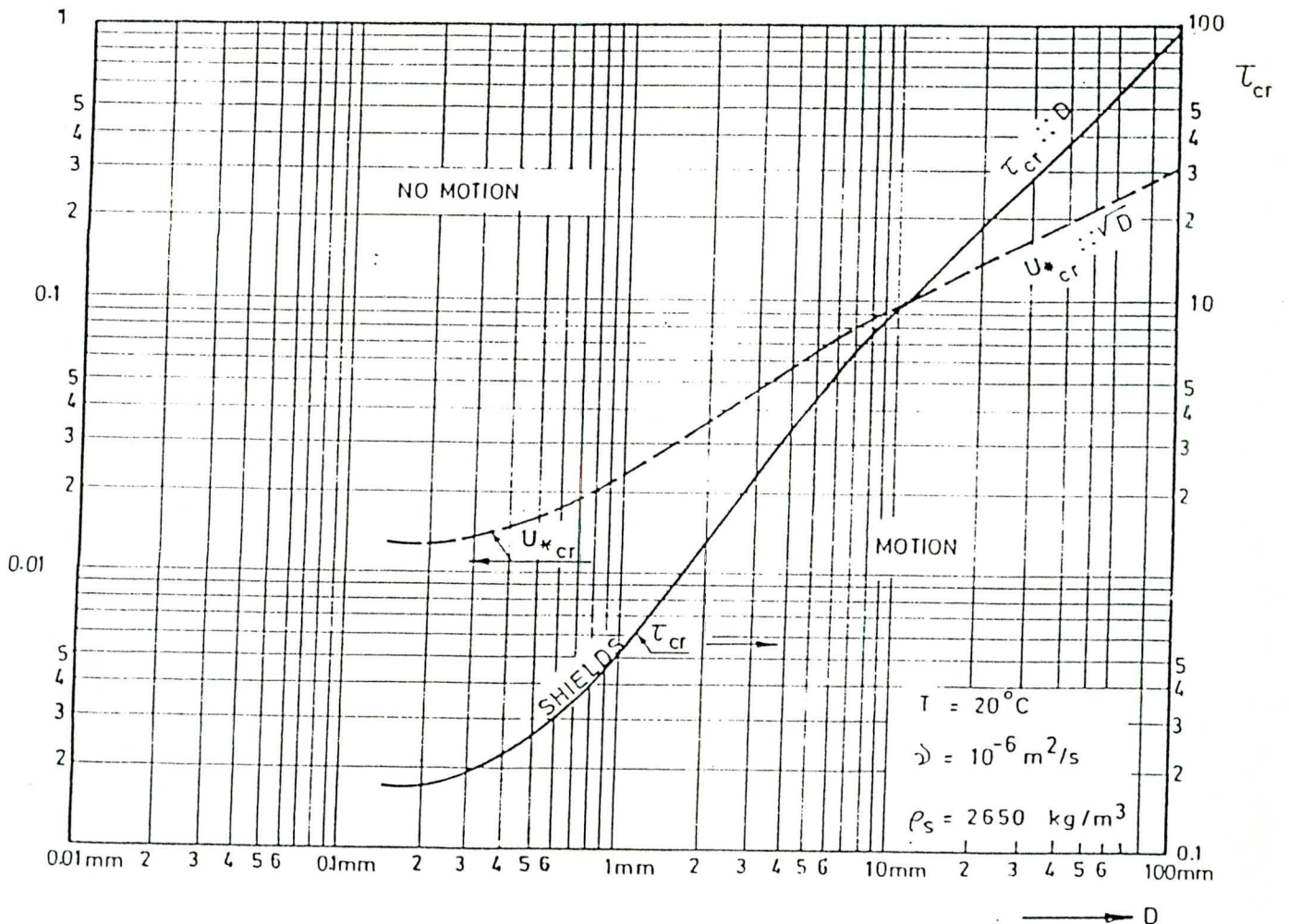


Fig. 2.1 Critical shear stress and critical shear velocity as a function of particle size, for $\rho_s = 2650 \text{ kg/m}^3$ (after Shields, 1936)

Figure 2.2 shows the critical bed shear stress according to Shields as a function of the particle diameter D for a temperature of $T = 10^\circ, 20^\circ$ and 30°C . The influence of temperature is significant for a particle diameter smaller than $600\ \mu\text{m}$.

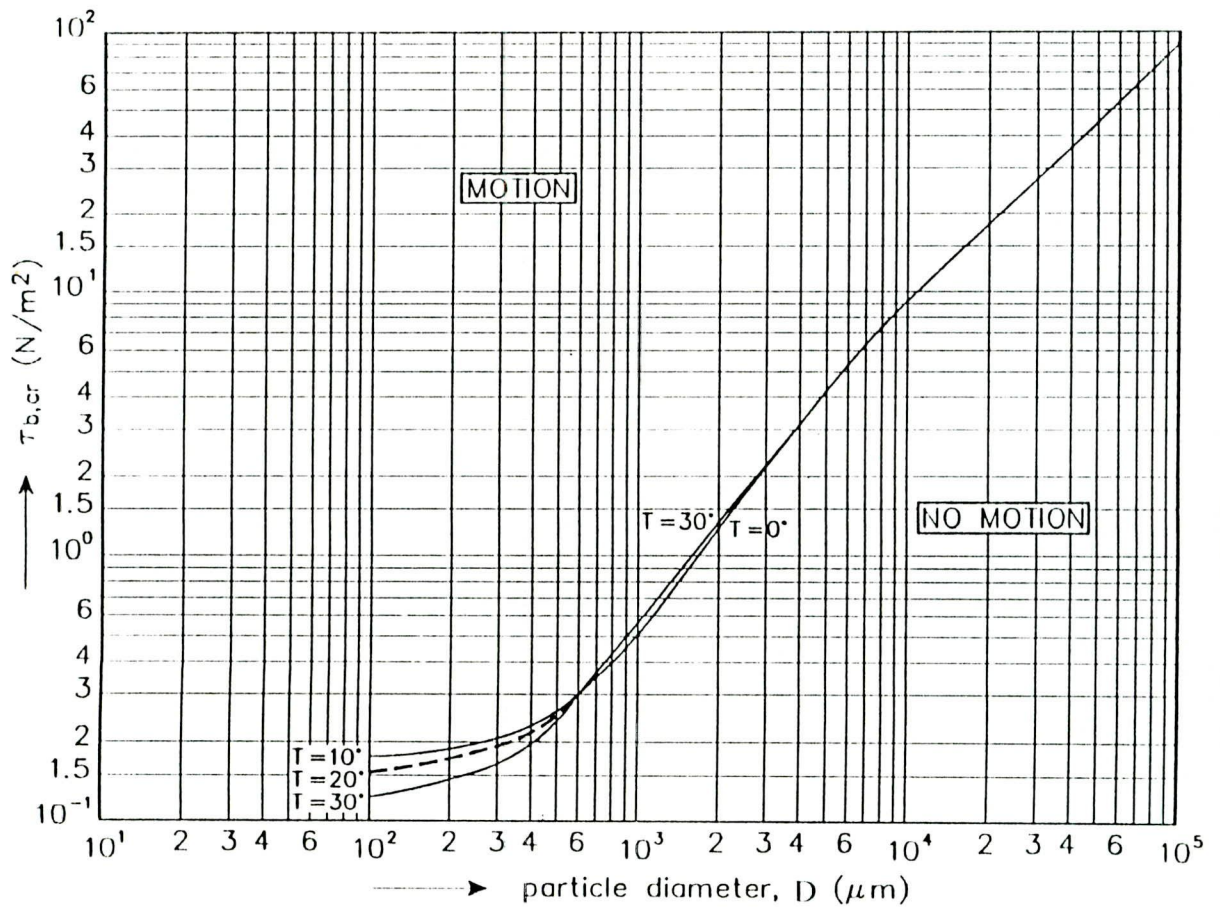


Fig. 2.2 Initiation of motion for a current over a plane bed, $\tau_{b,cr} = f(D)$ (after Shields, 1936)

2.6.1.2 Critical Shields value

Mathematically, the Shields value (θ) is defined as

$$\theta = \frac{U_*^2}{g(s-1)D} \quad (2.22)$$

The condition for the initiation of motion of a sediment particle on a horizontal bed is that the Shields value θ should be greater or at least equal to the critical Shields value θ_{cr} .

The critical Shields value is a function of the boundary Reynolds number $Re_\star = \frac{U_\star D}{\nu}$, the particle shape and the porosity of the deposited material. For a given sediment the critical Shields value can be written as

$$\theta_{cr} \leq \theta \quad (2.23)$$

in which

$$\theta_{cr} = f(Re_\star) = f\left(\frac{U_\star D}{\nu}\right) \quad (2.24)$$

Shields (1936) carried out experiments for determining the threshold values of sediment particles lying on a flat bed. The relation between the boundary Reynolds number and the critical Shields value is depicted in Fig. 2.3.

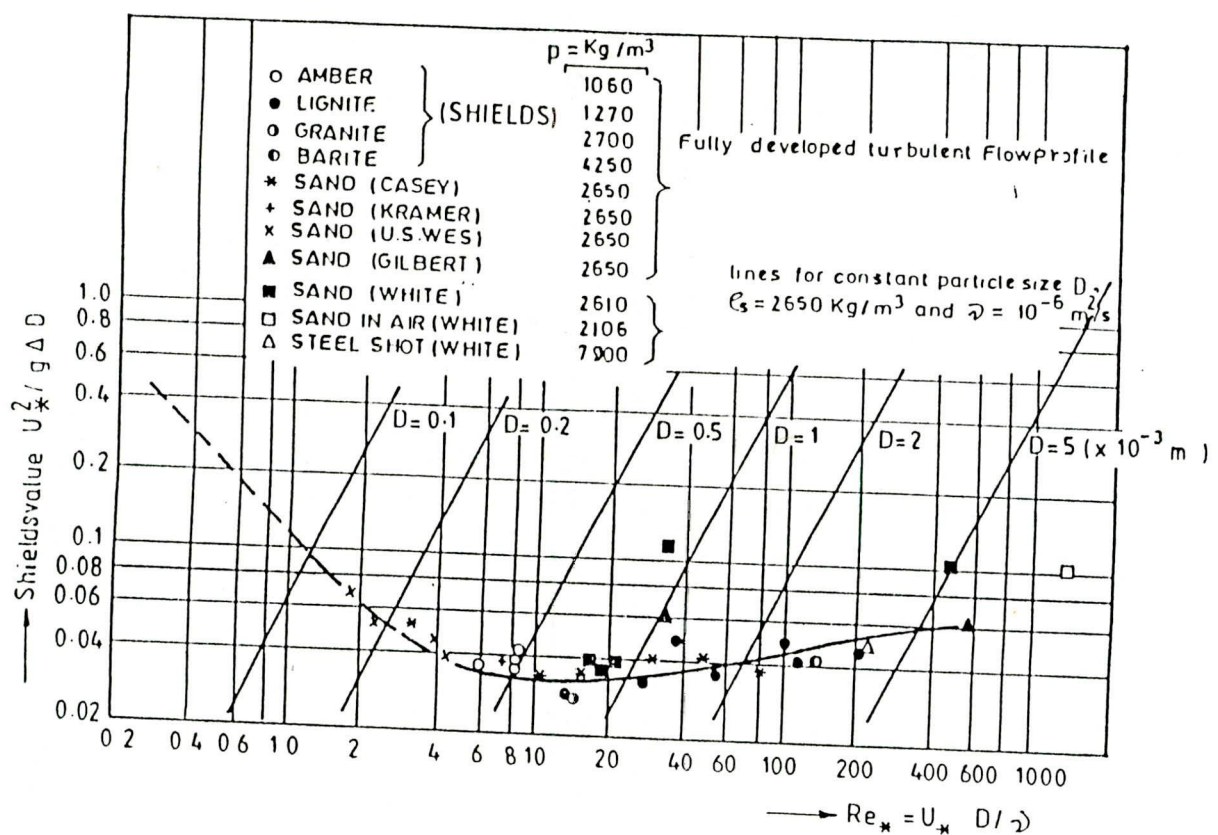


Fig. 2.3 Shields diagram (after Prins, 1978)

2.6.1.3 Critical shear velocity

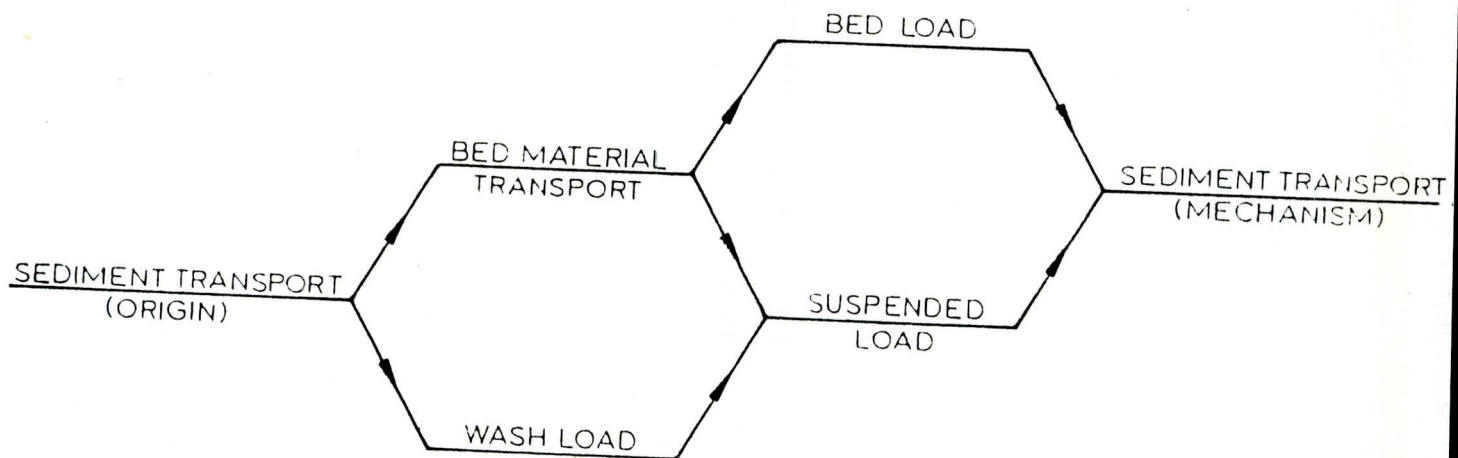
The threshold value according to the shear velocity is defined as follows:

- i. In case the shear velocity, U_* , is smaller than the critical shear velocity, U_{*cr} , the sediment particle on the bed will be in equilibrium.
- i. In case the shear velocity, U_* , is greater than or equal to the critical shear velocity, U_{*cr} , the sediment particle will be set in motion.

For the particle diameter of non-uniform bed material, the critical shear velocity U_{*cr} can be obtained for known value of D_{50} from Fig. 2.3.

2.7 Transport of Sediment

When the flow conditions reach the critical stage, the loose bed material starts moving. Above a certain flow velocity individual particles start moving along the bed by rolling, sliding and making small jumps. The sediment transport can be classified according to origin and mechanism as in the following scheme.



2.8 Factors Affecting Bed Forms and Resistances to Flow

The large number of variables which affect bed forms are interdependent. Some of the variables change with flow conditions and alter their roles from dependent to independent variables. It is difficult, specially in field studies, to differentiate between the independent and dependent variables. The principle variables involved in the analysis of flow in alluvial channels are:

$$f(U, d, S, \rho, \mu, g, D, \sigma, \rho_s, S_p, S_r, S_c, f_s) = 0 \quad (2.25)$$

where

U	=	average velocity of flow
d	=	average depth
S	=	slope of energy grade line
ρ	=	density of water
μ	=	dynamic viscosity of water
g	=	gravitational acceleration
D	=	diameter of the bed material
σ	=	size distribution of bed material
ρ_s	=	density of sediment
S_p	=	shape factor of the particles
S_r	=	shape factor for the reach of the stream
S_c	=	shape factor for the cross-section of the stream
f_s	=	seepage force in the bed of the stream.

In Eq. (2.25) fluid viscosity μ and particle shape factor S_p can be eliminated if the fall velocity of the bed material w_s is included in the list of the variables:

$$U = F(d, S, \rho, \rho_s, g, D, \sigma, w_s, S_r, S_c, f_s) \quad (2.26)$$

Depth d

It is observed that, in flumes and natural canals in which slope and bed materials are essentially constant, the bed forms change with change in flow depth. An increase in depth, without varying slope and bed material, may cause a dune bed to change to a plane bed or antidune, and that a decrease in depth may reverse the process.

Slope S

At steep slopes there is an increase in the gravity component of the submerged weight of the sediment in the direction of flow. With increase in slope keeping depth of flow constant, the bed configuration changes. Resistance to flow is a function of slope even when the bed configuration does not change.

Density

The density of sediment-water mixture can be computed from the relationship (Simons et al., 1963).

$$\gamma_m = \frac{\gamma \gamma_s}{\gamma_s - C_s (\gamma_s - \gamma)} \quad (2.27)$$

where C_s is the concentration of the suspended sediment by weight expressed as a percentage. The importance of the increased density of the fluid is seen in determining submerged weight of sediment and hence the magnitude of the lift and drag forces.

Size of bed material D

The effects of physical size of the bed material on bed configurations and resistance to flow include: (i) its influence on the fall velocity, (ii) its effect on grain roughness, (iii) its effect on the turbulent structure and the velocity field of flow.

Gradation of bed material σ

The gradation of the bed material has a significant effect on bed form. Bed forms of uniform sand are more angular and have a larger resistance to flow than graded sands with identical mean fall diameter.

Fall velocity w_s

Fall velocity is the primary variable that determines the interactions between the bed material and the fluid. For a given depth and slope, it significantly affects the bed form that

will occur, the actual dimensions of the bed form, and expect for the contribution of the grain roughness, the resistance to flow. If w_s is a variable an increase in its value causes:

- i) an increase in the resistance for dune bed,
- ii) a decrease in the resistance for ripple bed,
- iii) a change from ripples to dunes.

Shape factor for the reach and cross-section

The shape factor for the reach and cross-section enters into the analysis because of the non-uniformity of reach and cross-section of the natural stream. The shape factor for a reach of channel affects the energy losses. This is due to bends and banks, and the effect of shape factor on the velocity distribution, boundary shear and secondary circulation. The shape factor for the cross-section has a similar effect across a channel section causing variation in velocity, width, depth and boundary shear. Variations of these variables and combination of variables cause multiple bed roughness in a channel section.

Seepage force f_s

Seepage forces occur whenever there is inflow or outflow through the bed material and bank of a channel formed in a permeable alluvium. If there is inflow, the seepage force acts to reduce the effective weight and stability of the bed material. If there is outflow, the seepage force acts to increase the effective weight and stability of the bed material.

2.9 Alluvial Roughness

The roughness of the movable bed of an alluvial channel depends on:

1. the roughness of the bed material or grain roughness, and
2. the hydraulic resistance induced by the shape of the bed form or form drag.

For the roughness of an alluvial channel, therefore, can be written:

$$\tau_b = \tau'_b + \tau''_b \quad (2.28)$$

in which, τ_b = overall bed shear stress
 τ'_b = bed shear stress related to grain roughness
 τ''_b = bed shear stress related to form drag.

2.9.1 Grain roughness related bed shear stress τ'_b

The grain roughness related bed shear stress results from the skin friction exerted between the flow and each individual sediment particle. Division of the horizontal component of the total skin friction force ($F_{s,h}$) by the flow width and bed form length yields the grain force related bed shear stress acting against the flow (Fig. 2.4). It is to be mentioned that in case of a plane bed the skin friction force acts on the entire length of the bed, while in case of a dune the skin force acts on the luff side of a dune only.

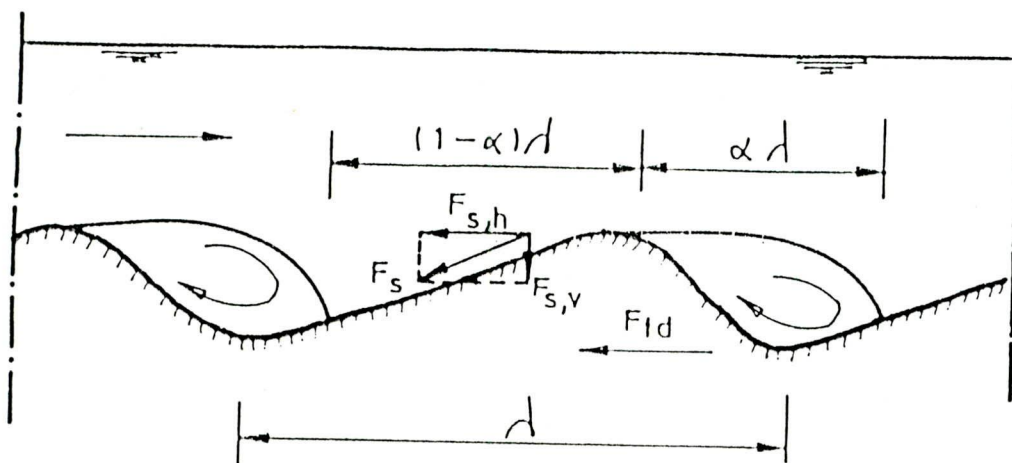


Fig. 2.4 Forces acting on a fluid around a bed form

2.9.2 Form drag related bed-shear stress τ''_b

The form drag related bed-shear stress results from pressure differences over the bed form. The flow is accelerated on the luff side, while the flow is decelerated on the lee side of the bed form. As a result the pressure on the luff side will be smaller than on the lee side. Integration of pressure over the length of the bed form results in horizontal force (F_{fd}) acting against the flow (Fig. 2.4). Dividing this force F_{fd} by the flow width and the bed form length

yields the form drag related bed shear stress. The shape of bed form varies with increasing flow velocities from a plane bed, ripples, dunes, washed out dunes, a flat bed, antidunes to chutes and pools. The form drag related bed shear stress and hence the total bed shear stress will change accordingly. In Fig. 2.5 the variation of the bed shear stress τ_b and the Darcy-Weisbach friction factor f with the depth average velocity is shown. In this figure it can be seen that the influence of the form drag related bed shear stress is only important for ripples, dunes and antidunes. In case of immobile bed and a transition flat bed, the influence of the form drag related bed shear stress can be neglected.

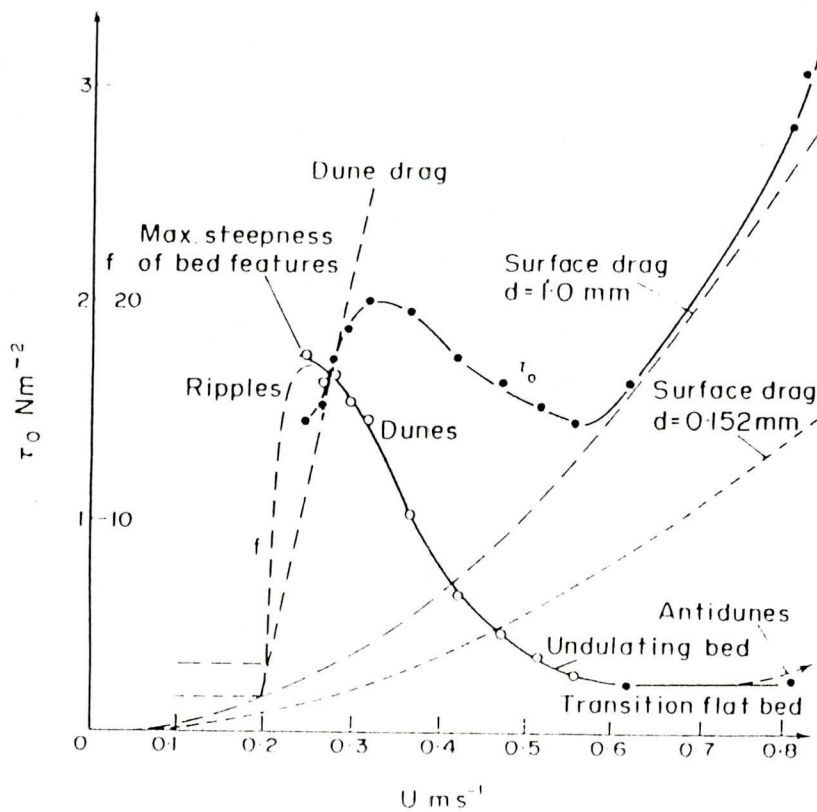


Fig. 2.5 Variation of bed shear stress τ_0 and Darcy-Weisbach friction factor, f , with mean velocity, U , in flow over a fine sand bed (after Raudkivi, 1990)

2.10 Parameters Describing Surface Drag and Form Drag

Many studies and analyses have considered various ways of expressing form and surface drags. Two general approaches are:

1. If S' corresponds to the fraction of the energy slope required to overcome surface drag and S'' the fraction required to offset form drag it is possible to write

$$S = S' + S'' \quad (2.29)$$

This idea was developed by Mayer-Peter and Muller (1948).

2. It is possible to define the hydraulic radius of a wide river as

$$R = \frac{Bd}{B}$$

If the numerator and the denominator of this ratio are multiplied by length L in such a way that $BL = A = 1$ and $BdL = V$, the volume, then

$$R = \frac{BdL}{BL} = \frac{V}{A} = V$$

Then the hydraulic radius represents the volume of a rectangular prism with a height equal to the depth of water. If V' corresponds to the necessary volume for damping turbulence related to surface friction it is possible to define the volume V'' required to damp the turbulence attributed to bed forms so that

$$V = V' + V'' \quad (2.30)$$

or

$$R = R' + R'' \quad (2.31)$$

This concept was first given by Einstein (1950).

2.11 Parameters for Describing Resistance to Flow

Friction velocity U_*

From Art. 2.9 we know that total bed shear is the sum of bed shear stress related to grain roughness and bed shear stress related to grain shear (Eq. 2.28). It is assumed that τ_b , τ'_b and τ''_b are caused by the same flow velocity U . Thus also

$$U_*^2 = (U'_*)^2 + (U''_*)^2 \quad (2.32)$$

or

$$RS = (RS)' + (RS)'' \quad (2.33)$$

Chezy's resistance factor C

The Chezy's formula expressed in Eq. 2.1 can be rearranged as

$$\frac{U^2}{C^2} = RS = (RS)' + (RS)'' \quad (2.34)$$

or

$$\frac{1}{C^2} = \frac{(RS)'}{U^2} + \frac{(RS)''}{U^2} = \left(\frac{1}{C'}\right)^2 + \left(\frac{1}{C''}\right)^2 \quad (2.35)$$

Darcy-Wiesbach friction factor f

Taylor and Brooks (1962) suggested that the Darcy-Weisbach friction factor f be divided into two parts, that due to grain roughness

$$f' = \frac{8gR'S}{U^2} \quad (2.36)$$

and that due to form roughness

$$f'' = \frac{8gR''S}{U^2} \quad (2.37)$$

In this case, the total friction factor

$$f = f' + f'' \quad (2.38)$$

Manning's roughness coefficient n

Using the same reasoning, Bajorunas (1952) assumed that the Manning's roughness coefficient n is composed of two parts

$$n = n' + n'' \quad (2.39)$$

where n' is due to the grain roughness and n'' is due to form roughness. The value of n' is obtained as

$$n' = \frac{n}{(R/R')^{2/3}} \quad (2.40)$$

2.12 Bed Forms

An understanding of the nature of bed forms is of critical importance for the analysis of resistance factors. When the bed form crest is perpendicular to the main flow direction, the bed forms are called transverse bed forms, such as ripples, dunes and antidunes. Bed forms with their crest parallel to the flow are called longitudinal bed forms such as ribbons and ridges. The morphological regimes for unidirectional currents over a sand bed ($D_{50} \leq 2000\mu\text{m}$) can be classified into:

- lower transport regime with flat bed, ribbons and ridges, ripples, dunes and bars.
- transition regime with washed out dunes and sand waves.
- upper transition regime with flat mobile bed and sand waves.

In literature, considering hydraulic point of view, roughly four groups of classification methods are available. Engelund (1967) used Froude number as a classification parameter, while Liu (1957) described the type of bed forms in terms of a suspension parameter and a particle-related Reynolds number. Simons and Richardson (1966) used the stream power and the median fall diameter as basic parameters. They expressed bed form type as a function of τ_b , U and D_r . Van Rijn (1993) used a dimensionless bed shear stress parameter and a dimensionless particle parameter to classify the bed form types. Van Rijn bed form type is a function of $[T, D_*]$ in which:

T = transport stage parameter

D_* = dimensionless particle diameter

In Table 2.1 a bed form classification according to Simons (1966) is given. The corresponding bed form types by Simons and Richardson (1966) are depicted in Fig. 2.6.

Table 2.1 Classification of bed forms (after Simons, 1966 and addition by Prins, 1978)

Flow regime	Bed form	Bed material concentration	Mode of sediment transport	Type of roughness	Roughness $C\sqrt{g}$
Lower regime	1. ripples 2. ripple on dunes 3. dunes	10-200 ppm 100-1200 ppm 200-2000 ppm	discrete steps	form roughness predominates	7.8-12.4 7.0-13.2
Transition	1. washed out dunes	1000-3000 ppm		variable	7.0-20.0
Upper regime	1. plane beds 2. antidunes 3. chutes and pools	2000-6000 ppm >2000 ppm >2000 ppm	continuous	grain roughness predominates	16.3-20.0 10.8-20.0 9.4-10.7

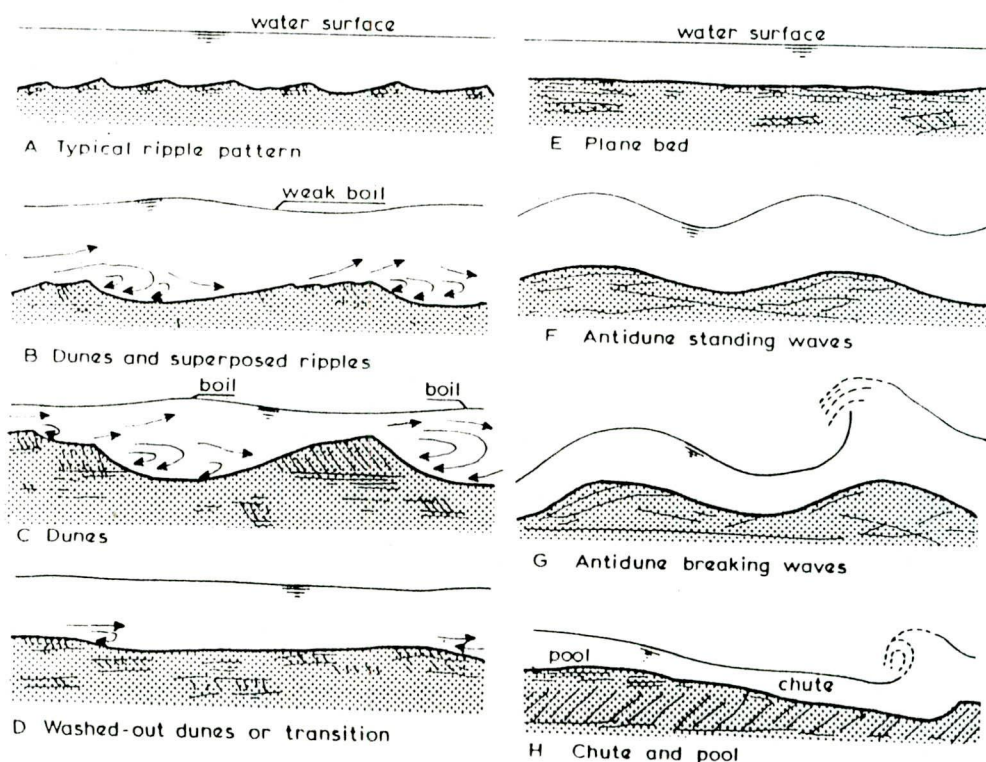


Fig. 2.6. Bed form types in rivers according to Simons and Richardson (1966)

Van Rijn (1984, 1989) used flume and field data to develop his classification. Van Rijn defined the following two parameters:

$$D_* = D_{s0} \left| \frac{(s-1)g}{v^2} \right|^{1/3} \quad (2.41)$$

$$T = \frac{(U_*)^2}{(U_{*cr})^2} - 1 \quad (2.42)$$

According to van Rijn, mini ripples are dominant features for $T < 3$ and $D_* < 10$. Mega ripples and mini ripples may be superimposed on the dunes for $3 \leq T \leq 10$ and $D_* < 10$. Mega ripples are ripples with a length scale of the order of the water depth ($L \approx d$); mini-ripples have a length scale of the order of the near-bed turbulence length scale ($L < d$). The asymmetrical dune-type bed forms with a length scale much larger than the water depth ($L \gg d$) are the dominant features for $10 \leq T \leq 15$. The upper regime which is defined to occur for $T \geq 25$, is characterized by a dominating suspended load transport. The classification proposed by van Rijn (1984) is summarized in Table 2.2 and Fig. 2.7.

Table 2.2 Classification of bed forms according to Van Rijn (1984)

Transport regime		Particle size	
		$1 \leq D_* < 10$	$D_* > 10$
Lower	$0 \leq T \leq 3$	mini-ripples	dunes
	$3 < T \leq 10$	mega-ripples and dunes	dunes
	$10 < T \leq 15$	dunes	dunes
Transition	$15 < T < 25$	wash out dunes, sand waves	
Upper	$T \geq 25, Fr < 0.8$	(symmetrical) sand waves	
	$T \geq 25, Fr \geq 0.8$	plane bed and/or antidunes	

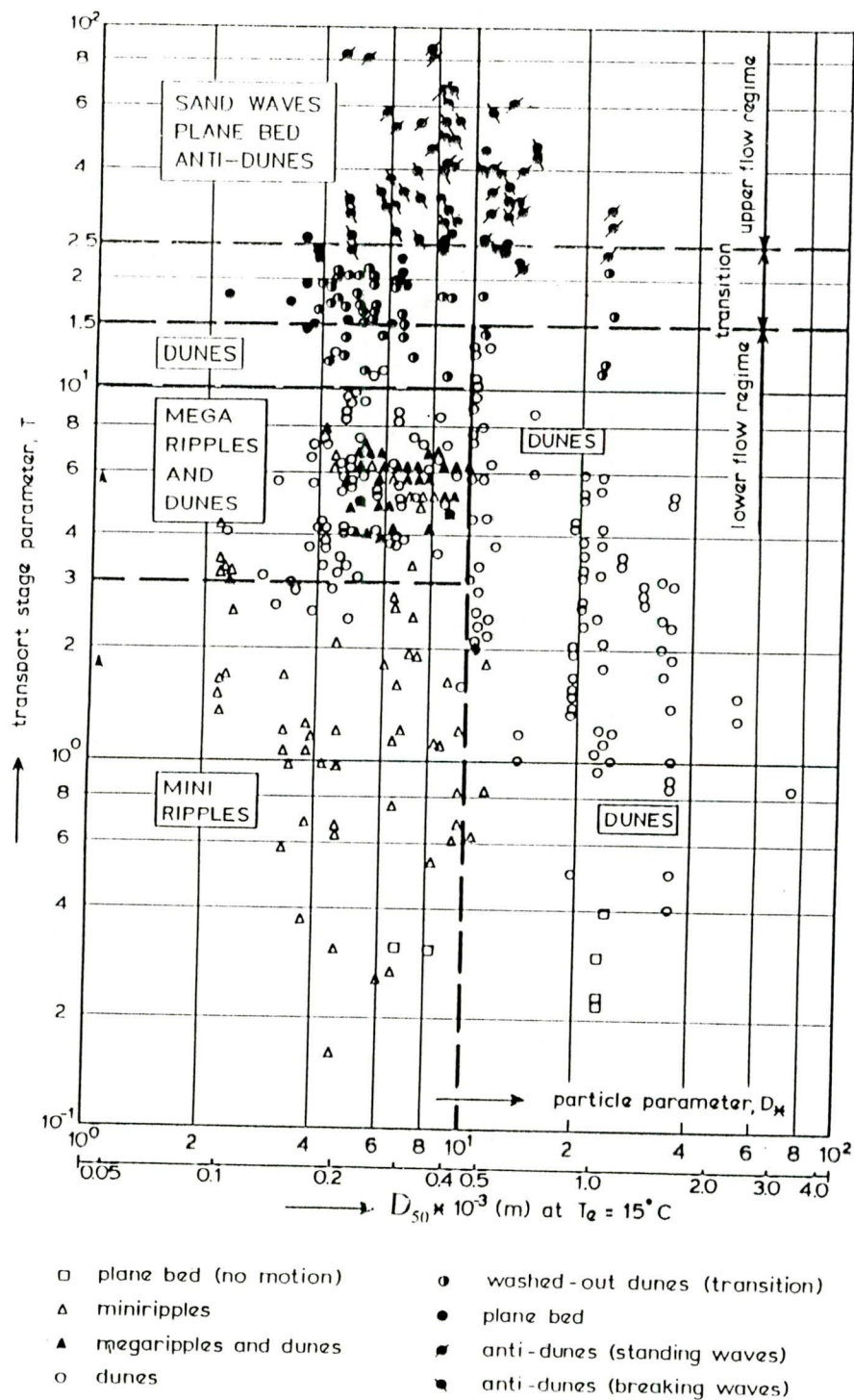


Fig. 2.7 Bed form classification diagram for currents, Van Rijn (1984, 1989)

Yalin(1992) classified bed forms as follows:

1. Ripples: Yalin defined ripples as the bed forms "imprinted" by the viscous flow structures (undulations) at the bed of turbulent flow. When ripples are forming, the bed roughness changes and the flow at the bed becomes saturated with transported grains. The length of the ripple is independent of flow depth.
2. Dunes and bars: Dunes and bars are due to the quasi-uniformities caused by the structure of turbulence. The length of the turbulent structure is proportional to one of the characteristic lengths d , B or $\frac{v}{U_*}$. Dunes and bars are defined as those bed forms which are produced by vertical bursts and horizontal bursts, respectively.

Turbulence is due to multitude of eddies having various sizes. These eddies are superimposed on each other and, ultimately, on the mean flow. Eddies are not permanent - they are born, they live and they die. In any turbulent flow, the largest eddies play an important part. Larger eddies are generated near the flow boundaries, that is, near the bed in case of an open channel flow. Immediately after its birth, the prospective eddy is ejected upwards and, as it moves away from the bed, it is conveyed downstream by the flow. During this motion, the upward velocity of the eddy progressively decreases but its size increases. Eventually the size of the eddy becomes a microturbulent eddy. However, soon after that the eddy hits the bed and is destroyed. The destruction of the eddy prompts the generation of a new (second) eddy. Having passed through the same stages, this second eddy causes, in turn, the generation of the third eddy, and so on. Bursting process, or simply burst, is the term which stands for the above outlined sequence of events, which occurs between the births of two consecutive eddies. The vertical turbulence is formed by the eddies whose axes of rotation are perpendicular to the vertical planes. Yet an open channel flow has turbulent eddies also in plan, whose axes are perpendicular to the horizontal plane, form horizontal turbulence.

3. Antidunes: If Froude number is greater than 0.60, then standing waves or antidunes occur. The relative height of standing waves increases with Froude number. When flow is supercritical they are usually able to deform the initially flat surface of a mobile bed as to produce bed forms - antidunes.

Since the bed forms are finite, a bed form exists if it has a non-zero height. This is the case when $\eta = \left(\frac{U_*}{U_{*cr}} \right)^2 > 1$. However, the existence of a bed form depends on the values

of the following parameters:

$$\frac{B}{d}, \quad Z = \frac{d}{D_{50}}, \quad X = \frac{D_{50} U_*}{v} \quad \text{and} \quad Fr = \frac{U}{\sqrt{gd}}$$

The value of the Froude number Fr mainly indicates whether the bed forms whose length is proportional to depth d are dunes or antidunes. Therefore, attention was focused on the remaining other three variables of the above. Based on X , Yalin classified regimes as smooth, transitional and rough.

The development of larger bed forms (dunes and bars) takes place past the bed covered by ripple. When $X \approx 2.5$, then it is mainly ripple which is present on the bed surface. Earlier developed ripples protect the bed against any further deformation. In the transitional regime when $\approx 2.5 < X \approx 35$ ripples are superimposed on larger bed forms. With the increment of X the prominence of ripples decreases and that of larger bed form increases. When $X > \approx 35$ in rough turbulent flow, ripples are no longer present and the larger bed forms have their maximum prominence.

2.13 Dimensions of Bed Forms

A study of the geometric properties of sand waves is important for three reasons: (i) to understand how the bed forms are related to the characteristics of fluid flow and bed material in an alluvial channel; (ii) to understand how these geometric elements affect the resistance to flow and sediment transport in an alluvial channel, and (iii) to get an insight into the dynamic forces of a stream responsible for transport and deposition of ancient deposits from a knowledge of relationship between the geometric properties of sand waves and flow variables. Some of the methods for predicting bed form dimensions are as follows.

2.13.1 Allen (1963) method

Allen (1963) has shown by physical reasoning and analysis of observed data the following relationship:

For dune and ripple bed

$$\text{Log } d = 0.8271 \text{ Log } H + 0.8901 \quad (2.43)$$

in which

d = depth of water

H = bed form height

For ripple bed ($H < 0.15\text{m}$)

$$\text{Log } H = 0.9508 \text{ Log } L - 1.0867 \quad (2.44)$$

For dune bed

$$\text{Log } H = 0.7384 \text{ Log } L - 1.0746 \quad (2.45)$$

in which

L = bed form length

2.13.2 Senturk (1967) method

From dimensional analysis and eliminating parameters of secondary importance, the following is the functional equation for bed form type:

$$\text{Bed form type} = f_{unc} \left(S, \frac{R}{D}, Fr, Fr_g, \frac{U_*}{w_s}, R_w \right) \quad (2.46)$$

where,

$$Fr_g = \text{Froude number related to grain size} = \frac{\rho U_*^2}{(\rho_s - \rho) g D_{50}}$$

$$R_w = \text{Reynolds number related to the fall velocity} = \frac{D_{65} w_{65}}{\nu}$$

Different phases of bed form predicted by Senturk are summarized as follows:

- (i) Ripples form for $U > U_{BM} > U_B$

where,

U_{BM} = velocity corresponding to the beginning of motion

$$U_B = 9.57 (gSR''_B)^{1/2} \quad (2.47)$$

$$R''_B = \text{Exp}_{10}(3.4936 - 0.091 \text{ Log } C + \text{Log } D_{65}) \quad (2.48)$$

$$C = \frac{D_{35}}{D_{65}} (s - 1) \frac{R_w^2}{S} \quad (2.49)$$

- (ii) Transition from plane bed to ripple occurs for $U < U_{BM} < U_X$

where

$$U_X = (21.6 - 0.373 \text{ Log } C) (gSR_X)^{1/2} \quad (2.50)$$

$$R_X = \text{Exp}_{10}(2.4 - 0.057 \text{ Log } C + \text{Log } D_{65}) \quad (2.51)$$

- (iii) The transition from dunes to plane bed with sediment transport occurs for $U > U_B > U_{BM}$ but $U < U_{PL}$

where,

$$2a(d + 6.5 \text{ Log } R') \sqrt{R'} = U_B - \frac{\sqrt{R'}(R' - R''_B)}{a(e + 6.5 \text{ Log } R')} \quad (2.52)$$

$$2a \sqrt{gS} \quad (2.53)$$

$$d = 6 + 6.5 \text{ Log } \frac{1}{D_{65}} \quad (2.54)$$

$$e = 11.65 + 6.5 \log \frac{1}{D_{65}} \quad (2.55)$$

$$U_{PL} = (6 + 6.5 \log \frac{R'}{D_{65}}) (gR'S)^{1/2} \quad (2.56)$$

(iv) Plane bed with sediment movement occurs for $U > U_{PL} > U_B > U_{BM}$

(v) The transition from ripples to dune bed occurs for $U_N < U < U_M$

where,

$$2a(c' + 11 \log R'') \sqrt{R''} - U_x = \frac{\sqrt{R''}(R'' - R_R'')}{a(b - 11 \log R'')} \quad (2.57)$$

$$b = 48 - \log C - 11 \log \frac{1}{D_{65}} - 9.57 \quad (2.58)$$

$$c' = b + 9.57 \quad (2.59)$$

The R''_R value is obtained from the equation

$$U_x = (-52 + 2.5 \log C + 18 \log \frac{R''}{D_{65}}) (gSR'')^{1/2} \quad (2.60)$$

To compute U_N the following equation may be solved for R'' :

$$U_x + \frac{\sqrt{R''}(R'' - R_x'')}{a(b - 11 \log R'')} = (-52 + 2.5 \log C + 18 \log \frac{R''}{D_{65}}) (gSR'')^{1/2} \quad (2.61)$$

$$U_N = (-52 + 2.5 \log C + 18 \log \frac{R''}{D_{65}}) (gSR'')^{1/2} \quad (2.62)$$

(vi) Well-formed ripples develop for $U_{BM} < U < U_N$

(vii) Well-formed dunes develop for $U_M < U < U_B$.

2.13.3 Vajda (1990) method

Vajda (1990) made the predictive evaluation of bed form characteristics in alluvial rivers of cohesionless bed. The prediction model is limited to subcritical flow. It can be applied locally in order to predict bed forms in an irregular cross-section. The most important aspect of this prediction model is the use of analytical equation for determining dimensionless critical bed shear called also critical mobility number instead of using Shields diagram or any modified Shields diagram.

The complexity of the alluvial roughness pattern makes a purely analytical approach to the corresponding resistance problem unpractical. It is assumed, in general, that alluvial bed form attains an equilibrium state after a long period of superimposed quasi-steady flow conditions. The bed form type and dimensions can in the subsequent equilibrium process be related empirically to the total equivalent bed shear $\tau_b = \rho U_*^2$. The dimensionless parameters to which observed equilibrium bed form geometry is usually related are:

- the dimensionless grain parameter

$$D_* = \left[\frac{(\rho_s - \rho)}{\rho} g / v^2 \right]^{1/3} D_{50} \quad (2.63)$$

- the dimensionless bed shear

$$\tau_* = \frac{U_*^2}{\frac{(\rho_s - \rho)}{\rho} g D_{50}} \quad (2.64)$$

or, rather, its excess shear version

$$T_* = \frac{\tau_*}{\tau_{*c}} - 1 \quad (2.65)$$

where τ_{*c} is the critical value of τ_*

- the relative depth $\eta = \frac{d}{D_{50}}$

The critical mobility number is originally related to grain Reynolds number

$$Re_* = \frac{U_* D_{50}}{v}. \text{ However, such a representation makes the excess shear } T_* \text{ pertaining to a}$$

particular D_{50} difficult. It can be made direct only in the modified Shields diagram (Fig. 2.8), in which the abscissa depends on D_* only. The analytical form of critical mobility curve can be written in the form

$$\tau_{*c} = \frac{0.2}{D_*} + 0.056 \tanh \left(\frac{D_*^{0.77}}{25} \right) \quad (2.66)$$

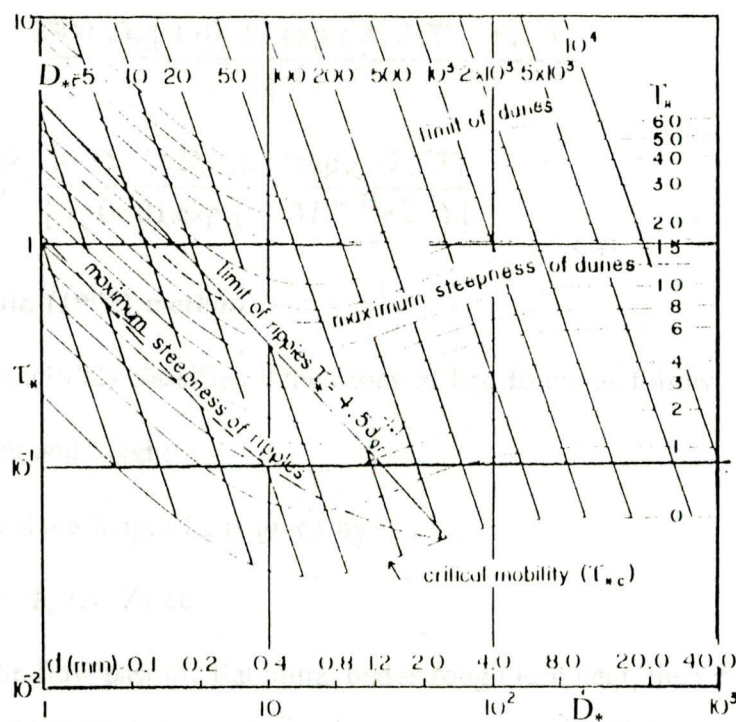


Fig. 2.8 Modified Shields diagram (after Vajda, 1990)

The sand ripples, on the other hand, are found to be independent from its relative depth, because their height is usually much smaller than the flow depth, but they strongly depends on D_* . According to Vajda(1990), sand ripples could actually be regarded as roughness the dimensions of which are variable with flow conditions. In view of this variability, the location of the nominal bed cannot be identified in alluvial conditions, rather with the mean bed elevation. It is similarly assumed that all the parameters can be related to a vertically averaged mean velocity pertaining to that bed level.

With the above assumptions, the tentative correlation functions of the equilibrium bed-form geometry can be written as follows.

Dune geometry:

$$L = 7R \quad (2.67)$$

$$\frac{H}{L} = \frac{T_*}{D_{*0}} \exp \left[\frac{-T_*/13}{1 + (\eta/169) [1 - \coth(\eta/169)]} \right] \quad (2.68)$$

Ripple geometry:

$$L = \frac{2300 D_{50} [1 + 0.01 \exp(2.3 D_*^{0.75} \tau_*^{0.5})]}{D_*^{1.5} \tau_*^{0.5}} \quad (2.69)$$

$$\frac{H}{L} = \frac{0.15 T_* (D_* \tau_*)^{0.5} \exp(-T_*/3)}{[1 + 0.01 \exp(2.3 D_*^{0.75} \tau_*^{0.5})]} \quad (2.70)$$

2.13.4 Yalin (1992) method

Yalin(1992) classified dimensions of bed forms as follows:

Dune length and height:

The dune length L_d is given by

$$L_d = \Phi_d(X, Z) 6d \quad (2.71)$$

If the flow past the flat initial bed is rough turbulent, then $\Phi_d(X, Z) \approx 1$. Yalin used the following component-equation. for the evaluation of $\Phi_d(X, Z)$:

$$\Phi_d(X, Z) = 1 + 0.01 \frac{(Z-40)(Z-400)}{Z} e^{-m} \quad (2.72)$$

in which $m = 0.055 \sqrt{Z} + 0.04X$.

The dune steepness $\left(\frac{H_d}{L_d}\right)$ varies as a function of the dimensionless flow intensity

η , and its value decreases with the increment of relative skin roughness (Z). Furthermore, the value of dune steepness must be affected by the grain size Reynolds number X . Hence, in general, the dune steepness must be a function of η , Z and X . Hence the dune steepness can be given by the form $\delta_d = \psi_d(X, \eta, Z)$.

Yalin expressed dune steepness as

$$\delta_d = \psi_{xd}(X) \psi_d(\eta, Z) = (\delta_d)_{\max} f_d(\zeta), \psi_{xd}(X) \quad (2.73)$$

where,

$$(\delta_d)_{\max} = 0.06 (1 - e^{-0.008Z})$$

$$f_d(\zeta) = \zeta e^{1-\zeta}$$

$$\zeta = \frac{\eta - 1}{\eta_d - 1}$$

$$\bar{n}_d = 14 (1 - e^{-0.003 Z})^{1/2}$$

and identify $\psi_{xd}(X)$ with a non-decreasing continuous function which is zero when $X = 0$ and which is nearly unity when $X \approx 35$. The component equation

$$\psi_{xd}(X) = 1 - e^{-(X/10)^2} \quad (2.74)$$

is such a function. The analogous decrement of the ripple steepness δ_r with the increasing X can be reflected by

$$\psi_{Xr}(X) = 1 - e^{-((X - 2.5)/14)^2} \quad \text{if } X > 2.5 \quad (2.75)$$

Ripples:

Ripple length can be expressed functionally as

$$L_r = \phi_r(X, \xi) D_{50} \quad (2.76)$$

where,

$$\xi = \left(\frac{\gamma_s D_{50}^3}{\rho v^2} \right)^{1/3}$$

Yalin expressed ripple length L_r as

$$\frac{L_r}{D_{50}} = \phi_r(X, \xi) = \frac{(L_r)_{\min}}{D_{50}} [4P(1-P)^{-1}] \quad (2.77)$$

where,

$$\frac{(L_r)_{\min}}{D} = \frac{2650}{\xi^{0.88}} \quad \text{and} \quad P = \sqrt{\frac{\eta}{21}}$$

The geometry of ripples does not depend on the flow depth. Hence Z can not be a variable in the expression of ripple steepness. Ripple steepness can be expressed functionally as $\delta_r = \psi_{Xr}(x) \psi_r(\eta)$. Yalin experimentally found that,

$(\delta_r)_{\max} \approx 0.14$, $\bar{\eta}_r - 1 \approx 10$ and $(\eta_r)_{\max} - 1 \approx 20$. where $\bar{\eta}_r$ and $(\eta_r)_{\max}$ are η -values which corresponds to $\delta_r = (\delta_r)_{\max}$ and $\delta_r = 0$ (at advanced stages) respectively. Introducing

normalized coordinates $\eta_r = \frac{\delta_r}{(\delta_r)_{\max}}$ and $\zeta' = \frac{\eta - 1}{\bar{\eta}_r - 1}$, the normalized ripple function $\eta_r = f_r(\zeta')$

Yalin adopted

$$f_r(\zeta') = r_{fd}(\zeta) = r \zeta' e^{1-\zeta'} \quad (2.78)$$

where correction factor r can be given by

$$r \equiv 1 \text{ if } \zeta' \leq 1; \quad r \equiv \zeta(z - \zeta') \text{ if } 1 < \zeta' < Z$$

The ripple steepness ultimately becomes

$$\frac{H_r}{L_r} \delta_r = \psi_{Xr}(X) 0.14 f_r(\zeta') \quad (2.79)$$

2.13.5 Van Rijn (1993) method

Van Rijn (1993) proposed a method that makes classification of bed forms, the prediction of bed form dimensions and the effective hydraulic roughness of the bed forms feasible. The bed form classification by Van Rijn has already been discussed in Art. 2.12. Dimensions of bed forms predicted by Van Rijn are as follows:

1. Ripples, lower regime

When the velocities are somewhat larger (10-20%) than the critical velocity for initiation of motion and the median particle size is smaller than 500 μm , mini ripples are generated at the bed surface. Ripples that are developed during this stage remain small with ripple length much smaller than the water depth. Yalin (1985) reports values in the range of:

$$H_r = 50 \text{ to } 200 D_{50} \quad (2.80)$$

$$L_r = 500 \text{ to } 1000 D_{50} \quad (2.81)$$

As the velocities near the bed become larger, the ripples become more irregular in shape, height and spacing. In that case the variance of the ripple length and height becomes rather larger. The largest ripples may have a length upto the water depth and are commonly called as mega-ripples. It is assumed that the ripples will completely disappear for $T \approx 10$. Tentative expressions for the relative height and length of mega-ripples are given by

$$\frac{H_r}{d} = 0.02 (1 - e^{-0.1T}) (10 - T) \quad \text{for} \quad 1 \leq D_* \leq 10 \quad \text{and} \quad 3 \leq T \leq 10 \quad (2.82)$$

$$L_r = 0.5d = 0.5R \quad (2.83)$$

2. Dunes, lower regime

Another typical bed form type of the lower flow regime is the dune-type bed form. Dunes have an isometrical profile with a rather steep leeside and a gentle stoss side. The length of the dunes is strongly related to the water depth with values in the range of 3 to 15d. Based on the analysis of flume and field data, Van Rijn (1982, 1984) proposed the following relationship for the dune height and length:

$$\frac{H_d}{d} = 0.11 \left(\frac{D_{50}}{d} \right)^{0.3} (1 - e^{-0.5T}) (25 - T) \quad (2.84)$$

$$L_d = 7.3d \quad (2.85)$$

in which

d = water depth from water surface to mean-bed level.

The dune height increases weakly with particle diameter for a given water depth. The dunes are assumed to be washed out for $T \geq 25$.

3. Washed-out dunes and sand waves, transition region

The bed forms generated at low velocities are washed out at high velocities. In the transition regime the sediment particles are transported mainly in suspension. This has a strong effect on the bed form shape. The bed forms in the transition regime which is most likely to occur, are washed out dunes and sand waves. Both types occur simultaneously. The dimensions of washedout dunes are same as the dimensions of dunes. These bed forms fully disappear for $T=25$.

The dimensions of the symmetrical sand waves are described by:

$$\frac{H_{sw}}{d} = 0.15 (1 - e^{-0.05(T-15)}) (1 - Fr^{-2}) \quad \text{for } T \geq 15 \quad (2.86)$$

$$L_{sw} = 10d \quad \text{for } T \geq 15 \quad (2.87)$$

Plane bed and sand waves, upper regime

Two sub-regimes can be distinguished in the upper transport regime:

Subcritical upper transition regime : $T \geq 25$ and $Fr \leq 0.8$

Supercritical upper transition regime : $T \geq 25$ and $Fr \geq 0.8$

In the subcritical upper regime the bed form types will be symmetrical sand waves with dimensions mentioned above. In the supercritical upper regime the bed form types will be plane bed and/or antidunes. Antidune bed forms are sand waves with a nearly symmetrical shape in phase with the water surface waves. Antidunes do not exist as a continuous train of bed waves. Antidunes are bed forms with a length scale of about 10 times the water depth.

2.14 Discussion on Alluvial Roughness Predictors

The development of roughness due to different bed patterns is of great importance because they are most often the main contributors of the flow resistance. The problem of resistance to flow over alluvial beds has received considerable attention during the 4th and 5th decades of this century. Attempts to determine resistance for alluvial channels have been based on modifications of fixed bed equations.

It has already been stated in chapter-1 that the roughness predictors of an alluvial channel in principle are of two kinds, viz:

- (i) Integral methods in which simultaneously the continuity and the Chezy or Manning equations are solved and the total roughness is found. These methods are based on overall flow parameters such as depth of water and depth-averaged flow velocity. Another integral method of predicting alluvial roughness utilizing is the principles of dimensional analysis.

- (ii) Separate estimate of grain roughness and form drag on basis of grain size distribution of the bed material and the anticipated bed forms. The total roughness is found by adding both roughnesses together.

The division of total resistance into grain resistance and form resistance was first introduced by Einstein and Barbarossa (1952). According to them the entire expression for the form resistance is a function of shape, size, and frequency of the irregularities along the length of the channel. In an absolutely uniform channel these losses are obviously equal to zero. The effect of these irregularities is to distort the flow pattern. When the discharge is least, the distortion of the flow pattern is greatest. As the discharge increases the distortion of the flow pattern becomes less and less because of the alignment of the flow becomes progressively straighter. Consequently, the additional friction loss diminishes as the discharge increases.

The thinking of form resistance as a part of total resistance is further modified by the researchers, with the increased knowledge of bed configuration of alluvial channels. The geometric characteristics of dunes is neither similar to ripples nor to that of antidunes. Moreover, superimposed ripples on dune bed made the problem more complicated. Bed form resistance changes with the change in size and length of a bed form as well as with the change in bed configurations - such as from ripples to dunes and from dunes to antidunes. On the other side, researchers are trying hard from analytical model study, laboratory flume study and using field data to formulate the form friction as a function of bed form height and length.

Einstein-Barbarossa (1952) method is the first attempt at predicting the stage-discharge relations for natural streams with an alluvial bed. The approach was based on the hypothesis that the resistance of an alluvial bed can be separated into two distinct entities - the resistance due to the presence of the grains and the resistance offered by the bed undulations. Einstein and Barbarossa have suggested the use of logarithmic relation, with a correlation term for viscous effects, to describe the resistance of the grains. The resistance corresponding to the bed undulations, U/U''_* , was shown to be a function of the average height, length and drag coefficient of the bed undulations; these in turn were assumed to be a function of intensity of shear on representative particles, ψ' . The concept of a form resistance diagram developed by Einstein-Barbarossa is now 45 years old. It is still probably the most widely quoted of any existing technique.

Bajorunas (1952) assumed that the Manning's roughness coefficient n is the sum of roughness coefficient n' due to grain roughness and roughness coefficient n'' due to form roughness. Bajorunas concurs that, for practical purposes, the Manning-Strickler equation is more convenient to use than logarithmic velocity equation for predicting grain roughnesses. Einstein and Chien (1958) suggested that the scatter of points of ψ' versus U/U''_* could be due to appreciable variations in the value of standard deviation of the bed materials. To check this, data from flumes and rivers, having almost the same sediment size, the same standard deviation and approximately the same value of ψ' were chosen, and the computed values of U/U''_* for these runs were compared. Garde and Albertson (1959) have shown that Froude number is one of the parameters defining the regimes of flow and the approximate size of bed undulations, when the undulations were pronounced. Thus it was hoped that the lines of constant Froude number could be drawn on the plots of ψ' versus U/U''_* ; but attempts in this direction did not lead to any systematization of the points on the plots of ψ' versus U/U''_* . Shen (1962) improved the Einstein-Barbarossa method and suggested that the resistance related to form is a function of both sediment transport and the Reynolds number related to fall velocity. Cunha (1967) analyzed data from a Portuguese river with a bed composed of relatively coarse material. He concluded that for ψ' greater than about 5, U''_*/U is a doubled-valued function of ψ' and presented a graphical relation between these two quantities.

Shinohara and Tsubaki (1959) on the basis of Nikuradse roughness value gave a prediction formula for the alluvial roughness. Vanoni and Nomicos (1960) have found the reduction in Manning's n to be substantial if the bed is plane; however, their experiments also revealed that, with dunes on the bottom, the effect of suspended load on the resistance coefficient is a secondary importance. Liu and Hwang (1961) performed a dimensional analysis of the resistance problem and proposed an equation for mean velocity in a straight alluvial channel. Garde and Ranga Raju (1963) noted that the resistance of an alluvial channel may be expressed in dimensionless form. Viscous effects partly govern the resistance for plane bed with fine sediment. But the role of viscosity in the determination of resistance in the ripple and dune bed regime was not clearly understood. A check on the accuracy of Liu and Hwang (1961) method was made by Garde and Ranga Raju (1966) by comparing the observed velocities with the computed velocities for data from flumes and natural streams. The error was in many cases greater than ± 50 percent. In view of the large changes in resistance in different regime, analyzing data from flumes, canals and natural streams, Garde and Ranga Raju (1966) proposed different resistance relationships for different regimes. By analyzing

additional data sets, Ranga Raju (1970) recognized needs of some modifications of 1966 method. He found a noticeable effect of the sediment size on the resistance relationships.

Simons and Richardson (1961) concluded that the forms of bed roughness that exist in an alluvial channel because of similarities in form, resistance to flow and sediment transport are divided into categories of lower flow regime, transition regime and upper flow regime. They also concluded that the form of bed roughness depends primarily on the slope of the energy grade line, depth, fall velocity or effective fall diameter of the bed material and slope of the channel. Simons and Richardson (1962) from flume study observed that the form of bed roughness in alluvial channels is a function of the sediment characteristics and the characteristics of the flow. The bed configuration can be changed by altering either discharge, slope, temperature or the median diameter or size distribution of the bed material. Simons and Richardson (1966) suggested a set of resistance equations for the computation of Chezy's C depending on each type of bed configuration.

Engelund (1966) proposed a hypothesis similar to Einstein-Barbarossa and divided energy gradient into components due to grain roughness and form drag. He proposed a new line of analysis based on similarity considerations. The essence of Engelund's similarity hypothesis is that two dynamically similar streams, the dimensionless shear due to grain takes on equal values. In the closing discussion to his paper (Engelund, 1967) he introduced some modifications. Using data by Guy et al. (1966), Engelund and Hansen (1967) obtained relations for both lower and upper flow regimes. These relations are obtained from Engelund's universal relationship between dimensionless grain shear stress and the total shear stress. Brownlie (1983) extended the curve of Engelund (1966) into regions of the upper flow regime. Engelund (1977) used another approach for dunes to relate the form friction coefficient to the bed form parameters.

Vanoni and Hwang (1967) undertook to determine experimentally what geometric characteristics of alluvial channel bed forms determine their hydraulic roughness. They concluded that ripple-covered beds are hydrodynamically rough in the sense that the friction factor is independent of Reynolds number. Also the pressure on a ripple attains its minimum value at the crest and its maximum value on the face near the point of reattachment. Raudkivi (1967) conducted a set of laboratory flume experiments using 0.40 mm diameter sand and developed a graphical relationship which gives mean velocity as a function of shear velocity.

Senturk (1965-1967) made a set of assumptions which leads to the determination of a group of formulas defining the resistance of flow in transition regions that also indicate the bed form expected.

Lovera and Kennedy (1969) proposed friction factor relations for flows with flat bed. Lovera and Kennedy constructed a chart for grain friction factor as a function of Reynolds number for constant values of relative depth. Alam and Kennedy (1969) developed a chart for predicting form drag friction as a function of relative depth for constant values of grain Froude number and constant values of Froude number.

A unique concept of the mechanics of alluvial channel flows was put forth by Maddock (1969). According to his view, the only determinate relationship among the variables for flow in alluvial streams is that between mean velocity, water discharge and sediment discharge. Moreover, this relationship is different for each of the three velocity ranges (low velocity, mid velocity and high velocity) he distinguished.

Mostafa and McDarmid (1971) avoided the division method and expressed Manning's n in a dimensionally homogeneous form. They express dimensionless Manning's coefficient as a function of Froude number and represent them graphically. Chu and Mostafa (1979) presented a technique which is essentially a mathematical expression of the graphical technique presented by Mostafa and McDarmid (1971). The new analysis allows a straightforward adaptation of the technique to numerical modeling applications.

The abrupt change in the gradient of the bed form at the crest causes the flow to separate and form an eddy. A kinematic theory taking into account the presence of the leeward eddy and the effect of the bed form shape on the flow field was first developed by Mercer (1971). In Mercer's analysis, the length of eddy was fixed arbitrarily at one-half of the bed form wave length. His development was followed and generalized by Mercer and Haque (1973). In the light of extensive information gathered by Mahmood et al. on bed forms, Haque and Mahmood (1983) analytically determined that form friction depends on the steepness ratio of dune and relative roughness.

Bathurst (1978) proposed an empirical relationship for Darcy-Weisbach friction factor f . In steep mountain streams the individual roughness elements are large and may even

protrude through the water surface. Bathurst (1985) delineated, with aid of data from rivers with slopes steeper than 0.4%, the lower limit of roughness of uniform flows. A detailed discussion of the problem of resistance to flow in gravel rivers can be found in Hey (1979). Brushin (1985) expressed the roughness of alluvial streams on the basis of Manning's roughness coefficient as a function of Nikuradse roughness and gravitational acceleration.

White et al. (1979) method for predicting the frictional resistance of alluvial channels is developed from experimental data. The method establishes a relationship between the total shear and effective shear stress for different sediment sizes for flows with Froude number less than 0.8, i.e. for lower flow regimes in which bed features are plane bed, ripples and dunes. They provided both graphical and equational representations of their technique, as well as a statistical analysis of the errors. White et al. (1987) extended White et al. (1979) method for upper flow regime flows in which the bed features are plane-bed or antidunes.

Brownlie (1983) developed a method for predicting alluvial roughness with the objective that it would be easily adapted to computer model applications. In this method sediment properties are described by the median particle size, specific weight and the geometric standard deviation under the assumption of log-normal distribution. Julian and Roman (1990) proposed resistance predictors for flow in steep channels. In Shen's (1990) study, the skin resistance, form resistance and the total resistances are independently measured for a series of rigid bed forms in the laboratory. The data showed that the sums of skin resistance and form resistance are close to the total resistance for all experimental runs conducted.

Van Rijn (1982) has shown that the equivalent roughness or effective grain roughness of a flat bed can be related to the D_{90} of the bed material. Based on flume and field data he expressed form roughness as a function of dune height and length. Van Rijn (1984, 1989) based on the analysis of dune data, introduced form factor in the functional relationship of form roughness. Van Rijn (1993) proposed a separate expression for ripple bed for form roughnesses.

Vajda (1990) developed a method for the rationalization of local resistance calculation both due to boundary friction and combined alluvial grain and bed form roughnesses. Yalin (1992) predicted ripple and dune steepness separately and expressed Chezy resistance

coefficient as the sum of grain roughness and form roughness. Karim and Kennedy (1983) formulated a friction-factor relation to account for the effect of bed configuration through the introduction of sediment discharge as one of the independent variables in a velocity function. Karim (1995) proposed a relation for Manning roughness coefficient that incorporates directly the role of bed configuration in determining alluvial bed resistance. A relation for bed-form height is developed, which is then used as an independent variable to account for the resistance due to bed form-drag.

CHAPTER 3

METHODOLOGY

3.1 Introduction

It has already been discussed in Art. 1.2 that roughness can be predicted by separate estimates of grain roughness and form drag and by integral methods based on overall flow parameters. Five integral methods for predicting alluvial roughness and eight methods where grain and form roughnesses are predicted separately are considered in this study for predicting alluvial roughness. These roughness predictors can be summarized as follows:

3.2 Roughness Predictors Based on Overall Roughness

A. Simons and Richardson (1966) method

Simons and Richardson (1966) suggested a set of resistance equations for the computation of Chezy's C depending on each type of bed configuration. A graphical relation, developed by Simons and Richardson (1966) that relates stream power, median fall diameter of bed material and bed form type is shown in Fig. 3.1. Once the bed configuration can be confirmed by trial and error, then the Chezy's roughness factor C can be computed from depth of flow, bed level slope and grain size D_{85} .

The following resistance equations (in English units) were suggested:

For a plane bed without sediment transport

$$C/\sqrt{g} = 5.9 \log (d/D_{85}) + 5.44 \quad (3.1)$$

For a plane bed with sediment transport

$$C/\sqrt{g} = 7.4 \log (d/D_{85}) \quad (3.2)$$

For ripples

$$C/\sqrt{g} = (7.66 - 0.3/U_*) \log d + 0.13/U_* + 11 \quad (3.3)$$

For dunes and antidunes

$$C/\sqrt{g} = 7.4 \log (d/D_{85}) \sqrt{1 - \frac{\Delta RS}{RS}} \quad (3.4)$$

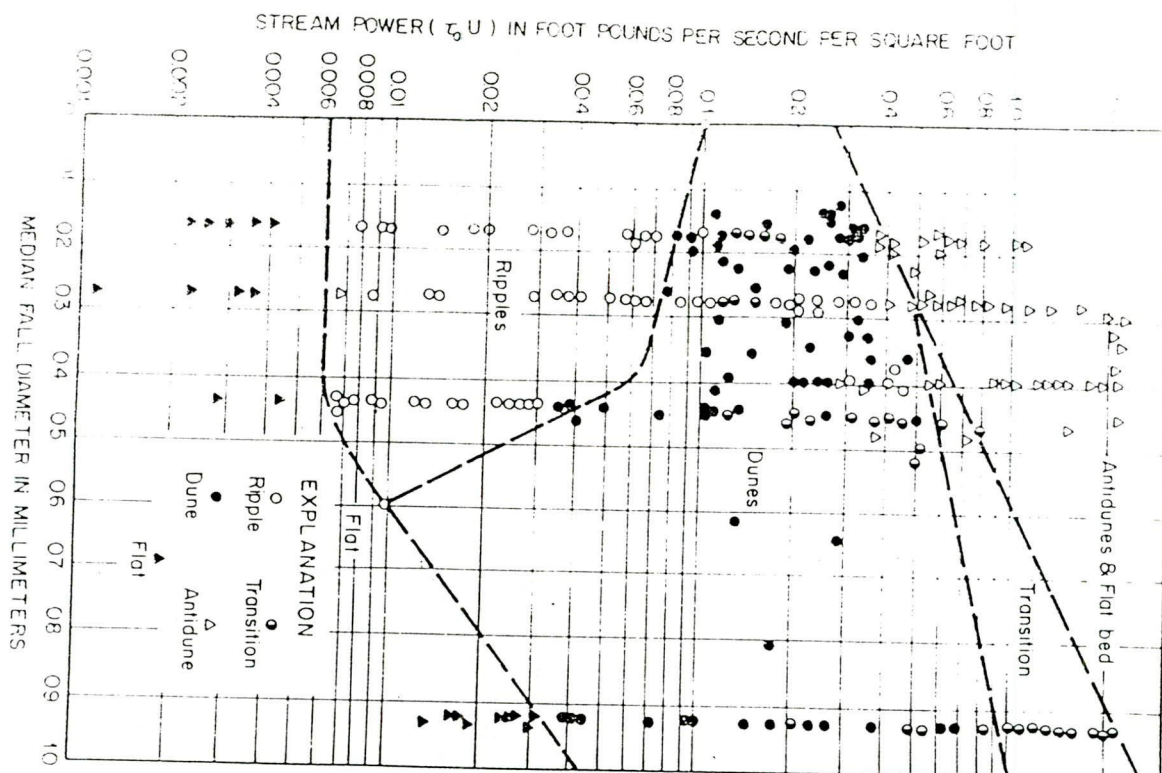


Fig. 3.1 Relation of bed form to stream power and median fall diameter of bed sediment (Simons and Richardson, 1966)

The term ΔRS is an adjustment for RS to compensate for the form roughness. For dunes, ΔRS is a function of RS as shown in Fig. 3.2. For antidunes, the correction term

$\sqrt{1 - \frac{\Delta RS}{RS}}$ is a function of sand size, shear stress and depth, as shown in Fig. 3.3.

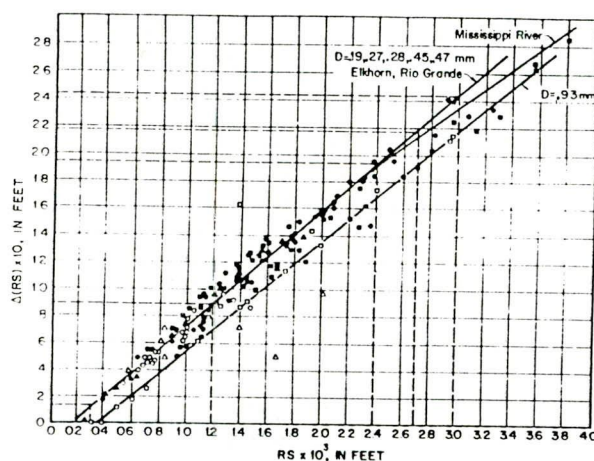


Fig. 3.2 Relation between ΔRS and RS for the dune bed configuration (Simons and Richardson, 1966)

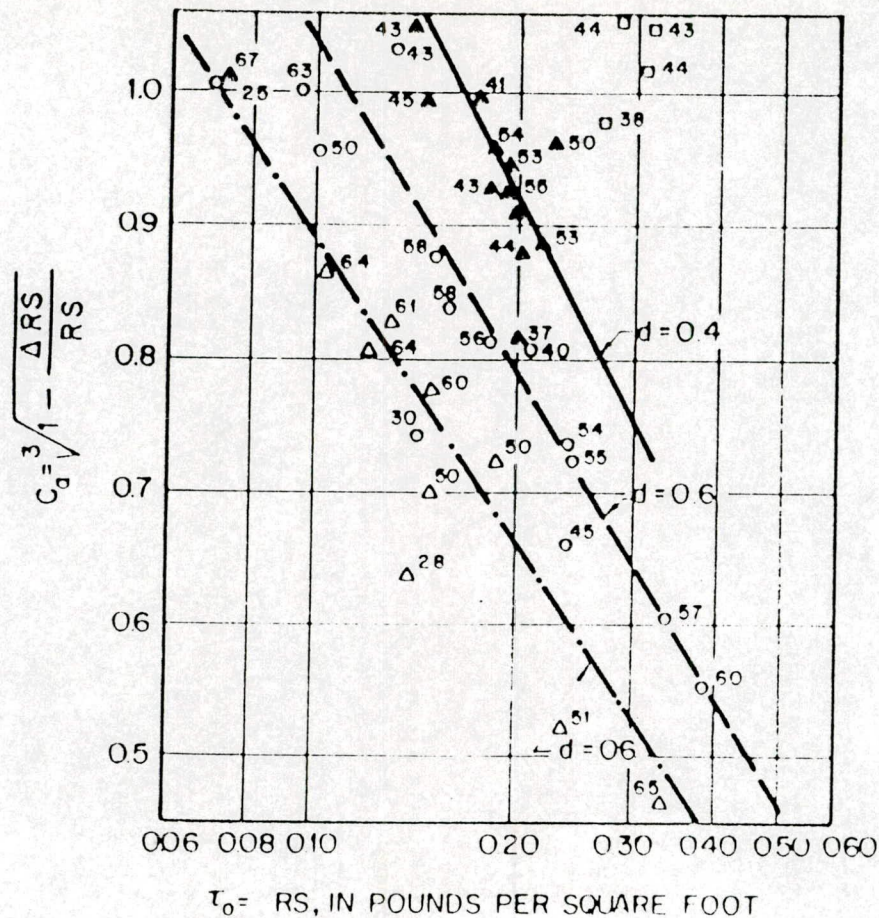


Fig. 3.3 Relation between the Chezy coefficient correction term, shear stress and depth for the antidune-bed configuration (Simons and Richardson, 1966)

Procedure:

The following procedure is suggested by Simons and Richardson to determine the average velocity of flow in a sand bed channel with known values of R, S, D_{50} and D_{85} :

- (i) A bed configuration is assumed.
- (ii) The value of $C/\sqrt{g}$ is calculated using the appropriate equation (Eqs. 3.1 - 3.4).
- (iii) Mean velocity of flow, U , is computed using Eq. (2.1)
- (iv) Stream power $\tau_0 U$ is computed using $\tau_0 = \gamma RS$.
- (v) Using the graphical relationship between stream power and median fall diameter shown in Fig. 3.1, the bed form is predicted and checked with the assumed one.
- (vi) If the assumed and predicted bed forms are different, steps from 1 to 5 are repeated using the bed form found.

B. Garde and Ranga Raju (1970) method

The original analysis for this technique was given by Garde and Ranga Raju (1966), later revised by Ranga Raju (1970), and summarized by Garde and Ranga Raju (1977). The revised version is considered here. Garde and Ranga Raju noted that the resistance of an alluvial stream may be expressed in the dimensionless form

$$\frac{U}{\sqrt{\frac{\rho_s - \rho}{\rho} g D_{50}}} = f \left[\frac{R}{D_{50}}, \frac{S}{\frac{\rho_s - \rho}{\rho}}, \frac{g^{1/2} D_{50}^{3/2}}{v} \right] \quad (3.5)$$

The functional relationship given in Eq. 3.5 may be rewritten after some modifications as

$$\frac{U}{\sqrt{g \frac{\rho_s - \rho}{\rho} R}} = f \left[\frac{R}{D_{50}}, \frac{S}{\frac{\rho_s - \rho}{\rho}}, \frac{g^{1/2} D_{50}^{3/2}}{v} \right] \quad (3.6)$$

Equations (3.5) and (3.6) were used as the basis of analysis of alluvial channel data from canals, rivers and laboratory flumes. By the use of graphical plotting they showed that

$$\frac{U}{\sqrt{g \frac{\rho_s - \rho}{\rho} R}} = f \left[\left(\frac{R}{D_{50}} \right)^{1/3}, \frac{S}{\frac{\rho_s - \rho}{\rho}}, \frac{g^{1/2} D_{50}^{3/2}}{v} \right] \quad (3.7)$$

Viscous effects partly governs the resistance for the plane bed regime with fine bed material. But the role played by viscosity in the determination of resistance in the ripple and dune bed regime is not clearly understood. Therefore, it was thought desirable to omit

the viscous term $\frac{g^{1/2} D_{50}^{3/2}}{v}$ from Eq. (3.7).

Data covering all the regimes of flow involving sediment motion collapsed neatly on a plot of $K_1 \frac{U}{\sqrt{g \frac{\rho_s - \rho}{\rho} R}}$ versus $K_2 \left(\frac{R}{D_{50}} \right)^{1/3} \left(\frac{S}{\frac{\rho_s - \rho}{\rho}} \right)$ as shown in Fig. 3.4.

The empirical coefficients K_1 and K_2 are functions of sediment size as shown in Fig. 3.5. For given values of R , S , ρ_s , ρ and D_{50} the coefficients K_1 and K_2 may be read and the

parameter $\left(\frac{R}{D_{50}} \right)^{1/3} \left(\frac{S}{\frac{\rho_s - \rho}{\rho}} \right)$ computed. The Froude number $K_1 \frac{U}{\sqrt{g R \frac{\rho_s - \rho}{\rho}}}$ may then

be read from Fig. 3.5 and the mean velocity U be computed.

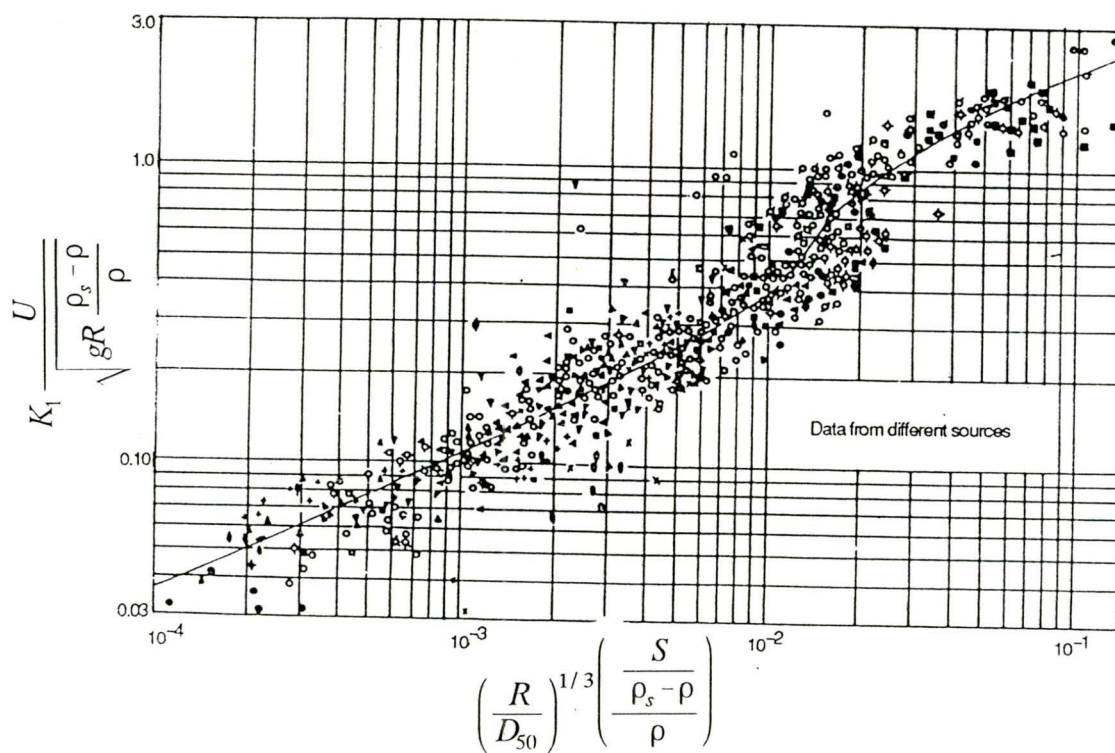


Fig. 3.4 Roughness predictor for alluvial channels (Ranga Raju, 1970)

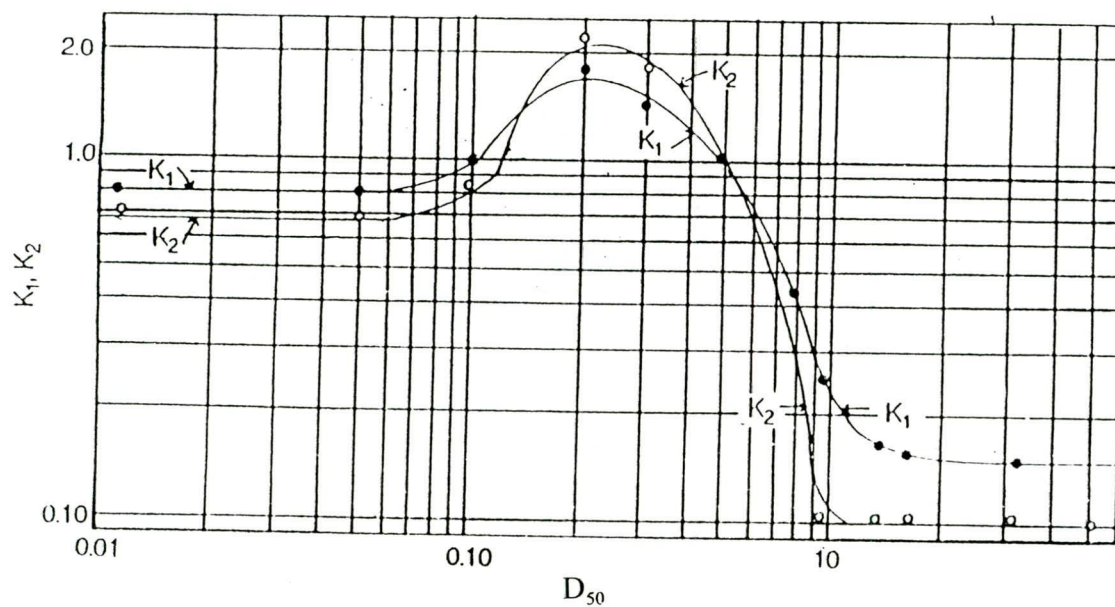


Fig. 3.5 Variation of K_1 and K_2 with sediment size (Ranga Raju, 1970)

Procedure:

The following procedure is suggested by Garde and Ranga Raju(1970) to determine the average velocity in a sand-bed channel with known values of R,S and D:

- (i) The values of K_1 and K_2 are computed using the graphical relation of K_1 and K_2 with the median grain size diameter D_{50} shown in Fig. 3.5.
- (ii) The value of $K_2 \left(\frac{R}{D_{50}} \right)^{1/3} \left(\frac{S}{\frac{\rho_s - \rho}{\rho}} \right)$ is calculated.
- (iii) Using Fig 3.4 the value of $K_1 \frac{U}{\sqrt{gR \frac{\rho_s - \rho}{\rho}}}$ is computed.
- (iv) In the expression $K_1 \frac{U}{\sqrt{gR \frac{\rho_s - \rho}{\rho}}}$ the parameters K_1 , R , ρ_s , ρ and g are known, then the velocity of flow U can be calculated.

C. Brownlie (1983) method

Using the π -Theorem, the variables involved in alluvial channels can be arranged into six dimensionless groups in the form

$$\frac{RS}{D_{50}} = \frac{(\rho_s - \rho)}{\rho} \tau_* = f \left(q_*, S, \sigma_g, P, \frac{\rho_s - \rho}{\rho} \right) \quad (3.8)$$

where, $q_* = \frac{q}{\sqrt{gD_{50}^3}}$ and $P = \frac{4q}{v}$

Since we are concerned with fully rough flow, P is expected to be of secondary importance. Furthermore, since only sand is under consideration, $\frac{\rho_s - \rho}{\rho}$ will be constant, and can be put aside. Therefore, Eq. (3.8) can be reduced to

$$\frac{\rho_s - \rho}{\rho} \tau_* = \text{Func} (q_*, S, \sigma_g) \quad (3.9)$$

The hydraulic radius R is computed for lower flow regime from

$$R/D_{50} = 0.3724(q_*)^{0.6539} S^{-0.2542} \sigma_g^{0.1050} \quad (3.10)$$

and for upper flow regime from

$$R/D_{50} = 0.2836(q_*)^{0.6248} S^{-0.28577} \rho_g^{0.08013} \quad (3.11)$$

Flow regime: After considering many possible dimensionless parameters, the following four were selected by Brownlie as indicators of flow regime:

$$F_g, \frac{D_{50}}{\delta}, S, \sigma_g$$

Here F_g = the grain Froude number defined as $\frac{U\sqrt{\rho}}{\sqrt{(\rho_s - \rho)gD_{50}}}$ and δ is the thickness of the

$$\text{laminar sub-layer} = \frac{11.6\nu}{U_*'}$$

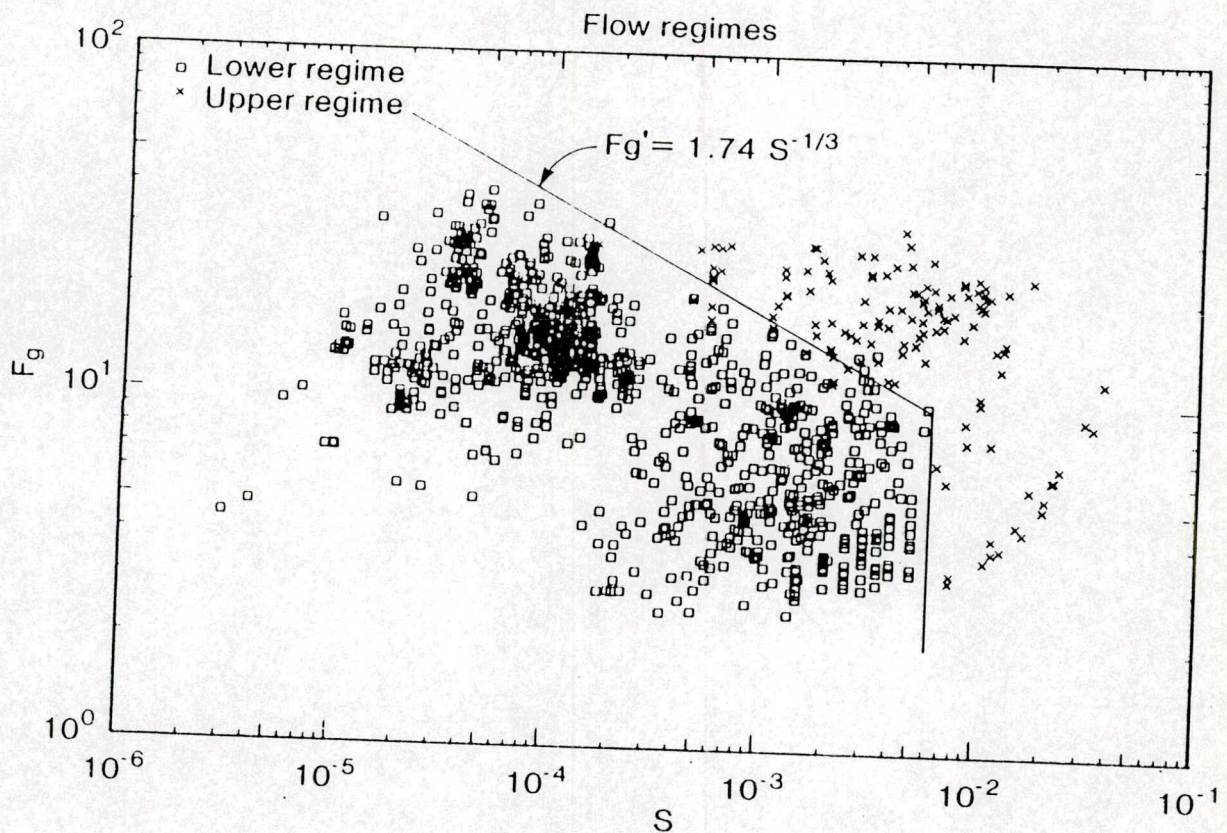


Fig. 3.6 Determination of flow regimes-grain Froude number F_g plotted against slope, S (Brownlie, 1983)

The flow regime relationship between F_g and S is shown in Fig. 3.6. The first point that is obvious from Fig. 3.6 is that beyond a slope of $S = 0.006$ only upper flow regime exists. For lower values of slope, an approximate dividing line can be defined by

$$F_g = F_g^* = 1.74 S^{-1/3} \quad (3.12)$$

The overlap along this line indicates that an additional variable will be needed to better define this transition zone. The transition region can be defined by the equations for the lower limit of upper flow regime

$$\text{Log } \frac{F_g}{F_g^*} = -0.02469 + 0.1517 \log \frac{D_{50}}{\delta} + 0.8381 \left(\log \frac{D_{50}}{\delta} \right)^2 \quad \text{for } \frac{D_{50}}{\delta} < 2 \quad (2.13)$$

$$\text{Log } \frac{F_g}{F_g^*} = \log (1.25) \quad \text{for } \frac{D_{50}}{\delta} \geq 2 \quad (3.14)$$

and for the upper limit of the lower flow regime

$$\text{Log } \frac{F_g}{F_g^*} = -0.2026 + 0.07026 \log \frac{D_{50}}{\delta} + 0.9330 \left(\log \frac{D_{50}}{\delta} \right)^2 \quad \text{for } \frac{D_{50}}{\delta} < 2 \quad (3.15)$$

$$\text{Log } \frac{F_g}{F_g^*} = \log 0.8 \quad \text{for } \frac{D_{50}}{\delta} \geq 2 \quad (3.16)$$

Between these values lies the transition regime.

Procedure:

For a given set of q , S , D_{50} and σ_g , the flow regime, depth of flow and roughness parameters may be predicted according to the following steps:

- (i) The ratio of the median grain size to the theoretical thickness of the laminar sub-layer D/δ is computed.
- (ii) The hydraulic radius R for both lower flow regime and upper flow regime is computed by using Eqs.(3.10) and (3.11).
- (iii) F_g is computed both for lower flow regime and upper flow regime using

$$\text{equation } F_g = \frac{U\sqrt{\rho}}{\sqrt{(\rho_s - \rho)gD_{50}}} \quad \text{with } U = q/R$$

- (iv) F_g^* is computed using Eq.(3.12)
- (v) F_g/F_g^* and D/δ are used to locate upper limit of lower flow regime and lower limit of upper flow regime using Eqs. (3.13) to (3.16)
- (vi) Flow regime thus determined is either lower, transition or upper.

D. White et al. (1987) method

By considering flume data for which Froude number is less than 0.8. White et al. (1987) found that there exists a relationship between the total shear mobility F_{fg} and the effective shear mobility F_{gr} . The form of relationship varies with sediment size D_* . The dimensionless general sediment mobility is given by

$$F_{gr} = \frac{(U_*)^m}{\sqrt{[gD_{35}(s-1)]}} \left[\frac{U}{\sqrt{32 \log(10d/D_{35})}} \right]^{1-m} \quad (3.17)$$

and sediment mobility for fine grain is given by

$$F_{fg} = \frac{U_*}{\sqrt{gD_{35}(s-1)}} \quad (3.18)$$

Sediment motion occurs only if F_{gr} exceeds the threshold value P . For the region F_{gr} greater than P , it is found that there is a linear relationship between F_{gr} and F_{fg} for each value of D_* , given by

$$\frac{F_{gr} - P}{F_{fg} - P} = \text{Func}(D_*) \quad (3.19)$$

White et al. (1987) suggested the following equation for F_{gr} for lower flow regime

$$\frac{F_{gr} - P}{F_{fg} - P} = 1 - 0.76 \left\{ 1 - \frac{1}{\text{Exp}[(\log D_*)^{1.7}]} \right\} \quad (3.20)$$

and the following equation for F_{gr} for upper flow regime

$$\frac{(F_{gr} - P) + 0.07(F_{gr} - P)^4}{F_{fg} - P} = 1.07 - 0.18 \log D_* \quad (3.21)$$

The velocity of flow can be obtained both for lower and upper flow regimes using Eq. (3.17) with

$$m = 0.00 \text{ and } p = 0.17 \quad \text{for } D_* > 60$$

and

$$m = 1.0 - 0.56 \log D_* \text{ and } p = 0.23/(D_{gr})^{0.5} + 0.14 \quad \text{for } 1 < D_* < 60.$$

The use of two separate relationships for lower and upper regimes create problem of determining the appropriate regime to use in particular circumstances. White et al. suggested that the following criteria be used:

$$U_E^L + U_E^U < 0.22 \quad \text{lower flow regime} \quad (3.22)$$

$$U_E^L + U_E^U > 0.22 \quad \text{upper flow regime} \quad (3.23)$$

where,

$$U_E^L = U_E \text{ for velocity } U \text{ computed for lower flow regime}$$

$$U_E^U = U_E \text{ for velocity } U \text{ computed for upper flow regime}$$

$$\text{and } U_E = \frac{US}{(g v)^{1/3} D_*}$$

Procedure:

For a given set of R, d_{35}, g and S , the velocity of flow U and the flow regime may be computed using the following steps:

- (i) Sediment mobility for fine grains F_{fg} is calculated using Eq. (3.18).
- (ii) General sediment mobility F_{gr} for lower flow regime is calculated using Eq. (3.20).
- (iii) The lower regime mean velocity U is calculated using Eq. (3.17).
- (iv) The dimensionless unit stream power U_E is calculated for lower regime flow

$$\text{using } U_E = \frac{US}{(g v)^{1/3} D_*}.$$

- (v) Using Eq.(3.21) the general sediment mobility F_{gr} for upper flow regime is calculated.
- (vi) The upper flow regime mean velocity of flow U is calculated using Eq. (3.17)
- (vii) As in step (iv), the value of U_E is calculated for upper flow regime.
- (viii) If the summation of U_E for both lower and upper flow regimes is greater than 0.22, then the velocity of flow is that of the upper flow regime.
- (ix) If the summation of U_E is less than 0.22, then the velocity of flow is that of lower flow regime.

E. Karim (1995) method

Karim (1995) proposed a new approach for predicting alluvial channel resistance in the framework of the familiar Manning equation. From physical considerations combined with dimensional analysis, a friction factor relationship is expressed as

$$\frac{U}{\sqrt{g(s-1)D_{50}}} = \text{Func} \left(\frac{d}{D_{50}}, S, Q_s^*, \lambda \right) \quad (3.24)$$

where,

Q_s^* = a dimensionless sediment discharge parameter,

λ = dimensionless parameter related to bed form

The bed configuration parameter λ is expressed as a ratio f/f_0 , where f is the Darcy-Weisbach friction factor (including contribution due to bed forms) and f_0 is the friction factor due to grain roughness only. The velocity relation developed by Karim is

$$\frac{U}{\sqrt{g(s-1)D_{50}}} = 6.683 \left(\frac{d}{D_{50}} \right)^{0.626} S^{0.503} \left(\frac{f}{f_0} \right)^{-0.465} \quad (3.25)$$

For natural sediment ($s = 2.65$) the suggested relation for n is given by

$$n = 0.037 (D_{50})^{0.126} (f/f_0)^{0.465} \quad (3.26)$$

The central problem in alluvial flow resistance depends on accurate formulation of relative dimensions for different bed configurations that occur during different stages of flow, and relating them to hydraulic resistance. Karim (1995) developed a relation for relative dune height. Figure 3.7 shows a plot of H/d as a function of U_* / w_s .

The best fit curve through the data points in Fig.3.7 can be expressed by the following equations:

$$\frac{H}{d} = -0.04 + 0.294 \left(\frac{U_*}{w_s} \right) + 0.00316 \left(\frac{U_*}{w_s} \right)^2 - 0.0319 \left(\frac{U_*}{w_s} \right)^3 + 0.00272 \left(\frac{U_*}{w_s} \right)^4 \quad (3.27)$$

for $0.15 < \frac{U_*}{w_s} < 3.64$, and

$$\frac{H}{d} = 0 \quad (3.28)$$

for $\frac{U_*}{w_s} < 0.15$ or $\frac{U_*}{w_s} > 3.64$

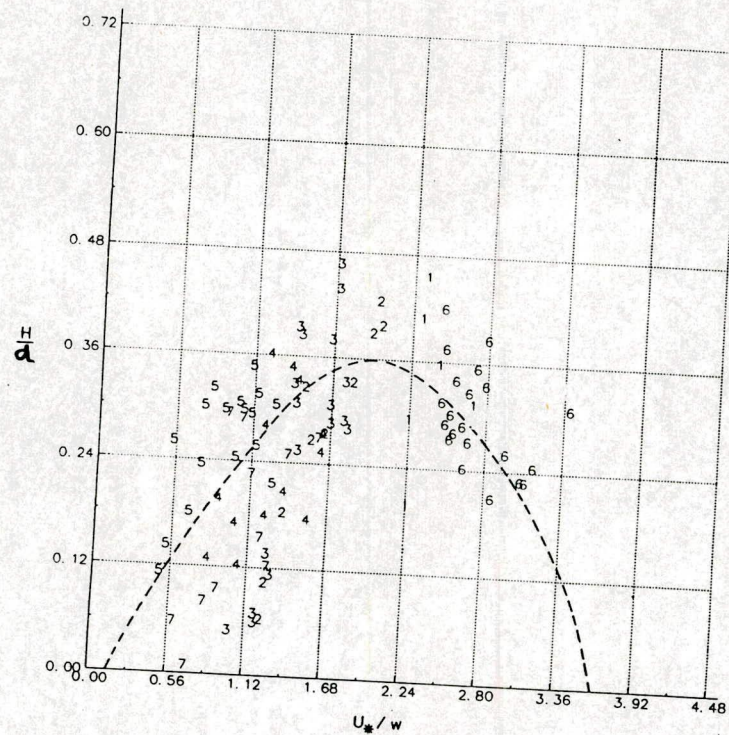


Fig. 3.7 Relative bed form height as function of U_*/w_s (Karim, 1995)

A linear relation is assumed between the friction factor ratio f/f_0 and relative bed form height, H/d and is given by

$$\frac{f}{f_0} = 1.20 + 8.92 \left(\frac{H}{d} \right) \quad (3.29)$$

Combination of Eqs. (3.27) and (3.28) with Eq. (3.29) yields

$$\frac{f}{f_0} = 1.20 + 8.92 \left[-0.04 + 0.294 \left(\frac{U_*}{w_s} \right) + 0.00316 \left(\frac{U_*}{w_s} \right)^2 - 0.0319 \left(\frac{U_*}{w_s} \right)^3 + 0.00272 \left(\frac{U_*}{w_s} \right)^4 \right] \quad (3.30)$$

when $0.15 < \frac{U_*}{w_s} < 3.64$ and

$$\frac{f}{f_0} = 1.20 \quad (3.31)$$

when $\frac{U_*}{w_s} < 0.15$ or $\frac{U_*}{w_s} > 3.64$

Equations (3.30) and (3.31) which determine the parameter f/f_0 , reflect the role of bed configuration hydraulic resistance.

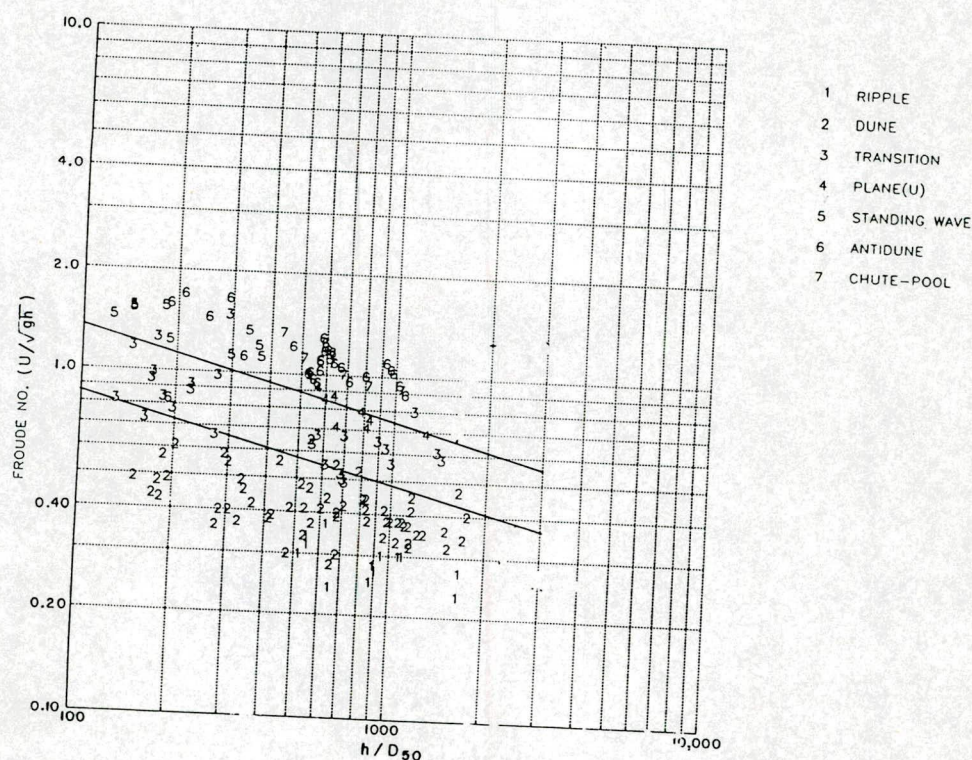


Fig. 3.8 Froude number criteria for bed regime prediction (Karim, 1995)

A graphical relation for bed regime prediction is shown in Fig. 3.8 which plots experimental data in the form of Froude number versus relative depth $\left(\frac{d}{D_{50}} \right)$. The two lines

in Fig. 3.8 which separate the transition regime from lower and upper flow regimes are given by

$$Fr_t = 2.716 \left(\frac{d}{D_{50}} \right)^{-0.25} \quad (3.32)$$

and

$$Fr_u = 4.785 \left(\frac{d}{D_{50}} \right)^{-0.27} \quad (3.33)$$

where Fr_t = Froude number at the beginning of transition regime and Fr_u = Froude number at the beginning of upper regime. In this analysis Eqs. (3.32) and (3.33) are used to determine bed regime as follows:

Lower regime : $Fr < Fr_t$
 Transition regime : $Fr_t < Fr < Fr_u$
 Upper regime : $Fr > Fr_u$

where, Fr = Froude number of flow.

For the transition regime, it is assumed that H/d is maximum (0.20) at $Fr = Fr_t$ and decreases to zero at $Fr = Fr_u$, i.e.

$$\frac{H}{d} = 0.20 \left(\frac{Fr_u - Fr}{Fr_u - Fr_t} \right) \quad (3.34)$$

For the transition regime, H/d is determined by the minimum values given by Eqs. (3.27) and (3.28) and Eq. (3.34) while H/d is determined for lower flow regime by Eqs. (3.27) and (3.28). For upper flow regime, $H/d = 0$.

Procedure:

For given values of discharge Q , energy slope S and sediment size D_{50} , the values of hydraulic radius R and the mean velocity of flow U are computed in an iteration scheme as follows:

- (i) A water surface elevation is assumed.
- (ii) The values of hydraulic radius R , flow area A , mean velocity of flow U and the Froude number Fr are computed.

- (iii) The values of U_* , Fr_t and Fr_u are calculated using Eqs. (2.14), (3.32) and (3.33), respectively.
- (iv) If $Fr < Fr_t$, then H/d is calculated using Eq.(3.27) or (3.28).
- (v) For $Fr_t < Fr < Fr_u$, H/d is assumed as the minimum of the values given by Eqs.(3.27), (3.28) and (3.34). $H/d = 0$ for $Fr > Fr_u$.
- (vi) Using Eq. (3.29) the value of f/f_0 is computed, value of n is computed by using Eq.(3.26) and U_2 by using Eq (3.25).
- (vii) If U_2 is not equal to U , within the specific criteria, another water surface elevation is assumed and the steps from (ii) to (vi) are continued until $U_2 = U$ is satisfied.

3.3 Roughness Predictors Based on Division of Roughness

A. Einstein and Barbarossa (1952) method

According to Einstein and Barbarossa (1952) the frictional loss due to grain roughness may be evaluated by use of Manning's equation or any other suitable open channel formula. In the Manning's equation the roughness factor n may be replaced by the grain roughness diameter K_s by means of the empirical formula derived by Strickler

$$\frac{U}{U_*} = 7.66 \left(\frac{R}{K_s} \right)^{1/6} \quad (3.35)$$

where U/U_* is a dimensionless quantity. It follows that in the above equation R is the hydraulic radius pertaining to the grain roughness. This hydraulic radius is called as R' . If the abbreviation U'_* is introduced for $\sqrt{SR'g}$, Eq. (3.35) becomes

$$\frac{U}{U'_*} = 7.66 \left(\frac{R'}{K_s} \right)^{1/6} \quad (3.36)$$

This is the Manning-Strickler equation. The logarithmic velocity equation of Prandtl-von Karman better supported by theory is

$$\frac{U}{U_*} = 5.75 \log \left(12.27 \frac{R}{K_s} \right) \quad (3.37)$$

Like Manning-Stricker equation the above equation can be written as

$$\frac{U}{U_*'} = 5.75 \log \left(12.27 \frac{R'}{K_s} \right) \quad (3.38)$$

This equation gives for a wide range of conditions $\left(4 < \frac{R'}{K_s} < 2000 \right)$ practically

the same results as Eq. (3.36). For rough surface flow the ratio of the roughness diameter K_s to the theoretical thickness δ' of the laminar sublayer is

$$\frac{K_s}{\delta'} = \frac{K_s U_*'}{11.6 \nu} > 5 \quad (3.39)$$

If $\frac{K_s}{\delta'}$ is smaller than 5, Eq. (3.38) must be corrected. The correction may be made by introducing a factor x into the equation which then becomes

$$\frac{U}{U_*'} = 5.75 \log \left(12.27 \frac{R'}{K_s} x \right) \quad (3.40)$$

in which the correction x is a function of K_s/δ' and is given by Fig. 3.9.

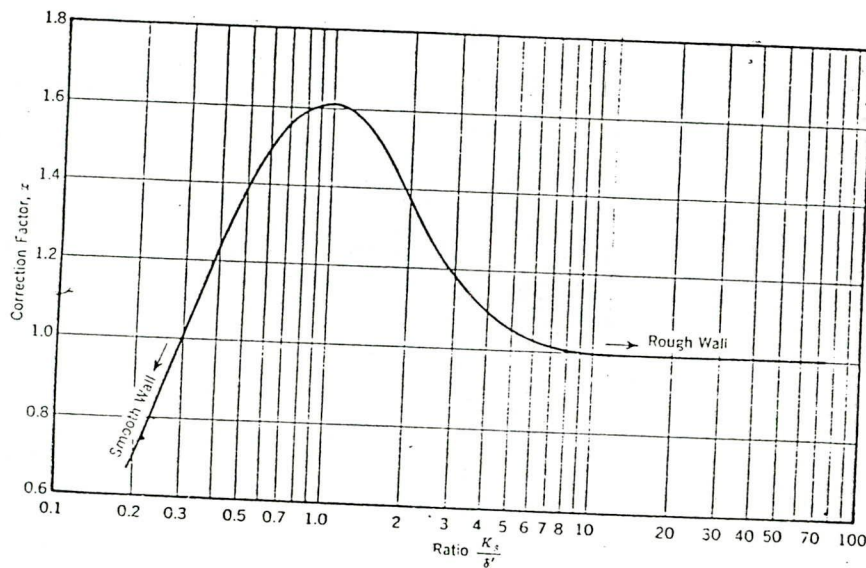


Fig. 3.9 Correction x in the logarithmic friction formula (Einstein, 1952)

Besides these usual frictional losses attributed to the grain roughness in the natural stream, there are additional friction losses. Frictional loss due to channel irregularities as a

function of sediment transport is shown in Fig. 3.10. Einstein (1950) pointed out that the form drag was related to the total sediment transport. Hence, he suggested a functional relationship

$$\frac{U}{U''} = \phi(\Psi') \quad (3.41)$$

where Ψ' is the intensity of shear on the representative particles and

$$\Psi' = \frac{\gamma_s - \gamma}{\gamma} \frac{D_{35}}{SR'} \quad (3.42)$$

Using Eqs.(2.36),(2.37) and (2.38) and also the relations $U' = \sqrt{gR' s}$ and $U'' = \sqrt{gR'' s}$,

once the velocity of flow, bed level slope and bed sediment size distribution are known, the hydraulic radius $R(= R' + R'')$ and friction factor f can be predicted.

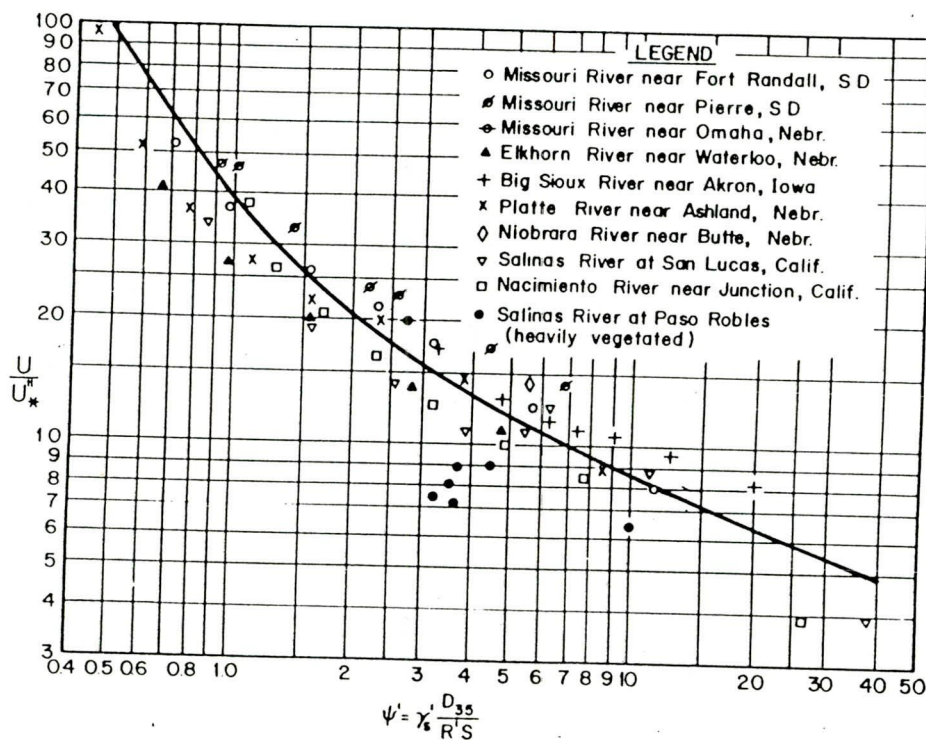


Fig. 3.10 Friction loss due to channel irregularities as a function of sediment transport (Einstein-Barbarossa, 1952)

Procedure:

For a given set of U , D and S , the depth of flow and roughness parameters may be obtained according to the following steps:

- (i) A value of R' is selected and the value of $U_*' = \sqrt{gR'S}$ is computed.
- (ii) The theoretical thickness δ' of the laminar sub-layer is calculated by using Eq.(3.39)
- (iii) If the left hand side of the Eq.(3.39) is less than 5 then the mean velocity U is calculated by using Eq. (3.40), otherwise U is calculated by using Eq. (3.38).
- (iv) Steps (i) to (iii) are repeated until predicted and measured values of U are same.
- (v) The dimensionless quantity Ψ' is calculated using Eq. (3.42).
- (vi) The shear velocity U_*'' is obtained using graphical relationship between U/U_*'' and Ψ' as shown in Fig. 3.10.
- (vii) The value of R'' is calculated using the equation $U_*'' = \sqrt{gR''S}$
- (viii) The hydraulic radius R is computed using Eq. (2.31).
- (ix) The friction factors f' and f'' are obtained using Eqs. (2.36) and (2.37).

B. Shen (1962) Method

Shen (1962) undertook to improve the Einstein-Barbarossa (1952) method in particular to eliminate the systematic deviation that had been found to Einstein-Barbarossa curve for the functional relationship between U/U_*'' vs. Ψ' as shown in Fig. 3.10.

In open channel flows for which the gravitational force is predominated, the Froude number must be considered. The Froude number $1/\Psi'$ (a dimensionless parameter representing the intensity of shear on sediment particle) is quite important in the development of different bed patterns. But the parameter Ψ' is not sufficient to characterize and predict bed forms.

Shen defined a parameter λ that varies with the particle Reynolds number $\frac{w_s D}{\nu}$ as shown

by Fig. 3.11.

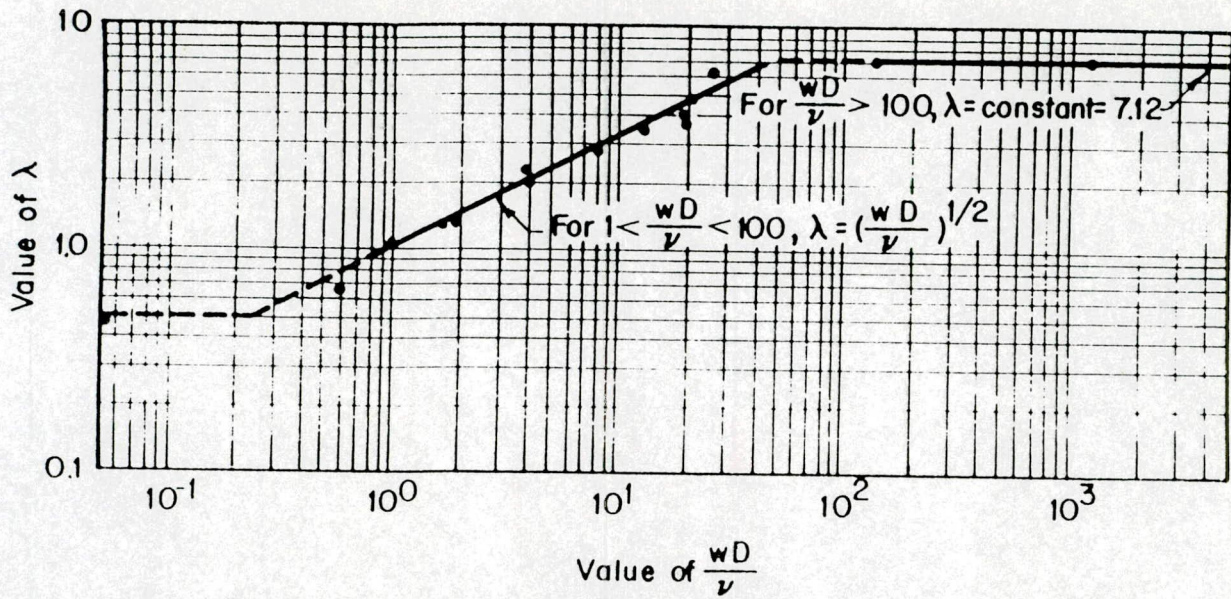


Fig. 3.11 Variation of the correction parameter λ with $w_s D / \nu$ (Shen, 1962)

The form resistance $\frac{U''}{U}$ is expressed as $A_1 + B_1 \log \frac{\Psi'}{\lambda}$ in which A_1 and B_1 are constants and $\lambda = \text{Func} \left(\frac{w_s D}{\nu} \right)$. This resistance resembles the logarithmic friction law

$$\frac{U}{U'} = A_2 + B_2 \log \left(R' \frac{x}{K_s} \right) \quad (3.43)$$

in which A_2 and B_2 are constants and $x = \text{Func} \left(\frac{U' D}{\nu} \right)$.

For fine sediments with a value of $\frac{w_s D}{\nu} < 100$, the magnitude of f'' always decreases as Ψ' decreases. For fine sediment form resistance is given by

$$\frac{U''}{U} = 0.03 + 0.11 \log \left(\frac{\Psi'}{\lambda} \right) \quad (3.44)$$

As the value of Ψ' decreases, the bed configuration changes from ripple to plane bed, through stages of dune and transition.

For coarser material with value $\frac{w_s D}{\nu} > 100$, the variation of f'' is given by

$$\frac{U_*''}{U} = 0.03 + 0.11 \log \left(\frac{\Psi'}{7.12} \right) \quad (3.45)$$

for $\Psi' < 10$ and

$$\frac{U_*''}{U} = 0.064 - 0.0909 \log \left(\frac{\Psi'}{7.12} \right) \quad (3.46)$$

for $\Psi' > 10$.

Procedure:

For a given set of U , D and S , the depth of flow and roughness parameters can be obtained according to the following steps:

- (i) A value of R' is selected and the value of U_*' is calculated using the equation.

$$U_*' = \sqrt{gR'S}$$

- (ii) The theoretical thickness δ' of the laminar sub-layer is calculated using Eq. (3.39).
- (iii) If the left hand side of the Eq. (3.39) is less than 5 then the mean velocity U is calculated by using Eq. (3.40), otherwise U is calculated by using Eq. (3.38).
- (iv) Steps (i) to (iii) are repeated until predicted and measured values of U are same.
- (v) The values of dimensionless quantity Ψ' and $w_s D/\nu$ are calculated.
- (vi) The value of U_*''/U is calculated using Eq. (3.44) or (3.45) or (3.46).
- (vii) The value of R'' is calculated using the equation $U_*'' = \sqrt{gR''S}$.
- (viii) The hydraulic radius R is computed using Eq. (2.31).
- (ix) The friction factors f' and f'' are obtained using Eqs. (2.36) and (2.37), respectively.

C. Engelund & Hansen (1967) method

Engelund and Hansen (1967) employed the divided slope approach as shown in Eq. (2.29). The total mean energy gradient S per unit length of the channel is partly due to a

certain friction loss S' occurring along the stream side of the dunes and partly to a series of expansion losses that may in principle be accounted for by Carnot's formula

$$S'' = \frac{\Delta H}{L''} = \frac{q^2}{2gL} \left[\frac{1}{d - \frac{1}{2}H} - \frac{1}{d + \frac{1}{2}H} \right]^2 \approx \frac{U^2}{2gL} \left(\frac{H}{d} \right)^2 \quad (3.47)$$

Substituting Eq. (3.47) into Eq. (2.29) yields

$$S = S' + \frac{U^2}{2gL} \left(\frac{H}{d} \right)^2 = S' + \frac{H^2}{2Ld} (Fr)^2 \quad (3.48)$$

The depth d may be replaced by the hydraulic radius R . Multiplying both sides by $\gamma R / (\gamma_s - \gamma) D_{50}$ gives

$$\frac{\gamma RS}{(\gamma_s - \gamma) D_{50}} = \frac{\gamma RS'}{(\gamma_s - \gamma) D_{50}} + \frac{\gamma}{(\gamma_s - \gamma)} \frac{H^2}{2LD_{50}} Fr^2 \quad (3.49)$$

Using

$$\tau_* = \frac{\gamma RS}{(\gamma_s - \gamma) D_{50}} \quad (3.50)$$

$$\tau_*' = \frac{\gamma R'S}{(\gamma_s - \gamma) D_{50}} \quad (3.51)$$

and

$$\tau_*'' = \frac{\gamma H^2}{(\gamma_s - \gamma) LD_{50}} \frac{U^2}{2gd} = \frac{\gamma H^2}{2(\gamma_s - \gamma) LD_{50}} Fr^2 \quad (3.52)$$

Eq. (3.49) becomes

$$\tau_* = \tau_*' + \tau_*'' \quad (3.53)$$

To evaluate the magnitude of R' , the relationship suggested is

$$\frac{U}{U_*'} = \frac{U}{\sqrt{gR's}} = 6 + 2.5 \ln \frac{R'}{K_s} \quad (3.54)$$

where $K_s = 2D_{65}$

Using flume data Engelund and Hansen (1967) obtained the following relationship for lower flow regime with a dune or ripple bed:

$$\tau_*' = 0.06 + 0.40\tau_*'^2 \quad (3.55)$$

or

$$\tau_* = 1.581(\tau_*' - 0.06)^{1/2} \quad (3.56)$$

for $\tau_*' < 0.55$

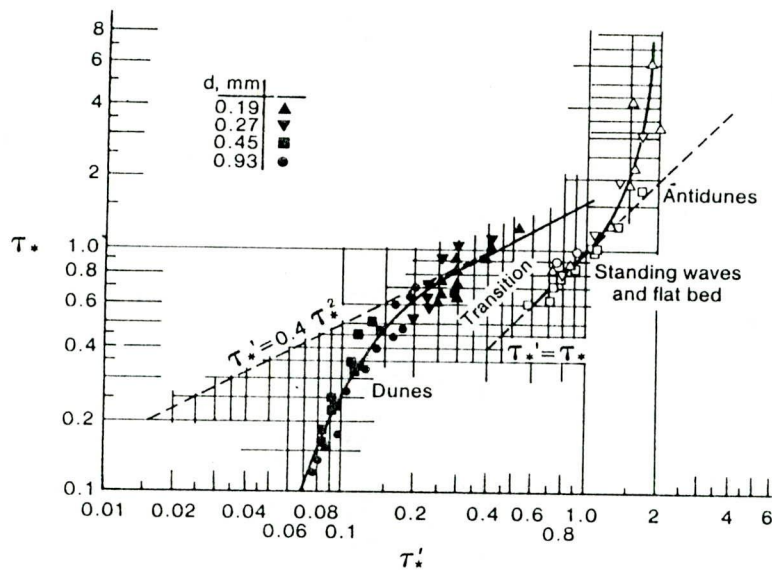


Fig. 3.12 Engelund's universal relationship between dimensionless grain shear stress τ'_* and total shear stress τ_* .

For upper flow regime with $0.55 < \tau'_* < 1$, we have

$$\tau'_* = \tau_* \quad (3.57)$$

These relations are shown in Fig. 3.12 with a discontinuity between lower and upper flow regimes occurring at about $\tau'_* = 0.55$.

Brownlie (1983) extended Eq. (3.55) from the curve in Fig. 3.12 into higher regions of the upper flow regime for $\tau'_* > 1$ and obtained the relationship:

$$\tau'_* = [0.702 (\tau_*)^{-1.8} + 0.298]^{-1/1.8} \quad (3.58)$$

or

$$\tau_* = [1.425 (\tau'_*)^{-1.8} - 0.425]^{-1/1.8} \quad (3.59)$$

Procedure

Engelund-Hansen (1967) method can be used in predicting depth of flow for a given set of q , D and S and sediment characteristics. The procedure is as follows:

- (i) A value of depth d' or hydraulic radius R' is assumed.

- (ii) The dimensionless grain shear stress τ_*' and the mean velocity of flow U are computed using Eqs. (3.51) and (3.54), respectively.
- (iii) If τ_*' is less than 0.55, the bed is in the lower flow regime. The total shear τ_* is computed by using Eq. (3.56). If τ_*' is greater than 0.55 and less than 1.00 then the flow is in upper regime and τ_* is computed by using Eq. (3.57). For τ_*' is greater than 1.00, the flow is in higher regions of upper flow regime and τ_* is computed by using Eq. (3.59).
- (iv) Using Eq. (3.50) the hydraulic radius R is computed.
- (v) The discharge per unit width q is computed on the basis of calculated U and R .
- (vi) The computed q is compared with the given q and the steps are repeated until these two q values are same.

D. Vanoni-Hwang (1967) method

Vanoni-Hwang (1967) undertook experimentally what geometric characteristics of alluvial channel bed forms determine their hydraulic roughness. Following Einstein and Barbarossa (1952), the bed shear stress is divided into a part τ' resulting from the grain roughness and a part τ'' caused by the form drag of the ripples and dunes.

The value of f' is assumed to be the friction factor of a pipe of diameter $4R$ coated with sand grains of size equal to the mean size of the sediment in the channel and discharging with a mean velocity U that is the same as that of the channel. The value of f' can be determined from a graph of Nikuradse data of friction factor against Reynolds number for several values of relative roughness or the following Karman-Prandlt resistance equation for turbulent flow in rough pipes used by Nikuradse in his graph:

$$\frac{1}{\sqrt{f'}} = 2.10 \log \frac{R}{K_s} + 1.74 \quad (3.60)$$

Vanoni & Hwang developed a relationship between the friction factors of beds covered with dunes and ripples and the size of other geometric properties of these bed forms, given by

$$f'' = F\left(\frac{R}{H} \cdot \frac{A_s}{A}\right) \quad (3.61)$$

in which H = the height of the roughness elements and A_s/A is the areal concentration of bed forms. By introducing an equivalent sand roughness size, K_s , for a dune or ripple bed, Eq. 3.61 can be simplified to

$$f'' = F\left(\frac{R}{K_s}\right) \quad (3.62)$$

which is equivalent to saying that K_s is a function of H and A_s/A . For low areal concentrations of roughness elements, K_s is proportional to the roughness height H times the concentration. Introducing this relationship into Eq. (3.62) gives

$$f'' = F\left(\frac{R}{\frac{A_s}{A} \cdot H}\right) \quad (3.63)$$

The dimension H for a dune or ripple bed was taken as the mean height $\bar{H}$ of the bed forms. The area A_s was taken as the horizontal projection of the lee faces of the ripples or dunes and A was taken as the total bed area over which A_s is measured. A_s may be assumed proportional to the vertical projection of the faces. The ratio A_s/A is called the exposure parameter and is denoted by e . The relationship for ripples and dunes can then be written as

$$f'' = F\left(\frac{R}{e\bar{H}}\right) \quad (3.64)$$

in which $R/(e\bar{H})$ = the modified relative roughness and $e\bar{H}$ is the characteristic roughness of the ripples and dunes. Experimental data were used to determine the function F of Eq. (3.64).

Using the data from experiments with loose sand beds, a graph of $\sqrt{1/f''}$ against the modified relative roughness $\frac{R}{e\bar{H}}$ was plotted. The line on the graph which was fitted has the equation

$$\frac{1}{\sqrt{f''}} = 3.5 \log \frac{R}{e\bar{H}} - 2.3 \quad (3.65)$$

To use existing data in making comparisons, it was assumed that the quantity e is proportional to $\frac{\bar{H}}{L}$, the steepness of ripples and dunes. With this assumption Eq. (3.65) becomes

$$\frac{1}{\sqrt{f''}} = 3.3 \log \frac{LR}{H^2} - 2.3 \quad (3.66)$$

Procedure:

For a given set of hydraulic radius R , slope of the energy grade line S and median particle size D_{50} , the friction factor can be obtained as follows:

- (i) The bed form height and length are predicted by using Vajda (1990) and Yalin (1992) methods. Vanoni-Hwang (1967) method is then applied separately after the bed form dimensions predicted.
- (ii) The grain friction factor f' is computed by using Eq. (3.60).
- (iii) The form friction factor f'' is computed by using Eq. (3.66).
- (iv) The total friction factor f is computed by using Eq. (2.38).

E. Alam - Kennedy (1969) method

Like many other investigators Alam and Kennedy (1969) recognized that the resulting force exerted by the bed on the flowing liquid can be regarded as composed of two parts. The Darcy-Weisbach friction factor f can be written using Eqs. (2.36), (2.37) and (2.38) as

$$f = f' + f'' = \frac{8gRS'}{U^2} + \frac{8gRS''}{U^2}$$

The flat bed friction factor f' was determined by means of the predictor developed by Lovera and Kennedy (1969). The graphical relation they obtained has the format of the well-known Moody pipe friction diagram and f' is expressed as

$$f' = f \left(\frac{UR}{v}, \frac{R}{D_{50}} \right) \quad (3.67)$$

To proceed with dimensional analysis, Alam and Kennedy (1969) identified the important physical quantities involved. They assumed that the bed configuration geometry can be characterized by two dimensions, the wave length L and height H of the bed features. The drag force per unit width F_D and associated with drag coefficient C_D for one bed feature can be related by

$$F_D = C_D \rho H \frac{U^2}{2} \quad (3.68)$$

or

$$C_D = \frac{f''}{4} \cdot \frac{L}{H} \quad (3.69)$$

Hence, examining f'' is equivalent to analyzing the more readily grasped C_D , provided L/H is one of the variables included in the analysis. It is seen that f'' depends on seven independent dimensionless groups expressed as

$$f'' = \text{Func} \left(\frac{U}{\sqrt{gD_{50}}}, \frac{4UR}{\nu}, \frac{D_{50}}{R}, \frac{H}{L}, \frac{L}{D_{50}}, \frac{\rho_s}{\rho}, \sigma \right) \quad (3.70)$$

The form-drag friction factor f'' would appear to be affected little by viscosity and at large Reynolds number the drag coefficients of bluff bodies are independent of Reynolds numbers. In addition ρ_s/ρ may be regarded as constant. Neglecting the Reynolds number, σ_g and ρ_s/ρ , Eq. (3.70) became

$$f'' = \text{Func} \left(\frac{U}{\sqrt{gD_{50}}}, \frac{D_{50}}{R}, \frac{H}{L}, \frac{L}{D_{50}} \right) \quad (3.71)$$

From bed form analysis Alam and Kennedy approximated that

$$f'' = \text{Func} \left(\frac{U}{\sqrt{gD_{50}}}, \frac{D_{50}}{4} R \right) \quad (3.72)$$

The graphical value of f' and f'' can be obtained by using Lovera-Kennedy (1969) chart for grain roughness friction factor f' as a function of Reynolds number UR/ν shown in Fig. 3.13 and Alam-Kennedy chart for drag friction factor f as a function of relative depth

R/D_{50} for constant grain Froude number $\frac{U}{\sqrt{gD_{50}}}$ shown in Fig. 3.14.

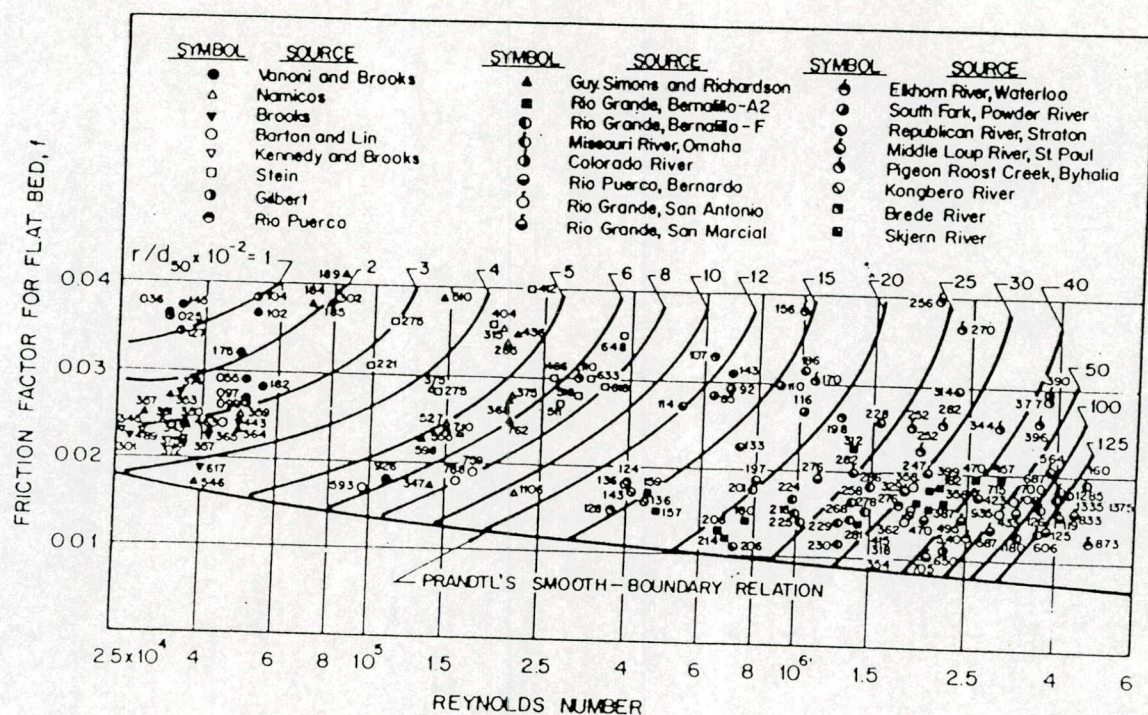


Fig. 3.13 Lovera and Kennedy chart for grain roughness friction factor (f') as a function of Reynolds number UR/ν for constant values of relative depth Rd/D_{50} (Data points shown on the original chart have been omitted, after Raudkivi, 1990).

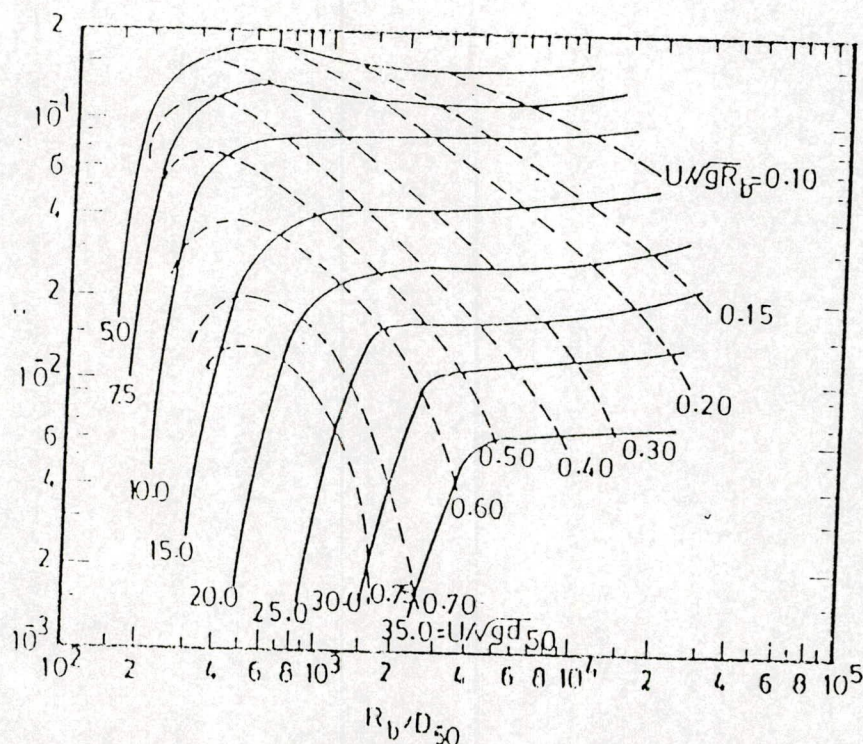


Fig. 3.14 Alam and Kennedy chart for form drag friction (f'') as a function of relative depth (R/D_{50}) for (i) constant values of grain Froude number, $U/(gD_{50})^{1/2}$ and (ii) constant values of Froude number, $U/(gR)^{1/2}$ (Data points shown on the original chart have been omitted, after Raudkivi, 1990).

Procedure:

The procedure of calculation by the Alam and Kennedy (1969) method is as follows:

- (i) The grain diameter D_{50} , slope S and kinematic viscosity ν are supposed to be known parameters. The depth-averaged flow velocity U is selected and assumed a value for the overall hydraulic radius, R .
- (ii) The nondimensional parameters $\frac{U}{\sqrt{gD_{50}}}$, R/D_{50} and UR/ν are then calculated.
- (iii) The friction factor f' related to grain roughness and the friction factor f'' related to the form drag is read from graphical relationships shown in Figs. (3.13) and (3.14).
- (iv) The overall friction factor f is computed using Eq. (2.38).
- (v) The overall hydraulic radius R can be computed using Eq. (2.6).
- (vi) If the predicted value of R is not same as that of the assumed value of R , then the above procedure is repeated.

F. Haque-Mahmood (1983) method

Haque and Mahmood (1983) recognized that the total drag at the bottom of the channel consists of two distinct parts: (1) the surface drag, and (2) the form drag. An attempt was made to calculate the form friction factor by integrating the pressure over a ripple or dune surface, and, thus, to discover the relationship between the form friction factor and the geometric parameters, such as steepness ratio and the relative roughness of these bed forms.

The observational fact is that the form friction factor is independent of the actual size of the bed form and depends only on the geometric shape of the flow region. Thus, only two parameters - one defining the shape of the lower boundary and the other defining the aspect ratio of the region - are needed for the computation of f'' . The numerical results of the parametric study are shown graphically in Fig. 3.15.

In this figure, a solid curve corresponds to a constant steepness ratio H/L of the bed form, and each dotted line represents a constant aspect ratio, $(d - \frac{H}{2})/L$, of the flow

region. The points denoted by open circles represent the solutions obtained by the finite element analysis. The curve for $H/L = 0.05$ is, however, obtained by interpolation. The position of a typical interpolation point is determined from the following identity:

$$\frac{H}{L} \left(\frac{H}{d - \frac{H}{2}} \right) \left(\frac{d - \frac{H}{2}}{L} \right) \quad (3.73)$$

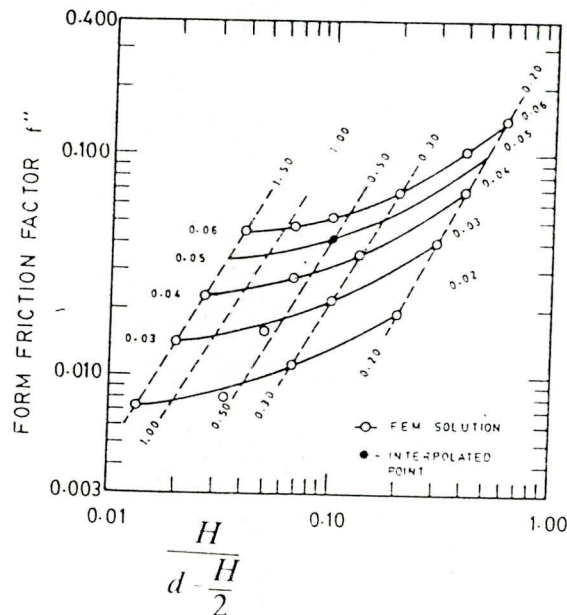


Fig. 3.15 Relation between form friction factor f'' and relative roughness

$$\left(\frac{H}{d - \frac{H}{2}} \right) \quad (\text{Haque \& Mahmood, 1983})$$

From Fig. 3.15, it may be noted that the dotted lines for $(d - \frac{H}{2})/L > 0.5$ are almost parallel, and the family of curves in this region can be expressed in the mathematical form

$$f'' = \phi \left(\frac{d - \frac{H}{2}}{L} \right) \cdot \left(\frac{H}{d - \frac{H}{2}} \right)^m \quad (3.74)$$

in which m is the slope of dotted lines and is found to have a numerical value of 1.653. The function ϕ depends on $(d - \frac{H}{2})/L$ and its behaviour is obtained by studying the

variation of f'' along $\left(\frac{H}{d - \frac{H}{2}} \right) = 1$. The variation of ϕ is shown in Fig. 3.16.

From this figure, it is evident that $(d - \frac{H}{2})/L > 0.5$ the function ϕ can be expressed quite accurately by

$$\phi = 4.9 \left(\frac{d - \frac{H}{2}}{L} \right)^{1.477} \quad (3.75)$$

and the form friction factor can be expressed by the equation

$$f'' = 4.9 \left(\frac{d - \frac{H}{2}}{L} \right)^{1.477} \left(\frac{H}{d - \frac{H}{2}} \right)^{1.653} \quad (3.76)$$

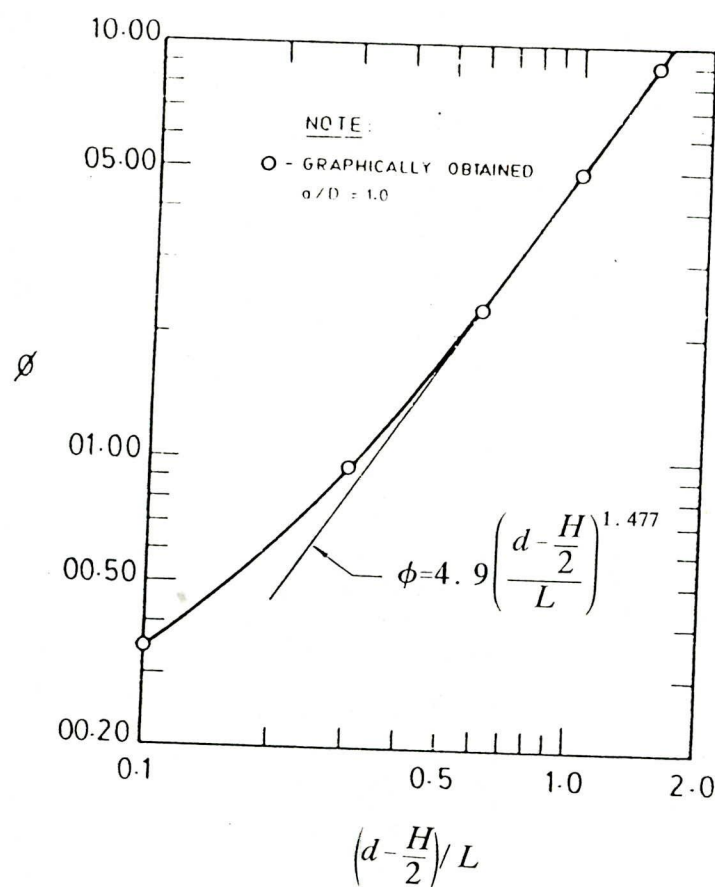


Fig. 3.16 Variation of ϕ with relative depth $(d - \frac{H}{2})/L$ (Haque & Mahmood, 1983)

Procedure:

For a given set of bed form height and length, the form friction factor f'' can be obtained by using the Haque-Mahmood method. The dimensions of bed form can be predicted

by using Vajda (1990) or Yalin (1992) method. The grain roughness can be predicted by using White-Colebrook formula. The procedure is as follows:

- (i) Bed form dimensions are computed by using Vajda (1990) or Yalin (1992) method.
- (ii) The grain roughness is predicted by using formula for grain roughness presented by Eq. (2.11).
- (iii) For relative depth $\left(d - \frac{H}{2}\right)/L$, the corresponding functional value of ϕ is predicted using Fig. 3.16.
- (iv) The form friction factor f'' is computed using Eq. (3.76).
- (v) The overall friction factor f is computed using Eq. (2.38).

G. Shen et al. (1990) method

According to Shen et al. (1990) the variation of shear stress along the upstream face of a bed form may be studied through the use of a local skin shear coefficient C_f , defined as

$$C_f = \frac{\tau_x}{\frac{1}{2} \rho U_x^2} = \frac{8gRS}{4U_*^2} = \frac{f'_x}{4} \quad (3.77)$$

where flow is along the longitudinal direction x along the base of dunes and parallel to the flow direction and

$$f''_x = \frac{8\tau'_x}{\rho U_x^2} \quad (3.78)$$

When boundaries are hydraulically smooth and the Reynolds number $Re < 100,000$, the local friction factor f'_x is given by the Blasius formula

$$f'_x = \frac{0.316}{Re^{0.25}} \quad (3.79)$$

which can be rewritten in terms of C_f as

$$C_f = \frac{0.079}{Re^{0.25}} \quad (3.80)$$

where $Re = q/\nu$

The local skin shear coefficients were computed for each measured shear stress using Eq. (3.77). The local skin shear coefficients were plotted against Reynolds number Re for different longitudinal distance from the upstream toe. For the bed form investigated, the measured data fit the relationship

$$C_f = \frac{0.041 \frac{x}{A} - 0.085}{(Re)^{0.25}} \quad (3.81)$$

where x = the longitudinal distance from the upstream toe.

Neglecting the small shear stress present within the separation zone, the longitudinal force per unit width due to skin shear F_s is given by

$$F_s = \int \tau_x dx \quad (3.82)$$

The bed skin friction factor f' is computed from

$$f' = \frac{8\tau'}{\rho U^2} = \frac{8}{\rho U^2} \left(\frac{F_s}{L} \right) \quad (3.83)$$

Shen et al. suggested that the equation

$$f' = \left(\frac{0.106 d}{d_c} \right) \frac{1}{(Re)^{0.25}} \quad (3.84)$$

fits the measured skin friction factor f' values very well.

The form friction factor f'' is computed using Eq. (2.37)

$$f'' = \frac{8gR''S}{U^2} = \frac{8\tau''}{\rho U^2} = \frac{8F_p}{L\rho U^2} \quad (3.85)$$

where the form shear stress $\tau'' = \frac{F_p}{L}$, pressure drag coefficient F_p taken as positive in the downstream direction.

The pressure drag force consists of two components: a viscous shear force and a turbulent pressure force. Generally the drag force consists of both components and can be expressed as

$$F_p = \frac{1}{2} \rho U^2 C_D H \quad (3.86)$$

or

$$C_D = \frac{F_P}{\frac{1}{2} \rho U^2 H}$$

Combining Eqs. (3.85) and (3.86) yields

$$C_D = \frac{1}{4} f'' \frac{L}{H} \quad (3.87)$$

The pressure drag coefficient C_D was plotted against the relative roughness H/d . These investigators proposed a relationship between C_D and H/d of the form

$$C_D = m \left(\frac{H}{d} \right)^{3/8}$$

where m = a coefficient dependent only on the bed form steepness ratio with a mid range value of $m = 4/9$ for $H/d \leq 0.35$. For relative roughness $H/d \geq 0.35$, a power relation with an exponent of $3/2$ and m equal to $3/2$ fits the data well. The pressure drag coefficient C_D may be related to the relative roughness as follows:

$$C_D = \frac{4}{9} \left(\frac{H}{d} \right)^{3/8} \text{ for } \frac{H}{d} \leq 0.35 \quad (3.88)$$

$$C_D = \frac{3}{2} \left(\frac{H}{d} \right)^{3/2} \text{ for } \frac{H}{d} > 0.35 \quad (3.89)$$

The form friction factor f'' can be computed from the pressure drag coefficient and the bed form steepness ratio, as

$$f'' = 4 C_D \frac{H}{L} \quad (3.90)$$

Procedure:

For a given set of bed form height and length the form friction factor f'' can be computed by using Shen (1990) method. The dimensions of bed form can be obtained by using Allen (1963), Vajda (1990) or Yalin (1992) method. Other known parameters are R , S , and D . The procedure is as follows:

- (i) Bed form dimension is predicted by using Allen (1963), Vajda (1990) or Yalin (1992) method.
- (ii) Pressure drag coefficient C_D is computed by using Eq. (3.88) for $H/d \leq 0.35$ or by using Eq. (3.89) for $H/d > 0.35$.

- (iii) The form friction factor f'' is computed using Eq. (3.90).
- (iv) The grain friction factor f' is computed using Eq. (3.84).
- (v) The overall friction factor f is computed using Eq. (2.38).

H. Van Rijn (1993) method

Van Rijn (1993) divided the total alluvial roughness as

$$K_s = K'_s + K''_s \quad (3.91)$$

and expressed the White and Colebrook equation for Chezy coefficient found from Eq. (2.9) as

$$C = 18 \log \left(\frac{12R}{K_s} \right)$$

in which

$$K'_s = 3D_{90} \text{ for } \theta < 1 \text{ (lower regime)}$$

and

$$K'_s = 3\theta D_{90} \text{ for } \theta \geq 1 \text{ (upper regime)}$$

where the mobility parameter θ is given by

$$\theta = \frac{U_*^2}{\frac{(\rho_s - \rho)}{\rho} g D_{50}}$$

The effective form roughness is related to bed form height H , the bed form steepness H/L and the bed form shape (γ). The functional relationship is as follows:

$$K''_s = F\left(H, \frac{H}{L}, \gamma\right) \quad (3.92)$$

The most general case is that of a bed consisting of mega ripples superimposed on dunes and sand waves. It is proposed to determine the overall form roughness by summation of individual values, as follows:

$$K''_s = K''_{sr} + K''_{sd} + K''_{ssw} \quad (3.93)$$

in which

K''_{sr} = form roughness related to ripples.

K''_{sd} = form roughness related to dunes

K''_{ssw} = form roughness related to sand waves.

Van Rijn proposed the following relationships for determining K''_{sr} , K''_{sd} and K''_{ssw} :

$$K''_{sr} = 20 \gamma_r H_r \left(\frac{H_r}{L_r} \right) \quad (3.94)$$

in which:

γ_r = ripple pence factor 1 for ripple alone and 0.7 for ripples superimposed on dunes or sand waves.

$$K''_{sd} = 1.1 \gamma_d H_d \left(1 - e^{-25 \frac{H_r}{L_r}} \right) \quad (3.95)$$

in which:

γ_d = form factor (=0.7 for field conditions).

Sand waves are defined as symmetrical bed forms with a length much larger than the water depth. The lee side slopes of symmetrical sand waves are relatively mild. Hence flow separation will not occur. Therefore, the form roughness of symmetrical sand waves is assumed to be zero. Thus

$$K''_{ssw} = 0. \quad (3.96)$$

Procedure:

When the velocity of flow U , slope of the channel S , and particle diameter D are known, the hydraulic radius and roughness parameters can be predicted as follows:

- (i) A hydraulic radius R is assumed.
- (ii) With assumed hydraulic radius the transport stage parameter T is calculated using Eq. (2.42).
- (iii) The regime of flow is obtained knowing the transport stage parameter, T .
- (iv) The respective bed form length is computed using Eq. (2.81), (2.83), (2.85) or (2.87) depending on whether the bed form is ripple, megaripple, dune or antidune.
- (v) The bed form height is computed using Eq. (2.80), (2.82), (2.84) or (2.86) depending on regime of flow.
- (vi) The Nikuradse grain roughness value is obtained by $K_s' = 3D_{90}$ if θ is less than 1.00 and by $K_s' = 3\theta D_{90}$ if θ is greater than 1.00.

- (vii) Nikuradse form roughness related to ripple K_{sr}'' is computed by using Eq. (3.108). Nikuradse form roughness related to dune K_{sd}'' and standing wave K_{sw}'' are calculated using Eqs. (3.94) and (3.95), respectively.
- (viii) The K_s'' value is the sum of K_{sr}'' , K_{sd}'' and K_{sw}'' .
- (ix) The Chezy's resistance factor C is computed by using Eq. (2.11).
- (x) The hydraulic radius is computed by using Eq. (2.1).
- (xi) If the computed and assumed values of R are not same the above procedure is repeated.

3.4 Prediction Accuracy

After predicting depth, velocity and roughness parameters by different methods, the accuracy of prediction by different methods has been determined. Researchers used different methods to express the accuracy of their own work or results. Van Rijn (1984 and 1993) compared his method with others, on the basis of percentage of predicted depth and Chezy's C that lies within $\pm 10\%$, $\pm 20\%$ and $\pm 30\%$ error ranges. Brownlie (1983) graphically expressed the depth predicted by his method against that of the computed depth. Karim (1995) expressed the accuracy of his method on the basis of the mean normalized error and the percentage of error on the predicted depth and velocity.

In this study, accuracy of different methods is determined on the basis of percentage of predicted depth, velocity and Manning's roughness value n that lies within $\pm 10\%$, $\pm 20\%$ and $\pm 30\%$ error ranges. Accuracy is also determined by the mean normalized error of depth, velocity and Manning's n (Karim, 1995). The computed values of coefficient roughness n is also expressed graphically against those predicted by different methods.

The accuracy of prediction measured by the mean normalized error (MNE) in predicted depths or velocities expressed in percent is defined as

$$MNE = \frac{100}{N} \sum_{i=1}^N \frac{|X_{ci} - X_{mi}|}{X_{mi}} \quad (3.97)$$

where,

- X_{ci} = predicted depths (or velocities) for i th flow
- X_{mi} = predicted depths (or velocities) for i th flow
- N = number of data of a station.

CHAPTER 4

DATA COLLECTION AND ANALYSIS

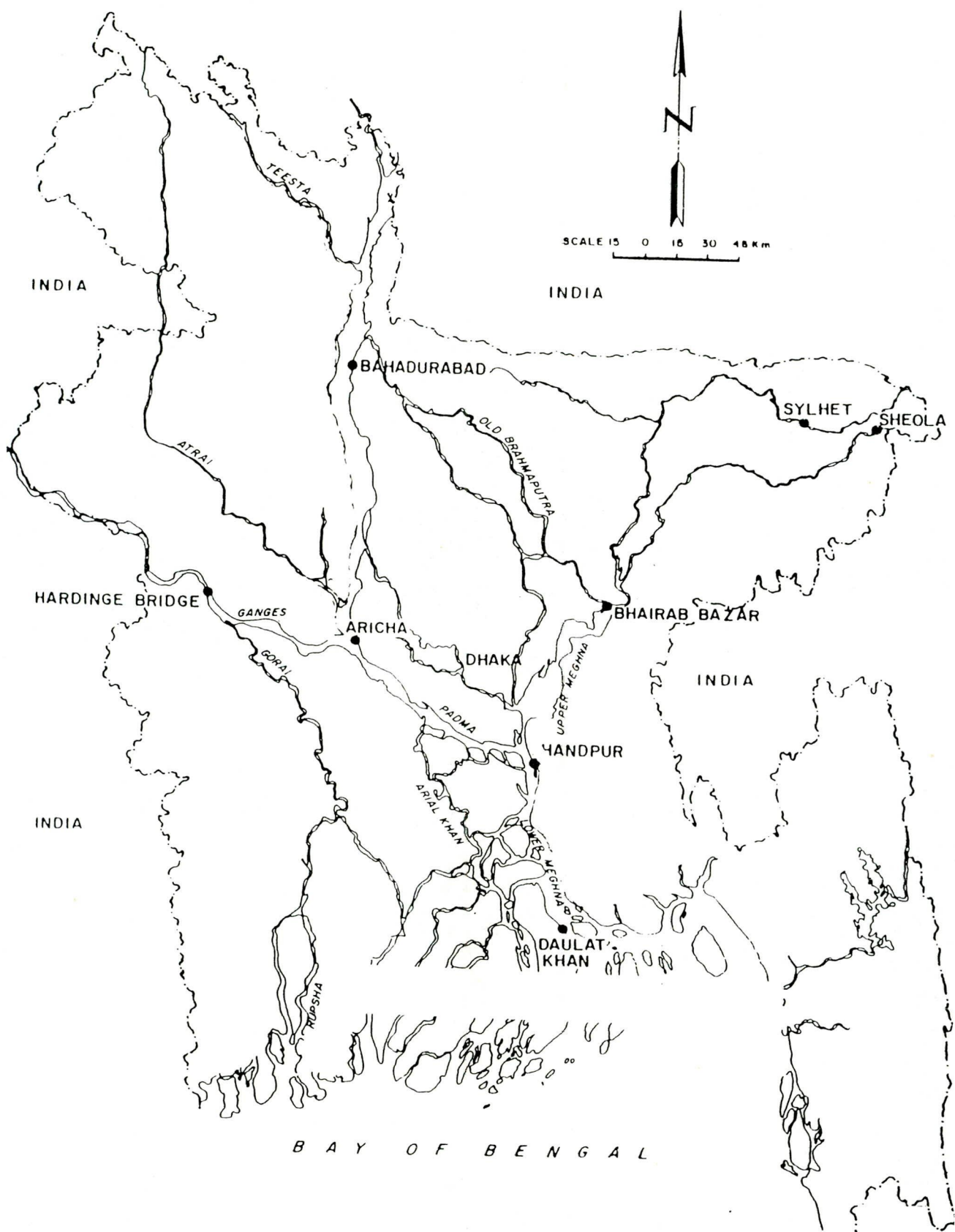
4.1 Introduction

It is stated in chapter 1 that the main objective of the present study is to determine the applicability of some alluvial roughness predictors for the river Ganges and to identify the methods that seem to predict roughness characteristics of the river Ganges satisfactorily. In this chapter, a brief description of the river Ganges is presented first, thereafter, data required for the study, sources of data, data collection etc. are considered.

4.2 The River Ganges

The river Ganges rises west on the Nanda Devi Range west of Nepal and down to Goalunda in Bangladesh. It has a length of about 2200 kilometers and drainage area of 978000 sq.kilometers (FAP 24, 1997). The Ganges is an international river with its basin area spreading over China, Nepal, India and Bangladesh. After travelling through several states of India, the Ganges enters Bangladesh at Lalgola, 18 kilometers downstream of Farakka. In Bangladesh it is called the river Ganges up to its confluence with the Brahmaputra (Jamuna) river near Aricha. Downstream of Aricha the combined Ganges and Jamuna flows are carried by the Padma river. The Padma river is 120 kilometers long and joins the Upper Meghna near Chandpur, after which it is called the Lower Meghna, which debouches into the Bay of Bengal at some 150 kilometers from the confluence. The main river system of Bangladesh is shown in Fig. 4.1. The lower Meghna river conveys the melt and rainwater from the Ganges and the Jamuna basin as well as from the Upper Meghna river into the sea.

The Ganges is a wide meandering river. Its width may at places be as large as 5 kilometers. The shape of the cross-section is quite variable. The meander belt of the river varies between 5 to 15 kilometers with eroding outer bends and depositing inner bends. Twenty years of BWDB cross-sectional data compiled by Hossain(1989) indicate that the meandering migration rate is of the order of some 150 meters per year. From the Indo-Bangladesh border to the confluence located at Aricha, there are 4(four) distinct and wide bends. The average sinuosity of the river in the reach appears to indicate a cyclic changes



4.1 The main river system of Bangladesh

over the years. However, a hydraulic flow analysis of the Ganges by FAP-4 shows that at present it is in a dynamic equilibrium. Planform analysis by Hossain(1989) indicates that the sinuosity of the river was 1.5 in 1956, decreased to 1.2 in 1976 and again increased to some 1.3 in 1986. Specially, the sinuosity is higher in the upper bends and lower at lower bends.

The Gorai is the major right bank distributory of the Ganges river. It branches off some 15 kilometers downstream of the Hardinge Bridge. The Gorai river bifurcates into a number of branches before debouching into the Bay of Bengal. The Gorai is of extreme importance for the Southwest region of Bangladesh as it conveys fresh water in the saline zone. Flow of the river Gorai is measured at Gorai Railway Bridge. The flows in the river Gorai have been affected by the flow diversion at Farakka and Ganges river morphology: a sand bar partly blocks the entrance to the Gorai river.

Hardinge Bridge and Baruria are two measuring stations of BWDB located on the river Ganges. The meander migration of the Ganges at Hardinge Bridge had stopped since the construction of railway bridge in 1910. Hardinge Bridge is a very old primary measuring station of BWDB. This station is located in a constricted river bend. The constriction of the Ganges river at Hardinge Bridge is to a width of 1.6 kilometers from the main river width of 3.8 kilometers. This constriction of the river width induced cyclic erosion-deposition of the river bed, with erosion during the monsoon flood and siltation during the low flood stage. It is seen that, in comparison with the sediment transport at the unconstricted section, the sediment transport is low at low discharges and high at high discharges. At low discharges, the velocity is lower at the constriction than an unconstricted section and at high discharges the velocity is higher at the constricted section than the unconstricted section.

Baruria gauging station is located downstream of the Ganges/Jamuna confluence and 6 kilometers downstream of Aricha. The discharge at Baruria is derived using the relation

$$Q(\text{Baruria}) = Q(\text{Bahadurabad}) + (Q(\text{Hardinge Bridge}) - Q(\text{Gorai}))$$

Baruria has a stable cohesive bank. The reach upstream of the confluence is continuously adjusting, but at the same time, fluctuating around bed level and hence the system is in dynamic equilibrium. It can be seen that downstream of the confluence the river bed is degrading during the rising stage while it is aggrading during the falling stage. This alternate aggrading and degrading give rise to the generation of the sand waves which migrate through downstream reach. At the confluence the annual fluctuation of the bed level is high, of the

order of 1.5 to 2 meters(confluence scour). The fluctuation gradually becomes insignificant downstream.

The river Ganges at the confluence had two channels in the past until 1982, one at Goalunda and the other at Baruria. The channel at Goalunda has been closed , firstly due to natural aggradation and later by human intervention.

4.3 Data Requirements

For uniform flow, the roughness parameters n , f and C can be calculated if velocity of flow U , energy line slope S and hydraulic radius R are known. Since the flow in an alluvial channel is assumed as quasi-uniform, data required to calculate roughness parameters n , f and C are Q , R and S . In predicting roughness the grain size that is in common use is the median particle diameter (D_{50}). Other particle sizes are also in use. Einstein-Barbarrosa (1952) used D_{65} , White et al. (1987) used D_{35} , Haque and Mahmood (1983) used D_{84} and Van Rijn used D_{90} in their respective roughness predictors. Brownlie (1983) used geometric standard deviation which may be calculated from D_{16} , D_{50} and D_{84} .

Shen (1962) used particle fall velocity w_s in his method, which can be calculated if kinematic viscosity of water ν and acceleration due to gravity g are known. Density of sediment ρ_s and density of water ρ are common in use by most of the roughness predictors.

It can be concluded from above that data required for this study are: discharge Q , energy slope S , top width B , cross sectional area A , kinematic viscosity of water ν , acceleration due to gravity g , density of water ρ , density of sediment ρ_s and particle sizes D_{16} , D_{35} , D_{50} , D_{65} , D_{84} and D_{90} . Since the energy line slope S_e is not available, there the water surface slope S_w is taken equal to the energy level slope.

4.4 Data Collection

Among the data required to carry out the proposed study, the cross-sectional area, discharge and water width data for the station Hardinge Bridge and Baruria are collected from the Hydrology Division, Bangladesh Water Development Board. The water surface slope and grain size distribution data are collected from the River Survey Project (FAP-24).

4.4.1 Discharge data

Observed discharge data for the station Hardinge Bridge and Baruria are available with the Hydrology Division of the BWDB. Complete discharge-cross sectional area- velocity data for the station Hardinge Bridge are available since 1970 with missing years of 1971 to 1973, 1977, 1978 and 1982. For Baruria discharge- cross sectional area- velocity data are available since 1968 with missing years of 1970 to 1973 and 1975 to 1981.

The Hydrology Division of BWDB measures discharge weekly during the monsoon season and at fortnight during rest of the year. At Hardinge Bridge daily discharge measurements are made during the lean season since October 1982. BWDB uses the velocity-area method for discharge measurements. During measurements Catamaran type survey boat is used. The position of the BWDB Catamaran along a preselected transect with preselected verticals is determined in the field by using a sailing line along the transect and one sextant taking the angle between the vessel and the poles. The position of the verticals along fixed transect line are preselected. The positions are determined by the rule that the discharge between two adjacent verticals should be within 10 percent of the total discharge. Velocity measurements are made at 2 points, at 0.2 and 0.8 of the depth of the verticals.

4.4.2 Grain size data

The size of sediments in a river changes in downward direction. The reduction in size is usually attributed to two processes, notably (i) abrasion, and (ii) longitudinal sorting. Abrasion is the reduction of size of particles during the transport process. Longitudinal sorting is effective when river is aggrading (Parker, 1990). Due to this aggradation coarser sediments, that are abundantly present at the level of the through of dunes, are stored in the river bed, thus causing a substantial reduction in sediment size in downward direction. Reduction in size is observed in the Ganges. The Ganges river at Lalgola, where it enters Bangladesh, have a median particle size D_{50} of 0.16 mm which reduces to 0.15 mm near Hardinge Bridge and further reduces to about 0.14 mm downstream near Baruria.

Grain size data for the station Hardinge Bridge and Baruria are collected from the River Survey Project (FAP-24) reports. River Survey Project (FAP- 24) collected 50 number of samples for Hardinge Bridge and 30 number of samples for Baruria during 1993-1994.

Sampling was done during sampling program and also during the routine gauging. During sampling program at each cross-section, three samples were collected. Two samples were collected near the right and the left banks and one in the middle of the river. Analyzed grain size from bed material samples and the calculated overall water surface slope for the stations Hardinge Bridge and Baruria by the River Survey Project (FAP-24) are shown in Table 4.1.

Table 4.1: Grain size of bed material and water surface slope of the Ganges at Hardinge Bridge and Baruria

Station	Grain size of bed material in mm					Slope
	D ₁₆	D ₃₅	D ₅₀	D ₈₄	D ₉₀	
Hardinge Bridge	0.100	0.120	0.150	0.180	0.210	5.5x10 ⁻⁵
Baruria	0.100	0.124	0.140	0.1850	0.220	4.0x10 ⁻⁵

River Survey Project (FAP-24) provides, from size analysis of bed material samples, the sizes of D₁₆, D₃₅, D₅₀, D₈₄ and D₉₀ for the station Hardinge Bridge and Baruria. But D₆₅ is not available from size analysis. Some roughness predictors express roughness of the grain as Nikuradse roughness value K_s having value equal to D₆₅. From analysis of S curve for grain size distribution, the value of D₆₅ is approximated as 0.165 mm both for Hardinge Bridge and Baruria.

4.5 Discharge Hydrograph

The river flow near Hardinge Bridge increases gradually in May-June and attains its peak level on average in September. At the end of September the discharge decreases sharply and during the months of January, February and March the discharge falls gradually and finally it attains its yearly minimum during the month of April. From eighteen years data from 1970 to 1995(excepting 1971 to 1973, 1977 to 1979 and 1982), it reveals that mean monthly discharge is the lowest during April, 819 m³/s, and the highest during September, 37,376m³/s. From daily discharge data the highest discharge recorded near Hardinge Bridge is 76,000 m³/s in the year 1987 and the lowest discharge recorded is 261 m³/s in the year 1993.

The river flow near Baruria increases gradually in April-May and attains its peak level on average in September. Then it decreases gradually and attains its lowest level on March. From eighteen years data from 1968(excepting 1971 to 1973 and 1975 to 1981), it reveals that the maximum discharge recorded near Baruria is 130,000 m³/s and the recorded minimum is 2860 m³/s. Mean monthly lowest discharge is 5772 m³/s during February and the highest is 71485 m³/s during September. Near Hardinge Bridge the mean monthly discharge is the lowest in April, whereas near Baruria, Ganges attains its mean monthly lowest in February. This is because, Jamuna begins to rise in April due to snow melting in Himalayas and contributes the largest portion that flow downstream of the confluence near Baruria. During April when Ganges suffers its lean discharge near Hardinge Bridge, then at downstream near Baruria the discharge of the Ganges begins to increase. The mean monthly discharge hydrographs from last 18(eighteen) years available data for Hardinge Bridge and Baruria are shown in Fig.4.2.

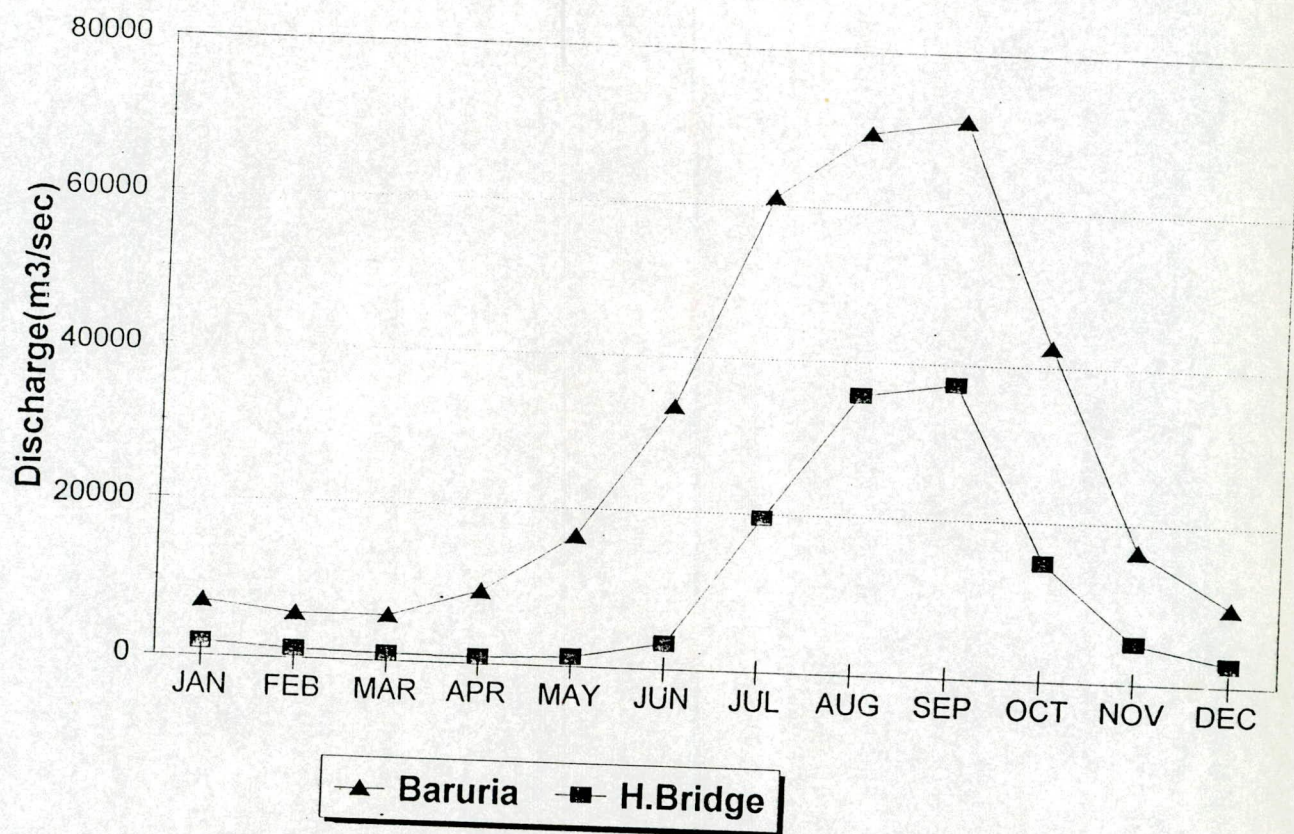


Fig. 4.2 The mean monthly discharge hydrograph

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

To investigate the applicability of the roughness predictors for the river Ganges, 13 (thirteen) roughness predictors have been selected, of which 5 (five) are based on overall roughness and 8 (eight) are based on division of roughness. These are applied to predict roughness for the river Ganges utilizing data for the stations Hardinge Bridge and Baruria. A computer programme written in FORTRAN-77 have been used for all types of computations.

Some methods considered in this study predict depth of flow, some methods predict velocity and some methods predict both depth and velocity when discharge is known. However, there are some methods which predict the roughness parameters directly, without predicting depth or velocity. A brief discussion on results of predicted depth and velocity are given in article 5.2. Using water level slope and computed depth and velocity, the values of roughness parameters n , C and f are calculated using Manning, Chezy and Darcy-Weisbach formulas, respectively. These roughness coefficients are then compared with the roughness coefficients predicted by different roughness predictors. A brief discussion on results of computed and predicted roughness parameters are given in article 5.3.

On the basis of percentage of error of the predicted depth and/or velocity and the MNE for depth and/or velocity, the ranks of different roughness predictors are determined. The predicted roughness parameters by different methods are also compared with computed values on the basis of percentage of error and the MNE. The applicability of different roughness predictors for the river Ganges with discussions on the results are given in article 5.4 and the resistance characteristics of the river Ganges are given in article 5.5.

5.2 Results Using Different Roughness Predictors

5.2.1 General

Out of total 13 (thirteen) roughness predictors considered in this study Engelund-Hansen (1967), Brownlie (1983) and Karim (1995) methods predict both depth and velocity,

Einstein (1952), Shen (1962) and Van Rijn (1993) methods predict only depth and Simons and Richardson (1966), Garde and Ranga Raju (1970) and White et al. (1987) methods predict only velocity and remaining Vanoni and Hwang (1967), Alam-Kennedy (1969), Haque and Mahmood (1983) and Shen et al. (1990) methods neither predict depth nor predict velocity but they predict the roughness parameters directly. At Hardinge Bridge, altogether 923 data sets having discharges equal to or greater than 1200 m³/s have been selected. At Baruria all available 577 data sets have been used. Using these data depths and velocities are calculated and are hereafter termed as computed depths and computed velocities, respectively. Applying the roughness predictors, depth of flow and/or velocity are then predicted and compared with computed values on the basis of percentage of error in the $\pm 10\%$, $\pm 20\%$ and $\pm 30\%$ error ranges. The mean normalized error (MNE) for predicted depth and/or velocity are also calculated. Results of predicted depths and velocities by different methods are given in the following article.

5.2.2 Results and Discussions

5.2.2.1 Simons and Richardson (1966) method

The Simons and Richardson (1966) method does not seem to give very accurate results. It seems to over-estimate the velocity. The percentages of error of the velocities predicted by this method with respect to computed velocities and the MNE are given in Table A.1 of Appendix-A. For the stations Hardinge Bridge and Baruria, only 12.56% and 32.58% predicted velocities lie within ± 30 percent error range. The MNE for velocities for the station Hardinge Bridge and Baruria are 225.62% and 71.59%, respectively.

Simons and Richardson (1966) classified bed forms as plane bed without sediment transport, plane bed with sediment transport, ripples, dunes and antidunes and suggested separate formulas for each bed form. According to Simons and Richardson method, the bed forms in the river Ganges ranges from ripples to antidunes. According to this method, the bed forms for the river Ganges are not clearly distinguishable in respect to velocity and discharge. For the station Hardinge Bridge, ripple forms for discharges ranging from 1210 to 3060 m³/s, while dune forms for the discharges ranging from 1200 to 31605 m³/s. However, at Baruria ripple forms for discharges ranging from 2860 to 14400 m³/s and dune forms for discharges ranging from 4030 to 87700 m³/s. Antidunes develop even at discharges as low as 2650 and 6720 m³/s, respectively, for the above mentioned stations.

The Froude number at Hardinge Bridge and Baruria ranges from 0.021 to 0.322 and 0.029 to 0.315, respectively. Antidunes can develop only when the Froude number is greater than 0.8 (Van Rijn, 1993), although this method predicts bed form as antidune for 202 data sets at Hardinge bridge and 181 data sets at Baruria.

5.2.2.2 Garde and Ranga Raju (1970) method

Garde and Ranga Raju (1970) suggested that in an alluvial channel an upper and a lower flow regimes exist, separated by a transition zone. However, all discharges in the river Ganges, for the stations Hardinge Bridge and Baruria, predicted by Garde and Ranga Raju (1970) method are, in the lower flow regime.

The Garde and Ranga Raju method predict velocities better when flows are in the moderate range. The percentage of error of velocities predicted by Garde and Ranga Raju (1970) method with respect to the computed velocities and the MNE are shown in Table A.2 of Appendix-A. The predicted velocities lie within ± 30 percent error range when measured flow ranges from 10,000 to 47,771 m³/s and from 9360 to 78400 m³/s for the stations Hardinge Bridge and Baruria, respectively. The percentage of error increases with the reduction of flow. At low discharges, this method predict velocities with very large positive errors. Similar is the case for very high discharges. With the increase of discharge in the higher range, predicted velocities give negative errors, i.e. the method under-predict the velocities. For the stations Hardinge Bridge and Baruria the computed velocities ranges from 0.159 to 3.535 m/s and from 0.191 to 3.14 m/s, respectively. The predicted velocities varies from 0.71 to 2.48 m/s and from 0.54 to 1.98 m/s, respectively. At Hardinge Bridge 13.00% and at Baruria 28.6% predicted velocities lie within ± 30 percent error range. For velocity, the MNE for the above two stations are 218.88 and 62.02 percent, respectively.

5.2.2.3 Brownlie (1983) method

Brownlie (1983) classified bed forms as lower and upper flow regimes with a transition in between them. The flow in the river Ganges by applying the Brownlie method is found to be in the lower flow regime.

The percent of error of depths and velocities predicted by Brownlie method with respect to the computed values and the MNE are shown in Tables A.3 and A.4, respectively of Appendix-A. This method predict depths and velocities better when the flows are moderate. At Hardinge Bridge, 62.62% data having computed velocities below 0.53 m/s and discharges between 1200 and 5543 m³/s under-predicts and gives 50% to 100% negative errors for the predicted depths. On the other hand, when these data are used for predicting velocities give large positive errors ranging from 51% to more than 150%. When discharge is large, the Brownlie method gives large positive error for depth and large negative error for velocity. For Hardinge Bridge 21.23% predicted depths having discharges ranging from 5130 to 42952 m³/s and computed velocities ranging from 0.58 to 2.09 m/s lie within $\pm 30\%$ error ranges. For Baruria 41.76% predicted depths having discharges ranging from 4650 to 62600 m³/s and computed velocities ranging from 0.43 to 1.85 m/s are within $\pm 30\%$ error ranges.

When used for predicting velocities, 20.48% data at Hardinge Bridge and 44.19% data at Baruria fall within ± 30 percent error range. The discharges of these data ranges from 5710 to 46943 m³/s and 4700 to 78400 m³/s, respectively. The MNE for depths and velocities for the station Hardinge Bridge are 46.07 and 95.55 percent and for Baruria is 35.40 and 34.43 percent, respectively.

5.2.2.4 White et al. (1987) method

White et al. (1987) introduced a frictional relationship which effectively describes the friction associated with ripple and dune bed corresponding to lower flow regime and the friction associated with plane bed, standing waves, antidunes and chutes and pools corresponding to higher flow regime. According to this method flows in the river Ganges, both at Hardinge Bridge and Baruria, corresponds to lower flow regime.

The percent of error of velocities predicted by White et al. (1987) method with respect to the computed velocities and the MNE are shown in Table A.5 of Appendix-A. Like most of the overall roughness predictors, White et al. method predict velocities better when the flows are in the moderate range. For the station Hardinge Bridge the computed velocities ranges from 0.159 to 3.535 m/s and at Baruria from 0.191 to 3.140 m/s, while the predicted velocities ranges from 0.726 to 1.532 m/s and from 0.484 to 1.243 m/s, respectively. For predicted velocities within ± 30 percent error range, the measured discharge ranges from 8050

to 42952 m³/s and from 6000 to 51000 m³/s, respectively. As the flow decreases the percentage of error increases giving large positive errors. Similar is the case for high discharges. With the increase of discharge the error of predicted velocity increases, giving large negative error. At Hardinge Bridge 12.89% and at Baruria 26% predicted velocities lie within ± 30 percent error range. For velocities, the MNE at Hardinge Bridge and Baruria are 190.72% and 55.51%, respectively.

5.2.2.5 Karim (1995) method

Karim (1995) classified bed forms as lower, transition and upper regimes. Transition regime begins as the bed form height begins to decrease and dunes are gradually washed-out leading to plane bed. Upper regime is limited to flows with flat bed and non-breaking antidunes.

From data analysis it is found that regime of flow predicted by Karim method is distinct at Hardinge Bridge. Lower regime is found to exist for flows upto 13,300 m³/s. However, all flows below 12,500 m³/s are within lower flow regime. In the transition regime, the discharge ranges between 12,500 and 29,000 m³/s. The upper flow regime begins when the discharge is 28,500 m³/s. At Baruria the flow regimes are overlapping to one another. Lower regime exists for discharges upto 36,100 m³/s, while transition begins at 15,400 m³/s. Similarly, while the transition regime exists upto 99,000 m³/s, the upper regime begins at 67,100 m³/s.

The percent of error of depths and velocities predicted by the Karim (1995) method with respect to the computed values and the MNE are shown in Tables A.6 and A.7, respectively, of Appendix-A. For the river Ganges, the Karim method predict depths and velocities in transition and upper regimes better than those at the lower regime. For the upper regime at Hardinge Bridge 98.04% depths and 91.18% velocities and at Baruria 100% depths and 100% velocities lie within ± 30 percent error ranges. For transition regime 70.4% and 99.5% depths and 47.96% and 95.79% velocities lie within ± 30 percent error ranges. When the discharge or velocity is low, Karim method gives erroneous result. At lower regime it under-predicts depth and over-predicts velocity. At Hardinge Bridge out of 723 lower regime flows only 39 depths and 6 velocities lie within ± 30 percent error range. For depth the MNE at Hardinge Bridge and Baruria are 43.15 percent and 18.97 percent and for velocities the MNE are 90.71 and 26.92 percent, respectively.

5.2.2.6 Einstein and Barbarossa (1952) method

The Einstein-Barbarossa (1952) method is the pioneer of the prediction of depth-discharge relationship based on the division of total depth into the depth required to overcome the grain roughness and the depth required to overcome the bed form.

The percent of error of depths predicted by Einstein-Barbarossa method with respect to the computed depths and the MNE are shown in Table A.8 of Appendix-A. This method predict depths better when velocities are moderate to high, in the range of 1.5 to 2.85 m/s. At very high velocity, the predicted depth is larger than the computed depth with large positive error, while at low velocity the predicted depth is smaller than the computed depth with large negative error. At Hardinge Bridge 10.40% and at Baruria 27.55% predicted depths lie within ± 30 percent error range. For depth, the MNE at Hardinge Bridge and Baruria are 78.18 and 53.17 percent, respectively. It does not predict bed form.

5.2.2.7 Shen (1962) method

Shen (1962) method predicts depth when velocity, slope and grain size are known. For prediction of the depth the Shen method is equally applicable to both at high and at low discharges.

The percent of error of depths predicted by Shen method with respect to the computed depths and the MNE are shown in Table A.9 of Appendix-A. At Hardinge Bridge 48.53% and at Baruria 47.66% predicted depths are found to lie within ± 30 percent error range. For depth, the MNE for the stations Hardinge Bridge and Baruria are found as 28.83 and 42.10 percent, respectively. This method does not predict bed form.

5.2.2.8 Engelund and Hansen (1967) method

According to the Engelund-Hansen (1967) method, the bed forms are classified as lower regime with ripple and dune bed, upper regime with standing waves and plane bed and higher regions of the upper regime with antidunes.

At Hardinge Bridge the lower regime exists for flow upto $7520 \text{ m}^3/\text{s}$ while upper flow regime exists for flows ranging from 5130 to $10200 \text{ m}^3/\text{s}$. When the discharge is below $5130 \text{ m}^3/\text{s}$, the flow is entirely in the lower regime. At Baruria the lower regime exists for flows upto $20100 \text{ m}^3/\text{s}$ while upper regime exists for flows ranging from 13800 to $31400 \text{ m}^3/\text{s}$. The higher regions of upper flow regime at Hardinge Bridge and Baruria begin when the flows are $9730 \text{ m}^3/\text{s}$ and $15400 \text{ m}^3/\text{s}$, respectively.

The percent of error of depths and velocities predicted by Engelund-Hansen (1967) method with respect to the computed values and the MNE are shown in Tables A.10 and A.11, respectively, of Appendix-A. The Engelund-Hansen method predicts depths and velocities better in higher regions of upper regime flow than in the lower and upper regimes. At Hardinge Bridge 17.35% predicted depths and 16.25% predicted velocities and at Baruria 66.81% predicted depths and 52.57% predicted velocities lie within ± 30 percent error range. The MNE for predicted depths at Hardinge Bridge and Baruria are 43.98 and 22.86 percent while for velocities are 87.56 and 28.10 percent, respectively.

5.2.2.9 Alam and Kennedy (1969) method

Alam and Kennedy (1969) determined flat bed friction factor f' using the graphical predictor presented by Lovera and Kennedy (1969). The Lovera-Kennedy chart presents grain friction factor f' as a function of Reynolds number UR/ν for constant values of relative depth R_b/D_{50} . For wide channels, the overall hydraulic radius related to bed R_b is the same as the overall hydraulic radius R . Lovera-Kennedy chart predicts f' for Reynolds number ranging from 2.5×10^4 to 5×10^6 and relative depth R/D_{50} ranging from 1×10^{-2} to 125×10^{-2} . For Hardinge Bridge and Baruria the Reynolds number ranges from 0.66×10^6 to 45.74×10^6 and from 0.83×10^6 to 33.33×10^6 and relative depth ranges from 202×10^2 to 929×10^2 and from 220×10^2 to 907×10^2 , respectively. Therefore it is clear that lovera-Kennedy chart does not cover the required range for predicting grain friction factor f' both for Hardinge Bridge and Baruria.

According to the Alam-Kennedy method, the form drag friction factor f'' is determined as a function of relative depth for constant values of grain Froude number $U/\sqrt{gD_{50}}$ and constant values of grain Froude number $U/\sqrt{gR}$ using a chart. This chart covers a wide range of relative depth from 1×10^2 to 1×10^5 and is constructed for grain Froude

number ranging from 5 to 35 and Froude number ranging from 0.10 to 0.75. For predicting f'' this range of relative depth has no difficulty for all data groups. However, the Froude number at Hardinge Bridge and Baruria ranges from 0.021 to 0.332 and from 0.029 to 0.315 and grain Froude number ranges from 4.17 to 92.28 and from 5.16 to 84.72, respectively. Again there arises some difficulties in using Alam-Kennedy chart for predicting f'' . Although the Alam-Kennedy method requires a trial- and- error solution, it has been included in our study but could not be applied for predicting roughness since the graphical charts for predicting f' and f'' do not cover most of the data of Hardinge Bridge and Baruria.

5.2.2.10 Van Rijn (1993) method

Van Rijn (1993) gave a complete method to classify bed form, shape and dimensions of bed forms and roughness of alluvial river. When Van Rijn's transport stage parameter T is negative, there is no movement of sediment. Both at Hardinge Bridge and Baruria the sediment particles on bed begin to move when the flow velocity is 0.3 m/s and above. For flow velocity upto 0.299 m/s, the particles on bed remain at rest. When the velocity is between 0.301 and 0.665 m/s, the bed form is ripple and for between 0.666 and 1.12 m/s the bed form is ripple superimposed dune. Dunes exist when the velocity is equal to or less than 1.73 m/s and the upper regime flow exists when the flow velocity is more.

At Hardinge Bridge mini ripple bed forms form for discharges ranging from 1360 to 8960 m^3/s . Ripples superimposed dune and dune type bed forms exist when the discharge ranges from 5710 to 16400 m^3/s and from 12500 to 32000 m^3/s , respectively. All flows above 32000 m^3/s are in the upper regime. At Baruria, ripple type bed form exists when the discharge ranges from 4180 to 18800 m^3/s . Ripple superimposed dune and dune bed exists for flows with discharge ranging from 9800 to 34500 m^3/s and from 22200 to 61600 m^3/s , respectively. All flows above 61600 m^3/s are obviously in upper regimes.

The Van Rijn (1993) method predicts depth better in dune and upper regimes. The percent of error of depths predicted by this method with respect to the computed depths and the MNE are shown in Table A.12 of Appendix-A. At Harding Bridge 16.9% and at Baruria 33.97% computed depths lie within ± 30 percent error range, respectively. The MNE for depths are 68.99 and 48.52 percent, respectively.

5.2.3 Remarks

From the results obtained it may be observed that, at low discharges, except the Shen (1962) method, other five methods which predicts depth, the predicted depth both at Hardinge Bridge and Baruria are lower than the computed ones. The Einstein-Barbarossa (1952) and the Van Rijn (1993) methods seem to fail to predict the depth accurately when the discharge is very low. The Engelund (1967) and the Karim (1995) methods also predict the depth lower than the computed depth when the discharge is low. However, they produce much better results than the Einstein & Barbarossa (1952) and Engelund-Hansen (1967) methods. The Shen (1962) method predicts the depth lower than the computed for Hardinge Bridge and highest for Baruria at low discharges. The depth predicted by the Van Rijn (1993) method is the largest at high discharges. The Brownlie (1983), Einstein-Barbarossa (1952), Shen (1962) and Engelund-Hansen (1967) methods also predict the depth higher than the computed depth at high discharges. Only the Karim (1995) method computes depth very close to the computed depth at high discharges.

From the results it may also be observed that all the five methods based on overall roughness predict velocities higher than the computed values when the discharge is low. At very low discharges the Garde-Ranga Raju (1970) and the White et al. (1987) methods do not seem to predict velocity accurately. The Simons-Richardson (1966), Brownlie (1983) and Karim (1995) methods also do not seem to predict the velocity accurately, but these methods appear to be somewhat better than the Garde-Ranga Raju (1970) and White et al. (1987) methods at low discharges. The Simons and Richardson (1966) method predicts velocity more close to the computed velocity than the other four overall roughness predictors. At high discharges, the Simons and Richardson (1966) and the Karim (1995) methods seem to predict velocity close to the computed velocity.

Among the methods selected, based on division of roughness, only the Engelund-Hansen (1967) method predicts velocity. Like the overall roughness predictors, the predicted velocity by Engelund-Hansen (1967) method is higher than the computed velocity at low discharges. At high discharges, however, this method under-predicts velocity.

Based on the percentages of predicted values lying within some fixed error ranges and the MNE of the predicted depth and velocity the methods are ranked such that the method showing the maximum number of predicted values within some specified error ranges and the minimum MNE has the rank of 1, the method having the next lower number of predicted values within the same error ranges and the next higher MNE has the rank of 2 and so on.

Percentages of depths lying within $\pm 30\%$ of error ranges predicted by different roughness predictors at Hardinge Bridge and Baruria are shown in Figures B.1 and B.2, respectively of Appendix-B. Also the MNE for predicted depths and the percentages of predicted depths lying within specified error ranges by different roughness predictors at Hardinge Bridge and Baruria are given in Table 5.1. Considering the percentage of predicted depths in the error ranges, the Shen (1962), Karim (1995) and Brownlie(1983) methods rank 1,2 and 3 at Hardinge Bridge and Karim (1995), Engelund-Hansen (1967) and Shen (1962) methods rank 1,2 and 3 at Baruria. Comparing the results presented in Table 5.1 it is apparent that the predicted results are considerably better at Baruria than at Hardinge Bridge.

The MNE for predicted depths by different roughness predictors at Hardinge Bridge and Baruria are shown in Figures B.3 and B.4, respectively of Appendix-B. On the basis of the MNE of depth, the Shen (1962), Karim (1995) and Engelund-Hansen (1967) methods rank 1,2 and 3, respectively at Hardinge Bridge. At Baruria, however, the Karim (1995), Engelund-Hansen (1967) and Brownlie (1983) methods rank 1, 2 and 3 respectively.

The MNE for predicted velocities and the percentages of predicted velocities lying within specified error ranges by different roughness predictors at Hardinge Bridge and Baruria are given in Table 5.2. Considering percentage of error of predicted velocities at Hardinge Bridge the Brownlie (1983), Engelund-Hansen (1967) and Karim methods and at Baruria the Karim (1995) Engelund-Hansen (1967) and Brownlie (1983) methods rank 1,2 and 3, respectively (Figures B.5 and B.6 of Appendix-B). The Shen method does not predict the velocities as because the velocities are the known parameters to this method. Considering the MNE for the velocities at Hardinge Bridge, the Engelund- Hansen (1967), Karim (1995) and Brownlie (1983) methods and at Baruria the Karim(1995), Engelund-Hansen (1967) and Brownlie (1983) methods rank 1,2 and 3, respectively (Figures 5.7 and 5.8)

The final choice of the methods applicable for the river Ganges will be made later in this chapter after comparing the values of n , C and f predicted by different methods with those obtained by the Manning, Chezy and Darcy-Weisbach formulas directly.

Table 5.1 Percentage of predicted depths lying within specified error ranges by different roughness predictors

Roughness predictor	MNE for depth		Percentage of predicted depths lying within specified error ranges					
	H.Bridge	Baruria	Hardinge Bridge			Baruria		
			±10%	±20%	±30%	±10%	±20%	±30%
Brownlie (1983)	46.07	35.40	5.53	13.65	21.24	16.12	29.12	41.76
Karim (1995)	43.15	18.97	8.02	13.33	22.54	33.62	58.06	78.34
Einstein & Barbarossa (1952)	78.18	53.17	3.79	6.39	10.40	9.70	17.67	27.55
Shen (1962)	28.83	41.98	22.86	36.08	48.54	18.37	34.52	47.61
Engelund & Hansen (1967)	43.98	22.86	5.64	11.08	17.35	20.28	41.60	68.81
Van Rijn (1993)	68.99	48.52	5.85	11.16	16.90	10.06	21.33	33.96

Table 5.2 Percentages of predicted velocities lying within specified error ranges different roughness predictors

Roughness predictor	MNE for velocity		Percentages of predicted velocities lying within specified error ranges					
	H.Bridge	Baruria	Hardinge Bridge			Baruria		
			±10%	±20%	±30%	±10%	±20%	±30%
Simons & Richardson (1966)	225.62	71.59	5.20	9.64	13.54	10.57	21.14	32.52
Garde & Ranga Raju (1970)	218.88	62.02	4.45	9.00	13.01	8.49	17.85	28.60
Brownlie (1983)	95.55	34.43	5.74	13.10	20.47	16.63	28.08	44.89
White et al. (1987)	190.72	55.51	3.79	8.02	12.89	11.26	18.54	26.00
Karim (1995)	90.71	26.92	7.80	10.94	15.82	32.75	53.03	65.16
Engelund-Hansen (1967)	87.56	28.10	5.20	11.05	11.25	21.50	41.25	62.56

5.3 Computation of the Roughness Parameters

5.3.1 General

It has already been stated that out of 13 (thirteen) roughness predictors 4 (four) does neither predict the depth nor the velocity. They can not be compared on the basis of predicted depth and/or velocity. But it is possible to predict roughness parameters n , C and f by all the 13 methods. In this section, the numerical values of the roughness parameters obtained by the different methods are compared with those obtained by the Manning, Chezy and Darcy-Weisbach formulas. As before the results are expressed in terms of the predicted values lying within the specified error ranges and the MNE with respect to the computed roughness parameters n , C and f .

It is to be noted that Manning, Chezy and Darcy-Weisbach formulas are valid for steady and uniform flows and for rigid boundary channels and not for alluvial channels where cross-section and thus velocity of flow and other flow parameters are continuously changing. However, assuming the river flow as quasi-steady and quasi-uniform these methods are widely used for predicting the roughness parameters.

It is also to be noted here that some of the methods considered in this study are based on total roughness and some are based on division of roughness. The Manning, Chezy and Darcy-Weisbach formulas give only the total roughness. Hence the comparison with these formulas can only be made on the basis of total roughness. The Strickler formula (Strickler, 1923) can be used to compute the values of Manning's grain roughness n' . It is a consensus among the various researchers that this formula gives the grain roughness value n' for both rigid and mobile bed channels, although there is considerable controversy regarding the value of K_s in this formula. Various researchers suggested values of K_s ranging from D_{50} to $5.1 D_{84}$ as given in Art. 2.3.7. Hopefully, the numerical value of n' is not very much sensitive to K_s since $n' \propto K_s^{1/6}$. Considering various values of K_s , it is found that the numerical value of n' at Hardinge Bridge varies from 0.0109 (when $K_s = D_{50}$) to 0.0147 (when $K_s = 5.1 D_{84}$) and that at Baruria from 0.0108 to 0.0148.

In the following two sections the roughness parameters predicted by different methods are compared with those computed by the Manning, Chezy and Darcy-Weisbach formulas. For brevity, the comparison is made on the basis of Manning's n only. The numerical values of

n , C and f obtained by different methods indicate that the methods which show close compliance with the Manning formula normally show close compliance with the Chezy and Darcy-Weisbach formula also. This is why detailed comparisons on the basis of Chezy's C and the Darcy-Weisbach friction factor f are not presented.

5.3.2 Roughness parameters by Manning, Chezy and Darcy-Weisbach formulas

The roughness parameters n , C and f have been computed by the Manning, the Chezy and the Darcy-Weisbach formulas, respectively, utilizing data for the stations Hardinge Bridge and Baruria and are termed as computed roughness parameters. From analysis of 923 data sets for Hardinge Bridge, the minimum values of the roughness parameters n and f and the maximum value of C are 0.0109, 0.0042 and 136.02, respectively while the maximum values of roughness parameters n and f and the minimum value of C are 0.1589, 0.9960 and 8.88, respectively. For 577 data sets of Baruria the minimum values of n and f and the maximum value of C are 0.0092, 0.0032 and 156.10, respectively. and the maximum values of n and f and the minimum value of C are 0.0902, 0.3794 and 14.38, respectively. The variation of the roughness parameters n , C and f with discharge at Hardinge Bridge and Baruria are shown in Figures 5.1 and 5.2, respectively. For both the stations the values of n and f decrease with increasing discharge while the values of C increase with increasing discharge. At Hardinge Bridge the maximum n value is 14.58 times larger than the minimum n value and the maximum f value is 237.14 times larger than the minimum f value. For Chezy's C the maximum value is 15.31 times larger than the minimum value. Similarly at Baruria the maximum n , f and C values are 9.85, 118.56 and 10.85 times larger than the minimum values. Among the roughness parameters the Manning's n has the advantage that it varies with discharge less than the Chezy's C and friction factor f .

5.3.3 Roughness parameters predicted by different methods

5.3.3.1 Simon and Richardson (1966) method

The comparison between the computed values of Manning's n using Manning formula and predicted values of Manning's n using the Simon and Richardson (1966) method at Hardinge Bridge and Baruria are shown in Figures B.9 and B.10, respectively, of Appendix-B. Similar to the computed Manning's n the predicted value decreases with increasing discharge. At high discharges it becomes almost constant. At low discharges the predicted values are

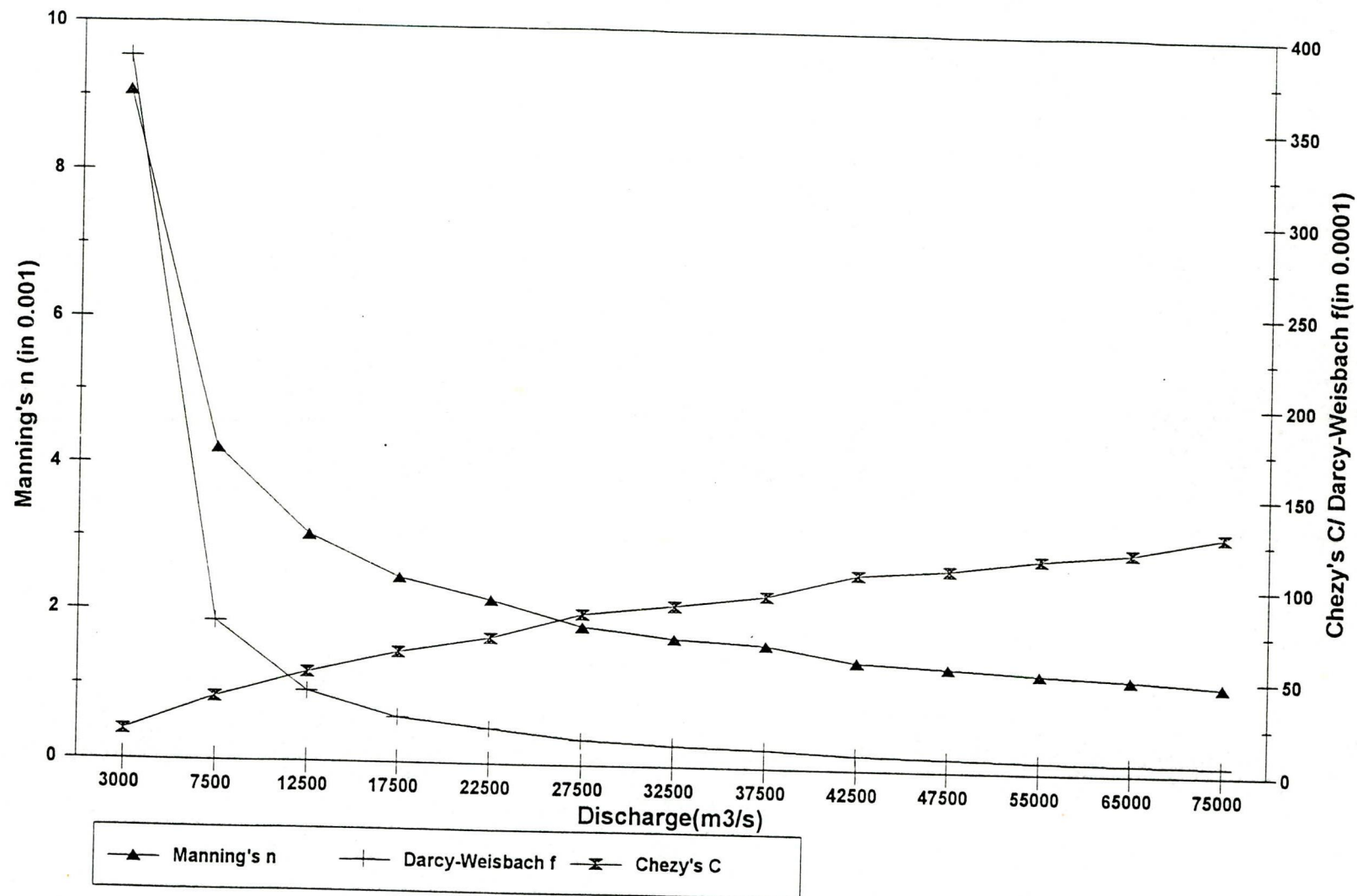


Fig. 5.1 Variation of roughness parameters n , C and f with discharge at Hardinge Bridge

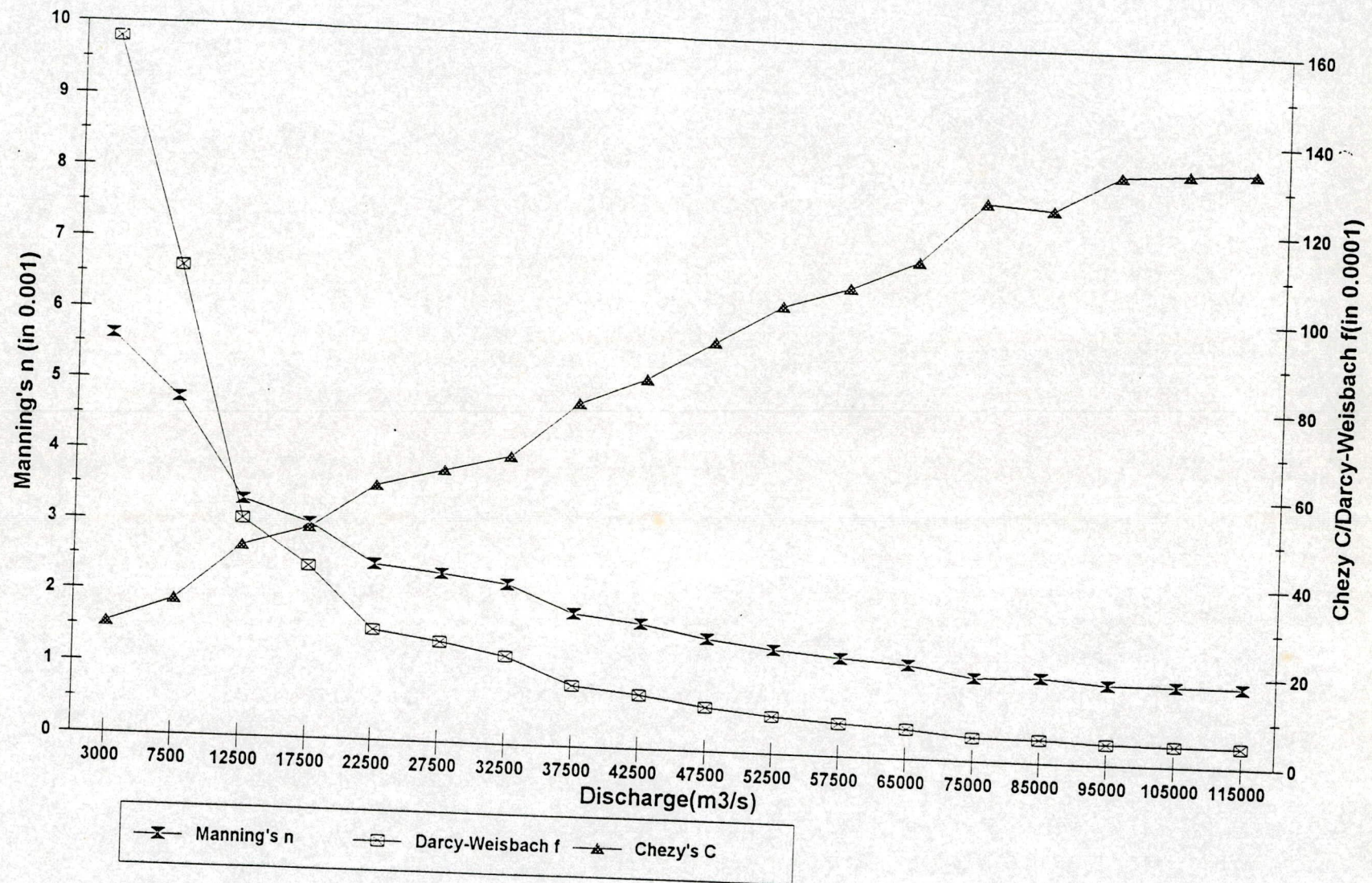


Fig. 5.2 Variation of roughness parameters n , C and f with discharge at Baruria

much lower than the measured value both at Hardinge Bridge and Baruria. The variation of the predicted and computed values of Manning's n with discharges are given in Table A.13 of Appendix-A. At Hardinge Bridge the predicted values of Manning's n is maximum when the predicted bed form is ripple, moderate when the bed form is dune and minimum when the bed form is in transition. Both for Hardinge Bridge and Baruria, although the ranges of predicted Manning's n are wide, there is a discontinuity of predicted roughness between ripple and dune and between dune and transition. The Manning's n value ranges from 0.030 to 0.0344 for ripple and from 0.012 to 0.0190 for dune and it is almost constant when the bed form is in transition lying between 0.0083 and 0.0087.

The MNE for Manning's n predicted by Simons and Richardson method at Hardinge Bridge and Baruria are 57.57 and 45.01 percent, respectively (Table A.14 of Appendix-A). For Hardinge Bridge and Baruria 19.93% and 24.97% predicted roughness coefficients lie within ± 30 percent error range. For Chezy's C and Darcy-Wiesbach f the MNE at Hardinge Bridge are 225.60 and 77.81 percent and at Baruria 56.08 and 102.13 percent, respectively.

5.3.3.2 Garde and Raga Raja (1970) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Garde and Raga Raja (1970) method at Hardinge Bridge and Baruria are shown in Figures B.11 and B.12, respectively, of Appendix-B. The roughness coefficient n predicted by the Garde and Raga-Raju method does not seem to respond properly with change in bed form, velocity and discharge. The variation of the predicted and computed values of Manning's n with discharges are given in Table A.15 of Appendix-A. At Hardinge Bridge the predicted value of Manning's n are practically constant ranging from 0.0217 to 0.0222. At Baruria the values of Manning's n is maximum at low discharges. The predicted value of Manning's n at Baruria varies in a narrow range from 0.0187 to 0.0217.

The MNE for Manning's n predicted by the Garde and Raga Raju (1970) method at Hardinge Bridge and Baruria are 61.14% and 49.27%, respectively (Table A.16 of Appendix-A). At Hardinge Bridge 13.76% and at Baruria 27.21% predicted roughness coefficient n lie within ± 30 percent error range. The MNE for Chezy's C and Darcy-Weisbach f for the station Hardinge Bridge are 218.85 and 87.43 percent and for Baruria 62.02 and 110.40 percent, respectively.

5.3.3.3 Brownlie (1983) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Brownlie (1983) method at Hardinge Bridge and Baruria are shown in Figures B.13 and B.14, respectively, of Appendix-B. The predicted values of the Manning's n by this method increases with increasing discharge while the value computed by Manning formula increases with decreasing discharge. The variation of the predicted and computed values of Manning's n with discharge is given in Table A.17 of Appendix-A. At Hardinge Bridge the predicted value of Manning's n ranges from 0.0202 to 0.0295 and at Baruria from 0.0200 to 0.0279, respectively. The minimum values of Manning's n are only 31.52% and 28.31% smaller than the maximum values at these two stations, respectively.

The MNE for Manning's n at Hardinge Bridge and Baruria are 65.45%, and 63.36%, respectively (Table A.18 of Appendix-A). At Hardinge Bridge 12.90% and at Baruria 26.17% predicted values of roughness coefficient n lie within ± 30 percent error range. The MNE for Chezy's C and Darcy-Weisbach f at Hardinge Bridge are 182.29 and 96.54 percent and at Baruria 53.81 and 142.36 percent, respectively.

5.3.3.4 White et al. (1987) method

The comparison between the values of Manning's n computed by Manning formula and predicted by White et al. (1989) method at Hardinge Bridge and Baruria are shown in Figures B.15 and B.16, respectively, of Appendix-B. The variation of predicted Manning's n with discharge is opposite to what usually happens in natural channels. However, the variation with discharge is so small that both for Hardinge Bridge and Baruria the n - values may be considered as constant. The variation of the predicted and computed values of Manning's n with discharges are shown in Table A.19 of Appendix-A. The predicted Manning's n ranges from 0.0214 to 0.0280 at Hardinge Bridge and from 0.0206 to 0.0271 at Baruria. It seems that the roughness predicted by the White et al. method fails to respond with change in bed form, velocity and discharge. The minimum value of Manning's n is only 24% lower than that of the maximum value both at Hardinge Bridge and Baruria.

The MNE for predicted Manning's n at Hardinge Bridge and Baruria are 62.26% and 58.90%, respectively (Table A.20 of Appendix-A). At Hardinge Bridge 13.97% and at Baruria

27.91% predicted Manning's n lie within ± 30 percent error range. The MNE for Chezy's C and Darcy-Weisbach f at Hardinge Bridge are 190.69 and 98.95 percent and at Baruria 55.52 and 153.61 percent, respectively.

5.3.3.5 Karim (1995) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Karim (1995) method at Hardinge Bridge and Baruria are shown in Figures B.17 and B.18, respectively, of Appendix-B. At high discharges the predicted values of Manning's n are constant. The prediction of the Manning's n at Baruria is better than that at Hardinge Bridge when the computed Manning's n lies between 0.0135 and 0.0300. The variation of the predicted and computed values of Manning's n with discharges is given in Table A.21 of Appendix-A. At Hardinge Bridge in the lower flow regime the computed Manning's n lies between 0.0248 and 0.1589 while the predicted Manning's n lies between 0.0152 and 0.0241. In the transition regime, the computed Manning's n lies between 0.0148 to 0.0377 and the predicted Manning's n lies between 0.0133 and 0.0170. In the upper flow regime the computed Manning's n lies between 0.0109 and 0.0248 while the predicted n value is fixed and is equal to 0.0133. At Baruria in the lower flow regime the predicted n value ranges from 0.0137 to 0.0239 while the computed Manning's ranges from 0.0207 to 0.0907. For the upper flow regime the predicted n value is 0.0132 while the computed Manning's n lie between 0.0092 and 0.0120.

The MNE for roughness coefficient n predicted by the Karim (1995) method at Hardinge Bridge and Baruria are 59.00% and 28.77%, respectively (Table A.22 of Appendix-A). At Hardinge Bridge 12.57% and at Baruria 54.25% predicted roughness coefficient n lie within ± 30 percent error range. The MNE for Chezy's C and Darcy-Weisbach f at Hardinge Bridge are 170.38 and 76.08 percent and at Baruria 44.90 and 43.95 percent, respectively.

5.3.3.6 Einstein and Barbarossa (1952) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Einstein-Barbarossa (1952) method at Hardinge Bridge and Baruria are shown in Figures B.19 and B.20, respectively, of Appendix-B. The variation of predicted Manning's n with discharge is reverse to what usually happens in natural channels. However,

both at Hardinge Bridge and Baruria the predicted n values are constant in nature. The variation of predicted and computed Manning's n with discharges are given in Table A.23 of Appendix-A. The grain roughness computed by this method is minimum at low discharges, increases with increasing discharge and attains its maximum value at peak discharges. At Hardinge Bridge, the predicted minimum grain roughness is 0.0098 and maximum is 0.0149 and at Baruria these values are 0.0102 and 0.0150, respectively. The variation is quite gradual. The form roughness increases with increasing discharge, but again decreases at high discharges. At Hardinge Bridge the predicted minimum and maximum values of n are 0.0009 and 0.0036 and at Baruria these values are 0.001 and 0.0039, respectively. According to the Einstein-Barbarossa method, the form roughness in a real channel is never zero. The form roughness predicted by this method is a minor fraction of grain roughness, but it is the principal constituent of the total roughness predicted by most of the methods. At Hardinge Bridge the predicted total roughness n has a maximum value of 0.0165 while the computed maximum value n is 0.1589. At Baruria the predicted Manning's n has a maximum value of 0.0172 while the computed maximum is 0.0907.

The MNE for Manning's n predicted by the Einstein and Barbarossa (1592) method at Hardinge Bridge and Baruria are 68.49% and 40.19%, respectively (Table A.24 of Appendix-A). At Hardinge Bridge 15.08% and at Baruria 38.30% predicted Manning's n lie within ± 30 percent error range. For Chezy's C and Darcy-Weisbach f the MNE at Hardinge Bridge are 244.48 and 78.17 percent and at Baruria 64.93 and 53.14 percent, respectively.

5.3.3.7 Shen (1962) method

The Comparison between the values of Manning's n computed by Manning formula and predicted by the Shen (1962) method at Hardinge Bridge and Baruria are shown in Figures B.21 and B.22, respectively, of Appendix-B. The variation of Manning's n with discharges is given in Table A.25 of Appendix-A. It is found that the predicted grain roughness decreases with decreasing velocity or discharge while the form roughness decreases with increasing velocity or discharge. The variation of grain roughness with increase in discharge is mild. For lean period flow, the Manning grain roughness is as low as 0.0099 at Hardinge Bridge and 0.0102 at Baruria. For flood flow the maximum values of the grain roughness predicted are 0.0149 and 0.0150, respectively. During lean period the form roughness n is 5 to 7 times larger than the grain roughness. For lean period flow the

maximum values of form roughness computed at Hardinge Bridge and Baruria are 0.0646 and 0.0669, respectively. At high discharges the form roughness gradually decreases and ultimately becomes zero.

The MNE for roughness coefficient n predicted by using the Shen (1962) method at Hardinge Bridge and Baruria are 20.74% and 25.55%, respectively (Table A.26 of Appendix-A). For Hardinge Bridge and Baruria, 66.20% and 64.47% of the predicted Manning's n lie within ± 30 percent error range. For Chezy's C and Darcy-Weisbach f the MNE at Hardinge Bridge are 21.10 and 28.82 percent and at Baruria 14.36 and 42.11 percent, respectively.

5.3.3.8 Engelund and Hansen (1967) method

The comparison between the predicted and computed values of Manning's roughness coefficient n at Hardinge Bridge and Baruria are shown in Figures B.23 and B.24, respectively, of Appendix-B. Both at Hardinge Bridge and Baruria there is a discontinuity of predicted roughness. At lower flow regime the computed Manning's n is much higher than the predicted value of n . In predicting alluvial roughness by the Engelund-Hansen method, it is found that the grain roughness is the dominant part of the total roughness. The variation of Manning's n with discharges is shown in Table A.27 of Appendix-A. The grain roughness increases with increasing discharge, but the range of variation is narrow. The form roughness decreases with increasing discharge at the lower flow regime, becomes zero at the upper regime and then again increases at higher regions of the upper flow regime.

The MNE for the Manning roughness coefficient n predicted by the Engelund and Hansen (1967) method are 61.52% and 36.73% at Hardinge Bridge and Baruria, respectively. The percentage of error of the predicted roughness coefficient n with respect to the computed value and the MNE are shown in Table A.28 of Appendix-A. At Hardinge Bridge 10.31% and at Baruria 37.27% of the predicted Manning's n lie within ± 30 percent error range. For Chezy's C and Darcy-Weisbach f the MNE at Hardinge Bridge are 162.21 and 84.13 percent and at Baruria 45.45 and 64.40 percent, respectively.

Bed form dimensions by Vajda (1990) method

Comparison between the values of Manning's n computed by Manning formula and predicted by the Vanoni and Hwang (1967) method with bed form dimensions by Vajda (1990) at Hardinge Bridge and Baruria are shown in Figures B.25 and B.26, respectively, of Appendix-B. The predicted roughness at Baruria seems to be more accurate than at Hardinge Bridge. At Baruria the predicted value covers almost the entire middle range and shows a good accuracy when Manning's n lie between 0.02 and 0.04. Predicted Manning's n is lower than the computed Manning's n at low discharges and higher at high discharges. The variation of the predicted and computed values of Manning's n with discharges are given in Table A.29 of Appendix-A. The predicted values of Manning's n at Hardinge Bridge and Baruria ranges from 0.0163 to 0.0494 and from 0.0107 to 0.0519, respectively. The grain roughness coefficient at Hardinge Bridge and Baruria ranges from 0.0096 to 0.0138 and from 0.0097 to 0.0141, respectively. The variation of the form roughness is large ranging from 0.0025 to 0.0398 at Hardinge Bridge and from 0.0026 to 0.0422 at Baruria.

The percentage of error of the roughness coefficient n predicted by Vanoni and Hwang (1967) method using the bed form dimensions predicted by Vajda (1990) and the MNE for Manning's roughness value n are given in Table 5.30. The MNE for Manning's n at Hardinge Bridge and Baruria are 58.25% and 151.63%, respectively. At Hardinge Bridge 19.82% and at Baruria 11.09% computed Manning's n lie within $\pm 30\%$ error range. The MNE for Chezy's C and friction factor f by this method at Hardinge Bridge are 93.02 and 129.71 percent and at Baruria 80.58 and 246.79 percent, respectively.

Bed form dimensions by Yalin (1992) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Vanoni and Hwang (1967) method with bed form dimensions by Yalin (1992) at Hardinge Bridge and Baruria are shown in Figures B.27 and B.28, respectively, of Appendix-B. The prediction of roughness at Baruria is much better than that at Hardinge Bridge. At Baruria the predicted values of Manning's n lie in the middle range and are very close to the computed values specially when the computed values lie between 0.02 and 0.04.

The variation of the predicted and computed values of Manning's n with discharges are shown in Table A.31 of Appendix-A. The predicted values of Manning's n at Hardinge Bridge and Baruria ranges from 0.0246 to 0.0333 and 0.0217 to 0.0335, respectively. The grain roughness coefficient, which is almost constant, ranges from 0.0113 to 0.0129 at Hardinge Bridge and from 0.0116 to 0.0121 at Baruria. The grain roughness increases slightly with increasing discharge. The variation of form roughness coefficient is, however, relatively large. The form roughness n'' is small at low discharges and increases with increasing discharge.

The percentages of error of the roughness coefficient n predicted by the Vanoni and Hwang (1967) method using the bed form dimensions predicted by Yalin (1992) and the MNE are given in Table A.32 of Appendix-A. The MNE for Manning's n at Hardinge Bridge and Baruria are 61.25% and 82.34%, respectively. At Hardinge Bridge 15.28% and at Baruria 26.52% predicted Manning's n lie within ± 30 percent error range. The MNE for Chezy's C and friction factor f by this method at Hardinge Bridge are 132.95 and 116.70 percent and at Baruria 50.82 and 266.64 percent, respectively.

5.3.3.10 Haque and Mahmood(1983) method

Bed form dimensions by Vajda (1990) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Haque and Mahmood (1983) method with bed form dimensions by Vajda (1990) at Hardinge Bridge and Baruria are shown in Figures B.29 and B.30, respectively, of Appendix-B. At Baruria, the predicted Manning's roughness values show discontinuity between 0.03 and 0.04. At Hardinge Bridge, although there exists discontinuity in predicted Manning's n , it is not as sharp as that at Baruria. Both for Hardinge Bridge and Baruria, the predicted values of Manning's n are always lower than the computed values at low discharges. For any discharge within the ripple range there may exist two roughness values, one for ripple bed and the other for dune bed. There is a discontinuity of the values of Manning's n between the ripples and the dunes. The variation of the predicted and computed values of Manning's n with discharges are given in Table A.33 of Appendix-A. At Hardinge Bridge the values of grain roughness n' vary from 0.0099 to 0.0150 and at Baruria from 0.0100 to 0.0154. The range of the form roughness n'' is wide. At Hardinge Bridge it ranges from 0.0001 to 0.0452 while at Baruria it ranges from 0.0001 to 0.0461.

The MNE for the predicted Manning's n by the Haque and Mahmood (1983) method using the bed form dimensions predicted by the Vajda (1990) method at Hardinge Bridge and Baruria are 56.23 and 163.43 percent, respectively (Table A.34 of Appendix-A). At Hardinge Bridge 20.48% and at Baruria 10.92% of the predicted Manning's n lie within ± 30 percent error range. The MNE for Chezy's C and Darcy-Weisbach f at Hardinge Bridge are 88.85 and 126.07 percent and at Baruria are 84.94 and 728.87 percent, respectively.

Bed form dimensions by Yalin (1992) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Haque and Mahmood (1983) method with bed form dimensions by Yalin (1992) at Hardinge Bridge and Baruria are shown in Figures B.31 and B.32, respectively, of Appendix-B. This method predicts Manning's n lower than the computed values at low discharges and larger at high discharges. The variation of the predicted and computed values of Manning's n with discharges are given in Table A.35 of Appendix-A. The predicted values of grain roughness n' at Hardinge Bridge ranges from 0.0121 to 0.0145 and at Baruria from 0.0126 to 0.0135, respectively. At Hardinge Bridge, it gradually increases with increasing discharge while at Baruria this range is independent of discharge. However, the variation of form roughness is wide at both the stations. At Hardinge Bridge it ranges from 0.0083 to 0.0201 and at Baruria from 0.0058 to 0.0189, respectively.

The MNE for Manning's n predicted by the Haque and Mahmood (1983) method using the bed form dimensions predicted by the Yalin (1992) method at Hardinge Bridge and Baruria are 59.63 and 77.23 percent, respectively (Table A.36 of Appendix-A). For Hardinge Bridge and Baruria only 15.17% and 26.00% of the predicted Manning's n lie within ± 30 percent error range. The MNE for Chezy's C and Darcy-Weisbach f at Hardinge Bridge are 139.64 and 107.04 percent and at Baruria 55.00 and 236.18 percent, respectively.

5.3.3.11 Shen et al. (1990) method

Bed form dimensions by Allen (1962) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Shen et al. (1990) method with bed form dimensions by Allen (1962)

at Hardinge Bridge and Baruria are shown in Figures B.33 and B.34, respectively, of Appendix-B. As is the case with the computed Manning's n , the predicted Manning's n value decreases with increasing discharge both at Hardinge Bridge and Baruria. The variation of the predicted values of Manning's n with discharges are given in Table A.37 of Appendix-A. The grain roughness n' ranges from 0.0043 to 0.0067, attains its maximum value at low discharges and then decreases with increasing discharge both at Hardinge Bridge and Baruria. The form roughness n'' ranges from 0.0160 to 0.0199 both at Hardinge Bridge and Baruria. In fact, both the grain roughnesses and form roughnesses predicted by this method are almost constant in nature.

The MNE for Manning's n computed by the Shen et al. (1990) method using the bed form dimensions predicted by Allen (1962) at Hardinge Bridge and Baruria are 59.15% and 47.61%, respectively (Table A.38 of Appendix-A). At Hardinge Bridge 13.88% and at Baruria 32.08% predicted Manning's n lie within ± 30 percent error range. The MNE for Darcy-Weisbach f at Hardinge Bridge and Baruria are 197.63% and 52.92%, respectively.

Bed form dimensions by Vajda (1990) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Shen et al. (1990) method with bed form dimensions by Vajda (1990) at Hardinge Bridge and Baruria are shown in Figures B.35 and B.36, respectively, of Appendix-B. The predicted roughness by this method is almost constant in nature. At high discharge, the computed value of Manning's n is close to the measured value. The variation of the predicted values of Manning's n with discharges is given in Table A.39 of Appendix-A. The computed values of grain roughness n' at Hardinge Bridge ranges from 0.0045 to 0.0084 and those for form roughness n'' ranges from 0.007 to 0.0249, while those at Baruria range from 0.0047 to 0.0078 and from 0.0009 to 0.0249, respectively. The grain roughness gradually decreases with increasing discharge, while the form roughness abruptly increases when the bed form changes from ripple to dune.

For Manning's n the MNE at Hardinge Bridge and Baruria are 56.60% and 76.95%, respectively (Table A.40 of Appendix-A). At Hardinge Bridge 18.10% and at Baruria 17.84% of the predicted values of Manning's n lie within ± 30 percent error range. For Chezy's C and Darcy-Weisbach f the MNE at Hardinge Bridge are 190.02 and 88.67 percent and at Baruria are 110.28 and 203.45 percent, respectively.

Bed form dimensions by Yalin (1992) method

The comparison between the values of Manning's n computed by Manning formula and predicted by the Shen et al. (1990) method with bed form dimensions by Yalin (1992) at Hardinge Bridge and Baruria are shown in Figures B.37 and B.38, respectively, of Appendix-B. The value of roughness coefficients n computed by this method increases with increasing discharge when the discharges are low and at relatively high discharges it changes within a fixed range. The predicted values by this method may be considered constant. The variation of the predicted values of Manning's n with discharges is given in Table A.41 of Appendix-A. Predicted values of Manning's n range from 0.0140 to 0.0204 at Hardinge Bridge and from 0.0109 to 0.0194 at Baruria. Both for Hardinge Bridge and Baruria the grain roughness n' ranges from 0.0045 to 0.0074 and the form roughness n'' ranges from 0.0042 to 0.0146. The predicted grain roughness decreases with increasing discharge. The predicted form roughness at Hardinge Bridge increases with increasing discharge at low discharges. It attains its maximum value at around 15000 m³/s and then again decreases with increasing discharge. At Baruria the predicted form roughness has a well-identifiable trend of increasing with increasing discharge.

The MNE for Manning's n at Hardinge Bridge and Baruria are 61.90% and 46.25%, respectively (Table A.42 of Appendix-A). At Hardinge Bridge 14.18% and at Baruria 27.39% of the predicted Manning's n lie within ± 30 percent error range. For Chezy's C and Darcy-Weisbach f , the MNE at Hardinge Bridge are 260.13 and 81.95 percent and at Baruria 83.79 and 87.57 percent, respectively.

5.3.3.12 Van Rijn (1993) method

Comparison between the values of Manning's n computed by Manning formula and predicted by the Van Rijn (1993) method at Hardinge Bridge and Baruria is shown in Figures B.39 and B.40, respectively, of Appendix-B. This method predicts Manning's n with reasonable accuracy except at very low discharges. However, there is a discontinuity of predicted roughness values at low discharges. At very high discharges, the predicted values are larger than the computed values. The variations of the predicted and computed values of Manning's n with discharges are given in Table A.43 of Appendix-A. According to Van Rijn method the predicted grain roughness n' for the river Ganges is minimum at low discharges

and increases with increasing discharge. At peak discharges the maximum values of the grain roughness coefficient n' are 0.0197 and 0.0195 for Hardinge Bridge and Baruria, respectively. For mini-ripples the form roughness is minimum, increases with increasing bed form height and becomes zero when the discharges at Hardinge Bridge and Baruria become equal to or greater than 32000 m³/s and 61600 m³/s, respectively.

The MNE for Manning's n predicted by the Van Rijn (1993) method at Hardinge Bridge and Baruria are 59.07% and 32.11%, respectively (Table A.44 of Appendix-A). At Hardinge Bridge 23.61% and at Baruria 52.68% of the predicted values of Manning's n lie within ± 30 percent error range. For Chezy's C and Darcy-Weisbach f , the MNE at Hardinge Bridge are 203.71 and 69.03 percent and at Baruria 30.20 and 48.47 percent, respectively.

5.3.4 Remarks

Almost all the overall roughness predictors predict Manning's n accurately in the moderate range of discharges both at Hardinge Bridge and Baruria. A few of them, however, predicts Manning's n accurately in the moderate as well as high discharges. But none predicts Manning's n accurately at low discharges. Among the selected 5 overall roughness predictors, only the Simon and Richardson (1966) method predicts Manning's n which covers a wide range of discharges. The roughness parameters those are found to be very close predicted by the Garde and Ranga Raju (1970), White et al. (1987) and Brownlie (1983) methods. The Karim (1995) method predicts roughness parameters well at moderate range of discharges and gives best result at high discharges both at Hardinge Bridge and Baruria (Figs. B.41 and B.42 of Appendix-B).

Among the selected methods based on the division of roughness, the roughness parameter n predicted by the Einstein-Barbarossa (1952) method increases with increasing discharge while the computed value decreases with increasing discharge. According to this method the grain roughness is the main constituent of the total roughness, while the form roughness is a minor fraction of the total roughness. The Shen (1962) method predicts Manning's roughness value over a wide range, between 0.0122 and 0.0745 at Hardinge Bridge and between 0.0139 and 0.0771 at Baruria. The variation of Manning's n computed by the Manning formula and predicted grain, from and total roughness n' , n'' and n by Shen (1962) method with discharge at Hardinge Bridge and Baruria are shown in Figs. 5.3 and 5.4,

respectively. The Engelund-Hansen (1967) method gives less accurate results than the Einstein-Barbarossa (1952) method, specially at Hardinge Bridge. The computed roughness parameter n usually decreases with the increase of discharge, but the roughness parameter n predicted by the Engelund-Hansen (1967) method increases with increasing discharge (Figs. B.43 and B.44 of Appendix-B).

In recent time attention is focused on predicting dimensions of bed forms and then predicting roughness values by using these bed form dimensions. In this study the bed form dimensions are predicted by using the Allen (1962), Vajda (1990) and Yalin (1992) methods. These predictors are developed mainly on the basis of laboratory study where bed level is plain before experimental runs. With the increment of velocity the bed forms like ripple, dune, plane bed and antidune are developed. In a natural channel, like the Ganges, low flow and flood flows are cyclic in every year. Though it may be possible to predict bed forms when discharge is high, but after a flood flow, when discharge is falling, specially at minimum discharge, it is difficult to predict bed form dimensions.

The predicted Manning's n by the Van Rijn (1993) method is lower at low discharges and higher at high discharges than the computed values (Figs. B.45 and B.46 of Appendix-B). According to this method the grain roughness for the river Ganges is minimum at low discharges and increases with increasing discharge. The form roughness is minimum for mini ripple, increases with increasing bed form height and becomes zero when the discharge at Hardinge Bridge and Baruria becomes very high. The predicted total roughness n , similar to the computed roughness, is maximum at low discharges and gradually decreases and attains its minimum value at high discharges. Although the predicted Manning's n is maximum at low discharges, it is much lower than the computed Manning's n .

The MNE for predicted Manning's n and percentages of predicted Manning's n lying within some specified error-ranges by different roughness predictors both at Hardinge Bridge and Baruria are given in Table 5.3. On the basis of the percentage of predicted values of Manning n in the error ranges, at Hardinge Bridge the Shen (1962), Van Rijn (1993) and Haque and Mahmood-1983 (bed form by Vajda) methods rank 1, 2 and 3, respectively (Fig. B.47 of Appendix-B). At Baruria the Shen (1962), Karim (1995) and Van Rijn (1993) methods rank 1, 2 and 3, respectively (Fig. B.48 of Appendix-B). On the basis of the MNE for Manning's roughness value n , at Hardinge Bridge the Shen (1962), Haque and Mahmood-

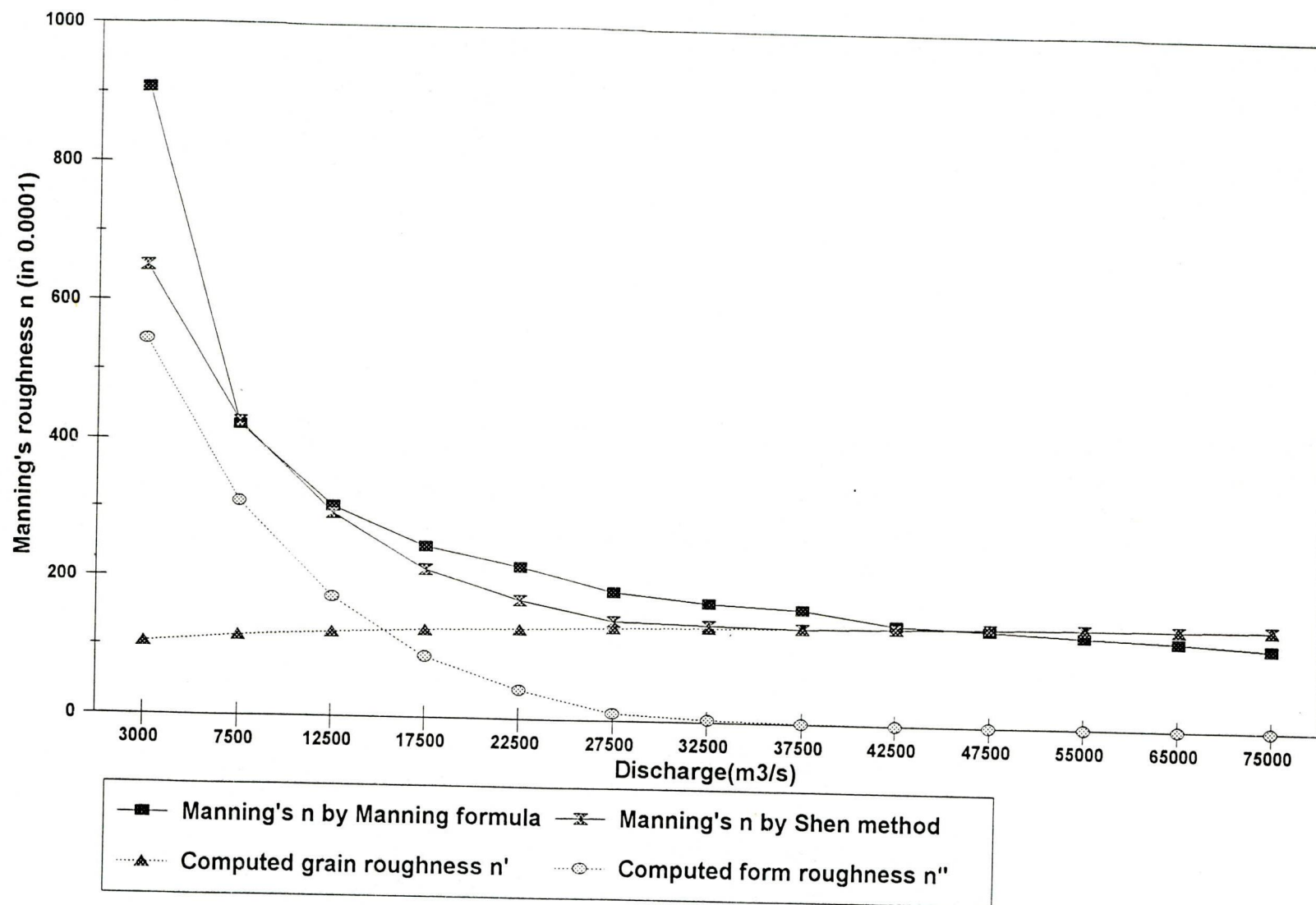


Fig. 5.3 Variation of Manning's n predicted by Shen (1962) method with discharge at Hardinge Bridge

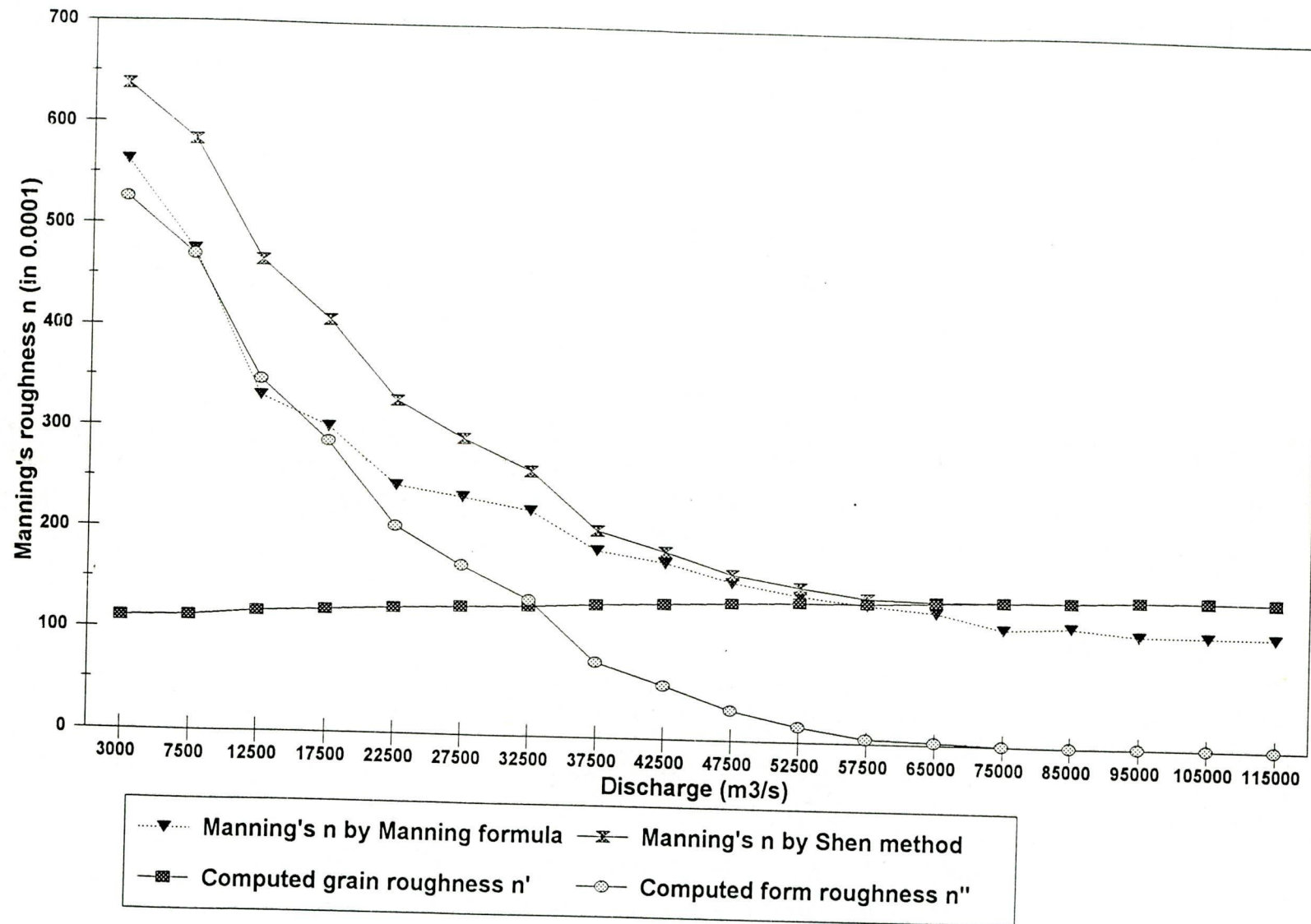


Fig. 5.4 Variation of Manning's n predicted by Shen (1962) method with discharge at Baruria

Table 5.3 Percentages of predicted Manning's n lying within specified error ranges by different roughness predictors

Name of roughness predictor		MNE for Manning's n		Percentages of Manning's n lying within specified error ranges					
		H.Bridge	Baruria	Hardinge Bridge			Baruria		
				±10%	±20%	±30%	±10%	±20%	±30%
Simons & Richardson (1966)		57.57	45.01	5.09	10.51	19.93	4.16	11.09	24.96
Garde & Ranga Raju (1970)		61.14	49.27	4.66	9.10	13.76	8.49	19.07	27.21
Brownlie (1983)		65.45	63.36	3.35	7.47	12.89	13.00	19.58	27.90
White et al. (1987)		62.26	58.90	3.79	8.23	13.97	11.09	18.89	27.90
Karim (1995)		59.00	28.77	5.30	9.10	12.56	20.62	39.51	54.25
Einstein & Barbarossa (1952)		68.49	40.19	4.76	10.07	15.06	13.86	27.90	38.30
Shen (1962)		20.74	25.49	30.23	46.81	66.20	28.60	49.05	64.48
Engelund-Hansen (1967)		61.52	36.73	3.15	6.73	10.31	13.35	23.40	37.27
Vanoni & Hwang (1967)	Vajda (1990)	58.25	151.63	5.85	11.70	19.82	2.60	5.20	11.10
	Yalin (1992)	61.25	82.34	5.85	10.51	15.28	8.14	16.29	26.51
Haque & Mahmood (1983)	Vajda (1990)	56.23	163.44	5.75	13.77	20.49	3.47	6.24	10.92
	Yalin (1992)	59.63	77.22	6.07	10.84	15.17	6.59	15.77	25.99
Shen et al. (1990)	Allen (1962)	59.15	47.61	5.31	9.22	13.88	14.04	23.04	32.08
	Vajda (1990)	56.60	76.95	4.87	10.62	18.10	5.20	11.78	17.84
	Yalin (1992)	61.90	46.25	4.87	9.85	14.18	7.28	14.56	27.39
Van Rijn (1990)		59.07	50.18	8.45	16.14	23.61	16.30	34.32	52.69

1983 (bed form by Vajda) and Shen et al. (1990 (bed form by Vajda)) methods rank 1, 2 and 3, respectively (Fig. B.49 of Appendix-B). At Baruria the Shen (1962), Karim (1995) and Engelund-Hansen (1967) methods rank 1, 2 and 3, respectively (Fig. B.50 of Appendix-B). The final choice of the roughness predictor applicable for the river Ganges will be made in the following section.

5.4 Roughness Predictors Applicable for the River Ganges

The Shen (1962) method ranks 1 in predicting depth at Hardinge Bridge. It also ranks 1 for predicting Manning's roughness coefficient n both at Hardinge Bridge and Baruria. However, it seems to be less accurate than the Karim (1995) and Engelund-Hansen (1967) methods for predicting depth at Baruria. Shen method does not predict velocity and bed form dimensions.

The Karim (1995) method ranks 2 in predicting depth at Hardinge Bridge and ranks 1 in predicting depth at Baruria. In predicting velocity, it ranks 1 at Baruria, but less accurate than Brownlie (1983) and Engelund-Hansen (1967) methods at Hardinge Bridge. In predicting Manning's roughness value n , the Karim method ranks 2 at Baruria, but at Hardinge Bridge it seems to be one of the least accurate methods for predicting the roughness parameters.

In predicting depth, velocity and Manning's roughness value n , the Engelund-Hansen (1967) method is less accurate than the Shen and Karim methods. Out of selected 6 methods, for predicting depth at Hardinge Bridge, Engelund-Hansen method ranks 3 on the basis of the MNE and ranks 4 on the basis of predicted depths lying within $\pm 30\%$ error range. At Baruria this method ranks 2 in predicting depth. The Engelund-Hansen method ranks 2 on the basis of the predicted velocities lying within $\pm 30\%$ error ranges both at Hardinge Bridge and Baruria. However, on the basis of the MNE of the predicted velocity, this method ranks 1 and 2 at Hardinge Bridge and Baruria, respectively. This method seems to fail to predict the roughness parameters accurately both at Hardinge Bridge and Baruria.

The accuracy of predicted depths by the Van Rijn (1993) method seems to be very poor. But the accuracy of predicted Manning's n seems to be more accurate. In predicting Manning's n Van Rijn method ranks 2 at Hardinge Bridge and ranks 3 at Baruria on the basis of the computed values lying within $\pm 30\%$ error ranges. On the basis of the MNE at Hardinge Bridge and Baruria, it ranks 6 and 2, respectively.

In predicting depth the Brownlie (1983) method ranks 3 and 4 at Hardinge Bridge and 4 and 3 at Baruria on the basis of the computed values lying within $\pm 30\%$ error ranges and the MNE, respectively. In predicting velocity, at Hardinge Bridge it ranks 1 and on the basis of computed velocities lie within $\pm 30\%$ error range and ranks 3 on the basis of the MNE. At Baruria it ranks 3 in both respects For predicting roughness it is among the least accurate methods.

At Hardinge Bridge the Shen (1962) method ranks 1 and Karim method ranks 2 in predicting depth. The variation of depth predicted by the Shen and Karim methods with the discharge for the station Hardinge Bridge are shown in Fig. B.51 of Appendix-B. The Shen method predicts depth better than the Karim method both at low and high discharges. The Karim method predicts depth better than the Shen method only when the discharge ranges between 25000 and 40,000 m³/s. As because the Shen method does not predict velocity, the two methods can not be compared on the basis of velocity. On the basis of the accuracy of the predicted Manning's n , the Shen method ranks 1, the Van Rijn method ranks 2 while the Karim method is among those of the least accurate methods. The variation of Manning's n predicted by different methods with discharges at Hardinge Bridge is shown in Fig. 5.5. Among the roughness predictors selected for this study only the Shen method shows a good agreement with the measured roughness at all discharges. Even at low discharges the Shen method seems to predict the roughness parameters satisfactorily.

At Hardinge Bridge the MNE is 28.83% for depth, 20.74% for Manning's n , 21.10% for Chezy C and 28.82% for Darcy-Weisbach friction factor f by the Shen(1962) method.

According to Strickler formula the grain roughness n' ranges between 0.0109 and 0.0147 at Hardinge Bridge. The predicted grain roughness by Shen method ranges between 0.0099 and 0.0149, which shows a very good agreement with the grain roughness computed by the Strickler formula.

Thus it may be concluded that, for predicting grain roughness, form roughness and total roughness, the Shen (1962) method seems to be the best for Hardinge Bridge.

At Baruria the Karim method ranks 1, the Engelund-Hansen method ranks 2 and the Shen method ranks 3 in predicting the depth. At low discharges neither the Karim method nor

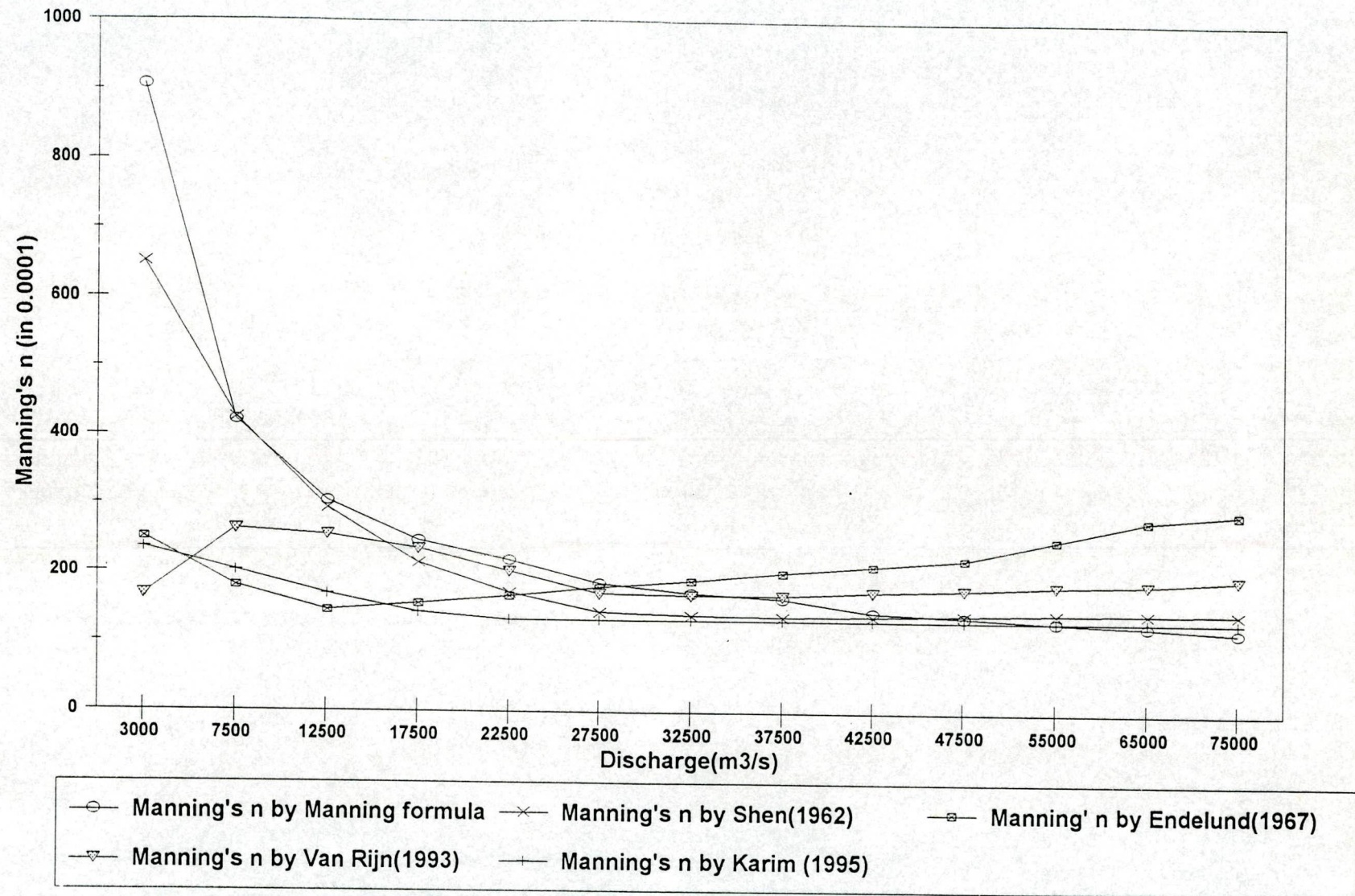


Fig. 5.5 Comparison between computed Manning's n value and predicted Manning's n value using different roughness predictors at Hardinge Bridge

the Shen method predicts the depth very well (Fig. B.52 of Appendix-B). The predicted depths by the Karim method shows a good agreement with the computed depths when the flows are 45,000 m³/s or above. When the discharges lie between 25000 and 450000 m³/s, the depths predicted by the Karim method seems to be reasonable. However, when the discharges are below 25000 m³/s, the accuracy of this method for predicting depths are very low. The Shen method shows very good agreement in predicting depth for discharges between 40,000 and 70,000 m³/s. But at low and high discharges this method does not produce very good accuracy.

On the basis of predicted Manning's roughness value n , the Shen method ranks 1 and the Karim method ranks 2. The variation of Manning's n predicted by different methods with discharges at Baruria are shown in Fig. 5.6. Only the the Manning's n predicted by the Shen method shows good agreement with the computed values at all discharge. The Karim method though ranks 2 in predicting Manning's n , the values predicted by this method varies a little (almost constant) and lie closed to the computed average values. The Karim method is slightly better than the Shen method in predicting Manning's n when discharges are more than 65000 m³/s.

At Baruria the MNE by Shen method is 42.10% for depth, 25.55% for Manning's n , 14.36% for Chezy C and 42.11% for Darcy-Weisbach friction factor f .

According to Strickler formula the grain roughness n' ranges between 0.0108 and 0.148 at Baruria. The predicted grain roughness by Shen method lie between 0.0109 and 0.0150 and is almost same as that computed by the Strickler formula.

Thus we may conclude that, similar to Hardinge Bridge, for predicting grain, form and total roughnesses, the Shen (1962) method seems to be the best for Baruria also.

5.5 Resistance Characteristics of the River Ganges:

Considering the results presented in the previous sections, it is now possible to show how the resistance characteristics of the river Ganges vary over a yearly cycle both for the stations Hardinge Bridge and Baruria.

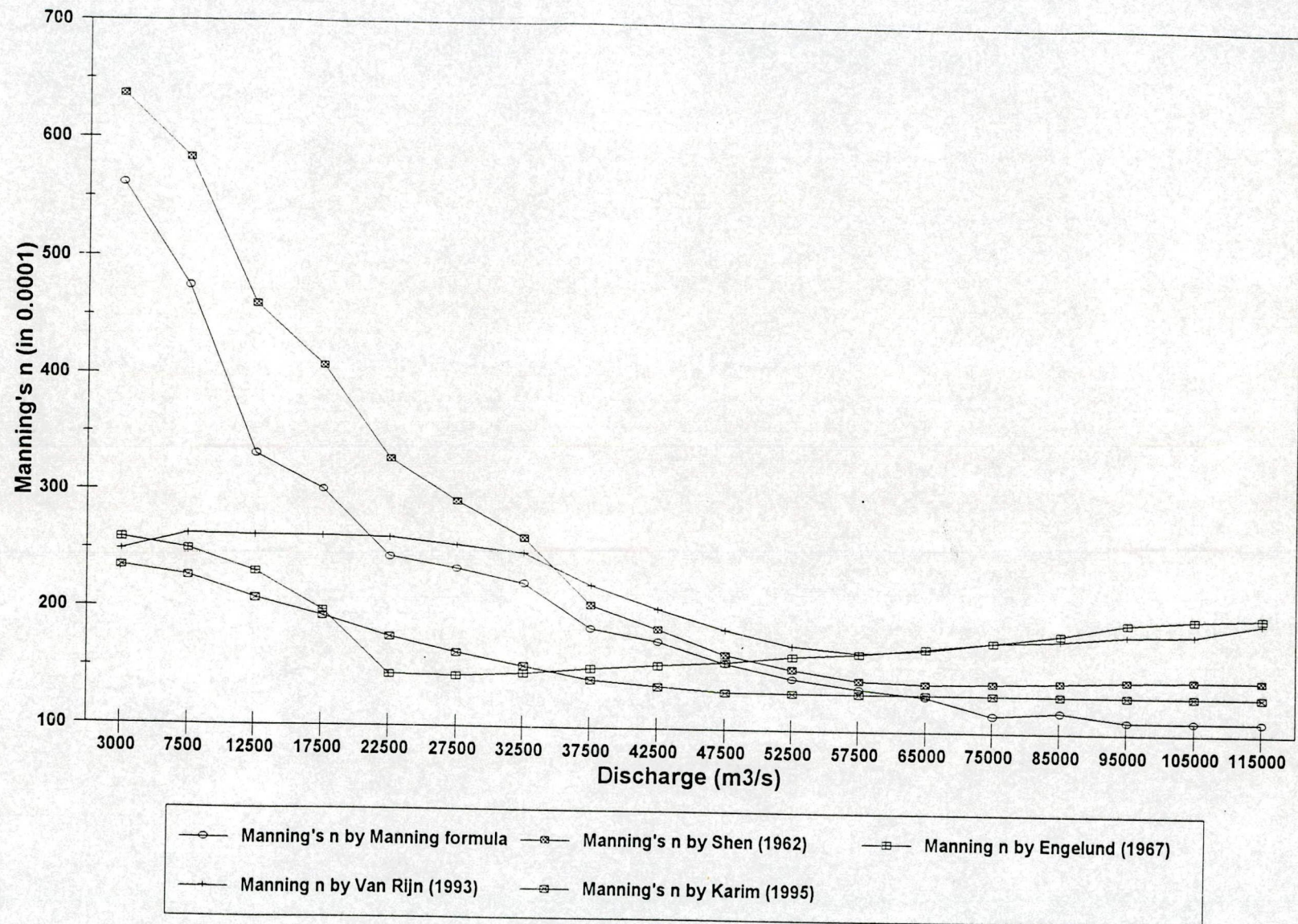


Fig. 5.6 Comparison between computed Manning's n value and predicted Manning's n value using different roughness predictors at Baruria

At Hardinge Bridge and Baruria the minimum recorded flows are 261 and 2860 m³/s and the maximum flows are 76000 and 130,000 m³/s, respectively. Theoretically the bed is plane at low discharges when the bed material does not move, then the ripples form at relatively high discharges. With further increment of flows the bed form changes to dune and washed out dune while the bed forms are in lower and transition regimes. In lower and transition regimes, the Froude numbers are relatively low. Standing waves occur when Froude numbers are 0.6 and above (Yalin, 1992) on free surfaces of open channels. From analysis of data the Froude number ranges from 0.021 to 0.331 at Hardinge Bridge and from 0.029 to 0.315 at Baruria. The Reynolds number ranges from 0.66x10⁶ to 45.74x10⁶ at Hardinge bridge and from 0.83x10⁶ to 33.33x10⁶ at Baruria.

It may be observed from the present study that for the river Ganges, the bed undulations remain for most of the period of the year when discharge is small. During flood flow the bed undulations are due to erosion and during low flow the bed undulations are due to siltation or non-erosion of the existing bed forms. Surveys over dunes in some major rivers of Bangladesh by the River Survey Project (FAP-24) confirmed that over 40% of the beds are always occupied by dunes at any flow stages. Julien and Klaassen (1995) showed that mean dune steepness does not always decrease at high transport stages in large rivers and that large bed forms may exist even at high transport stages. Julien and Klaassen (1995) also demonstrated the importance of considering Froude number in addition to the transport stages in large rivers, since the Froude number in large rivers are comparatively much lower. Thus it may be concluded that the bed forms of the river Ganges both at Hardinge Bridge and Baruria seems to remain in the lower flow regime, i.e. ripples or dunes for most of the period of the year when discharge is small.

At Hardinge Bridge the Manning's n ranges from 0.0109 to 0.1589, the Darcy-Weisbach friction factor f ranges from 0.0042 to 0.996 and Chezy's C ranges from 8.88 to 136.03 for discharges ranging from 1200m³/s to 76000m³/s. At Baruria the Manning's n ranges from 0.0092 to 0.0907, the Darcy-Weisbach friction factor f ranges from 0.0032 to 0.3794 and the Chezy's C ranges from 14.38 to 156.10 for discharges ranging from 2680m³/s to 130000m³/s.

The mean monthly variation of Manning's n since 1970 at Hardinge Bridge and Baruria are shown in Fig. 5.7. For the station Hardinge Bridge, the Manning's n decreases

during the flood season and increases during the dry season. At Hardinge Bridge the variation of Manning n is very large. It attains its mean monthly maximum value in April and minimum value in September. During flood flow, from July to October, the variation is mild. From October-November it again start increasing and reaches its maximum value in April. At Hardinge Bridge the form roughness is more responsive to the discharge and its non-linear variation with discharge is the dominant factor in the variation of total roughness.

The variation of grain roughness n' , form roughness n'' and total roughness in terms of n , C and f with discharge at Hardinge Bridge is shown in Fig. 5.8. The value of form roughness n'' is maximum at low discharges and decreases with increasing discharge. The grain roughness n' is less responsive to discharge, linear in nature and increases slightly with increasing discharge. The values of grain roughness n' at Hardinge Bridge ranges from 0.0099 to 0.0149 and at Baruria ranges from 0.0109 to 0.0150. The variation of Darcy-Weisbach friction factor f with discharge is similar to Manning's n . But it varies more than Manning's n with discharge. The variation of Chezy's C with discharge is reverse to that of Manning's n and Darcy-Weisbach f , i.e. it increases with increasing discharge.

The mean monthly resistance to flow at Baruria decreases during flood season and increases during the dry season. The variation of Manning's n at Baruria is not as wide as that at Hardinge Bridge. It attains its mean monthly maximum value in March and minimum in August. After March the value of n starts decreasing. From July to September its value remains almost constant. From October the value of n again increases and attains its maximum value in March.

The variation of grain roughness n' , form roughness n'' and total roughness in terms of n , C and f with discharge at Baruria is shown in Fig. 5.9. Similar to Hardinge Bridge at Baruria grain roughness n' is less responsive to discharge and increases with increasing discharge. The maximum to minimum ratio of grain roughness is 1.5. The form roughness n'' that is more responsive to discharge is the dominant factor in the variation of total roughness. The value of form roughness is maximum at low discharges and decreases with increasing discharge. The form roughness becomes zero at high discharges. The variation of Darcy-Weisbach friction factor f with discharge is similar to that of Manning's n , but the variation of Chezy's C with discharge is opposite to those of Manning's n and Darcy-Weisbach friction factor f .

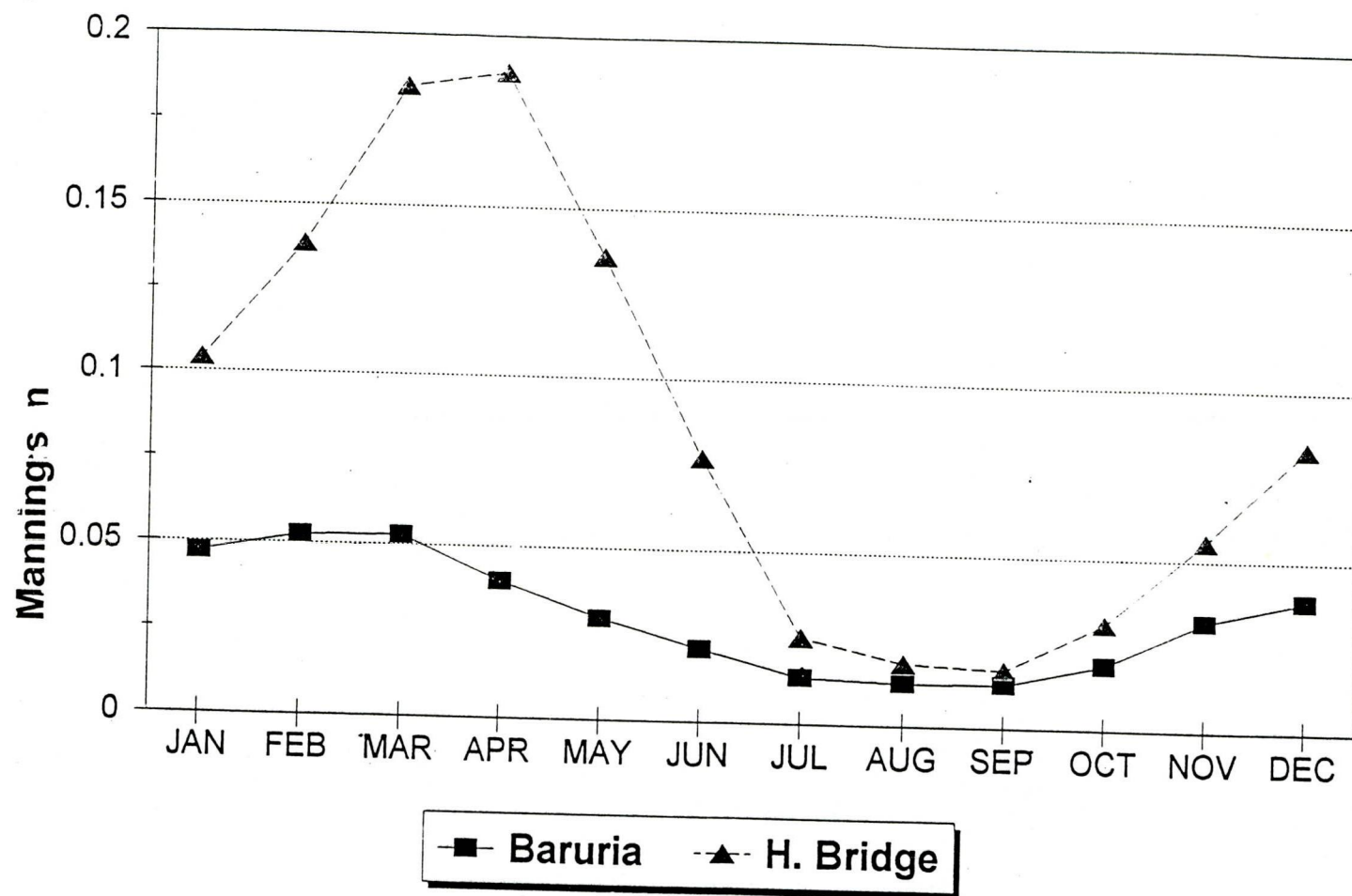


Fig. 5.7 Mean monthly variation of Manning's n at Hardinge Bridge and Baruria

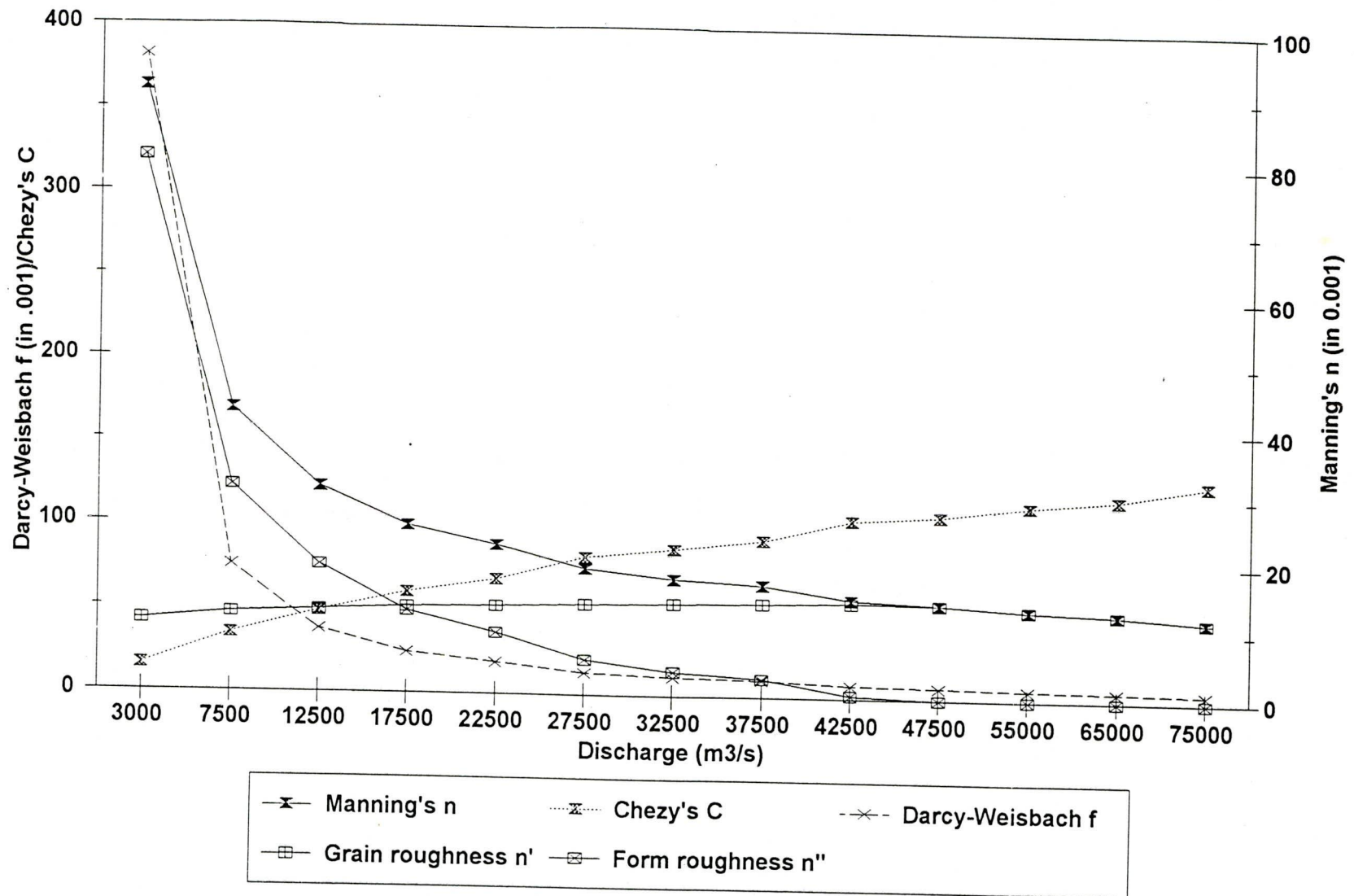


Fig. 5.8 Variation of different roughness parameters with discharge at Hardinge Bridge

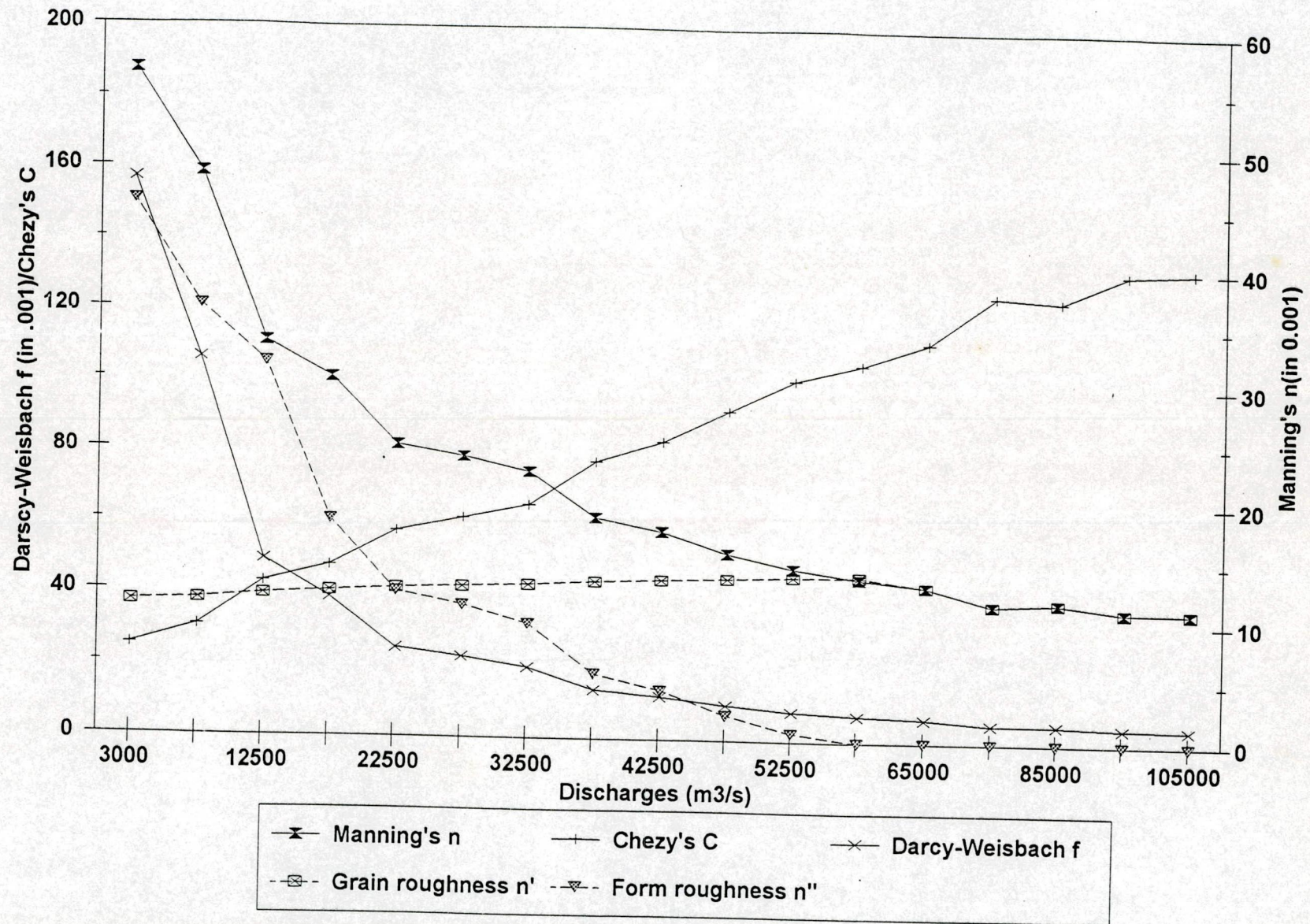


Fig. 5.9 Variation of different roughness parameters with discharge at Baruria

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions may be drawn from the present study:

1. Among the various roughness predictors considered, the Shen (1962) method seems to predict the resistance characteristics of the river Ganges satisfactory. It shows a close compliance with the measured depth and the measured roughness. It also seems to predict the grain roughness quite satisfactory.
2. For the river Ganges most of the roughness predictors predict Manning's n satisfactorily in the moderate range of discharges. A few of them, however, predicts Manning's n reasonably in the moderate range as well as at high discharges. But most of the roughness predictors overpredicts roughness at high discharges and underpredicts at low discharges.
3. It is observed from the present study that for the river Ganges, the bed forms normally remain throughout the year except at very high discharges. During flood flow the bed form is due to erosion and during low flow the bed form is due to siltation or non-erosion of the existing bed forms. The bed forms for the river Ganges lie within the lower flow regime, i.e. ripples and dunes in most of period the year. From analysis of data the Froude number for the river Ganges at Hardinge Bridge ranges from 0.021 to 0.322 and at Baruria it ranges from 0.029 to 0.315. The Reynolds number for the river Ganges at Hardinge Bridge ranges from 660000 to 45740000 and at Baruria it ranges from 830000 to 33330000.
4. The roughness parameters n , C and f for the river Ganges shows a cyclic variation over the year. The roughness parameters n and f are maximum during the dry season when the discharge is minimum. These values are minimum during flood season when the discharge is maximum. For the river Ganges at Hardinge Bridge the values of Manning's n ranges from 0.0109 to 0.1589, Darcy-Weisbach friction factor ranges from 0.0042 to 0.9960 and Chezy's C ranges from 8.88 to 136.02 for discharges

ranging from 1200 to 76000m³/s. At Baruria the values of Manning's n ranges from 0.0092 to 0.0907, Darcy-Weisbach friction factor f ranges from 0.0032 to 0.3794 and Chezy's C ranges from 14.38 to 156.10 for discharges ranging from 2860 to 130000 m³/s.

5. The Manning's n for the river Ganges increases with decreasing discharge, attains its maximum value during March, then decreases gradually with increasing discharge and attains its minimum value during August and September. The Darcy-Weisbach friction factor f also shows a similar variation over the year. The variation of Chezy's C is reverse to that of Manning's n and Darcy-Weisbach friction factor f. The Chezy's C increases with increasing discharge and decreases with decreasing discharge.
6. For the river Ganges the Manning's grain roughness increases slightly with increasing discharge. At low discharges the grain roughness is the minor part of the total roughness. At high discharges the grain roughness alone is either equal to or close to the total roughness.
7. Like the total roughness, the form roughness decreases with increasing discharge. It is more responsive to discharge than the grain roughness. At high discharges, the form roughness is either zero or very close to zero, i.e. its influence is negligible. The form roughness increases more gradually with the decrease in discharges. At low discharges the influence of the form roughness relative to the total roughness is prominent and becomes the major constituent of the total roughness.

6.2 Recommendations

The following recommendations are made based on the present study:

1. There are many roughness predictors suggested by different researchers. In the present study Shen (1962) method has shown a good compliance with the measured roughness for the river Ganges. More elaborate study using some new roughness predictors can be carried out for the river Ganges.

2. The present study has been undertaken to study the roughness characteristics of the river Ganges. The study can be extended for other major and minor alluvial rivers of Bangladesh.
3. The present trend in determining the alluvial roughness is by predicting the dimensions of the bed forms and then computing the form roughness. But the proper solution is still now much illuded to man. Most bed form predictors are developed considering initially a plain bed and bed form develops from plain bed to ripple, ripple to dune and so on with successive increament of discharge (velocity). But more attention is needed in developing bed form predictors considering cyclic variation of discharge (velocity) over the year.
4. In this study, the uniform flow formulas like the Manning, Chezy and Darcy-Weisbach formulas are used to compute alluvial roughnesses for the river Ganges. Also the roughness predictors used in this study were developed on the basis of steady uniform flow. But in reality the river flow is neither steady nor uniform. A lot of works is still to be done in developing methods for predicting roughness of the alluvial rivers for unsteady flow condition.
5. In the present study, the applicability of some available alluvial roughness predictors has been investigated. A study may be undertaken to develop a new roughness predictor for the river Ganges and other alluvial rivers of Bangladesh.

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APPENDIX-A

Table A.1: Percentages of predicted velocities lying within specified error-ranges
Method: Simons and Richardson (1966)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	23	2.49	76000	12500	3.535	1.136	225.62	22	3.81	130000	22200	3.140	1.127	71.59
0 to 10	25	2.71	58000	12200	3.005	1.017	-	39	6.76	98700	5330	2.709	0.381	-
-10 to -20	9	0.98	58000	13700	3.295	1.198	-	18	3.12	103000	4650	2.960	0.430	-
10 to 20	32	3.47	57464	2630	2.834	0.386	-	43	7.45	106000	5880	2.579	0.369	-
-20 to -30	4	0.43	20400	19500	1.584	1.445	-	18	3.12	53800	4700	1.797	0.452	-
20 to 30	23	2.49	47771	1760	2.476	0.307	-	48	8.32	86700	4530	2.240	0.336	-
-30 to -40	5	0.54	25800	22145	1.985	1.684	-	43	7.45	63800	5230	2.042	0.484	-
30 to 40	50	5.42	46943	1310	2.305	0.220	-	30	5.20	96300	4180	2.240	0.298	-
-40 to -50	10	1.08	31605	27300	2.266	2.000	-	43	7.45	73800	6010	2.580	0.541	-
40 to 50	48	5.20	39400	1210	2.085	0.234	-	33	5.72	78400	4890	1.980	0.313	-
-50 to -100	0	0.00	00	00	00	0.000	-	16	2.77	87700	61500	2.732	2.208	-
50 to 75	55	5.96	42800	1210	2.088	0.269	-	43	7.45	62600	9360	1.847	0.581	-
75 to 100	61	6.61	42952	1210	1.902	0.266	-	46	7.97	51000	3400	1.453	0.219	-
100 to 150	66	7.15	28276	1310	1.416	0.190	-	50	8.67	40200	2860	1.313	0.191	-
150 & above	512	55.47	21156	1200	1.165	0.159	-	85	14.73	34000	4830	1.012	0.256	-
Total:	923	100.00	76000	1200	3.535	0.159	-	577	100.00	130000	2860	3.140	0.191	-

Table A.2: Percentages of predicted velocities lying within specified error-ranges
Method: Garde and Ranga Raju (1970)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	20	2.17	33700	13700	1.798	1.269	218.85	21	3.64	51000	21500	1.42	1.02	62.02
0 to 10	21	2.28	42952	12500	1.901	1.136	-	28	4.85	37700	12000	1.32	0.79	-
-10 to -20	26	2.82	42800	17900	2.088	1.492	-	22	3.81	62600	29200	1.85	1.20	-
10 to 20	16	1.73	32000	10700	1.600	1.009	-	32	5.55	40200	11600	1.15	0.75	-
-20 to -30	24	2.60	47771	22145	2.476	1.727	-	42	7.28	78400	33500	1.98	1.41	-
20 to 30	13	1.41	28276	10000	1.403	0.971	-	20	3.47	34000	9360	1.01	0.66	-
-30 to -40	45	4.88	57464	25800	2.834	1.985	-	69	11.96	96300	38400	2.24	1.55	-
30 to 40	16	1.73	22000	8050	1.222	0.824	-	19	3.29	32100	6010	0.96	0.54	-
-40 to -50	26	2.82	76000	33700	3.535	2.496	-	85	14.73	106000	47700	2.71	1.86	-
40 to 50	13	1.41	21156	9670	1.165	0.872	-	18	3.12	27000	6000	0.86	0.52	-
-50 to -100	1	0.11	58000	58000	3.295	3.295	-	34	5.89	130000	61500	3.14	2.25	-
50 to 75	43	4.66	16400	5710	1.012	0.660	-	49	8.49	18800	4700	0.92	0.45	-
75 to 100	29	3.14	11700	4530	0.801	0.538	-	26	4.51	16600	4650	0.64	0.43	-
100 to 150	52	5.63	8900	2630	0.687	0.386	-	53	9.19	17600	4530	0.63	0.35	-
150 & above	578	62.62	5820	1200	0.529	0.159	-	59	10.23	12000	2860	0.47	0.19	-
Total:	923	100.00	76000	1200	3.535	0.159	218.85	577	100.0	130000	2860	3.14	0.19	62.02

Table A.3: Percentages of predicted depth lying within specified error-ranges
Method: Brownlie (1983)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	23	2.49	28276	10000	1.40	0.97	46.07	49	8.49	34500	6010	1.08	0.54	35.40
0 to 10	28	3.03	32000	11600	1.64	1.07	-	44	7.63	40200	12000	1.31	0.79	-
-10 to -20	48	5.20	21156	6410	1.16	0.72	-	45	7.80	27000	5230	0.87	0.48	-
10 to 20	27	2.93	42952	13700	1.90	1.27	-	30	5.20	51000	21500	1.45	1.02	-
-20 to -30	44	4.77	13145	5130	0.89	0.58	-	52	9.01	18800	4650	0.92	0.43	-
20 to 30	26	2.82	42800	17900	2.09	1.49	-	21	3.64	62600	31400	1.85	1.30	-
-30 to -40	54	5.85	8900	3060	0.69	0.41	-	55	9.53	17600	4710	0.63	0.35	-
30 to 40	21	2.28	46943	22145	2.33	1.73	-	38	6.59	71700	38400	1.90	1.52	-
-40 to -50	113	12.24	5543	1350	0.53	0.27	-	52	9.01	12000	4180	0.47	0.30	-
40 to 50	28	3.03	57464	25800	2.83	1.99	-	48	8.32	96300	43600	2.24	1.66	-
-50 to -100	465	50.38	4300	1200	0.42	0.16	-	10	1.73	7630	2860	0.34	0.19	-
50 to 75	45	4.88	76000	31605	3.54	2.27	-	105	18.20	106000	47700	2.71	1.86	-
75 to 100	1	0.11	58000	58000	3.30	3.30	-	28	4.85	130000	61500	3.14	2.37	-
Total:	923	100.00	76000	1200	3.54	0.16	46.07	577	100.00	130000	2860	3.14	0.19	35.40

Table A.4: Percentages of predicted velocities lying within specified error-ranges
Method: Brownlie (1983)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	32	3.47	35812	11600	1.741	1.074	95.55	46	7.97	40200	12000	1.313	0.789	34.43
0 to 10	21	2.28	28276	10000	1.403	0.971	-	46	7.97	34500	6010	1.077	0.541	-
-10 to -20	38	4.12	42952	13700	2.015	1.269	-	33	5.72	51000	25600	1.520	1.149	-
10 to 20	30	3.25	21156	8050	1.165	0.824	-	33	5.72	27000	5230	0.867	0.484	-
-20 to -30	37	4.01	46943	22145	2.334	1.682	-	66	11.42	78400	33500	1.988	1.408	-
20 to 30	31	3.36	14704	5710	0.973	0.673	-	31	5.37	18500	4700	0.917	0.452	-
-30 to -40	54	5.85	61300	28200	3.080	2.074	-	113	19.85	106000	43600	2.579	1.658	-
30 to 40	27	2.93	11700	5840	0.801	0.639	-	28	4.85	18800	4650	0.667	0.431	-
-40 to -50	15	1.63	76000	40500	3.535	2.736	-	56	9.71	130000	53300	3.140	2.140	-
40 to 50	22	2.38	10394	4530	0.743	0.538	-	25	4.33	17600	5890	0.636	0.428	-
-50 to -100	00	0.00	000	000	0.000	0.000	-	0	0.00	0000	0000	0.000	0.000	-
50 to 75	58	6.28	7736	2630	0.618	0.386	-	54	9.36	14300	4530	0.561	0.336	-
75 to 100	94	10.18	5454	1350	0.487	0.268	-	36	6.24	9600	4180	0.427	0.298	-
100 to 150	239	25.89	4300	1210	0.417	0.220	-	10	1.73	7630	2860	0.334	0.191	-
150 & above	225	24.38	2020	1200	0.258	0.159	-	-	-	-	-	-	-	-
Total:	923	100.00	76000	1200	3.535	0.159	95.55	577	100.00	130000	2860	3.140	0.191	34.43

Table A.5: Percentages of predicted velocities lying within specified error-ranges
Method: White et al. (1987)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	20	2.17	32000	11600	1.600	1.074	190.72	38	6.59	40200	12000	1.179	0.789	55.51
0 to 10	15	1.63	28276	10000	1.403	0.971		27	4.68	34500	9800	1.045	0.685	-
-10 to -20	23	2.49	42952	13700	1.901	1.223	-	21	3.64	43100	21500	1.313	1.019	-
10 to 20	16	1.73	22000	9920	1.222	0.919	-	21	3.64	32100	6540	0.961	0.564	-
-20 to -30	30	3.25	39700	16900	2.015	1.420	-	24	4.16	51000	25600	1.520	1.196	-
20 to 30	15	1.63	16400	8050	1.012	0.824	-	19	3.29	27000	6000	0.857	0.522	-
-30 to -40	24	2.60	46943	22145	2.305	1.727	-	45	7.80	71700	33500	1.858	1.408	-
30 to 40	24	2.60	14703	6410	0.973	0.726	-	22	3.81	18500	5230	0.917	0.484	-
-40 to -50	53	5.74	57464	25800	2.834	1.985	-	85	14.73	96300	43400	2.240	1.658	-
40 to 50	15	1.63	13145	5710	0.894	0.673	-	18	3.12	18800	7890	0.719	0.564	-
-50 to -100	27	2.93	76000	33700	3.535	2.496	-	106	18.37	130000	47700	3.140	1.975	-
50 to 75	32	3.47	11700	5130	0.801	0.580	-	36	6.24	17600	4650	0.663	0.431	-
75 to 100	40	4.33	8900	3540	0.662	0.480	-	30	5.20	14300	5330	0.561	0.381	-
100 to 150	49	5.31	5820	2630	0.593	0.386	-	60	6.50	13400	4180	0.511	0.324	-
150 & above	540	58.50	5454	1200	0.451	0.159	-	25	2.71	8150	2860	0.376	0.191	-
Total:	923	100.00	76000	1200	3.535	0.159	190.72	577	100.00	130000	2860	3.140	0.191	55.51

Table A.6: Percentages of predicted depth lying within specified error-ranges
Method: Karim (1995)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	49	5.31	57464	25800	2.834	1.985	43.15	112	19.41	96300	6000	2.240	0.522	18.97
0 to 10	25	2.71	76000	33700	3.535	2.453	-	82	14.21	106000	12000	2.579	0.790	-
-10 to -20	46	4.98	46943	10000	2.330	0.971	-	99	17.16	71700	4700	1.857	0.452	-
10 to 20	3	0.33	58000	43000	3.295	2.905	-	42	7.28	130000	59500	3.140	2.140	-
-20 to -30	85	9.21	42952	5710	2.015	0.666	-	111	19.24	51000	4650	1.441	0.341	-
20 to 30	0	0.00	0000	0000	0.000	0.000	-	6	1.04	103000	73800	2.960	2.580	-
-30 to -40	103	11.16	32000	2630	1.600	0.386	-	67	11.61	18800	4180	0.719	0.324	-
30 to 40	0	0.00	0000	0000	0.000	0.000	-	0	0.00	0000	0000	0.000	0.000	-
-40 to -50	190	20.59	21156	1210	1.165	0.220	-	50	8.67	17600	3400	0.917	0.219	-
40 to 50	0	0.00	0000	0000	0.000	0.000	-	0	0.00	0000	0000	0.000	0.000	-
-50 to -100	422	45.72	4370	1200	0.450	0.159	-	8	1.39	6880	2860	0.314	0.191	-
Total:	923	100.00	76000	1200	3.535	0.159	43.15	577	100.00	130000	2860	3.140	0.191	18.97

Table A.7: Percentages of predicted velocities lying within specified error-ranges
Method: Karim (1995)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	27	2.93	76000	33700	3.535	2.453	90.71	90	15.60	106000	12000	2.579	0.789	26.92
0 to 10	45	4.88	57464	25800	2.834	1.985	-	99	17.16	96300	6000	2.240	0.522	-
-10 to -20	1	0.11	58000	58000	3.295	3.295	-	41	7.11	130000	61500	3.140	2.254	-
10 to 20	28	3.03	47771	13700	2.476	1.269	-	76	13.17	71700	5230	1.858	0.484	-
-20 to -30	0	0.00	0000	0000	0.00	0.000	-	0	0.00	0000	0000	0.000	0.000	-
20 to 30	45	4.88	42800	8050	2.088	0.824	-	70	12.13	62600	4650	1.847	0.431	-
-30 to -40	0	0.00	0000	0000	0.000	0.000	-	0	0.00	0000	0000	0.000	0.000	-
30 to 40	47	5.09	42952	5710	1.901	0.673	-	61	10.57	50800	5890	1.388	0.446	-
-40 to -50	0	0.00	0000	0000	0.000	0.000	-	0	0.00	0000	0000	0.000	0.000	-
40 to 50	49	5.31	32000	3660	1.644	0.480	-	39	6.76	26100	5330	0.953	0.381	-
-50 to -100	0	0.00	0000	0000	0.000	0.000	-	0	0.00	0000	0000	0.000	0.000	-
50 to 75	111	12.03	28276	1760	1.416	0.309	-	68	11.79	17600	4180	0.636	0.298	-
75 to 100	148	16.03	5820	1210	0.593	0.220	-	25	4.33	15400	3400	0.917	0.219	-
100 to 150	314	34.02	4730	1200	0.450	0.190	-	8	1.39	6880	2860	0.314	0.191	-
150 & above	108	11.70	1970	1220	0.255	0.159	-	0	0.00	0000	000	0.00	0.00	-
Total:	923	100.00	76000	1200	3.535	0.159	90.71	577	100.00	130000	2860	3.140	0.191	26.92

Table A.8: Percentages of predicted depth lying within specified error-ranges
Method: Einstein-Barbarossa (1952)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	17	1.84	47771	25800	2.476	1.985	78.18	22	3.81	71700	31400	1.881	1.298	53.17
0 to 10	18	1.95	57464	29300	2.834	2.146	-	34	5.89	78400	37600	2.003	1.408	-
-10 to -20	11	1.19	42700	22145	2.330	1.727	-	12	2.08	49300	29200	1.453	1.220	-
10 to 20	13	1.41	57276	31605	2.806	2.266	-	34	5.89	96300	42700	2.240	1.525	-
-20 to -30	30	3.25	46943	16900	2.305	1.420	-	19	3.29	62600	25600	1.847	1.149	-
20 to 30	7	0.76	45700	35800	2.673	2.453	-	38	6.59	86700	38400	2.240	1.555	-
-30 to -40	26	2.82	42800	13700	2.088	1.269	-	18	3.12	37700	12000	1.313	0.789	-
30 to 40	7	0.76	61300	33700	3.080	2.496	-	23	3.99	83200	49600	2.370	1.968	-
-40 to -50	29	3.14	42952	12500	1.901	1.136	-	36	6.24	40200	11600	1.179	0.754	-
40 to 50	3	0.33	55194	40500	3.073	2.736	-	21	3.64	104000	47700	2.543	1.855	-
-50 to -100	750	81.26	28276	1200	1.416	0.159	-	255	44.19	34500	2860	1.045	0.191	-
50 to 75	12	1.30	76000	41400	3.535	2.797	-	33	5.72	106000	52000	2.710	2.140	-
75 to 100							-	22	3.81	107000	61500	2.884	2.323	-
100 to 150							-	10	1.73	130000	67100	3.140	2.554	-
Total:	923	100.00	76000	1200	3.535	0.159	78.18	577	100.00	130000	2860	3.140	0.191	53.17

Table A.9: Percentages of predicted depth lying within specified error-ranges
Method: Shen (1962)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	141	15.28	57276	1210	2.834	0.220	28.83	45	7.80	96300	3400	2.240	0.219	41.98
0 to 10	70	7.58	53100	1350	2.768	0.272	-	61	10.57	87000	4960	2.232	0.326	-
-10 to -20	91	9.86	57464	1300	2.702	0.290	-	15	2.60	78400	2860	1.980	0.191	-
10 to 20	31	3.36	58000	2630	3.005	0.386	-	77	13.34	86700	4830	2.243	0.310	-
-20 to -30	97	10.51	46943	1210	2.305	0.266	-	4	0.69	6190	5610	0.296	0.272	-
20 to 30	18	1.95	61300	3660	3.080	0.480	-	72	12.48	95700	4890	2.476	0.313	-
-30 to -40	123	13.33	39400	1350	2.085	0.227	-	2	0.35	62600	5250	1.847	0.256	-
30 to 40	12	1.30	72303	5710	3.386	0.673	-	55	9.53	106000	4180	2.579	0.296	-
-40 to -50	223	24.16	42800	1200	2.088	0.191	-	0	0.00	0000	0000	0.000	0.000	-
40 to 50	4	0.43	76000	43000	3.535	2.905	-	54	9.36	98700	4530	2.577	0.336	-
-50 to -100	112	12.13	42952	1220	1.901	0.159	-	0	0.00	0000	0000	0.000	0.000	-
50 to 75	1	0.11	58000	58000	3.295	3.295	-	103	17.85	107000	5070	2.884	0.369	-
75 to 100							-	42	7.28	130000	5890	3.140	0.446	-
100 to 150							-	34	5.89	103000	4650	2.960	0.431	-
150 & above							-	13	2.25	12000	5230	0.789	0.484	-
Total:	923	100.00	76000	1200	3.535	0.159	28.83	577	100.00	130000	2860	3.140	0.191	41.98

Table A.10: Percentages of predicted depth lying within specified error-ranges
Method: Engelund-Hansen (1967)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	26	2.82	42952	19800	1.901	1.580	43.98	57	9.88	60300	5230	1.672	0.484	22.86
0 to 10	26	2.82	42800	22400	2.088	1.806	-	60	10.40	71700	6010	1.899	0.541	-
-10 to -20	27	2.93	32000	13700	1.644	1.269	-	72	12.48	51000	4650	1.453	0.431	-
10 to 20	23	2.49	46943	28092	2.334	2.041	-	51	8.84	96300	47500	2.240	1.835	-
-20 to -30	44	4.77	28276	5130	1.416	0.580	-	106	18.37	40200	5070	1.245	0.369	-
20 to 30	14	1.52	47771	31605	2.533	2.266	-	51	8.84	86700	47700	2.370	2.004	-
-30 to -40	84	9.10	22000	2030	1.222	0.321	-	88	15.25	34000	4180	1.012	0.298	-
30 to 40	23	2.49	57464	33700	2.834	2.496	-	38	6.59	106000	52000	2.595	2.254	-
-40 to -50	232	25.14	14100	1210	0.946	0.220	-	27	4.68	17400	3400	0.917	0.219	-
40 to 50	8	0.87	58000	40500	3.026	2.736	-	16	2.77	107000	61500	2.794	2.485	-
-50 to -100	406	43.99	8900	1200	0.687	0.159	-	6	1.04	17600	2860	0.629	0.191	-
50 to 75	10	1.08	76000	48100	3.535	2.988	-	5	0.87	130000	67100	3.140	2.823	-
Total:	923	100.00	76000	1200	3.535	0.159	43.98	577	100.00	130000	2860	3.140	0.191	22.86

Table A.11: Percentages of predicted velocities lying within specified error-ranges
Method: Engelund-Hansen (1967)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	26	2.82	42800	22400	2.088	1.806	87.56	68	11.79	78400	6010	1.98	0.54	28.10
0 to 10	22	2.38	42952	19800	1.901	1.582	-	56	9.71	60300	5230	1.67	0.48	-
-10 to -20	32	3.47	47771	28092	2.471	2.041	-	74	12.82	96300	47500	2.25	1.86	-
10 to 20	22	2.38	32000	16900	1.667	1.420	-	40	6.93	51000	4700	1.45	0.45	-
-20 to -30	29	3.14	57464	33700	2.834	2.453	-	65	11.27	106000	52000	2.63	2.14	-
20 to 30	19	2.06	27200	6410	1.495	0.726	-	58	10.05	43100	4650	1.31	0.43	-
-30 to -40	16	1.73	72303	41400	3.386	2.797	-	14	2.43	130000	67100	3.14	2.58	-
30 to 40	26	2.82	28276	5710	1.403	0.660	-	68	11.79	40200	5330	1.18	0.38	-
-40 to -50	1	0.11	76000	76000	3.535	3.535	-	0	0.00	0000	0000	0.00	0.00	-
40 to 50	24	2.60	22000	3660	1.222	0.480	-	45	7.80	34500	4530	1.04	0.34	-
-50 to -100	0	0.00	0000	0000	0.000	0.000	-	0	0.00	0000	0000	0.00	0.00	-
50 to 75	134	14.52	164000	1350	1.056	0.268	-	70	12.13	32100	4180	0.96	0.30	-
75 to 100	168	18.20	13145	1210	0.894	0.220	-	13	2.25	15600	3400	0.72	0.22	-
100 to 150	344	37.27	8900	1200	0.687	0.178	-	6	1.04	17600	2860	0.63	0.19	-
150 & above	60	6.50	1970	1260	0.255	0.159	-							-
Total:	923	100.00	76000	1200	3.535	0.159	87.56	577	100.00	130000	2860	3.14	0.19	28.10

Table A.12: Percentages of predicted depth lying within specified error-ranges
Method: Van Rijn (1993)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	30	3.25	46943	10000	2.305	0.971	68.99	17	2.95	52900	5520	1.825	0.484	48.52
0 to 10	24	2.60	42700	11600	2.286	1.074	-	41	7.11	71700	6000	1.858	0.522	-
-10 to -20	32	3.47	39400	9460	2.085	0.884	-	18	3.12	62600	5230	1.847	0.508	-
10 to 20	17	1.84	47771	12900	2.476	1.162	-	47	8.15	78400	6010	1.980	0.541	-
-20 to -30	40	4.33	42800	8050	2.088	0.824	-	24	4.16	20100	4700	0.808	0.452	-
20 to 30	13	1.41	57464	13700	2.702	1.269	-	49	8.49	69500	11600	2.003	0.754	-
-30 to -40	39	4.23	33700	6410	1.798	0.724	-	36	6.24	18800	4650	0.734	0.431	-
30 to 40	12	1.30	56600	31500	2.834	2.243	-	49	8.49	96300	14400	2.240	0.829	-
-40 to -50	30	3.25	42952	4530	1.901	0.538	-	26	4.51	16600	5890	0.917	0.432	-
40 to 50	8	0.87	57276	33500	2.806	2.343	-	31	5.37	85200	12000	2.232	0.789	-
-50 to -100	645	69.88	10394	1200	0.743	0.159	-	106	18.37	17600	2860	0.629	0.191	-
50 to 75	16	1.73	58000	33700	3.005	2.453	-	57	9.88	86700	30500	2.370	1.196	-
75 to 100	7	0.76	61300	40500	3.080	2.736	-	30	5.20	106000	52000	2.579	2.048	-
100 to 150	10	1.08	76000	43000	3.535	2.905	-	36	6.24	107000	53300	2.884	2.254	-
150 & above							-	10	1.73	130000	67100	3.140	2.554	-
Total:	923	100.00	76000	1200	3.535	0.159	90.71	577	100.00	130000	2860	3.140	0.191	48.52

Table A.13 Variation of predicted values of Manning's n with discharge
Method: Simons and Richardson (1966)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	Q≤5000	0.0428	0.1589					0.0083	0.0344
	5000<Q≤15000	0.0210	0.0640					0.0083	0.0187
	15000<Q≤25000	0.0161	0.0345					0.0083	0.0189
	25000<Q≤35000	0.0123	0.0286					0.0083	0.0186
	Q>35000	0.0109	0.0232					0.0083	0.0086
	Total	0.0109	0.1589					0.0083	0.0344
Baruria	Q≤5250	0.0290	0.0907					0.0122	0.0329
	5250<Q≤15000	0.0207	0.0856					0.0083	0.0342
	15000<Q≤25000	0.0203	0.0446					0.0083	0.0309
	25000<Q≤35000	0.0170	0.0303					0.0083	0.0183
	35000<Q≤45000	0.0140	0.0240					0.0083	0.0188
	Q>45000	0.0092	0.0205					0.0083	0.0188
	Total	0.0092	0.0907					0.0083	0.0342

Table A.14: Percentages of predicted Manning's n lying within specified error-ranges
Method: Simons and Richardson (1966)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	30	3.25	61300	12200	3.080	1.017	57.57	14	2.43	47700	4650	1.606	0.430	45.01
0 to 10	17	1.84	72300	12500	3.386	1.136	-	10	1.73	53800	4720	1.797	0.454	-
-10 to -20	40	4.33	57464	2180	2.834	0.336	-	26	4.51	130000	5700	3.140	0.463	-
10 to 20	10	1.08	76000	14400	3.535	1.198	-	14	2.43	55200	5230	1.810	0.508	-
-20 to -30	86	9.32	46943	1270	2.330	0.220	-	51	8.84	107000	5330	2.794	0.381	-
20 to 30	1	0.11	13700	13700	1.269	1.269	-	29	5.03	60600	5520	2.042	0.484	-
-30 to -40	66	7.15	42800	1210	2.088	0.234	-	85	14.73	102000	4530	2.519	0.336	-
30 to 40	3	0.33	20400	19500	1.523	1.445	-	22	3.81	66500	6010	2.325	0.541	-
-40 to -50	77	8.34	42952	1210	1.902	0.266	-	75	13.00	96300	4180	2.240	0.298	-
40 to 50	2	0.22	22900	19800	1.684	1.584	-	13	2.25	71100	14400	2.323	0.837	-
-50 to -100	577	62.51	28276	1200	1.416	0.159	-	211	36.57	62600	2860	1.847	0.191	-
50 to 75	6	0.65	27600	22145	2.007	1.727	-	19	3.29	80600	12000	2.580	0.789	-
75 to 100	8	0.87	31600	2810	2.266	2.041	-	8	1.39	87700	70400	2.732	2.370	-
Total:	923	100.00	76000	1200	3.535	0.159	57.57	577	100.00	130000	2860	3.140	0.191	45.01

Table A.15 Variation of predicted values of Manning's n with discharge
Method: Garde and Ranga Raju (1970)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	Q≤5000	0.0428	0.1589					0.0217	0.0221
	5000<Q≤15000	0.0210	0.0640					0.0218	0.0221
	15000<Q≤25000	0.0161	0.0345					0.0219	0.0221
	25000<Q≤35000	0.0123	0.0286					0.0219	0.0222
	Q>35000	0.0109	0.0232					0.0220	0.0222
	Total	0.0109	0.1589					0.0217	0.0222
Baruria	Q≤5250	0.0290	0.0907					0.0191	0.0214
	5250<Q≤15000	0.0207	0.0856					0.0187	0.0217
	15000<Q≤25000	0.0203	0.0446					0.0203	0.0217
	25000<Q≤35000	0.0170	0.0303					0.0212	0.0217
	35000<Q≤45000	0.0140	0.0240					0.0213	0.0216
	Q>45000	0.0092	0.0205					0.0213	0.0217
	Total	0.0092	0.0907					0.0187	0.0217

Table A.16: Percentages of predicted Manning's n lying within specified error-ranges
Method: Garde and Ranga Raju (1970)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	23	2.49	42952	12500	1.901	1.136	61.14	30	5.20	37700	12000	1.313	0.789	49.27
0 to 10	20	2.17	33700	13700	1.798	1.269	-	19	3.29	51000	21500	1.425	1.019	-
-10 to -20	22	2.38	32000	10000	1.600	0.971	-	44	7.63	40200	9800	1.152	0.685	-
10 to 20	19	2.06	42800	17900	2.088	1.492	-	17	2.95	62600	29200	1.847	1.196	-
-20 to -30	26	2.82	28276	8050	1.403	0.824	-	31	5.37	32100	6000	0.961	0.522	-
20 to 30	17	1.84	46943	22145	2.305	1.682	-	16	2.77	60300	31400	1.670	1.298	-
-30 to -40	41	4.44	21156	5710	1.165	0.673	-	37	6.41	20100	5230	0.808	0.484	-
30 to 40	9	0.98	42700	22400	2.330	1.806	-	22	3.81	71700	37600	1.858	1.408	-
-40 to -50	38	4.12	13145	4530	0.894	0.538	-	50	8.67	18800	4650	0.917	0.431	-
40 to 50	19	2.06	57464	25800	2.834	1.985	-	30	5.20	78400	38400	2.003	1.555	-
-50 to -100	631	68.36	8900	1200	0.687	0.159	-	112	19.41	17600	2860	0.629	0.191	-
50 to 75	39	4.23	61300	29300	3.080	2.146	-	74	12.82	96300	43600	2.370	1.658	-
75 to 100	18	1.95	76000	33700	3.535	2.496	-	63	10.92	106000	47700	2.710	1.975	-
100 to 150	1	0.11	58000	58000	3.295	3.295	-	32	5.55	130000	61500	3.140	2.323	-
Total:	923	100.00	76000	1200	3.535	0.159	61.14	577	100.00	130000	2860	3.140	0.191	49.27

Table A.17 Variation of predicted values of Manning's n with discharge
Method: Brownlie (1983)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	Q≤5000	0.0428	0.1589					0.0202	0.0239
	5000<Q≤15000	0.0210	0.0640					0.0233	0.0257
	15000<Q≤25000	0.0161	0.0345					0.0256	0.0267
	25000<Q≤35000	0.0123	0.0286					0.0268	0.0276
	Q>35000	0.0109	0.0232					0.0276	0.0295
	Total	0.0109	0.1589					0.0202	0.0295
Baruria	Q≤5250	0.0290	0.0907					0.0200	0.0220
	5250<Q≤15000	0.0207	0.0856					0.0211	0.0239
	15000<Q≤25000	0.0203	0.0446					0.0231	0.0254
	25000<Q≤35000	0.0170	0.0303					0.0241	0.0257
	35000<Q≤45000	0.0140	0.0240					0.0250	0.0261
	Q>45000	0.0092	0.0205					0.0254	0.0290
	Total	0.0092	0.0907					0.0200	0.0290

Table A.18: Percentages of predicted Manning's n lying within specified error-ranges
Method: Brownlie (1983)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	16	1.73	28276	10000	1.40	0.97	65.45	34	5.89	34500	9800	1.08	0.68	63.36
0 to 10	15	1.63	27200	11600	1.50	1.07	-	31	5.37	40200	12000	1.18	0.79	-
-10 to -20	20	2.17	22000	9460	1.22	0.88	-	23	3.99	32100	6000	0.96	0.52	-
10 to 20	18	1.95	37400	13700	1.77	1.22	-	15	2.60	37700	21500	1.31	1.00	-
-20 to -30	33	3.58	16400	6410	1.01	0.73	-	32	5.55	20100	5230	0.81	0.48	-
20 to 30	17	1.84	42952	13700	1.90	1.27	-	16	2.77	50800	25600	1.39	1.15	-
-30 to -40	29	3.14	13145	5710	0.89	0.66	-	43	7.45	18800	4700	0.92	0.45	-
30 to 40	14	1.52	38100	17900	1.95	1.49	-	14	2.43	51000	29200	1.45	1.22	-
-40 to -50	36	3.90	10394	3660	0.74	0.48	-	32	5.55	17600	4650	0.64	0.43	-
40 to 50	12	1.30	42800	19800	2.09	1.58	-	11	1.91	62600	31400	1.85	1.30	-
-50 to -100	613	66.41	7736	1200	0.61	0.16	-	99	17.16	14300	2860	0.56	0.19	-
50 to 75	25	2.71	46943	22145	2.33	1.73	-	46	7.97	71700	37600	1.90	1.41	-
75 to 100	35	3.79	57464	25800	2.83	1.99	-	53	9.19	96300	43600	2.24	1.66	-
100 to 150	36	3.90	72303	33500	3.39	2.34	-	96	16.64	106000	47700	2.71	1.86	-
150 & above	4	0.43	76000	43000	3.54	2.91	-	32	5.55	130000	61500	3.14	2.32	-
Total:	923	100.00	76000	1200	3.54	0.16	65.45	577	100.00	130000	2860	3.14	0.19	63.36

Table A.19 Variation of predicted values of Manning's n with discharge
Method: White et al. (1987)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	Q≤5000	0.0428	0.1589					0.0214	0.0263
	5000<Q≤15000	0.0210	0.0640					0.0242	0.0266
	15000<Q≤25000	0.0161	0.0345					0.0254	0.0272
	25000<Q≤35000	0.0123	0.0286					0.0257	0.0276
	Q>35000	0.0109	0.0232					0.0261	0.0280
	Total	0.0109	0.1589					0.0214	0.0280
								0.0213	0.0244
Baruria	Q≤5250	0.0290	0.0907					0.0206	0.0254
	5250<Q≤15000	0.0207	0.0856					0.0229	0.0271
	15000<Q≤25000	0.0203	0.0446					0.0241	0.0261
	25000<Q≤35000	0.0170	0.0303					0.0243	0.0257
	35000<Q≤45000	0.0140	0.0240					0.0243	0.0263
	Q>45000	0.0092	0.0205					0.0203	0.0271
	Total	0.0092	0.0907						

Table A.20: Percentages of predicted Manning's n lying within specified error-ranges
Method: White et al. (1987)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	19	2.06	28276	10000	1.403	0.971	62.26	29	5.03	34500	9800	1.045	0.685	58.90
0 to 10	26	1.73	27200	11600	1.495	1.074	-	35	6.07	40200	12000	1.163	0.789	-
-10 to -20	22	2.38	22000	8050	1.222	0.824	-	29	5.03	27000	6010	0.953	0.541	-
10 to 20	19	2.06	37400	13700	1.773	1.223	-	16	2.77	37700	21500	1.313	0.995	-
-20 to -30	35	3.79	16400	6410	1.012	0.724	-	34	5.89	20100	5230	0.917	0.484	-
20 to 30	18	1.95	42952	16900	1.901	1.420	-	18	3.12	50800	25600	1.391	1.149	-
-30 to -40	32	3.47	11700	5710	0.812	0.639	-	41	7.11	18800	4650	0.677	0.431	-
30 to 40	14	1.52	38100	17900	1.954	1.492	-	12	2.08	51000	29200	1.453	1.283	-
-40 to -50	49	5.31	10394	3540	0.743	0.480	-	40	6.93	17600	5330	0.629	0.381	-
40 to 50	14	1.52	42800	22200	2.088	1.682	-	16	2.77	62600	31400	1.847	1.298	-
-50 to -100	590	63.92	6480	1200	0.593	0.159	-	85	14.73	13400	2860	0.511	0.191	-
50 to 75	28	3.03	46943	22145	2.334	1.727	-	52	9.01	78400	38100	1.980	1.525	-
75 to 100	40	4.33	57464	28400	2.834	2.088	-	65	11.27	96300	47300	2.240	1.714	-
100 to 150	27	2.93	76000	33700	3.535	2.496	-	91	15.77	107000	47700	2.884	1.975	-
150 & above							-	14	2.43	130000	67100	3.140	2.485	-
Total:	923	100.00	76000	1200	3.535	0.159	62.26	577	100.00	130000	2860	3.140	0.191	58.90

Table A.20: Percentages of predicted Manning's n lying within specified error-ranges
Method: White et al. (1987)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	19	2.06	28276	10000	1.403	0.971	62.26	29	5.03	34500	9800	1.045	0.685	58.90
0 to 10	26	1.73	27200	11600	1.495	1.074	-	35	6.07	40200	12000	1.163	0.789	-
-10 to -20	22	2.38	22000	8050	1.222	0.824	-	29	5.03	27000	6010	0.953	0.541	-
10 to 20	19	2.06	37400	13700	1.773	1.223	-	16	2.77	37700	21500	1.313	0.995	-
-20 to -30	35	3.79	16400	6410	1.012	0.724	-	34	5.89	20100	5230	0.917	0.484	-
20 to 30	18	1.95	42952	16900	1.901	1.420	-	18	3.12	50800	25600	1.391	1.149	-
-30 to -40	32	3.47	11700	5710	0.812	0.639	-	41	7.11	18800	4650	0.677	0.431	-
30 to 40	14	1.52	38100	17900	1.954	1.492	-	12	2.08	51000	29200	1.453	1.283	-
-40 to -50	49	5.31	10394	3540	0.743	0.480	-	40	6.93	17600	5330	0.629	0.381	-
40 to 50	14	1.52	42800	22200	2.088	1.682	-	16	2.77	62600	31400	1.847	1.298	-
-50 to -100	590	63.92	6480	1200	0.593	0.159	-	85	14.73	13400	2860	0.511	0.191	-
50 to 75	28	3.03	46943	22145	2.334	1.727	-	52	9.01	78400	38100	1.980	1.525	-
75 to 100	40	4.33	57464	28400	2.834	2.088	-	65	11.27	96300	47300	2.240	1.714	-
100 to 150	27	2.93	76000	33700	3.535	2.496	-	91	15.77	107000	47700	2.884	1.975	-
150 & above							-	14	2.43	130000	67100	3.140	2.485	-
Total:	923	100.00	76000	1200	3.535	0.159	62.26	577	100.00	130000	2860	3.140	0.191	58.90

Table A.22: Percentages of predicted Manning's n lying within specified error-ranges
Method: Karim (1995)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	35	3.79	57276	29300	2.806	2.124	59.00	63	10.92	96300	6010	2.240	0.541	28.77
0 to 10	14	1.52	72303	33700	3.386	2.496	-	56	9.71	104000	12000	2.543	0.790	-
-10 to -20	24	2.60	57464	22400	2.834	1.806	-	72	12.48	78400	5230	1.988	0.484	-
10 to 20	11	1.19	76000	40500	3.535	2.736	-	37	6.41	106000	47700	2.710	1.989	-
-20 to -30	31	3.36	46943	11600	2.305	1.074	-	64	11.09	62600	4700	1.847	0.452	-
20 to 30	1	0.11	58000	58000	3.295	3.295	-	21	3.64	107000	61500	2.884	2.254	-
-30 to -40	55	5.96	42800	6410	2.088	0.726	-	85	14.73	51000	4650	1.453	0.431	-
30 to 40	0	0.00	0000	0000	0000	0000	-	14	2.43	130000	65400	3.140	2.370	-
-40 to -50	76	8.23	42952	3660	1.901	0.480	-	65	11.27	34000	5070	1.313	0.369	-
40 to 50	0	0.00	0000	0000	0.000	0000	-	2	0.35	103000	76100	2.960	2.633	-
-50 to -100	676	73.24	28276	1200	1.403	0.159	-	98	16.98	17600	2860	0.917	0.191	-
Total:	923	100.00	76000	1200	3.535	0.159	59.00	577	100.00	130000	2860	3.140	0.191	28.77

Table A.23 Variation of predicted values of Manning's n with discharge
Method: Einstein-Barbarossa (1952)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	Q≤5000	0.0428	0.1589	0.0098	0.0114	0.0014	0.0024	0.0112	0.0138
	5000<Q≤15000	0.0210	0.0640	0.0111	0.0127	0.0022	0.0034	0.0132	0.0161
	15000<Q≤25000	0.0161	0.0345	0.0122	0.0133	0.0016	0.0036	0.0150	0.0165
	25000<Q≤35000	0.0123	0.0286	0.0128	0.0140	0.0010	0.0036	0.0145	0.0165
	Q>35000	0.0109	0.0232	0.0133	0.0149	0.0009	0.0019	0.0145	0.0160
	Total	0.0109	0.1589	0.0098	0.0149	0.0009	0.0036	0.0112	0.0165
Baruria	Q≤5250	0.0290	0.0907	0.0102	0.0114	0.0016	0.0024	0.0118	0.0138
	5250<Q≤15000	0.0207	0.0856	0.0109	0.0123	0.0019	0.0031	0.0127	0.0154
	15000<Q≤25000	0.0203	0.0446	0.0117	0.0128	0.0027	0.0035	0.0143	0.0163
	25000<Q≤35000	0.0170	0.0303	0.0122	0.0132	0.0030	0.0038	0.0152	0.0169
	35000<Q≤45000	0.0140	0.0240	0.0128	0.0136	0.0020	0.0039	0.0156	0.0172
	Q>45000	0.0092	0.0205	0.0131	0.0150	0.0010	0.0038	0.0150	0.0171
	Total	0.0092	0.0907	0.0102	00.015	0.0010	0.0039	0.0118	0.0172

Table A.24: Percentages of predicted Manning's n lying within specified error-ranges
Method: Einstein-Barbarossa (1952)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	22	2.38	57464	22400	2.702	1.806	68.49	25	4.33	71700	31400	1.881	1.298	40.19
0 to 10	22	2.38	57276	29300	2.834	2.146	-	55	9.53	96300	37600	2.240	1.408	-
-10 to -20	33	3.58	46943	16900	2.305	1.420	-	27	4.68	62600	25600	1.847	1.161	-
10 to 20	16	1.73	53100	35800	2.768	2.453	-	54	9.36	86700	38400	2.243	1.555	-
-20 to -30	37	4.01	42800	13700	2.088	1.223	-	22	3.81	43100	12000	1.313	0.789	-
20 to 30	9	0.98	61300	33700	3.080	2.496	-	38	6.59	104000	47700	2.543	1.855	-
-30 to -40	27	2.93	42952	11600	1.901	1.074	-	50	8.67	40200	9800	1.163	0.685	-
30 to 40	11	1.19	76000	41400	3.535	2.797	-	28	4.85	106000	52000	2.579	2.048	-
-40 to -50	23	2.49	28276	9920	1.403	0.919	-	38	6.59	34000	6000	1.012	0.522	-
40 to 50	1	0.11	58000	58000	3.295	3.295	-	18	3.12	107000	61500	2.794	2.254	-
-50 to -100	722	78.22	21156	1200	1.165	0.159	-	201	34.84	20100	2860	0.917	0.191	-
50 to 75							-	21	3.64	130000	65400	3.140	2.370	-
Total:	923	100.00	76000	1200	3.535	0.159	68.59	577	100.00	130000	2860	3.140	0.190	40.19

Table A.25 Variation of predicted values of Manning's n with discharge
Method: Shen (1962)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	$Q \leq 5000$	0.0428	0.1589	0.0099	0.0114	0.0352	0.0646	0.0466	0.0745
	$5000 < Q \leq 15000$	0.0210	0.0640	0.0111	0.0127	0.081	0.0428	0.0208	0.0540
	$15000 < Q \leq 25000$	0.0161	0.0345	0.0122	0.0133	0.0004	0.0165	0.0122	0.0133
	$25000 < Q \leq 35000$	0.0123	0.0286	0.0131	0.0144	0.000	0.0074	0.0139	0.0205
	$Q > 35000$	0.0109	0.0232	0.0136	0.0153	0.0000	0.0013	0.0139	0.0153
	Total	0.0109	0.1589	0.0099	0.0153	0.0000	0.0646	0.0122	0.0745
Baruria	$Q \leq 5250$	0.0290	0.0907	0.0102	0.0114	0.0434	0.00669	0.0548	0.0771
	$5250 < Q \leq 15000$	0.0207	0.0856	0.0109	0.0123	0.0234	0.0589	0.0357	0.0698
	$15000 < Q \leq 25000$	0.0203	0.0446	0.0117	0.0128	0.0130	0.0369	0.0258	0.0486
	$25000 < Q \leq 35000$	0.0170	0.0303	0.0122	0.0132	0.0064	0.0255	0.0196	0.0377
	$35000 < Q \leq 45000$	0.0140	0.0240	0.0128	0.0136	0.0009	0.0139	0.0146	0.0266
	$Q > 45000$	0.0092	0.0205	0.0131	0.0150	0.000	0.0076	0.0139	0.0207
	Total	0.0092	0.0907	0.0102	0.0150	0.000	0.0669	0.0139	0.0771

Table A.26: Percentages of predicted Manning's n lying within specified error-ranges
Method: Shen (1962)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m^3/s)	$Q_{\min}$ (m^3/s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m^3/s)	$Q_{\min}$ (m^3/s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	190	20.59	57464	1210	2.834	0.220	20.74	60	10.40	96300	3400	2.240	0.219	25.49
0 to 10	89	9.64	53100	1350	2.768	0.272	-	105	18.20	87000	4830	2.240	0.310	-
-10 to -20	120	13.00	47771	1210	2.476	0.266	-	9	1.56	71700	2860	1.858	0.191	-
10 to 20	33	3.58	61300	2630	3.080	0.386	-	110	19.06	104000	4890	2.543	0.313	-
-20 to -30	166	17.98	46943	1310	2.305	0.219	-	2	0.35	62600	5250	1.847	0.256	-
20 to 30	13	1.41	76000	6410	3.535	0.726	-	90	15.60	106000	4180	2.579	0.298	-
-30 to -40	252	27.30	38100	1200	1.954	0.177	-	0	0.00	0000	0000	0.000	0.000	-
30 to 40	1	0.11	58000	58000	3.295	3.295	-	85	14.73	107000	5070	2.884	0.350	-
-40 to -50	57	6.18	42952	1260	1.901	0.166	-	0	0.00	0000	0000	0.000	0.000	-
40 to 50	0	0.00	0000	0000	0.000	0.000	-	52	90.01	99000	5330	2.727	0.381	-
-50 to -100	2	0.22	1380	1330	0.185	0.159	-	0	0.00	0000	0000	0.000	0.000	-
50 to 75							-	40	6.93	130000	4650	3.140	0.431	-
75 to 100							-	20	3.47	14400	4700	0.837	0.452	-
100 to 150							-	4	0.69	6540	6000	0.564	0.522	-
Total:	923	100.00	76000	1200	3.535	0.159	20.74	577	100.00	130000	2860	3.140	0.191	25.49

Table A.27 Variation of predicted values of Manning's n with discharge
Method: Engelund-Hansen (1967)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	$Q \leq 5000$	0.0428	0.1589	0.0119	0.0132	0.0141	0.0204	0.0216	0.0261
	$5000 < Q \leq 15000$	0.0210	0.0640	0.0129	0.0141	0.0000	0.0158	0.0137	0.0229
	$15000 < Q \leq 25000$	0.0161	0.0345	0.0141	0.0143	0.003	0.0068	0.0150	0.0173
	$25000 < Q \leq 35000$	0.0123	0.0286	0.0144	0.0145	0.0069	0.0103	0.0174	0.0198
	$Q > 35000$	0.0109	0.0232	0.0145	0.0146	0.0103	0.0209	0.0198	0.0285
	Total	0.0109	0.1589	0.0119	0.0146	0.0000	0.0204	0.0139	0.0285
Baruria	$Q \leq 5250$	0.0290	0.0907	0.0120	0.0126	0.0187	0.0205	0.0251	0.0263
	$5250 < Q \leq 15000$	0.0207	0.0856	0.0123	0.0139	0.0000	0.0201	0.0137	0.0261
	$15000 < Q \leq 25000$	0.0203	0.0446	0.0130	0.0143	0.0000	0.0162	0.0139	0.0233
	$25000 < Q \leq 35000$	0.0170	0.0303	0.0140	0.0144	0.0000	0.0038	0.0140	0.0157
	$35000 < Q \leq 45000$	0.0140	0.0240	0.0142	0.0145	0.0016	0.0058	0.0146	0.0166
	$Q > 45000$	0.0092	0.0205	0.0143	0.0148	0.0029	0.0126	0.0152	0.0217
	Total	0.0092	0.0907	0.0120	0.0148	0.0000	0.0205	0.0139	0.0263

Table A.28: Percentages of predicted Manning's n lying within specified error-ranges
Method: Engelund-Hansen (1967)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	15	1.63	42952	22145	1.901	1.682	61.52	39	6.76	60300	5520	1.672	0.484	36.73
0 to 10	14	1.52	39700	22400	2.037	1.806	-	38	6.59	71700	6010	1.858	0.541	-
-10 to -20	21	2.28	37400	17900	1.773	1.492	-	27	4.68	49300	5230	1.533	0.508	-
10 to 20	12	1.30	42800	25800	2.088	1.980	-	31	5.37	78400	12000	1.988	0.789	-
-20 to -30	18	1.95	32000	13700	1.600	1.269	-	57	9.88	51000	4650	1.425	0.431	-
20 to 30	15	1.63	46943	28200	2.305	2.074	-	23	3.99	65700	47500	2.021	1.855	-
-30 to -40	29	3.14	28276	5710	1.416	0.673	-	70	12.13	40200	5890	1.313	0.432	-
30 to 40	11	1.19	42400	31500	2.336	2.243	-	40	6.93	96300	47700	2.240	1.975	-
-40 to -50	36	3.90	22000	3660	1.222	0.480	-	79	13.69	34500	4530	1.077	0.336	-
40 to 50	5	0.54	47771	33500	2.476	2.343	-	16	2.77	86700	53900	2.287	2.133	-
-50 to -100	701	75.95	16400	1200	1.056	0.159	-	85	14.73	27000	2860	0.953	0.191	-
50 to 75	28	3.03	57464	33700	2.834	2.453	-	50	8.67	106000	52000	2.595	2.208	-
75 to 100	11	1.19	61300	40500	3.080	2.736	-	19	3.29	107000	61500	2.884	2.485	-
100 to 150	7	0.76	76000	55100	3.535	3.073	-	3	0.52	130000	67100	3.140	2.855	-
Total:	923	100.00	76000	1200	3.535	0.159	61.52	577	100.00	130000	2860	3.140	0.191	36.73

Table A.29 Variation of predicted values of Manning's n with discharge
Method: Vanoni & Hwang(1967) Bed form by Vajda(1990)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
H.Bridge	Q≤5000	0.0428	0.1589	0.0096	0.0138	0.0025	0.0398	0.0163	0.0494
	5000<Q≤15000	0.0210	0.0640	0.0099	0.0116	0.0239	0.0377	0.0355	0.0476
	15000<Q≤25000	0.0161	0.0345	0.0106	0.0122	0.0202	0.0318	0.0323	0.0428
	25000<Q≤35000	0.0123	0.0286	0.0109	0.0126	0.0177	0.0296	0.0302	0.0404
	Q>35000	0.0109	0.0232	0.0112	0.0130	0.0151	0.0271	0.0282	0.0383
	Total	0.0109	0.1589	0.0096	0.0138	0.0025	0.0398	0.0163	0.0494
Baruria	Q≤5250	0.0290	0.0907	0.0097	0.0138	0.0032	0.0419	0.0170	0.0516
	5250<Q≤15000	0.0207	0.0856	0.0097	0.0141	0.0026	0.0422	0.0167	0.0519
	15000<Q≤25000	0.0203	0.0446	0.0097	0.0141	0.0026	0.0422	0.0167	0.0518
	25000<Q≤35000	0.0170	0.0303	0.0097	0.0108	0.0334	0.0420	0.0442	0.0518
	35000<Q≤45000	0.0140	0.0240	0.0098	0.0105	0.0359	0.0418	0.0463	0.0516
	Q>45000	0.0092	0.0205	0.0098	0.0114	0.0285	0.0417	0.0398	0.0515
	Total	0.0092	0.0907	0.0097	0.0141	0.0026	0.0422	0.0167	0.0519

Table A.30: Percentages of predicted Manning's n lying within specified error-ranges
Method: Vanoni & Hwang (1967) Bed form by Vajda (1990)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	16	1.73	13145	3060	0.894	0.415	58.25	8	1.39	13400	5270	0.512	0.396	151.63
0 to 10	38	4.12	28276	3660	1.403	0.474	-	7	1.21	17600	7400	0.917	0.507	-
-10 to -20	36	3.90	10394	3140	0.743	0.469	-	11	1.91	21500	4830	1.019	0.355	-
10 to 20	18	1.95	15800	4530	1.056	0.538	-	4	0.69	16600	7320	0.636	0.503	-
-20 to -30	46	4.98	7736	1480	0.609	0.315	-	29	5.03	21900	6000	0.996	0.344	-
20 to 30	29	3.14	42952	5970	1.902	0.660	-	5	0.87	14300	7890	0.614	0.530	-
-30 to -40	59	6.39	5454	1210	0.507	0.266	-	24	4.16	15700	5230	0.896	0.276	-
30 to 40	24	2.60	31400	5710	1.644	0.673	-	7	1.21	18800	11200	0.719	0.593	-
-40 to -50	111	12.03	4730	1310	0.451	0.227	-	27	4.68	16400	4650	0.739	0.256	-
40 to 50	10	1.08	19600	6410	1.315	0.726	-	8	1.39	17400	9360	0.734	0.618	-
-50 to -100	364	39.44	3970	1200	0.398	0.159	-	101	17.50	15200	2860	0.636	0.191	-
50 to 75	39	4.23	46943	8050	2.305	0.824	-	20	3.47	32100	10500	0.961	0.675	-
75 to 100	29	3.14	57464	11600	2.834	1.074	-	22	3.81	40200	17600	1.313	0.822	-
100 to 150	51	5.53	72303	13700	3.386	1.268	-	52	9.01	62600	17900	1.847	0.897	-
150 & above	53	5.74	76000	22400	3.535	1.806	-	252	43.67	130000	29200	3.140	1.149	-
Total:	923	100.00	76000	1200	3.535	0.159	58.25	577	100.00	130000	2860	3.140	0.191	151.63

Table A.31 Variation of predicted values of Manning's n with discharge
Method: Vanoni & Hwang (1967) Bed form by Yalin (1992)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	Q≤5000	0.0428	0.1589	0.0113	0.0118	0.0131	0.0218	0.0246	0.0333
	5000<Q≤15000	0.0210	0.0640	0.0113	0.0120	0.0205	0.0218	0.0318	0.0333
	15000<Q≤25000	0.0161	0.0345	0.0115	0.0123	0.0191	0.0218	0.0314	0.0333
	25000<Q≤35000	0.0123	0.0286	0.0116	0.0126	0.0177	0.0217	0.0303	0.0333
	Q>35000	0.0109	0.0239	0.0117	0.0129	0.0160	0.0214	0.0117	0.0129
	Total	0.0109	0.1589	0.0113	0.0129	0.0131	0.0218	0.0117	0.0333
Baruria	Q≤5250	0.0290	0.0907	0.0116	0.0119	0.0112	0.0192	0.0231	0.0308
	5250<Q≤15000	0.0207	0.0856	0.0116	0.0119	0.0097	0.0211	0.0217	0.0327
	15000<Q≤25000	0.0203	0.0446	0.0116	0.0121	0.0153	0.0214	0.0270	0.0333
	25000<Q≤35000	0.0170	0.0303	0.0116	0.0118	0.0185	0.0216	0.0301	0.0334
	35000<Q≤45000	0.0140	0.0240	0.0116	0.0117	0.0189	0.0214	0.0305	0.0331
	Q>45000	0.0092	0.0205	0.0116	0.0120	0.0189	0.0217	0.0306	0.0335
	Total	0.0092	0.0907	0.0116	0.0121	0.0112	0.0218	0.0217	0.0335

Table A.32: Percentages of predicted Manning's n lying within specified error-ranges
Method: Vanoni & Hwang (1967) Bed form by Yalin (1992)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	28	3.03	21156	6410	1.165	0.701	61.25	29	5.03	20100	6540	0.756	0.564	82.34
0 to 10	26	2.82	28276	8050	1.403	0.824	-	19	3.29	27000	9800	0.868	0.685	-
-10 to -20	31	3.36	13145	5710	0.894	0.639	-	32	5.55	18800	6000	0.917	0.522	-
10 to 20	13	1.41	26200	9920	1.416	0.919	-	14	2.43	32100	11600	0.961	0.754	-
-20 to -30	25	2.71	10394	4530	0.743	0.538	-	31	5.37	17600	4700	0.636	0.452	-
20 to 30	18	1.95	42952	10000	1.902	0.971	-	28	4.85	34500	13800	1.045	0.829	-
-30 to -40	36	3.90	7736	3540	0.646	0.474	-	35	6.07	14300	4650	0.561	0.417	-
30 to 40	13	1.41	21400	11600	1.644	1.074	-	22	3.81	40200	17900	1.152	0.921	-
-40 to -50	58	6.28	5543	2630	0.529	0.375	-	51	8.84	12000	4530	0.469	0.336	-
40 to 50	15	1.63	33700	12900	1.793	1.162	-	14	2.43	37700	21500	1.313	1.019	-
-50 to -100	521	56.45	4730	1200	0.451	0.159	-	32	5.55	8150	2860	0.376	0.191	-
50 to 75	35	3.79	46943	13700	2.305	1.268	-	32	5.55	51000	22200	1.453	1.149	-
75 to 100	29	3.14	57464	19800	2.834	1.584	-	25	4.33	62600	33500	1.847	1.408	-
100 to 150	54	5.85	72303	22400	3.386	1.806	-	85	15.25	96300	38400	2.240	1.555	-
150 & above	21	2.28	76000	33700	3.535	2.496	-	125	21.66	130000	47700	3.140	1.968	-
Total:	923	100.00	76000	1200	3.535	0.159	61.25	577	100.00	130000	2860	3.140	0.191	82.34

Table A.33 Variation of predicted values of Manning's n with discharge
Method: Haque & Mahmood (1983) Bed form by Vajde (1990)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	Q≤5000	0.0428	0.1589	0.0099	0.0150	0.0001	0.0435	0.0151	0.0534
	5000<Q≤15000	0.0210	0.0640	0.0102	0.0123	0.0227	0.0406	0.0350	0.0508
	15000<Q≤25000	0.0161	0.0345	0.0111	0.0132	0.0164	0.0324	0.0296	0.0434
	25000<Q≤35000	0.0123	0.0286	0.0114	0.0139	0.0122	0.0299	0.0261	0.0413
	Q>35000	0.0109	0.0232	0.0116	0.0147	0.0082	0.0282	0.0229	0.0398
	Total	0.0109	0.1589	0.0099	0.0150	0.0001	0.0435	0.0151	0.0534
Baruria	Q≤5250	0.0290	0.0907	0.0101	0.0152	0.0005	0.0456	0.0157	0.0577
	5250<Q≤15000	0.0207	0.0856	0.0100	0.0154	0.0001	0.0461	0.0155	0.0561
	15000<Q≤25000	0.0203	0.0446	0.0100	0.0154	0.0002	0.0460	0.0155	0.0560
	25000<Q≤35000	0.0170	0.0303	0.0101	0.0113	0.0339	0.0459	0.0452	0.0560
	35000<Q≤45000	0.0140	0.0240	0.0101	0.0110	0.0374	0.0455	0.0484	0.0556
	Q>45000	0.0092	0.0205	0.0101	0.0119	0.0294	0.0454	0.0413	0.0555
	Total	0.0092	0.0907	0.0100	0.0154	0.0001	0.0461	0.0155	0.0577

Table A.34: Percentages of predicted Manning's n lying within specified error-ranges
Method: Haque & Mahmood (1983) Bed form by Vajda (1990)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	21	2.28	28276	3540	1.403	0.486	56.24	11	1.91	13400	5270	0.790	0.396	163.44
0 to 10	32	3.47	42952	3060	1.902	0.415	-	9	1.56	17600	5740	0.917	0.416	-
-10 to -20	48	5.20	10394	2680	0.743	0.344	-	12	2.08	14400	4830	0.837	0.347	-
10 to 20	26	2.82	35812	3660	1.741	0.480	-	4	0.69	10400	6010	0.541	0.507	-
-20 to -30	44	4.77	7736	1270	0.609	0.282	-	22	3.81	21900	4700	1.019	0.308	-
20 to 30	17	1.84	15635	4530	1.056	0.538	-	5	0.87	16600	7320	0.636	0.503	-
-30 to -40	64	6.93	5454	1210	0.507	0.266	-	25	4.33	21900	4650	0.961	0.256	-
30 to 40	28	3.03	42800	6160	2.088	0.666	-	4	0.69	14300	7890	0.614	0.550	-
-40 to -50	185	20.04	4730	1260	0.451	0.207	-	14	2.43	15700	5440	0.818	0.457	-
40 to 50	22	2.38	46943	5710	2.305	0.673	-	6	1.04	18800	11200	0.719	0.593	-
-50 to -100	271	29.36	3700	1200	0.385	0.159	-	110	19.06	16400	2860	0.686	0.191	-
50 to 75	33	3.58	57464	6410	2.834	0.726	-	19	3.29	27000	9360	0.953	0.618	-
75 to 100	34	3.68	57276	10000	2.806	0.971	-	21	3.64	34500	14500	1.313	0.728	-
100 to 150	50	5.42	76000	13700	3.353	1.223	-	49	8.49	62600	17900	1.847	1.897	-
150 & above	48	5.20	58000	22400	3.296	1.806	-	226	46.10	130000	22200	3.140	1.086	-
Total:	923	100.00	76000	1200	3.535	0.159	56.24	577	100.00	130000	2860	3.140	0.191	163.44

Table A.35 Variation of predicted values of Manning's n with discharge
Method: Haque & Mahmood (1983) Bed form by Yalin (1992)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	$Q \leq 5000$	0.0428	0.1589	0.0121	0.0129	0.0083	0.0201	0.0211	0.0323
	$5000 < Q \leq 15000$	0.0210	0.0640	0.0121	0.0129	0.0174	0.0201	0.0302	0.0323
	$15000 < Q \leq 25000$	0.0161	0.0345	0.0122	0.0134	0.0146	0.0201	0.0280	0.0323
	$25000 < Q \leq 35000$	0.0123	0.0286	0.0124	0.0139	0.0122	0.0198	0.0261	0.0321
	$Q > 35000$	0.0109	0.0232	0.0126	0.0145	0.0095	0.0190	0.0240	0.0316
	Total	0.0109	0.1589	0.0121	0.0145	0.0083	0.0201	0.0211	0.0323
Baruria	$Q \leq 5250$	0.0290	0.0907	0.0126	0.0135	0.0058	0.0160	0.0193	0.0287
	$5250 < Q \leq 15000$	0.0207	0.0856	0.0126	0.0136	0.0043	0.0184	0.0179	0.0310
	$15000 < Q \leq 25000$	0.0203	0.0446	0.0126	0.0132	0.0109	0.0187	0.0239	0.0314
	$25000 < Q \leq 35000$	0.0170	0.0303	0.0126	0.0127	0.0151	0.0187	0.0278	0.0316
	$35000 < Q \leq 45000$	0.0140	0.0240	0.0126	0.0127	0.0156	0.0187	0.0283	0.0314
	$Q > 45000$	0.0092	0.0205	0.0126	0.0131	0.0157	0.0189	0.0284	0.0316
	Total	0.0092	0.0907	0.0126	0.0136	0.0043	0.0189	0.0179	0.0316

Table A.36: Percentages of predicted Manning's n lying within specified error-ranges
 Method: Haque & Mahmood (1983) Bed form by Yalin (1992)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m^3/s)	$Q_{\min}$ (m^3/s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m^3/s)	$Q_{\min}$ (m^3/s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	33	3.58	28276	6410	1.403	0.724	59.63	17	2.95	20100	9800	0.808	0.695	77.22
0 to 10	23	2.49	42952	8050	1.902	0.824	-	21	3.64	27000	11600	0.953	0.788	-
-10 to -20	29	3.14	21156	5710	1.165	0.656	-	31	5.37	18800	8850	0.917	0.619	-
10 to 20	15	1.63	35812	10000	1.741	0.971	-	23	3.99	34000	13800	1.012	0.896	-
-20 to -30	29	3.14	11700	4530	0.801	0.538	-	37	6.41	17600	6010	0.663	0.536	-
20 to 30	11	1.19	23300	10700	1.465	1.009	-	21	3.64	34500	17900	1.148	0.961	-
-30 to -40	42	4.55	8900	3540	0.687	0.474	-	32	5.55	14300	5150	0.561	0.464	-
30 to 40	25	2.71	42800	12500	2.088	1.136	-	12	2.08	40200	25000	1.313	1.086	-
-40 to -50	44	4.77	5820	2630	0.529	0.386	-	47	8.15	13400	4650	0.512	0.393	-
40 to 50	11	1.19	46943	13700	2.305	1.215	-	14	2.43	43100	22200	1.302	1.149	-
-50 to -100	537	58.18	4730	1200	0.451	0.159	-	62	10.75	9600	2860	0.408	0.191	-
50 to 75	35	3.79	57464	13700	2.834	2.268	-	29	5.03	62600	25600	1.847	1.216	-
75 to 100	24	2.60	57276	22145	2.806	1.682	-	33	5.72	71700	36300	1.857	1.464	-
100 to 150	56	6.07	76000	22400	3.535	1.806	-	110	19.06	96300	40100	2.243	1.658	-
150 & above	9	0.98	58000	33700	3.296	2.496	-	88	15.25	130000	52000	3.140	2.048	-
Total:	923	100.00	76000	1200	3.535	0.159	59.63	577	100.00	130000	2860	3.140	0.191	77.22

Table A.37 Variation of predicted values of Manning's n with discharge
Method: Shen et al. (1990) Bed form by Allen (1962)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	Q≤5000	0.0410	0.1589	0.0054	0.0067	0.0162	0.0195	0.0223	0.0254
	5000<Q≤15000	0.0210	0.0640	0.0048	0.0058	0.0166	0.0181	0.0218	0.0233
	15000<Q≤25000	0.0161	0.0345	0.0046	0.0052	0.0163	0.0176	0.0214	0.0224
	25000<Q≤35000	0.0123	0.0286	0.0044	0.0051	0.0161	0.0175	0.0211	0.0221
	Q>35000	0.0109	0.0232	0.0043	0.0049	0.0160	0.0174	0.0207	0.0218
	Total	0.0109	0.1589	0.0043	0.0067	0.0160	0.0195	0.0207	0.0254
Baruria	Q≤5250	0.0290	0.0907	0.0052	0.0063	0.0169	0.0194	0.0231	0.0247
	5250<Q≤15000	0.0207	0.0856	0.0050	0.0062	0.0166	0.0199	0.0223	0.0250
	15000<Q≤25000	0.0203	0.0446	0.0049	0.0056	0.0158	0.0185	0.0213	0.0235
	25000<Q≤35000	0.0170	0.0303	0.0048	0.0052	0.0166	0.0179	0.0217	0.0303
	35000<Q≤45000	0.0140	0.0240	0.0046	0.0050	0.0169	0.0179	0.0218	0.0226
	Q>45000	0.0092	0.0205	0.0043	0.0049	0.0163	0.0180	0.0212	0.0225
	Total	0.0092	0.0907	0.0043	0.0063	0.0158	0.0194	0.0212	0.0303

Table A.38: Percentages of predicted Manning's n lying within specified error-ranges
Method: Shen et al. (1990) Bed form by Allen (1962)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	24	2.60	42952	11600	1.902	1.074	59.15	47	8.15	40200	6000	1.313	0.522	47.61
0 to 10	25	2.71	42800	13700	2.088	1.223	-	34	5.89	50800	6010	1.391	0.541	-
-10 to -20	21	2.28	32000	10000	1.644	0.971	-	29	5.03	34500	5230	1.077	0.484	-
10 to 20	15	1.63	39400	16900	2.085	1.420	-	23	3.99	62600	12000	1.847	0.790	-
-20 to -30	28	3.03	28276	6410	1.403	0.726	-	38	6.59	32100	4700	0.961	0.452	-
20 to 30	15	1.63	46943	19800	2.305	1.584	-	14	2.43	60300	36100	1.670	1.303	-
-30 to -40	47	5.09	21156	5710	1.165	0.660	-	39	6.76	18800	4650	0.745	0.431	-
30 to 40	14	1.52	57464	22145	2.834	1.727	-	20	3.47	71700	31400	1.857	1.297	-
-40 to -50	38	4.12	13145	3660	0.894	0.480	-	41	7.11	16600	5070	0.917	0.369	-
40 to 50	21	2.28	57276	25800	2.806	1.985	-	29	5.03	96300	42700	2.240	1.525	-
-50 to -100	624	67.61	8900	1200	0.687	0.159	-	87	15.08	17600	2860	0.629	0.191	-
50 to 75	37	4.01	72303	29300	3.386	2.146	-	71	12.31	87000	38400	2.287	1.555	-
75 to 100	14	1.52	76000	33700	3.535	2.496	-	66	11.44	106000	47700	2.710	1.855	-
100 to 150							-	39	6.76	130000	59500	3.140	2.140	-
Total:	923	100.00	76000	1200	3.535	0.159	59.15	577	100.00	130000	2860	3.140	0.191	47.61

Table A.39 Variation of predicted values of Manning's n with discharge
Method: Shen et al. (1990) Bed form by Vajda (1990)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	Q≤5000	0.0428	0.1589	0.0056	0.0084	0.0007	0.0229	0.0086	0.0291
	5000<Q≤15000	0.0210	0.0640	0.0050	0.0059	0.0148	0.0225	0.0203	0.0280
	15000<Q≤25000	0.0161	0.0345	0.0047	0.0055	0.0120	0.0201	0.0175	0.0250
	25000<Q≤35000	0.0123	0.0286	0.0046	0.0056	0.0099	0.0190	0.0155	0.0237
	Q>35000	0.0109	0.0232	0.0045	0.0055	0.0078	0.0176	0.0133	0.0222
	Total	0.0109	0.1589	0.0045	0.0089	0.0007	0.0229	0.0086	0.0291
Baruria	Q≤5250	0.0290	0.0907	0.0051	0.0076	0.0023	0.0241	0.0099	0.0302
	5250<Q≤15000	0.0207	0.0856	0.0047	0.0078	0.0009	0.0249	0.0079	0.0302
	15000<Q≤25000	0.0203	0.0446	0.0050	0.0073	0.0010	0.0248	0.0080	0.0300
	25000<Q≤35000	0.0170	0.0303	0.0048	0.0052	0.0211	0.0250	0.0261	0.0298
	35000<Q≤45000	0.0140	0.0240	0.0047	0.0052	0.0225	0.0250	0.0273	0.0297
	Q>45000	0.0092	0.0205	0.0043	0.0049	0.0183	0.0250	0.0231	0.0296
	Total	0.0092	0.0907	0.0051	0.0078	0.0009	0.0250	0.0079	0.0302

Table A.40: Percentages of predicted Manning's n lying within specified error-ranges
Method: Shen et al. (1990) Bed form by Vajda (1990)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m ³ /s)	$Q_{\min}$ (m ³ /s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	17	1.84	57464	13000	2.702	1.066	56.60	18	3.12	32100	6430	0.961	0.536	76.95
0 to 10	28	3.03	57276	10000	2.806	0.971	-	12	2.08	34000	5520	1.012	0.484	-
-10 to -20	32	3.47	56400	6410	2.834	0.726	-	16	2.77	17800	5230	0.790	0.508	-
10 to 20	21	2.28	72303	12900	3.386	1.162	-	22	3.81	40200	6010	1.313	0.541	-
-20 to -30	44	4.77	42800	5710	2.088	0.656	-	13	2.25	18800	4700	0.685	0.452	-
20 to 30	25	2.71	76000	13700	3.535	1.268	-	22	3.81	62600	17900	1.847	0.897	-
-30 to -40	52	5.63	37400	3660	1.773	0.480	-	20	3.47	17600	4650	0.837	0.431	-
30 to 40	10	1.08	58647	17900	3.179	1.492	-	16	2.77	51000	22000	1.425	1.028	-
-40 to -50	47	5.09	42952	3060	1.902	0.415	-	22	3.81	15600	5270	0.917	0.396	-
40 to 50	12	1.30	57291	22145	3.166	1.727	-	13	2.25	49300	25200	1.453	1.130	-
-50 to -100	594	64.36	10394	1200	0.743	0.159	-	156	27.04	21900	2860	1.019	0.191	-
50 to 75	36	3.90	58000	22400	3.296	1.806	-	39	6.76	96300	29200	2.240	1.161	-
75 to 100	5	0.54	44700	33700	2.941	2.496	-	46	7.97	87000	37600	2.234	1.408	-
100 to 150							-	115	19.93	107000	38400	2.884	1.555	-
150 & above							-	47	8.15	130000	47700	3.140	2.004	-
Total:	923	100.00	76000	1200	3.535	0.159	56.60	577	100.00	130000	2860	3.140	0.191	76.95

Table A.41 Variation of predicted values of Manning's n with discharge
Method: Shen et al. (1990) Bed form by Yalin (1992)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	Q≤5000	0.0410	0.1589	0.0059	0.0072	0.0068	0.0141	0.0140	0.0204
	5000<Q≤15000	0.0210	0.0640	0.0051	0.0061	0.0132	0.0144	0.0187	0.0200
	15000<Q≤25000	0.0161	0.0345	0.0049	0.0055	0.0119	0.0146	0.0174	0.0196
	25000<Q≤35000	0.0123	0.0286	0.0047	0.0055	0.0107	0.0146	0.0161	0.0194
	Q>35000	0.0109	0.0232	0.0046	0.0054	0.0092	0.0144	0.0145	0.0191
	Total	0.0109	0.1589	0.0046	0.0072	0.0068	0.0146	0.0140	0.0204
Baruria	Q≤5250	0.0290	0.0907	0.0065	0.0074	0.0054	0.0115	0.0120	0.0184
	5250<Q≤15000	0.0207	0.0856	0.0056	0.0068	0.0042	0.0133	0.0109	0.0194
	15000<Q≤25000	0.0203	0.0446	0.0053	0.0060	0.0090	0.0138	0.0149	0.0195
	25000<Q≤35000	0.0170	0.0303	0.0052	0.0056	0.0118	0.0142	0.0171	0.0194
	35000<Q≤45000	0.0140	0.0240	0.0050	0.0053	0.0122	0.0141	0.0174	0.0192
	Q>45000	0.0092	0.0205	0.0045	0.0052	0.0124	0.0146	0.0174	0.0193
	Total	0.0092	0.0907	0.0045	0.0074	0.0042	0.0146	0.0109	0.0195

Table A.42: Percentages of predicted Manning's n lying within specified error-ranges
 Method: Shen et al. (1990) Bed form by Yalin (1992)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	$Q_{\max}$ (m^3/s)	$Q_{\min}$ (m^3/s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %	No.	% of Total	$Q_{\max}$ (m^3/s)	$Q_{\min}$ (m^3/s)	$U_{\max}$ (m/s)	$U_{\min}$ (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	22	2.38	57464	13700	2.834	1.268	61.90	26	4.51	51000	25600	1.441	1.196	46.25
0 to 10	23	2.49	56600	17900	2.761	1.492	-	16	2.77	62600	33500	1.847	1.354	-
-10 to -20	34	3.68	42800	12500	2.088	1.136	-	21	3.64	40200	22200	1.313	1.081	-
10 to 20	12	1.30	57276	22145	2.806	1.727	-	21	3.64	60300	38100	1.825	1.525	-
-20 to -30	18	1.95	31400	10000	1.644	0.971	-	38	6.59	34500	17900	1.148	0.904	-
20 to 30	22	2.38	72303	22400	3.386	1.806	-	36	6.24	78400	40100	1.980	1.643	-
-30 to -40	38	4.12	42952	8050	1.902	0.824	-	30	5.20	32100	11600	0.961	0.754	-
30 to 40	24	2.60	76000	28400	3.535	2.088	-	35	6.07	96300	47500	2.240	1.797	-
-40 to -50	51	5.53	28276	5710	1.403	0.656	-	43	7.45	20100	9360	0.917	0.627	-
40 to 50	13	1.41	57291	31605	3.166	2.266	-	34	5.89	86700	48600	2.240	1.855	-
-50 to -100	656	71.07	11700	1200	0.801	0.159	-	179	31.02	18800	2860	0.667	0.191	-
50 to 75	10	1.08	58000	33700	0.296	2.496	-	68	11.79	106000	47700	2.710	2.004	-
75 to 100							-	29	5.03	130000	61500	3.140	2.370	-
100 to 150							-	1	0.17	103000	103000	2.960	2.960	-
Total:	923	100.00	76000	1200	3.535	0.159	61.90	577	100.00	130000	2860	3.140	0.191	46.25

Table A.43 Variation of predicted values of Manning's n with discharge
Method: Van Rijn(1993)

Station	Discharge (m ³ /s)	Manning roughness co-efficient, n							
		Measured roughness value n		Computed roughness value n					
				Grain roughness		form roughness		Total roughness	
		Min	Max	Min	Max	Min	Max	Min	Max
H.Bridge	Q≤5000	0.0428	0.1589	0.0049	0.0120	0.0000	0.0173	0.0116	0.0276
	5000<Q≤15000	0.0210	0.0640	0.0109	0.0141	0.0097	0.0162	0.0238	0.0271
	15000<Q≤25000	0.0161	0.0345	0.0130	0.0158	0.0000	0.0128	0.0155	0.0258
	25000<Q≤35000	0.0123	0.0286	0.0144	0.0176	0.0000	0.0084	0.0158	0.0228
	Q>35000	0.0109	0.0232	0.0156	0.0197	0.0000	0.0000	0.0156	0.0197
	Total	0.0109	0.1589	0.0049	0.0197	0.0000	0.0173	0.0116	0.0276
Baruria	Q≤5250	0.0290	0.0907	0.0058	0.0123	0.0000	0.0163	0.0120	0.0270
	5250<Q≤15000	0.0207	0.0856	0.0060	0.0129	0.0027	0.0164	0.0125	0.0270
	15000<Q≤25000	0.0203	0.0446	0.0118	0.0141	0.0113	0.0148	0.0254	0.0263
	25000<Q≤35000	0.0170	0.0303	0.0126	0.0150	0.0079	0.0138	0.0230	0.0265
	35000<Q≤45000	0.0140	0.0240	0.0140	0.0162	0.0000	0.0116	0.0161	0.0256
	Q>45000	0.0092	0.0205	0.0148	0.0195	0.0000	0.0088	0.0131	0.0161
	Total	0.0092	0.0907	0.0058	0.0195	0.0000	0.0164	0.0120	0.0270

Table A.44: Percentages of predicted Manning's n lying within specified error-ranges
Method: Van Rijn(1993)

Errors %	Station: Hardinge Bridge							Station: Baruria						
	No.	% of total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %	No.	% of Total	Q _{max} (m ³ /s)	Q _{min} (m ³ /s)	U _{max} (m/s)	U _{min} (m/s)	MNE %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0 to -10	47	5.09	46943	10000	3.305	0.971	59.07	22	3.81	62600	37600	1.847	1.408	50.18
0 to 10	31	3.36	42700	11600	2.334	1.074	-	26	4.51	71700	38400	1.899	1.555	-
-10 to -20	48	5.20	42800	8050	2.088	0.824	-	12	2.08	49100	31400	1.585	1.298	-
10 to 20	23	2.49	57464	13700	2.702	1.269	-	28	4.85	78400	43600	2.003	1.658	-
-20 to -30	52	5.63	42952	5710	1.901	0.660	-	25	4.33	51000	25600	1.453	1.161	-
20 to 30	17	1.84	57256	31500	2.834	2.250	-	26	4.51	96300	47500	2.240	1.835	-
-30 to -40	42	4.55	37400	3660	1.773	0.480	-	22	3.81	43100	18600	1.313	0.921	-
30 to 40	13	1.41	53100	35800	2.768	2.453	-	34	5.89	86700	48600	2.287	1.855	-
-40 to -50	50	5.42	10394	2630	0.743	0.386	-	54	9.36	40200	9800	1.152	0.685	-
40 to 50	6	0.65	61300	33700	3.080	2.496	-	25	4.33	95700	47700	1.479	1.989	-
-50 to -100	579	62.73	5820	1200	0.529	0.159	-	236	40.90	32600	2860	1.000	0.191	-
50 to 75	14	1.52	76000	40500	3.535	2.736	-	43	7.45	106000	52000	2.170	2.140	-
75 to 100	1	0.11	58000	58000	3.295	3.295	-	23	3.99	130000	61500	3.140	2.370	-
Total:	923	100.00	76000	1200	3.535	0.159	59.07	577	100.00	130000	2860	3.140	0.191	50.18

APPENDIX - B

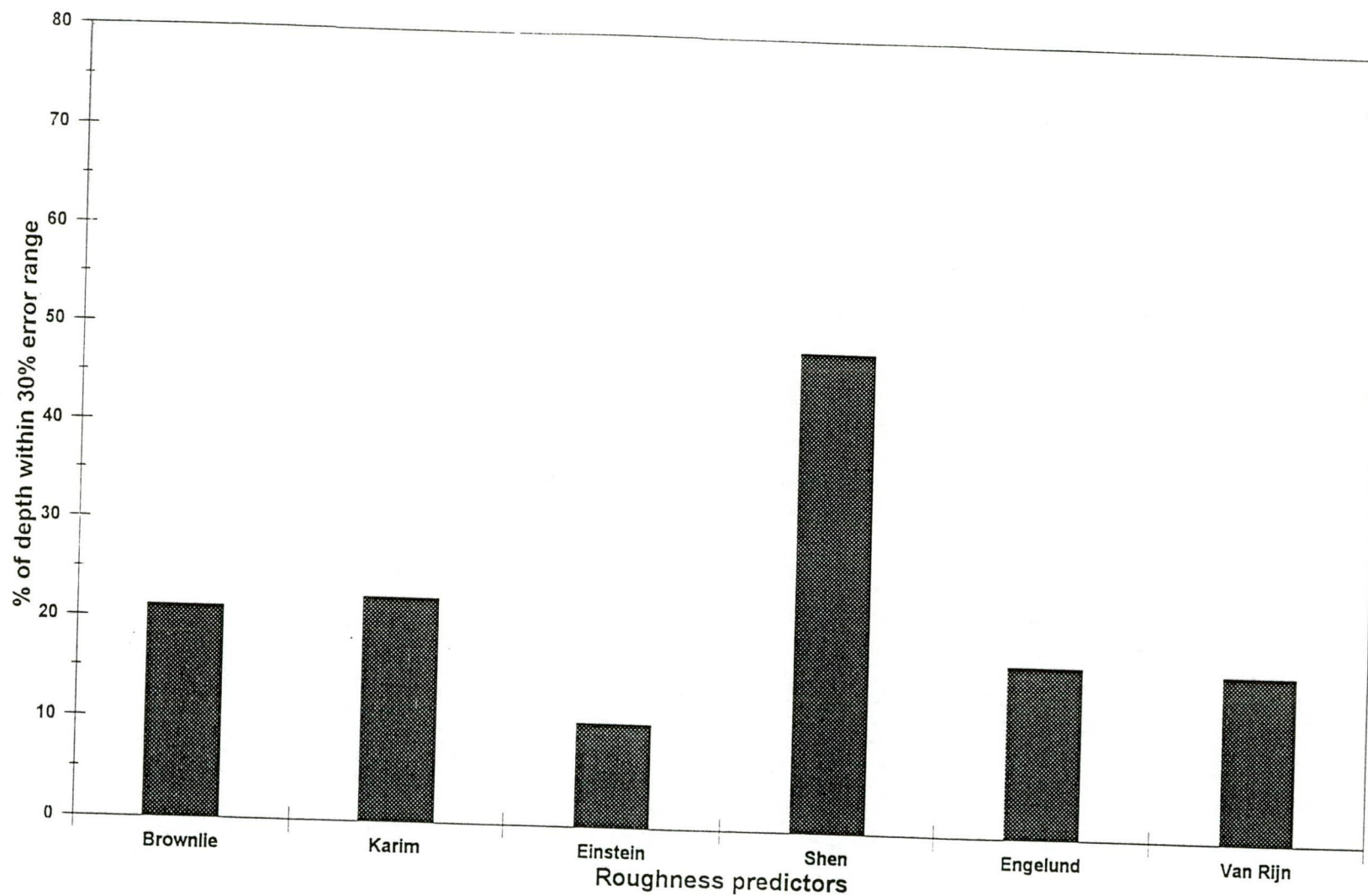


Fig. B.1 Percentage of depths lying within $\pm 30\%$ error ranges predicted by different roughness predictors at Hardinge Bridge

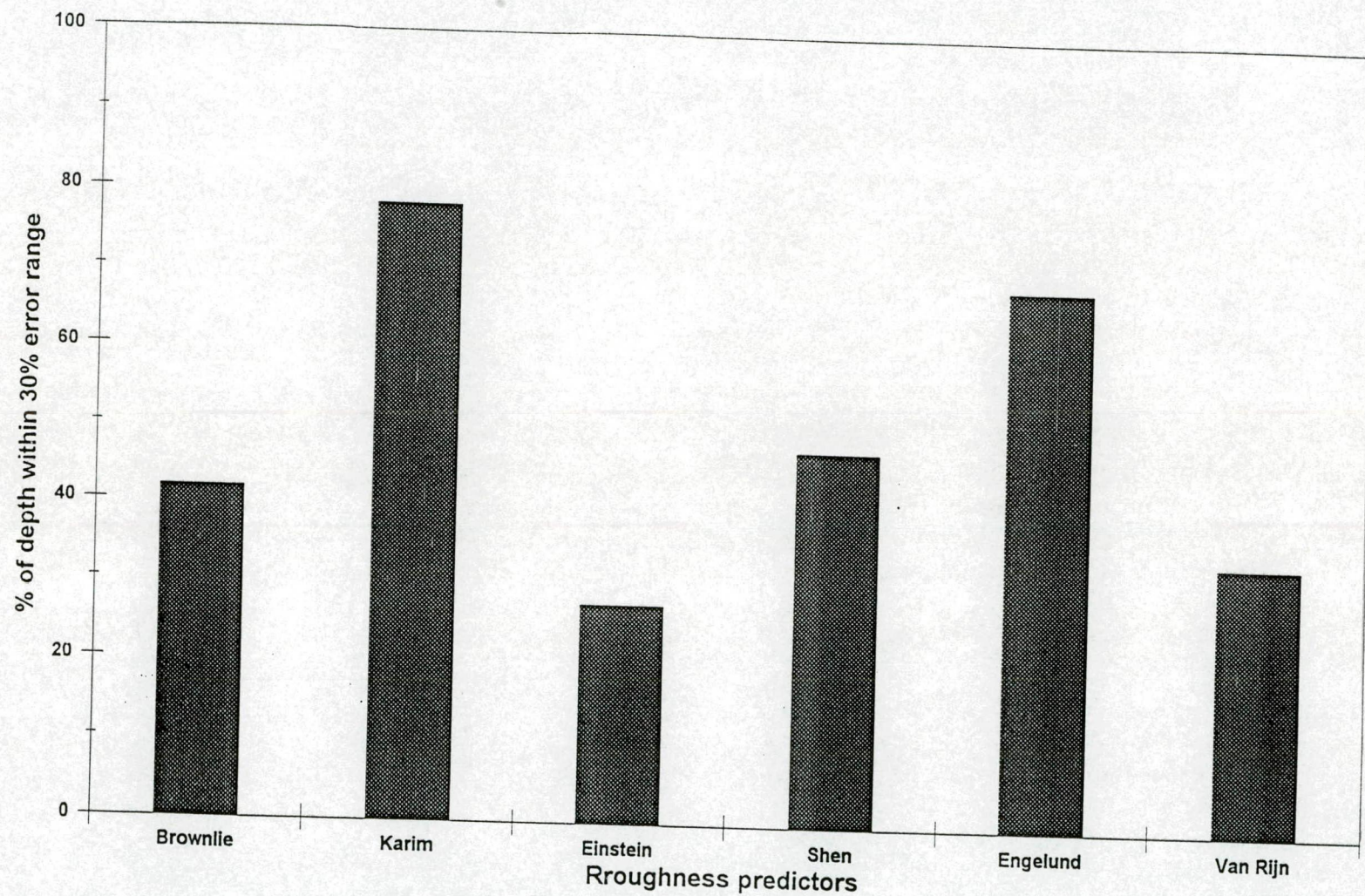


Fig. B.2 Percentage of depths lying within $\pm 30\%$ error ranges predicted by different roughness predictors at Baruria

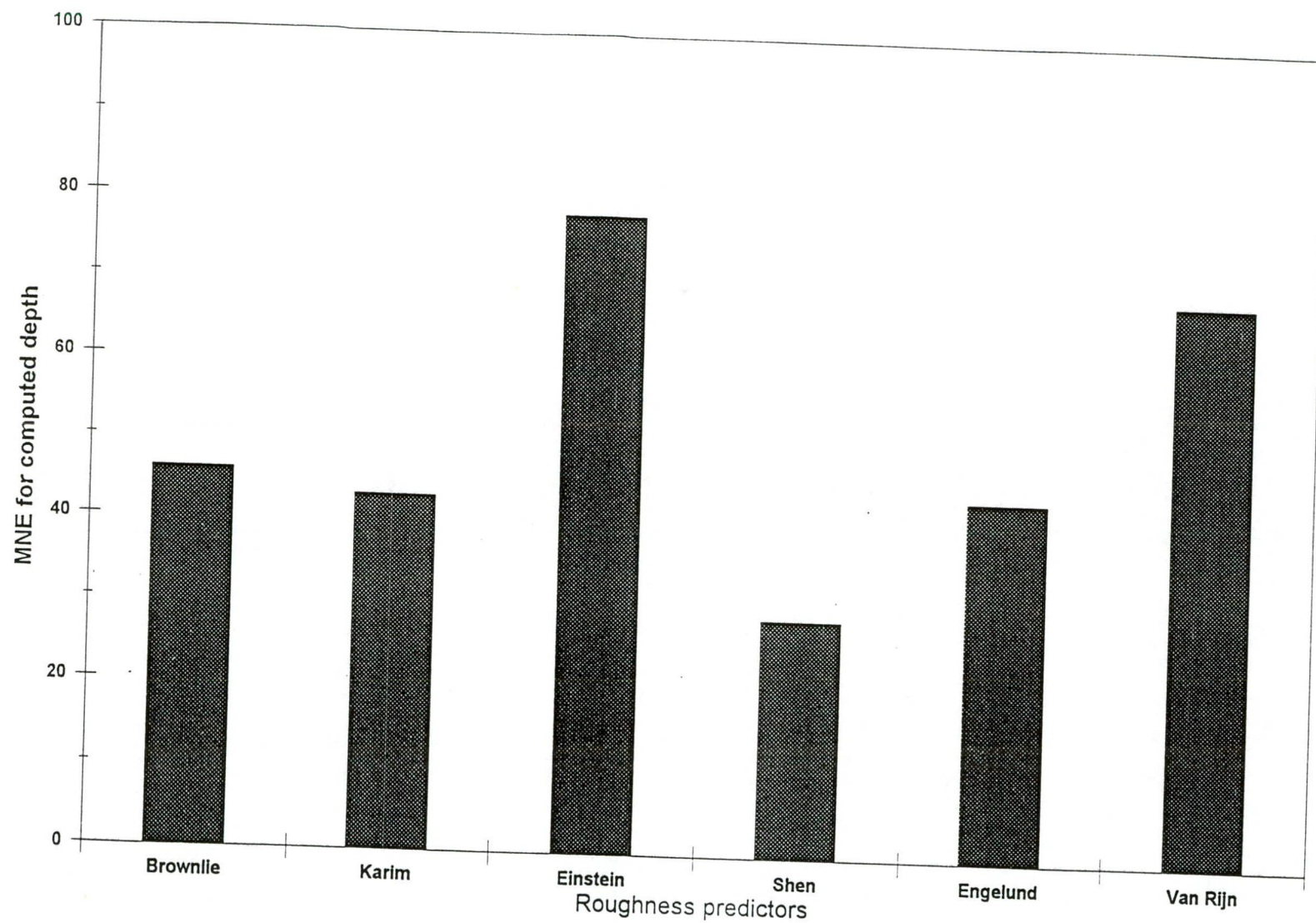


Fig. B.3 The MNE for predicted depths by different roughness predictors at Hardinge Bridge

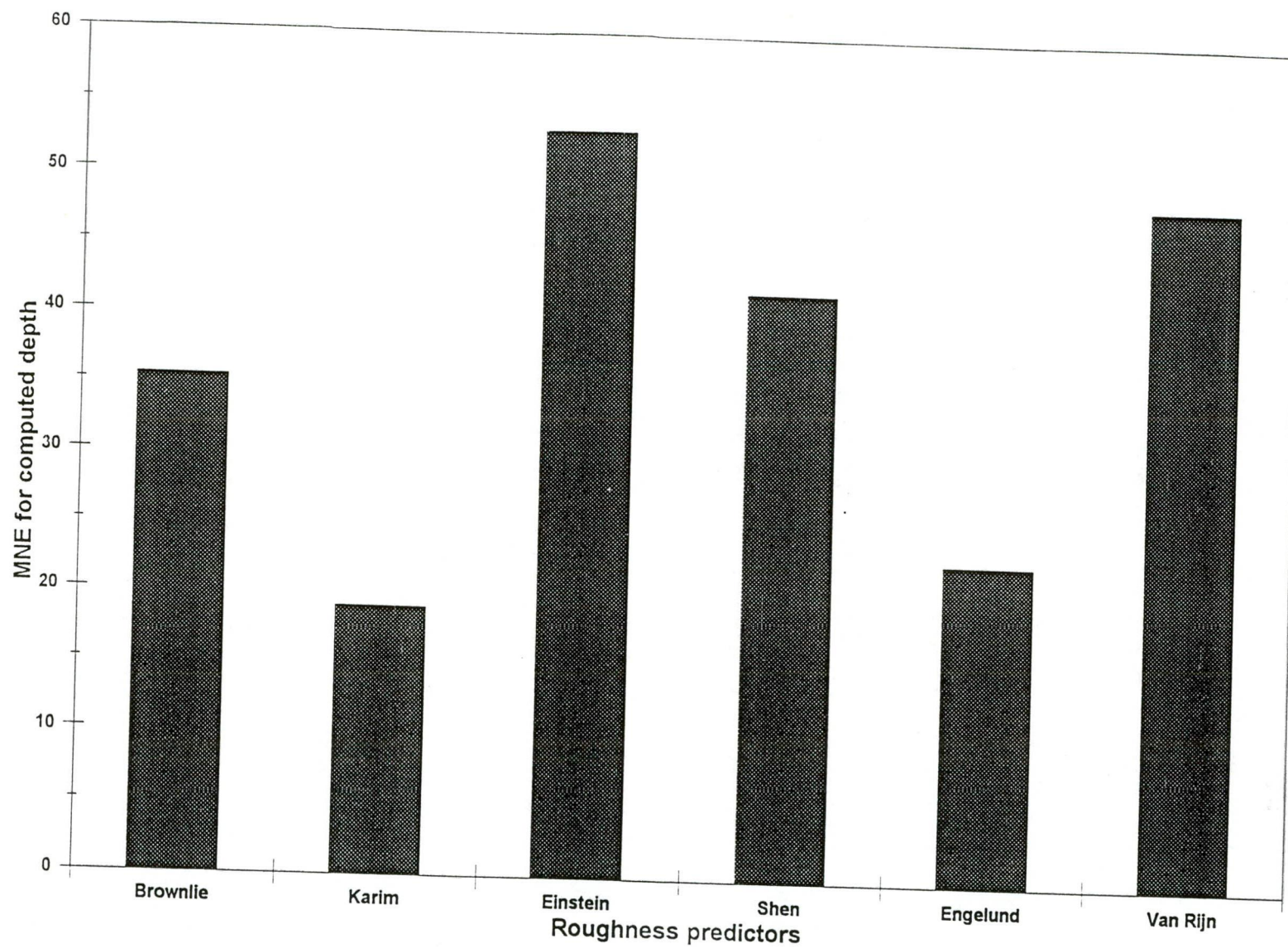


Fig. B.4 The MNE for predicted depths by different roughness predictors at Baruria

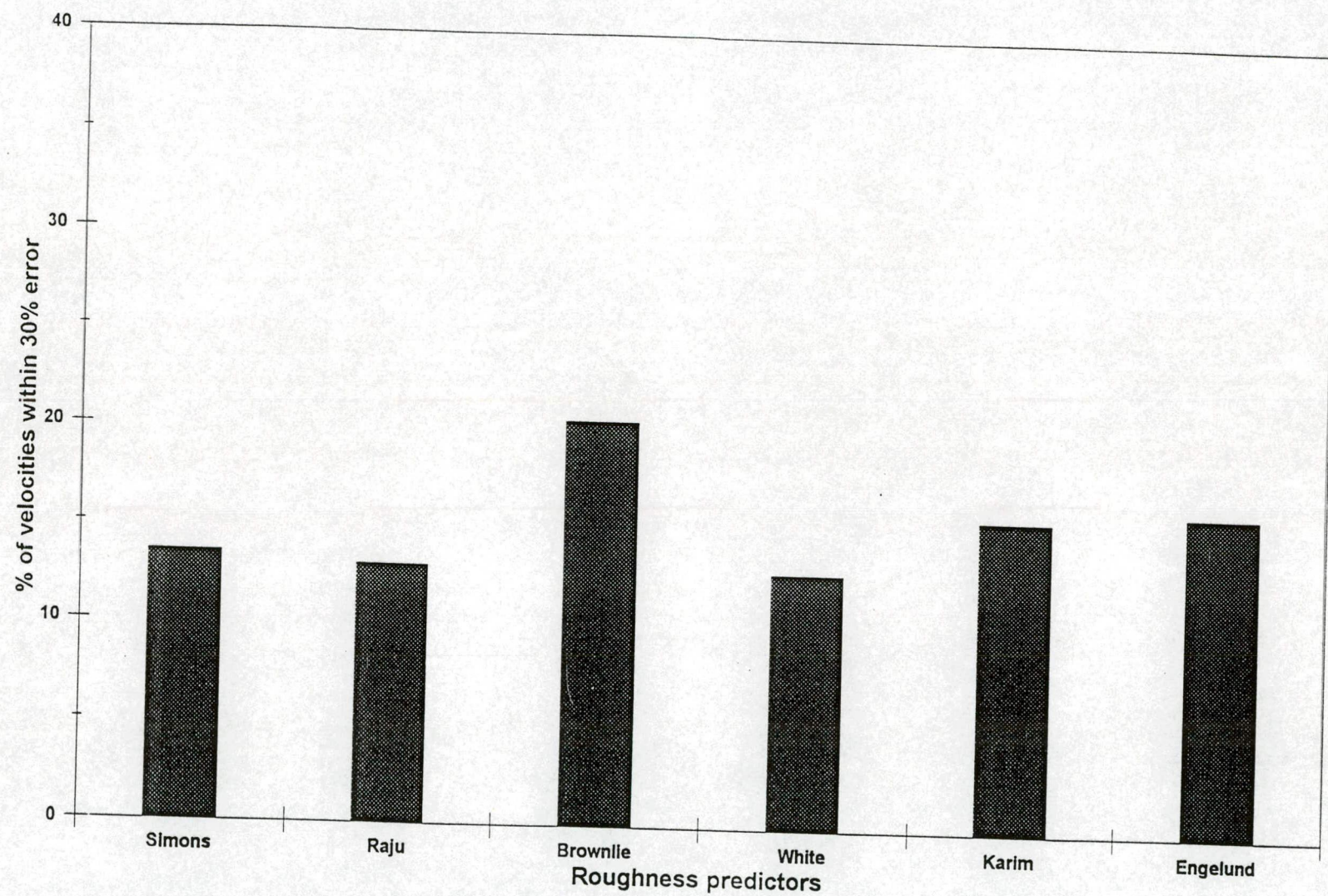


Fig. B.5 Percentage of velocities lying within $\pm 30\%$ error ranges predicted by different roughness predictors at Hardinge Bridge

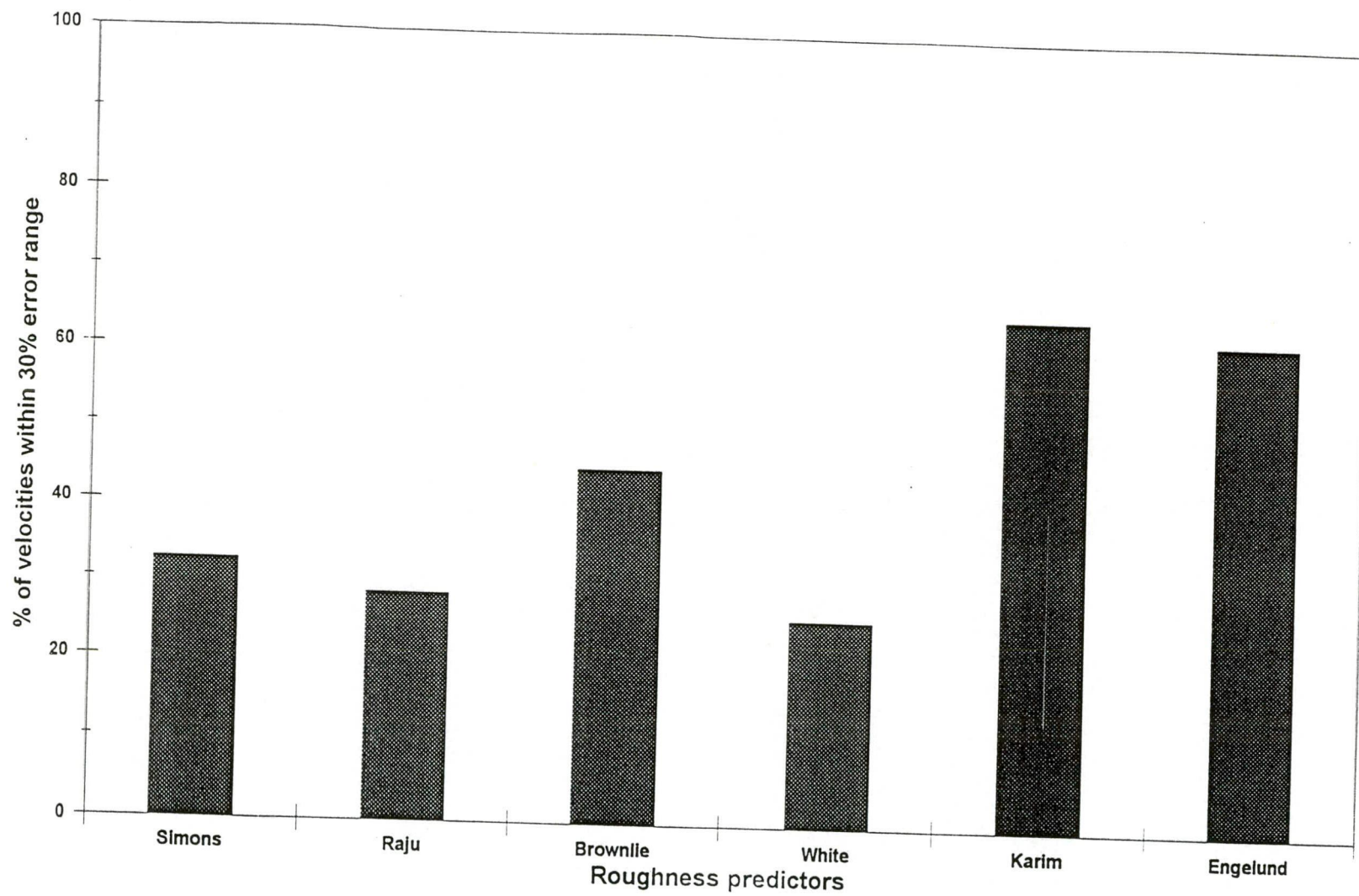


Fig. B.6 Percentage of velocities lying within 30% error ranges predicted by different roughness predictors at Baruria

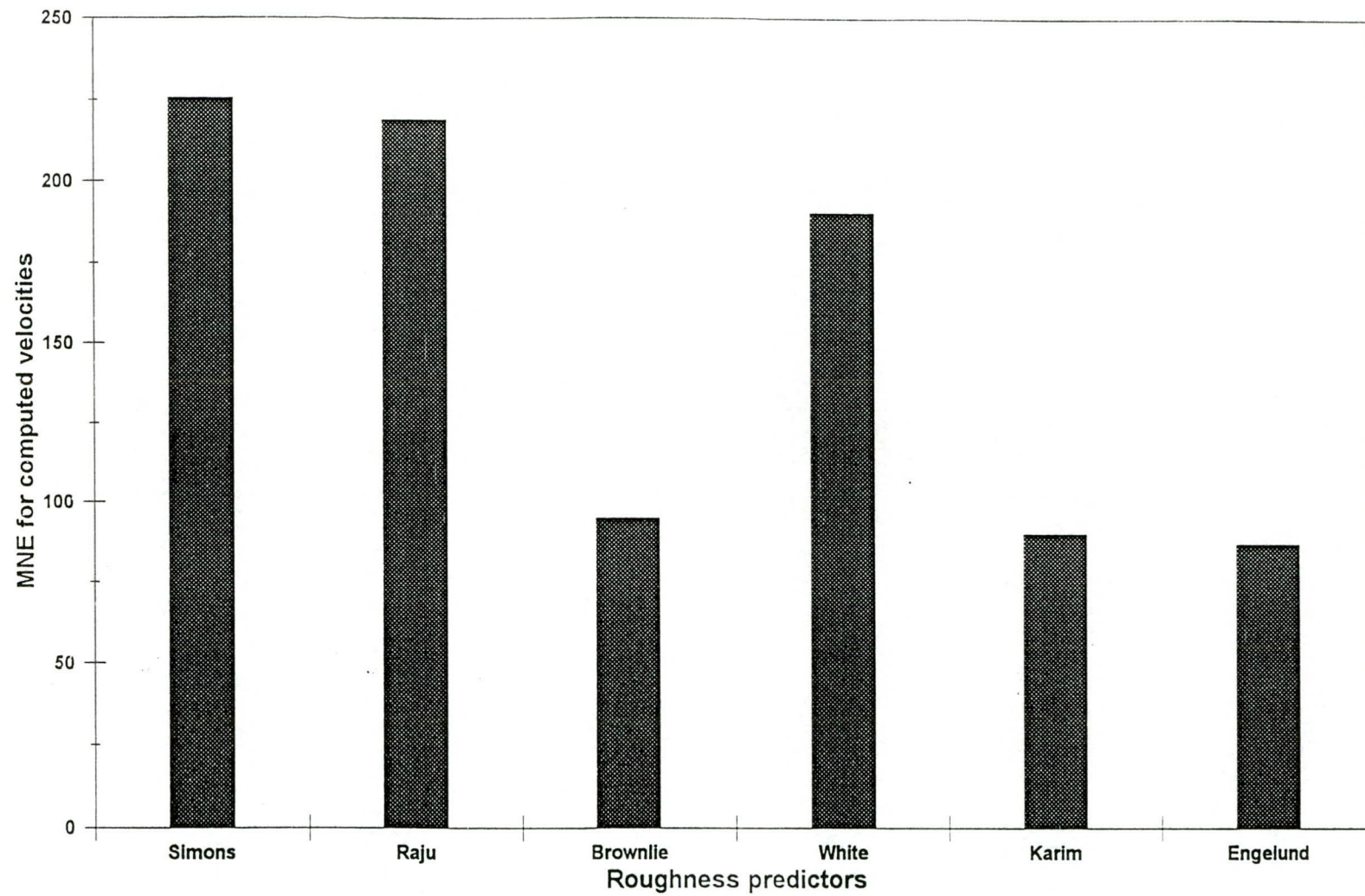


Fig. B.7 The MNE for velocities predicted by different roughness predictors at Hardinge Bridge

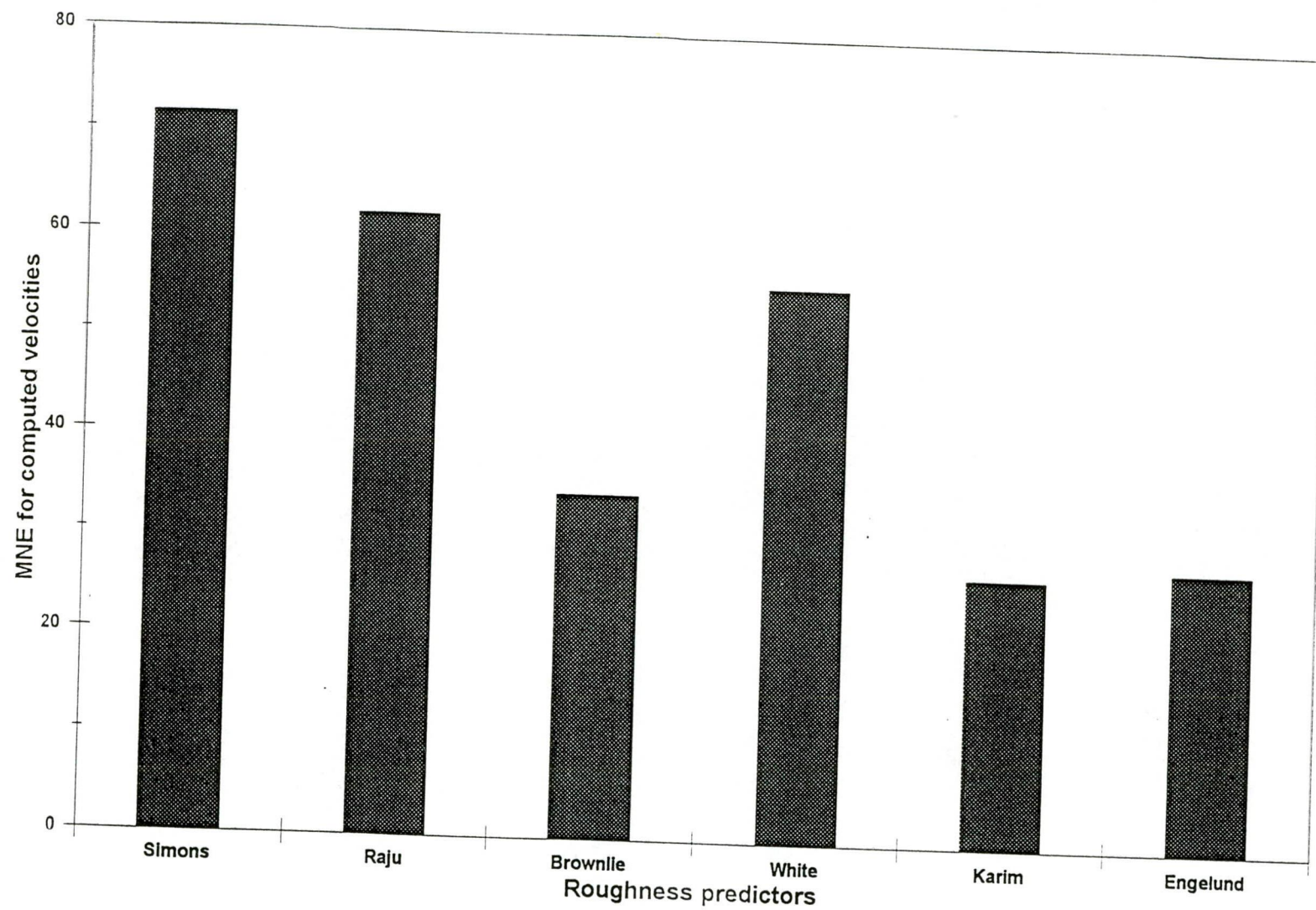


Fig. B.8 The MNE for velocities predicted by different roughness predictors at Baruria

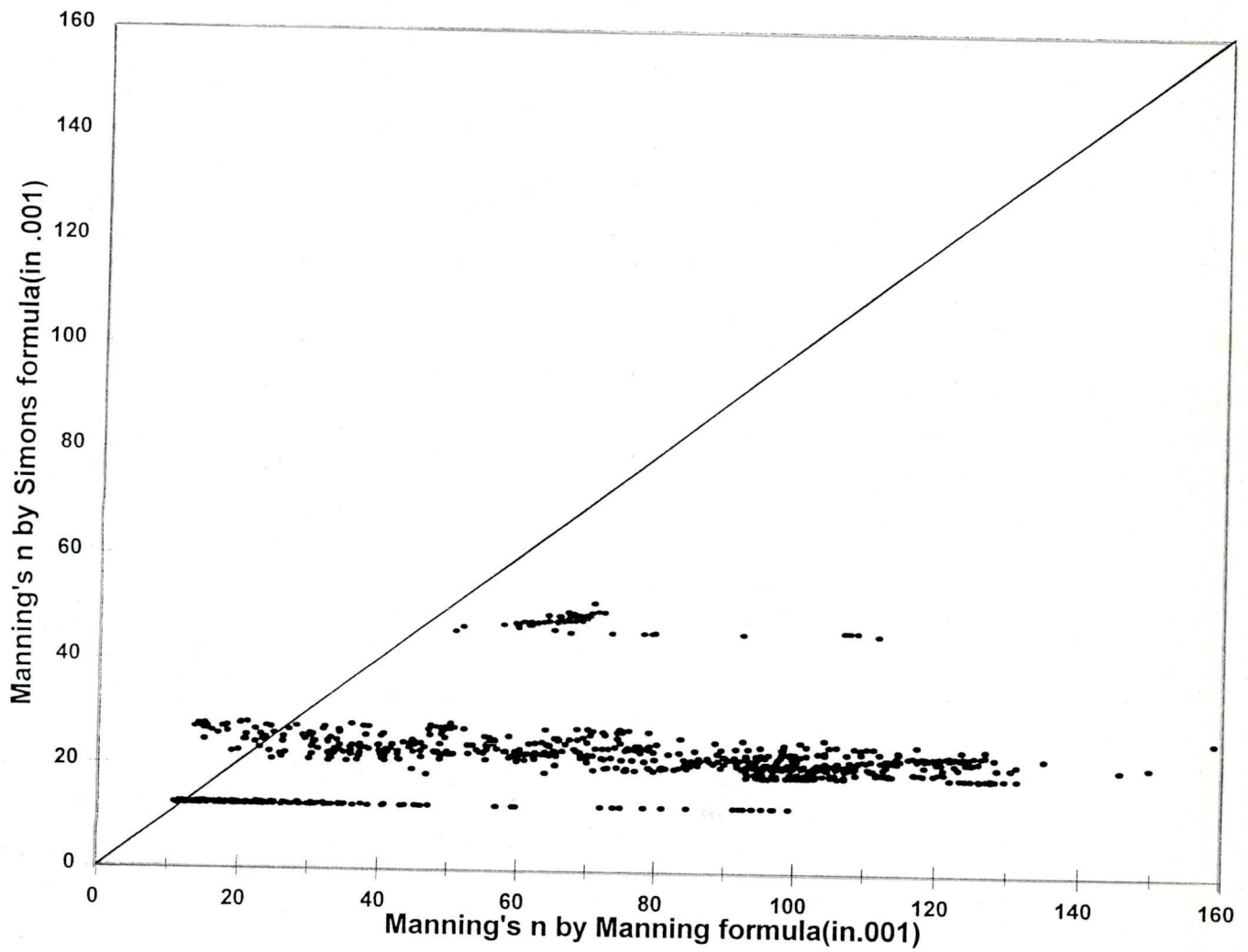


Fig. B.9 Comparison between the values of Manning's n computed by Manning formula and Simons and Richardson (1966) method at Hardinge Bridge

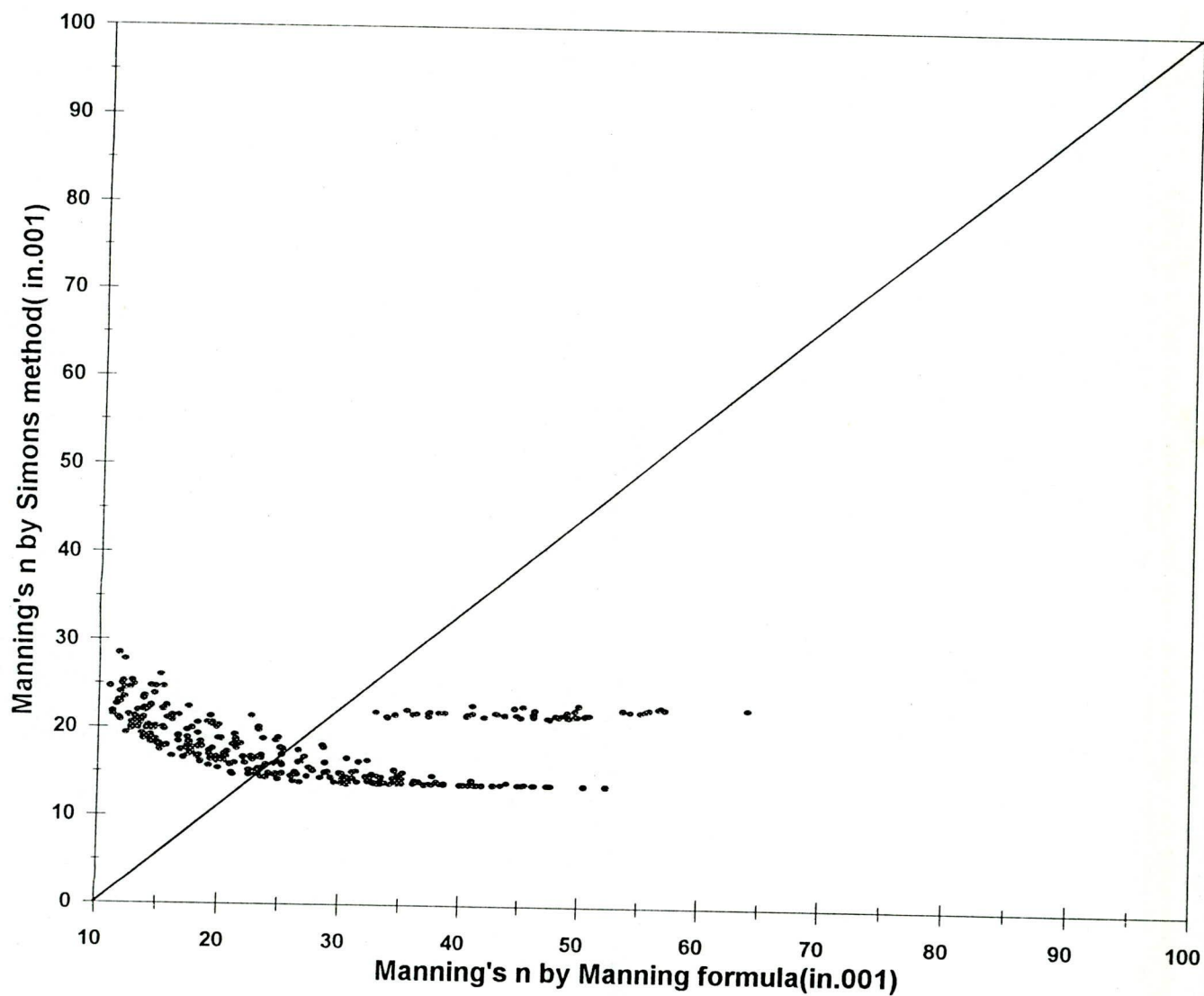


Fig. B.10 Comparison between the values of Manning's n computed by Manning formula and Simons and Richardson (1966) method at Baruria

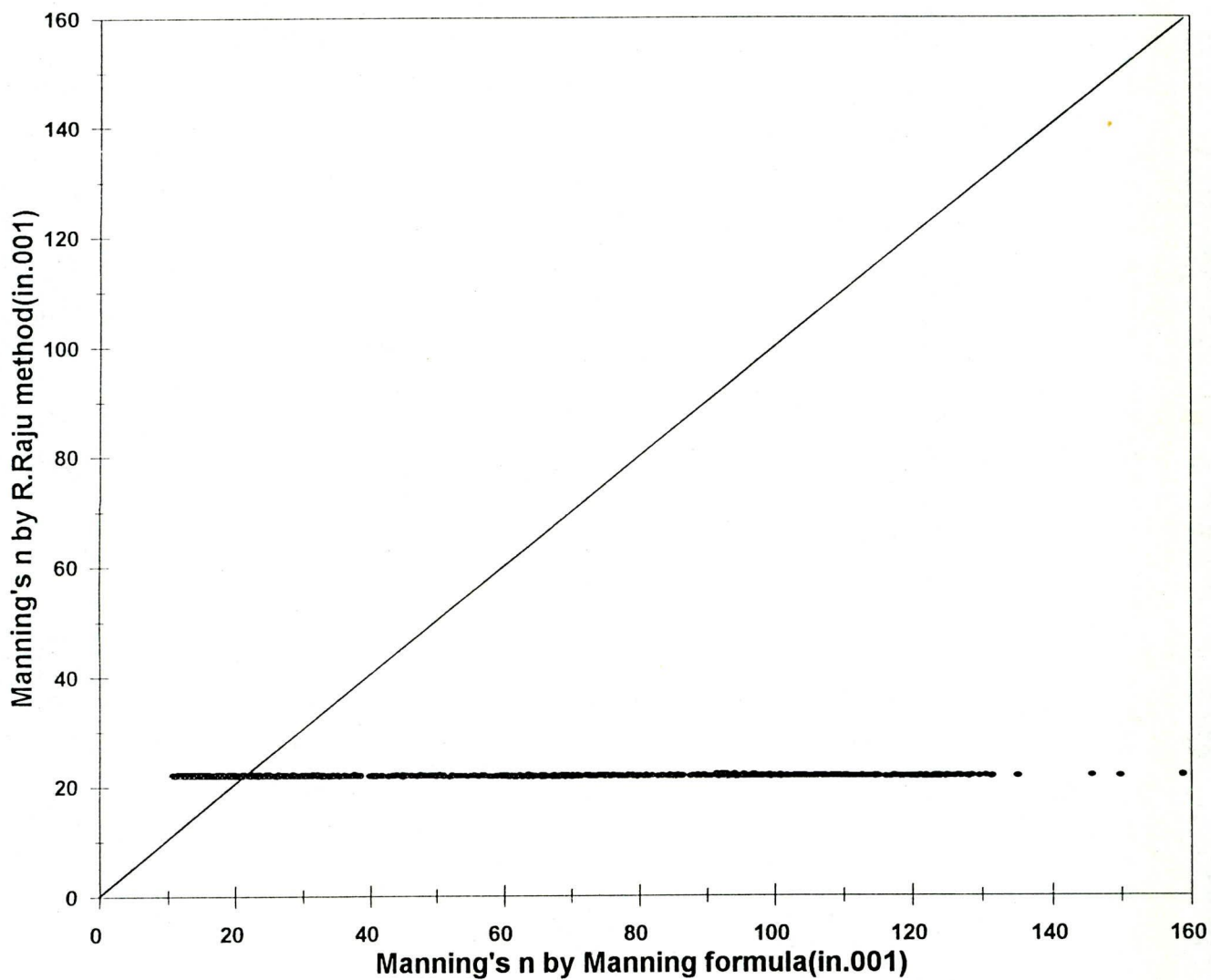


Fig. B.11 Comparison between the values of Manning's n computed by Manning formula and Garde and Ranga Raju (1970) method at Hardinge Bridge

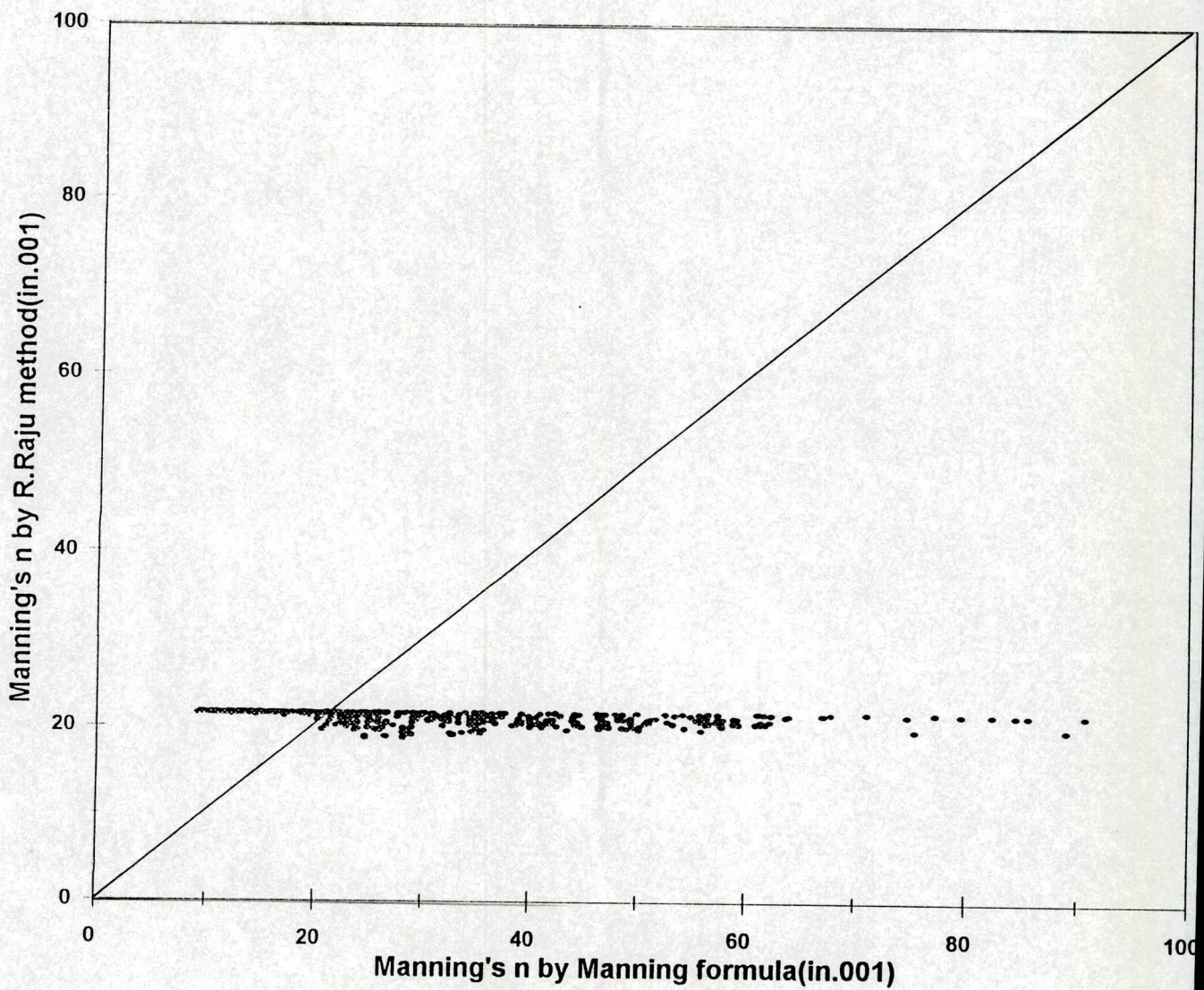


Fig. B.12 Comparison between the values of Manning's n computed by Manning formula and Garde and Ranga Raju (1970) method at Baruria

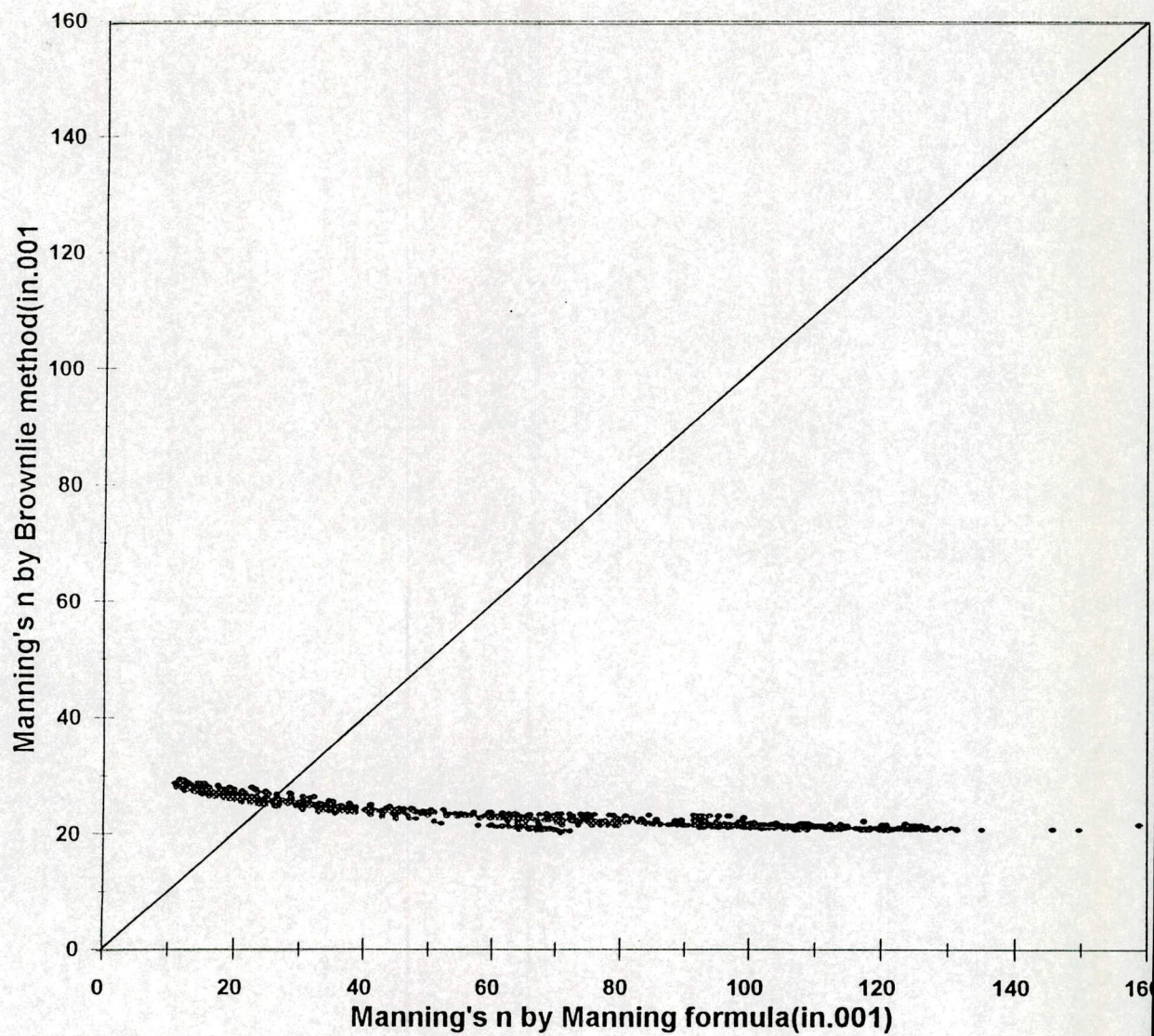


Fig. B.13 Comparison between the values of Manning's n computed by Manning formula and Brownlie (1983) method at Hardinge Bridge

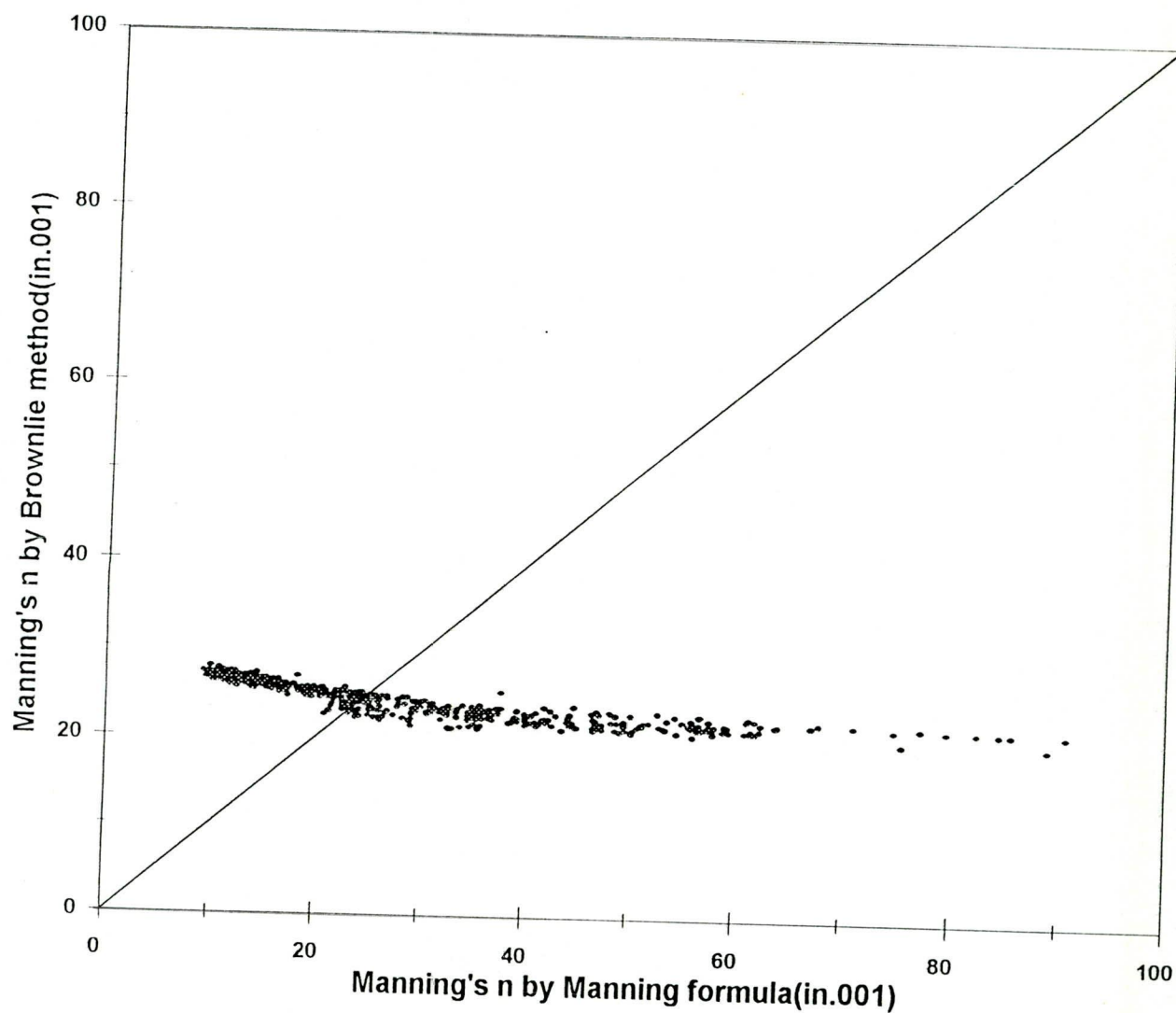


Fig. B.14 Comparison between the values of Manning's n computed by Manning formula and Brownlie (1983) method at Baruria

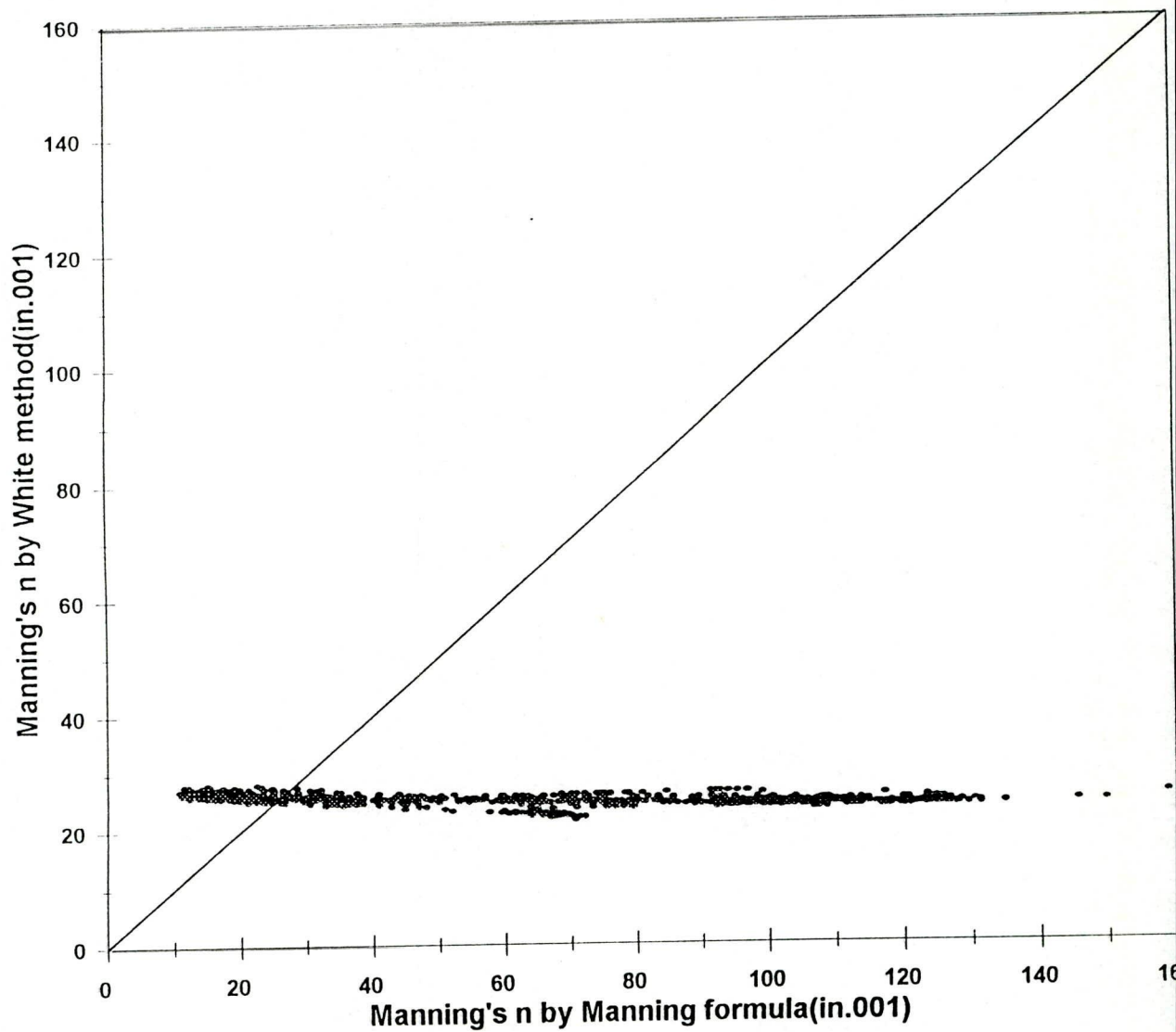


Fig. B.15 Comparison between the values of Manning's n computed by Manning formula and White et al. (1987) method at Hardinge Bridge

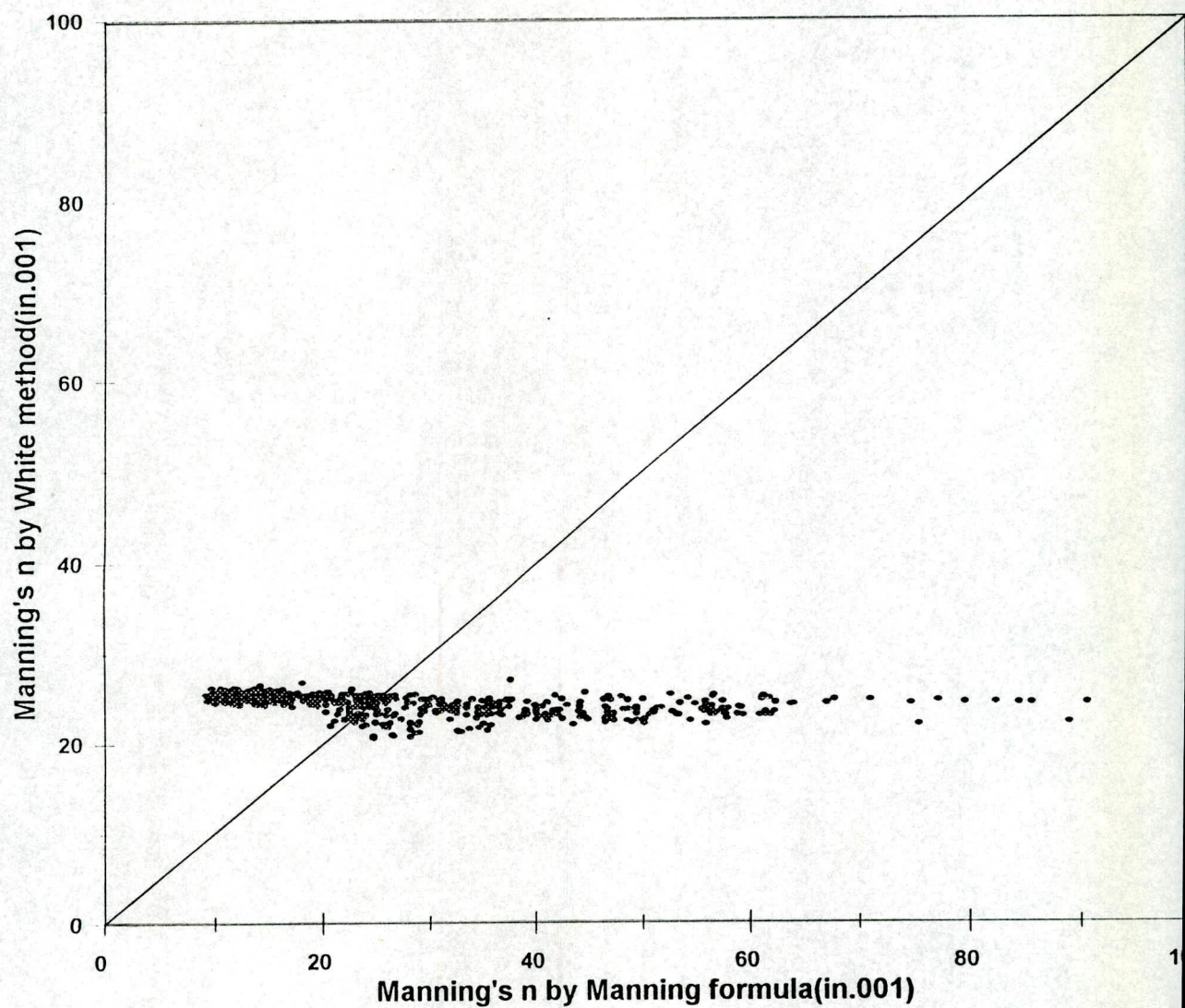


Fig. B.16 Comparison between the values of Manning's n computed by Manning formula and White et al. (1987) method at Baruria

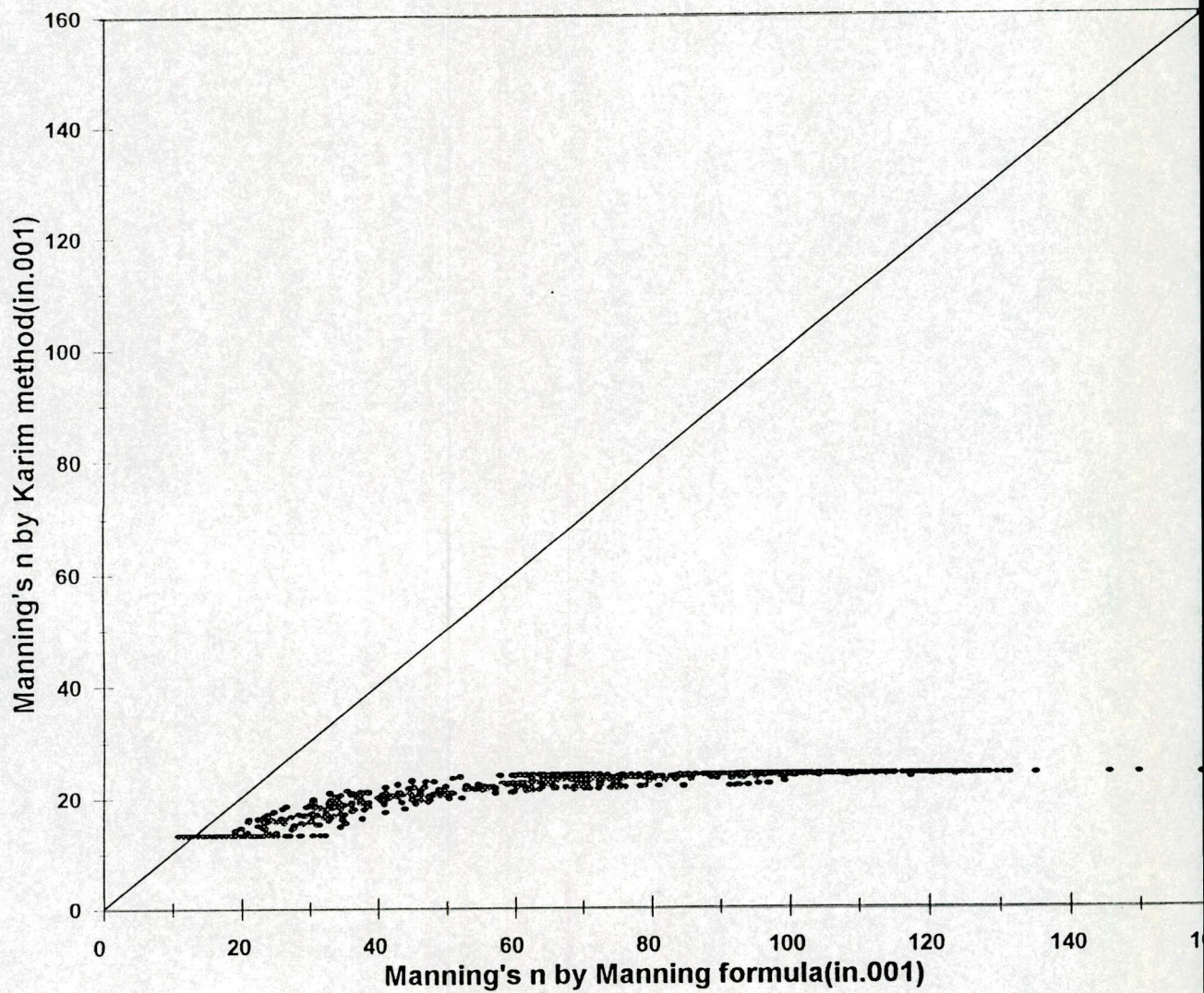


Fig. B.17 Comparison between the values of Manning's n computed by Manning formula and Karim (1995) method at Hardinge Bridge

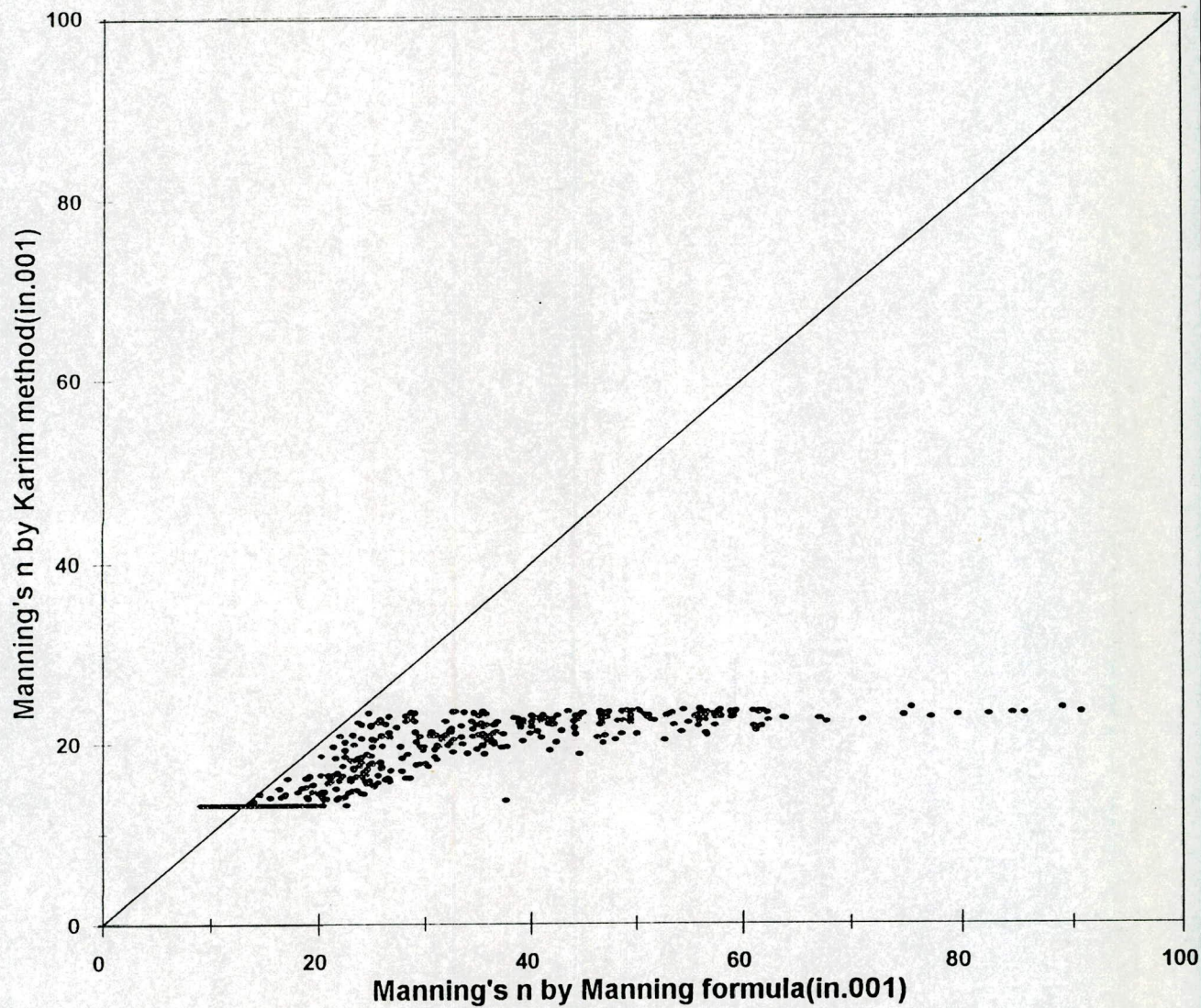


Fig. B.18 Comparison between the values of Manning's n computed by Manning formula and Karim (1995) method at Baruria

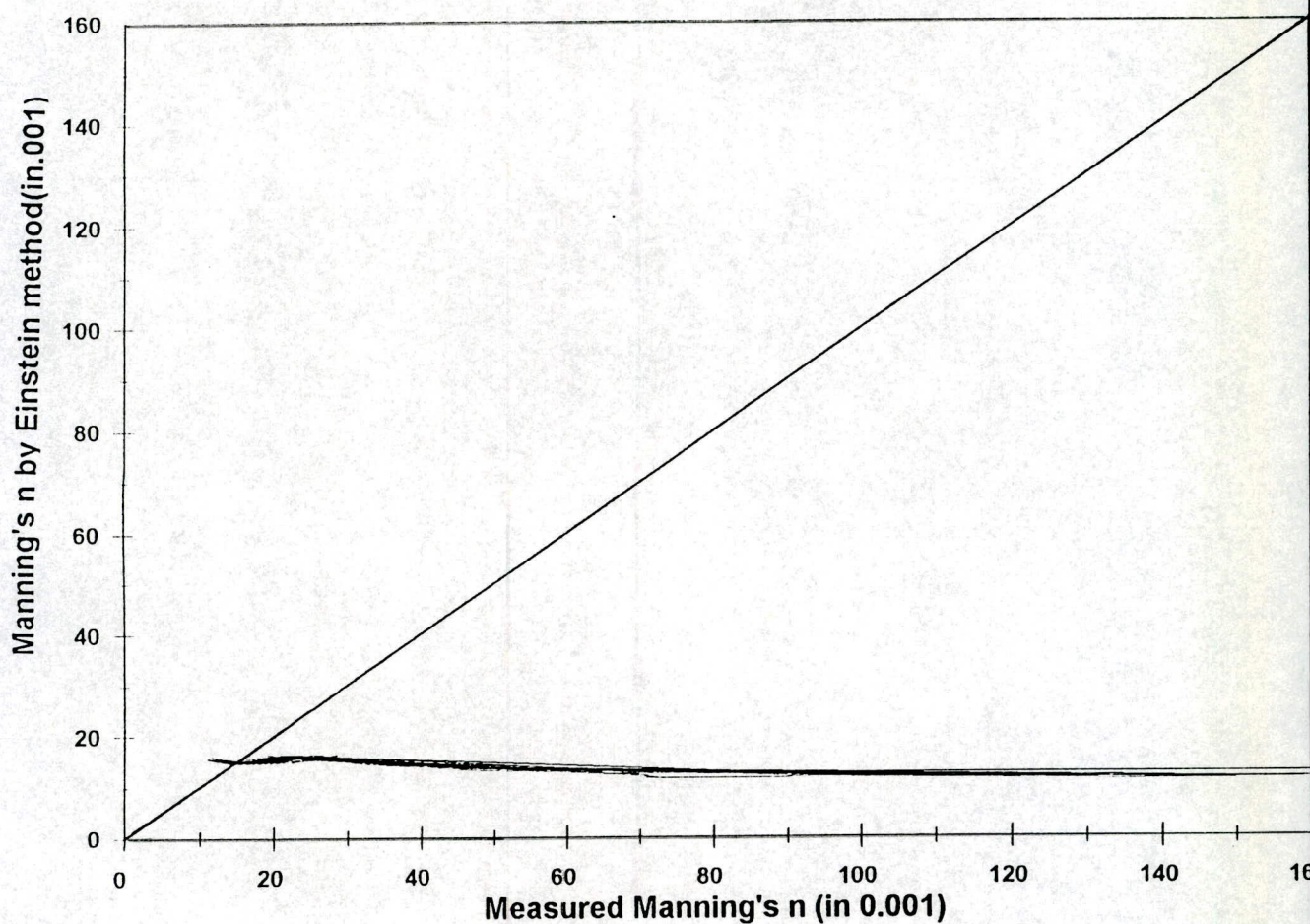


Fig. B.19 Comparison between the values of Manning's n computed by Manning formula and Einstein-Barbarossa (1952) method at Hardinge Bridge

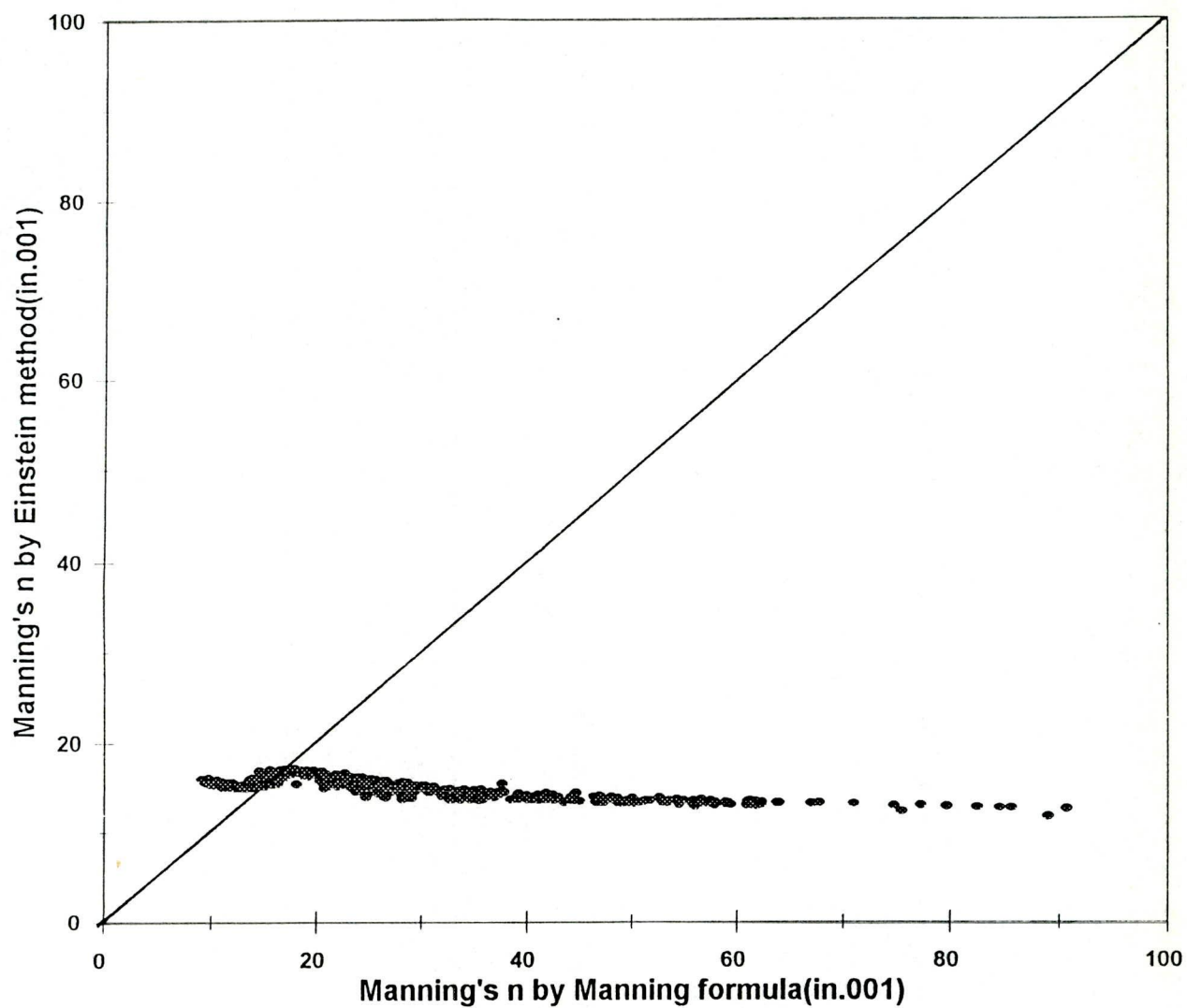


Fig. B.20 Comparison between the values of Manning's n computed by Manning formula and Einstein-Barbarossa (1952) method at Baruria

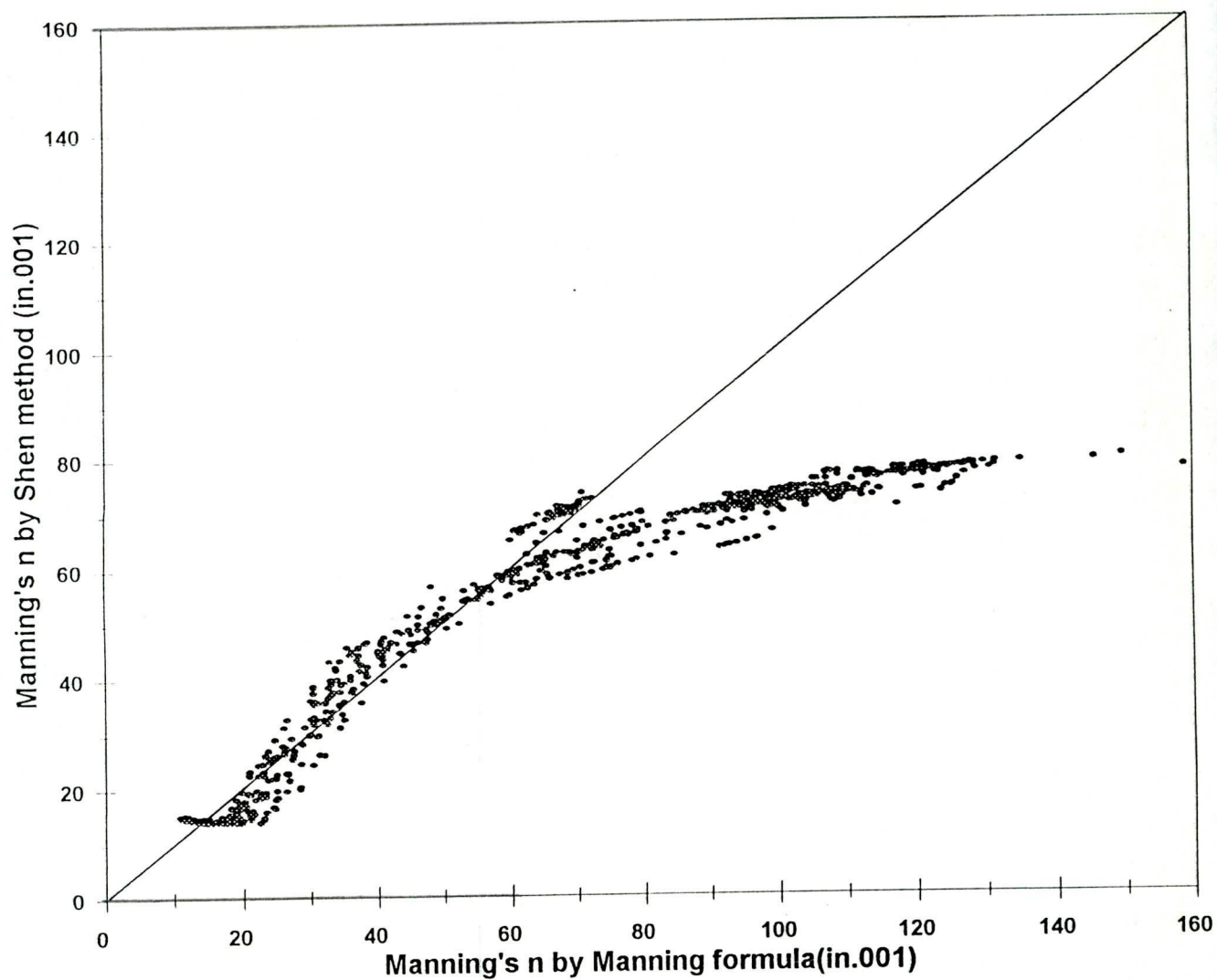


Fig. B.21 Comparison between the values of Manning's n computed by Manning formula and Shen (1962) method at Harding Bridge

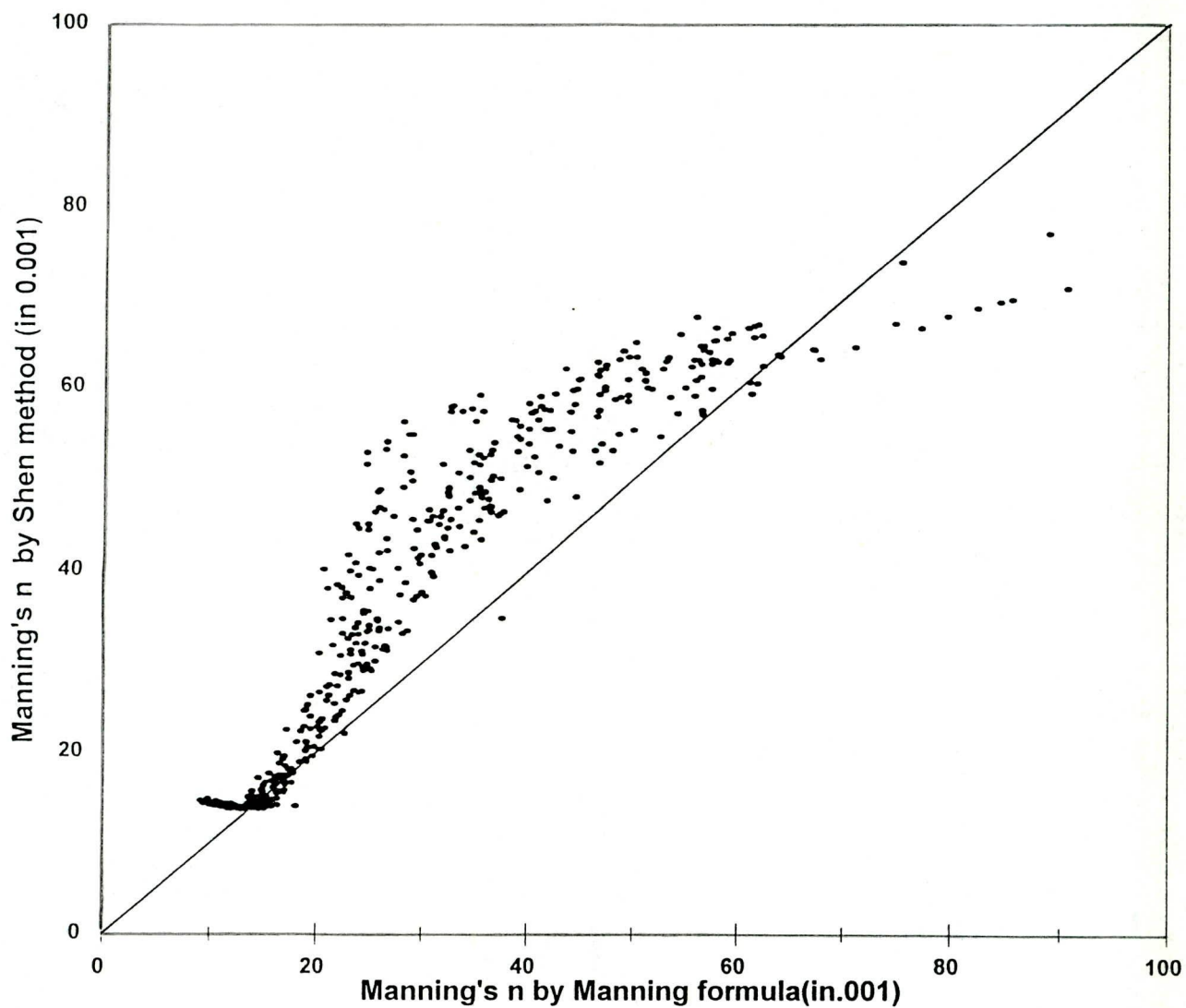


Fig. B.22 Comparison between the values of Manning's n computed by Manning formula and Shen (1962) method at Baruria

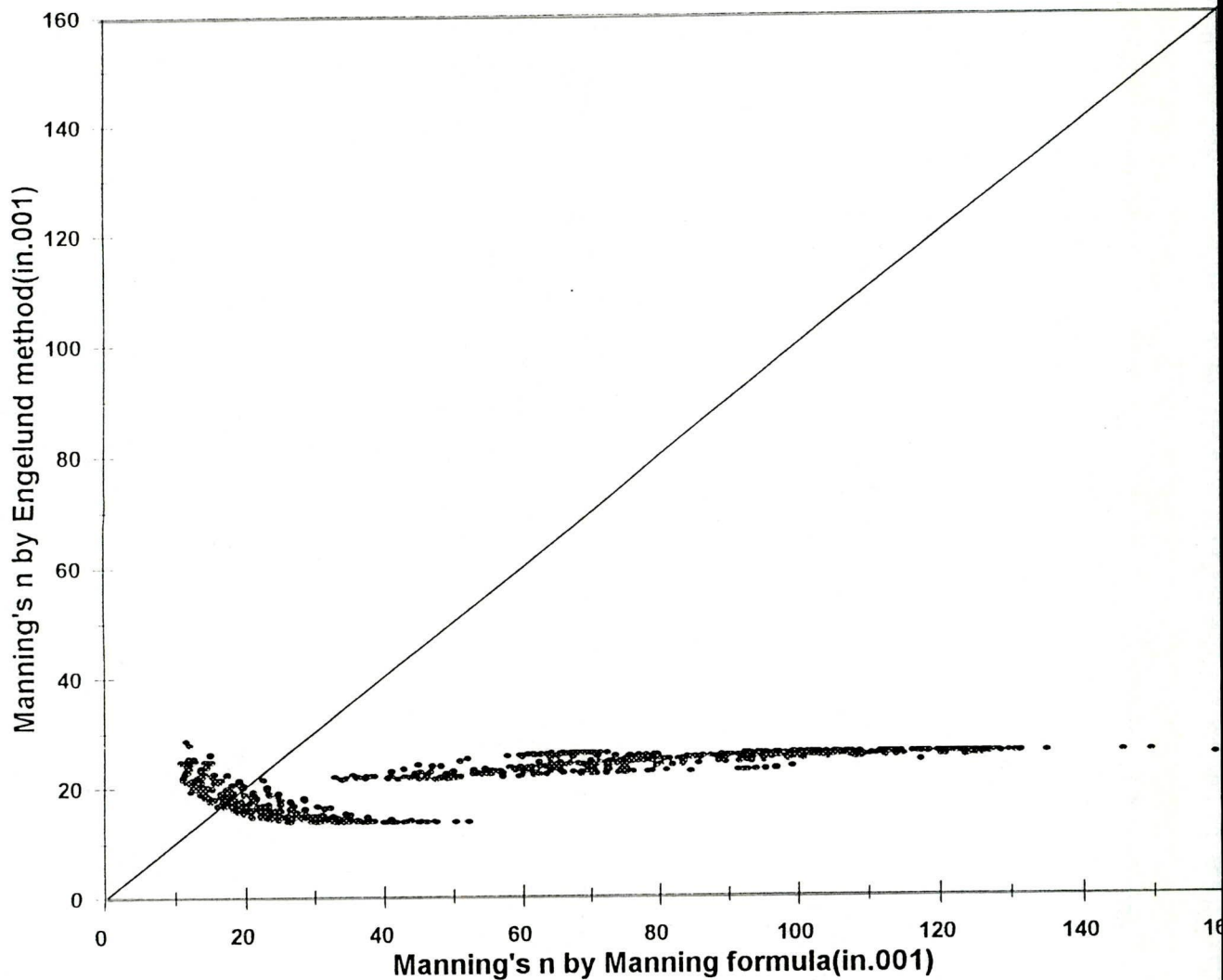


Fig. B.23 Comparison between the values of Manning's n computed by Manning formula and Engelund-Hansen (1967) method at Hardinge Bridge

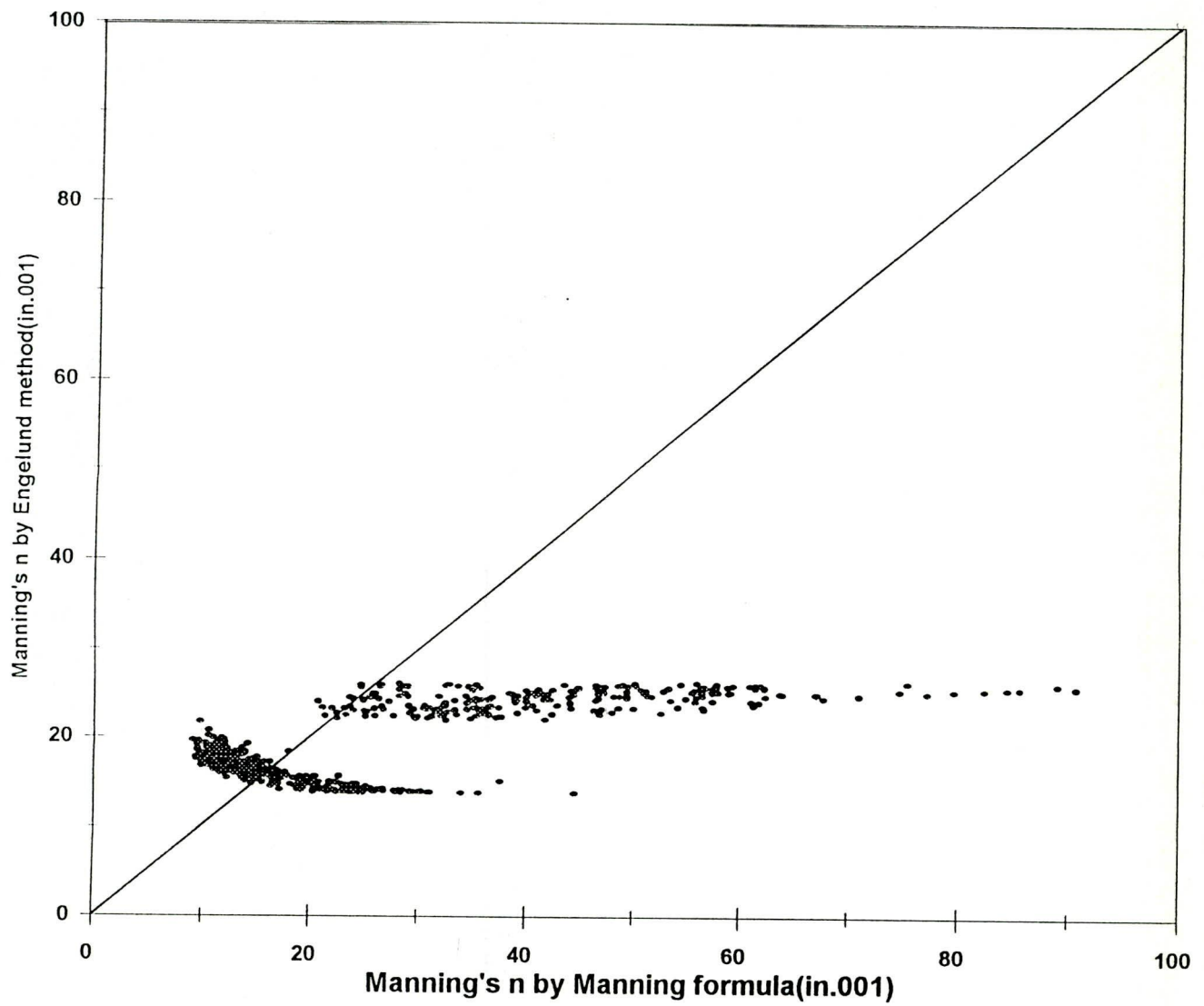


Fig. B.24 Comparison between the values of Manning's n computed by Manning formula and Engelund-Hansen (1967) method at Baruria

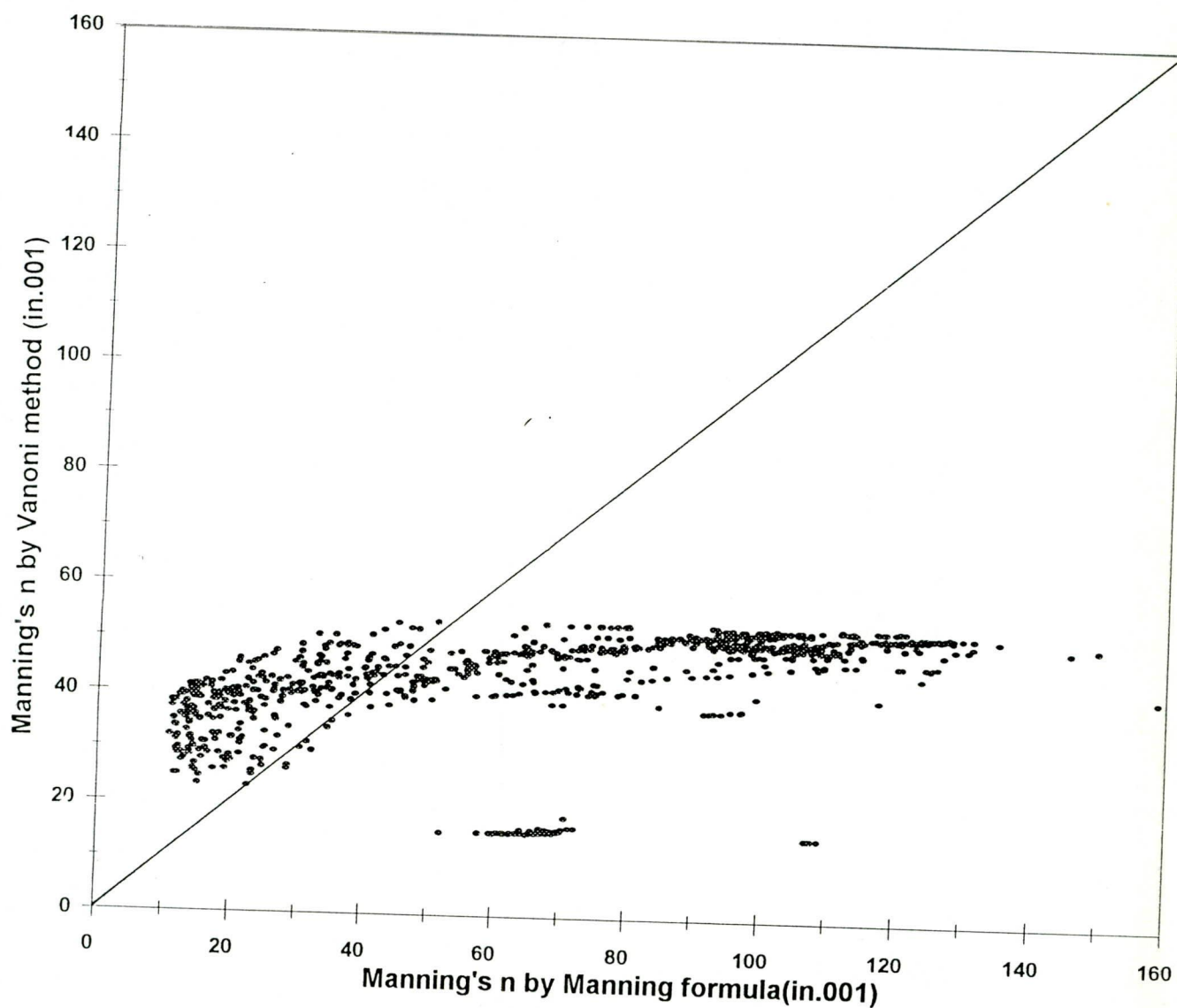


Fig. B.25 Comparison between the values of Manning's n computed by Manning formula and Vanoni and Hwang (1967) method with bed form dimensions by Vajda (1990) at Hardinge Bridge

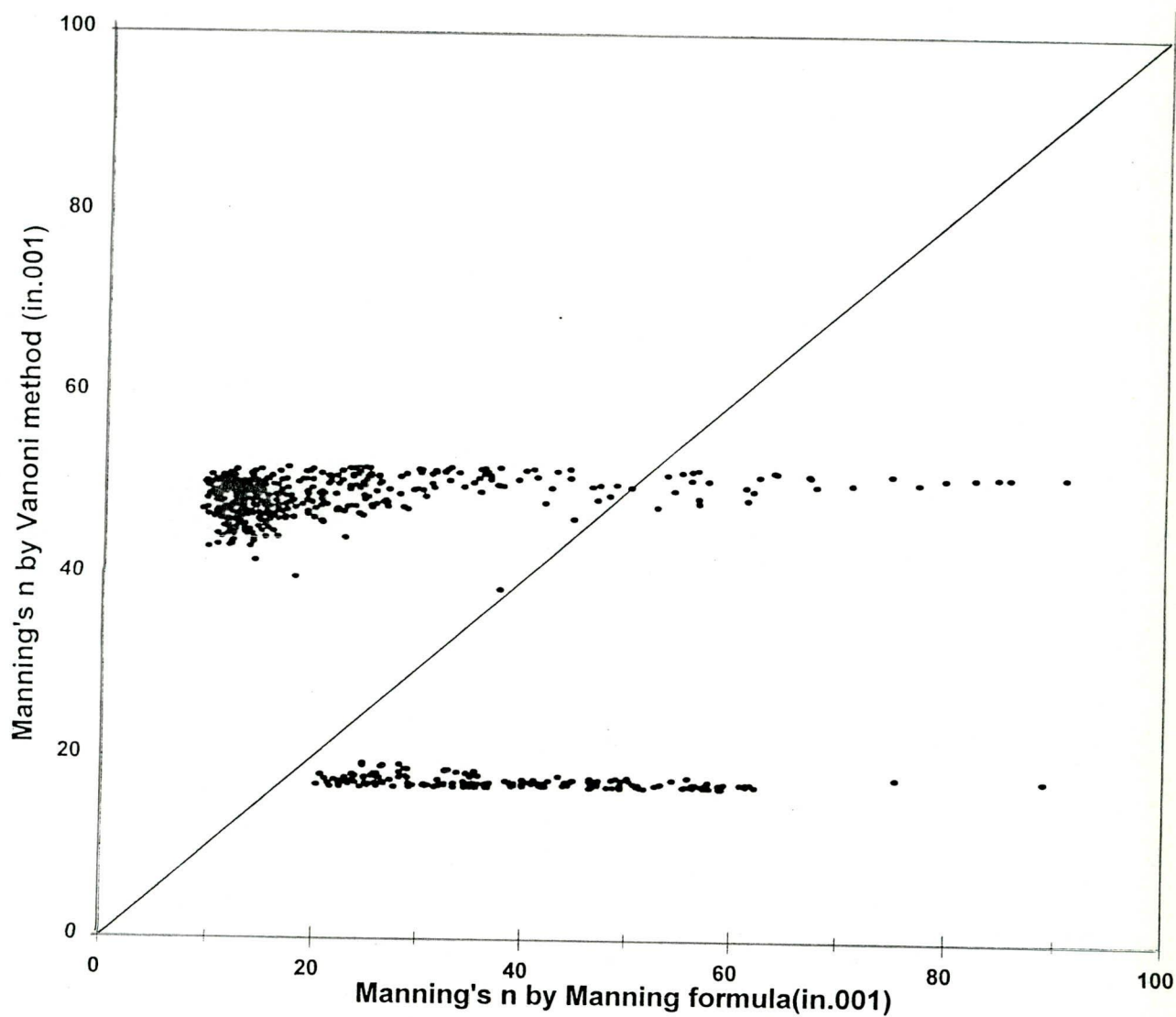


Fig. B.26 Comparison between the values of Manning's n computed by Manning formula and Vanoni and Hwang (1967) method with bed form dimensions by Vajda (1990) at Baruria

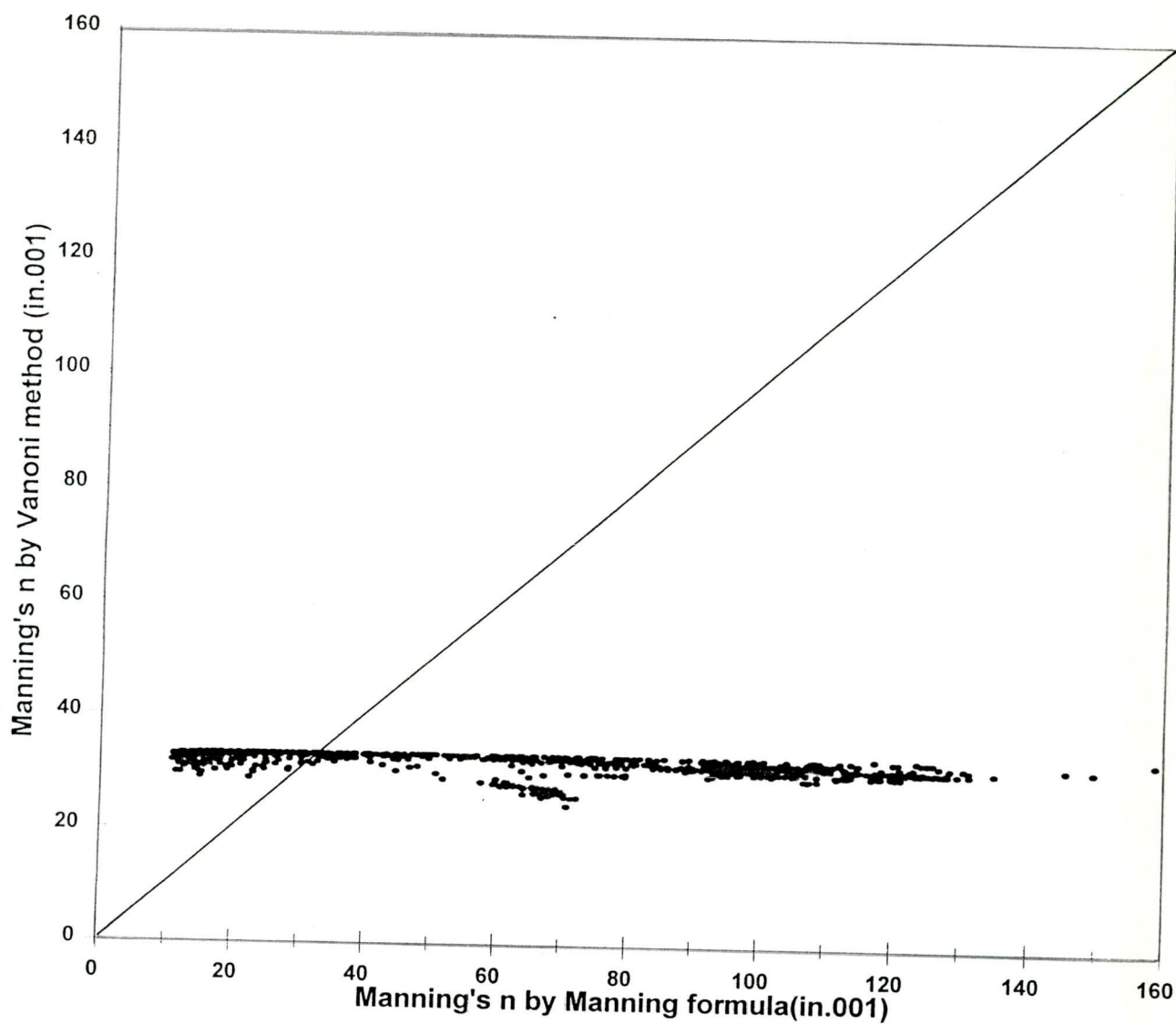


Fig. B.27 Comparison between the values of Manning's n computed by Manning formula and Vanoni and Hwang (1967) method with bed form dimensions by Yalin (1992) at Hardinge Bridge

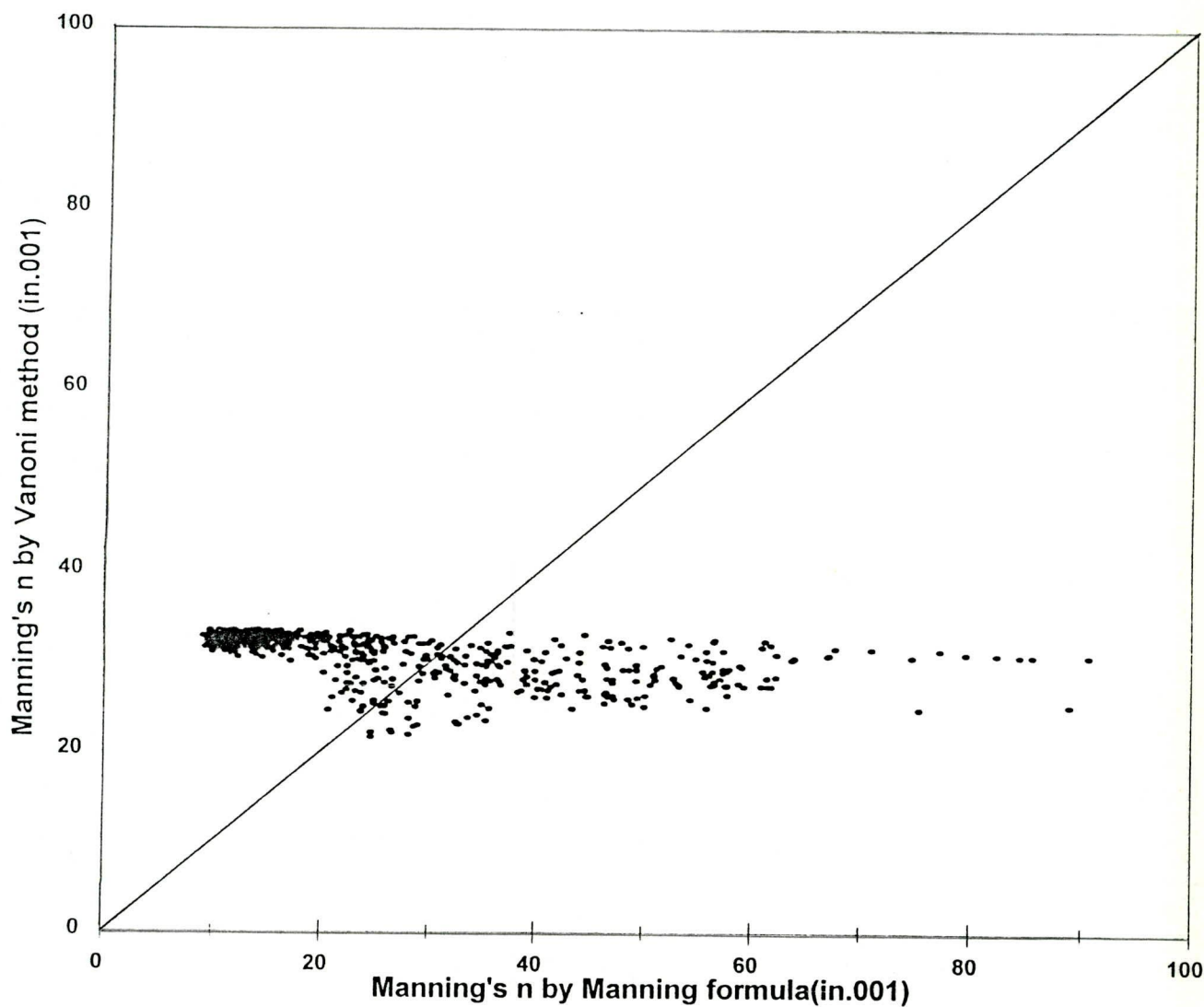


Fig. B.28 Comparison between the values of Manning's n computed by Manning formula and Vanoni and Hwang (1967) method with bed form dimensions by Yalin (1992) at Baruria

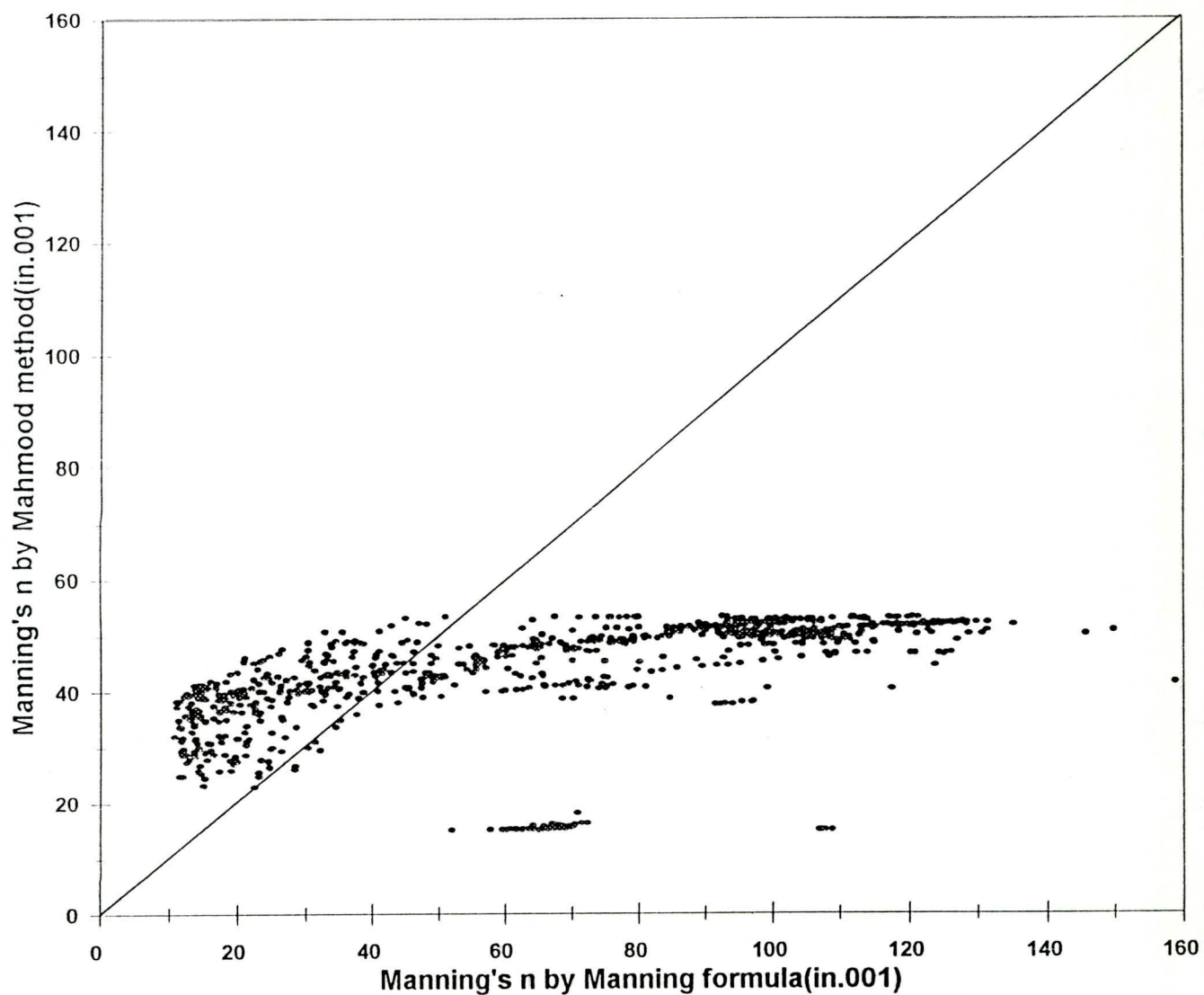


Fig. B.29 Comparison between the values of Manning's n computed by Manning formula and Haque and Mahmood (1983) method with bed form dimensions by Vajda (1990) at Hardinge Bridge

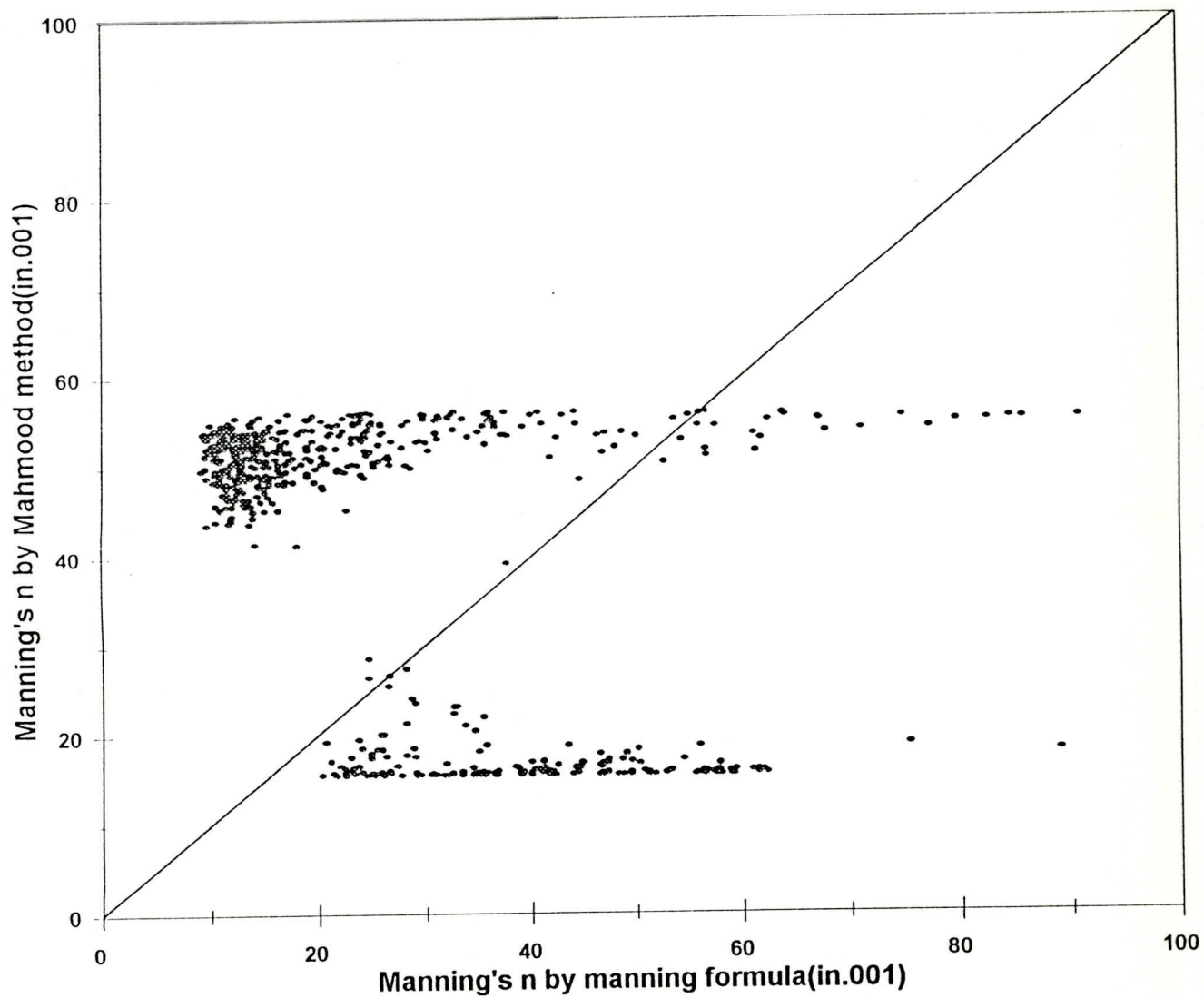


Fig. B.30 Comparison between the values of Manning's n computed by Manning formula and Haque and Mahmood (1983) method with bed form dimensions by Vajda (1990) at Baruria

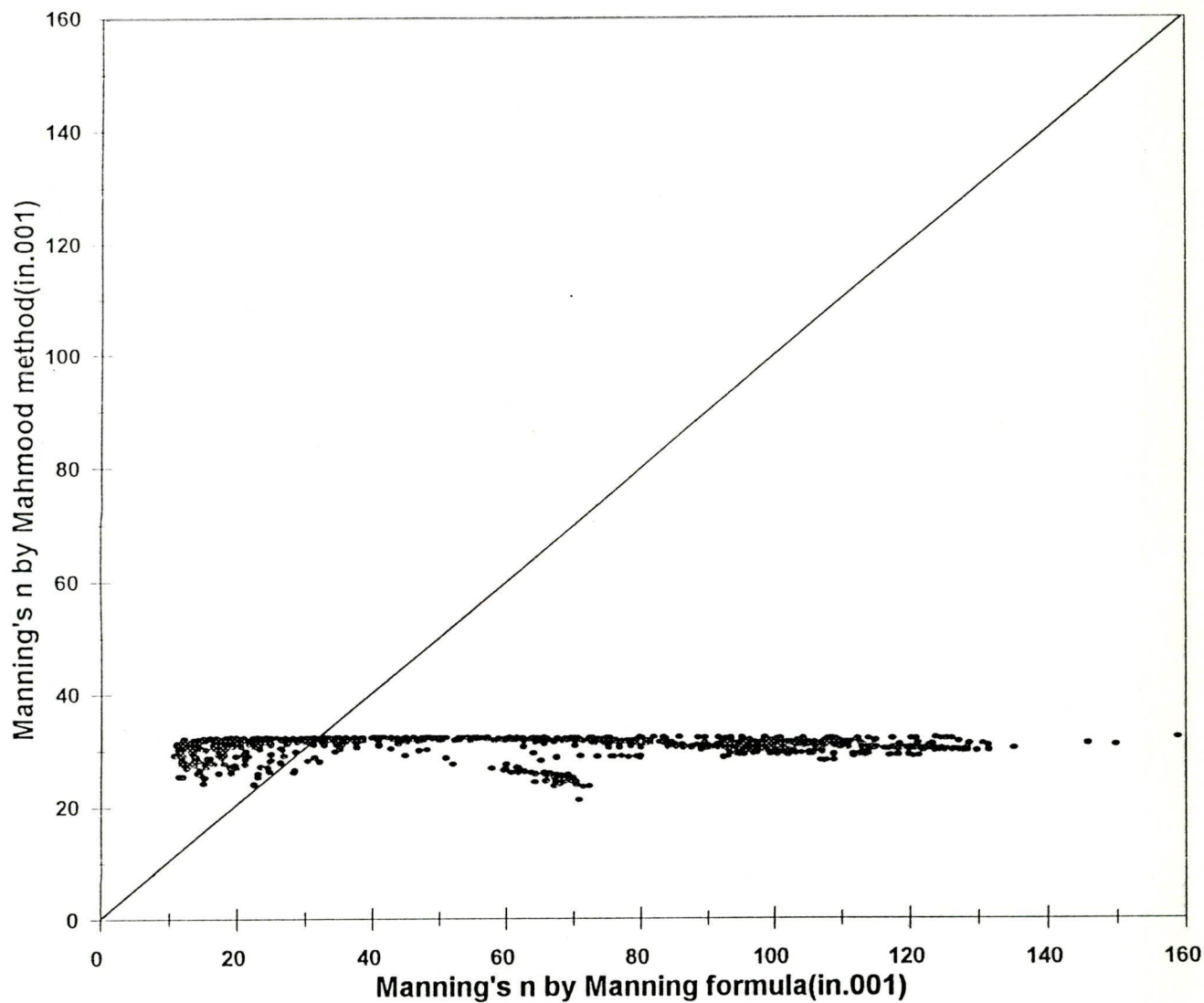


Fig. B.31 Comparison between the values of Manning's n computed by Manning formula and Haque and Mahmood (1983) method with bed form dimensions by Yalin (1992) at Hardinge Bridge

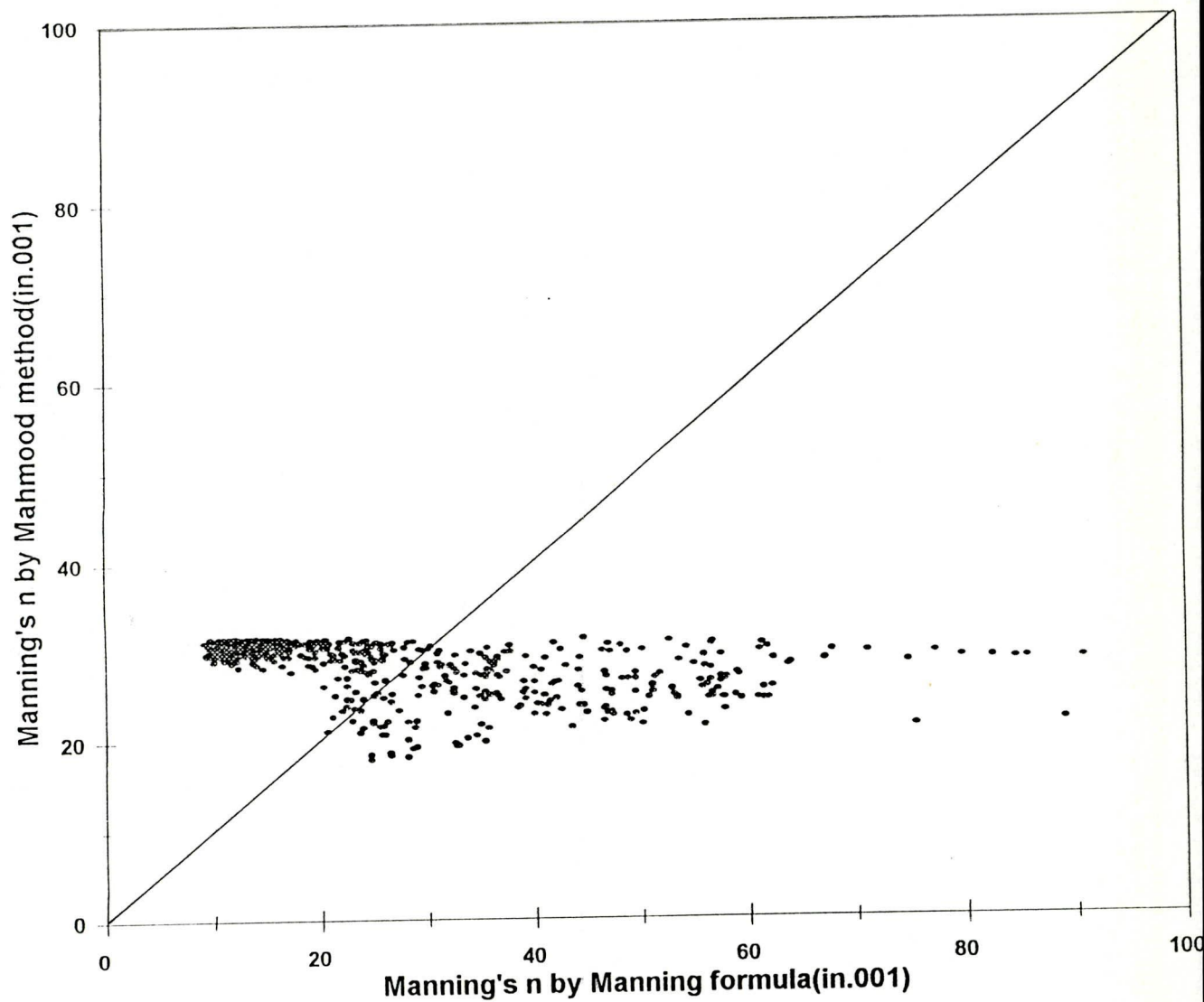


Fig. B.32 Comparison between the values of Manning's n computed by Manning formula and Haque and Mahmood (1983) method with bed form dimensions by Yalin (1992) at Baruria

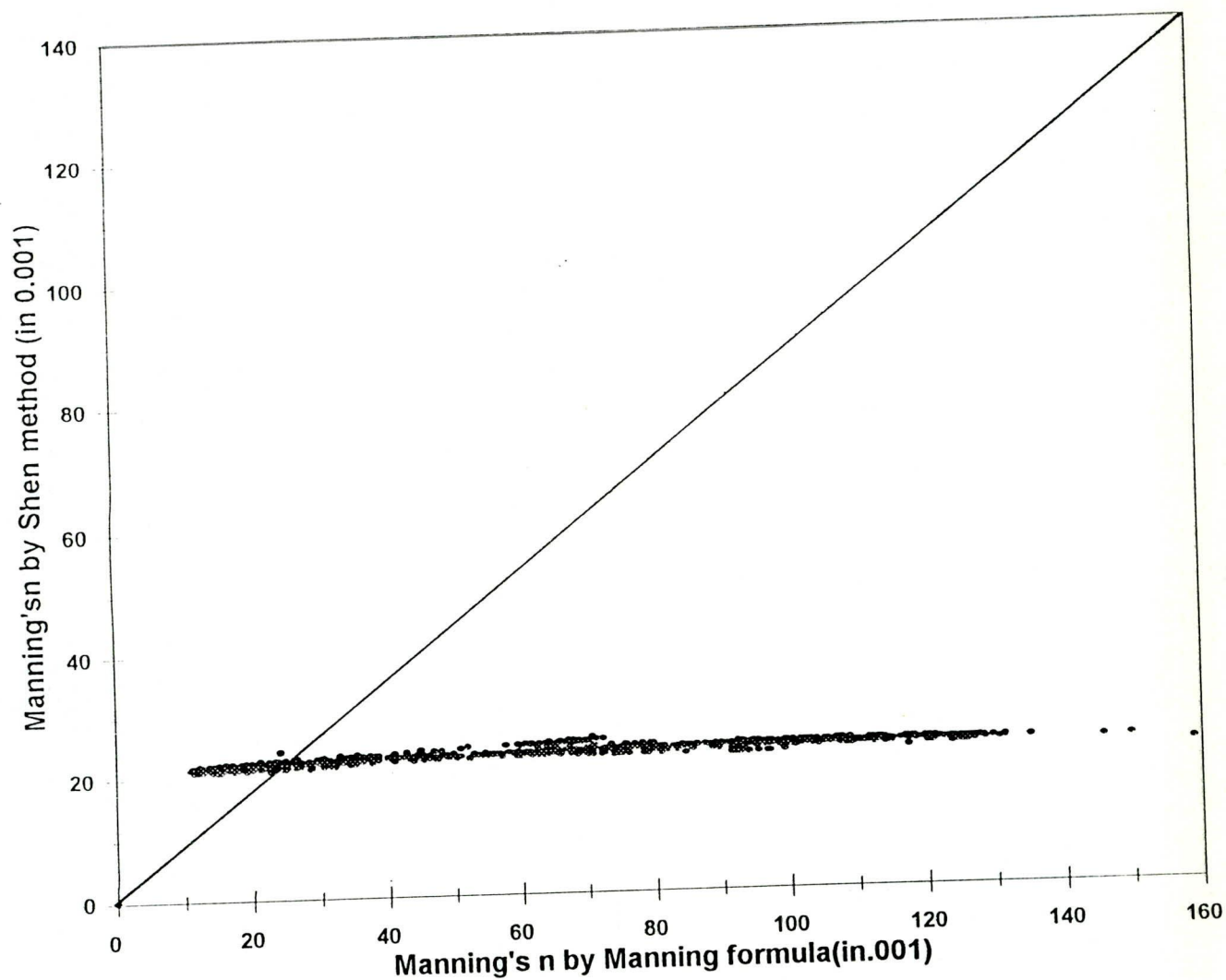


Fig. B.33 Comparison between the values of Manning's n computed by Manning formula and Shen et al. (1990) method with bed form dimensions by Allen (1962) at Hardinge Bridge

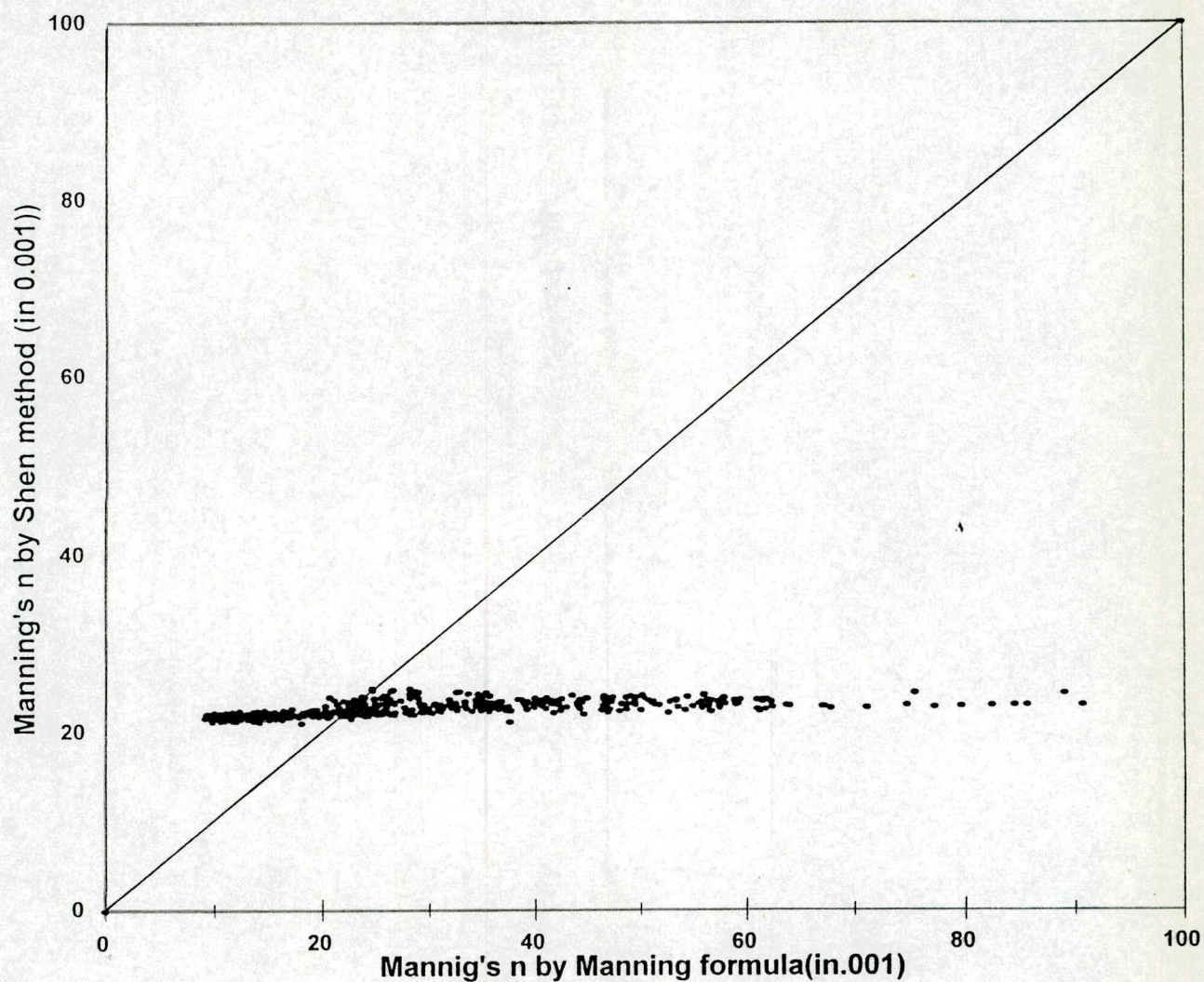


Fig. B.34 Comparison between the values of Manning's n computed by Manning formula and Shen et al. (1990) method with bed form dimensions by Allen (1962) at Baruria

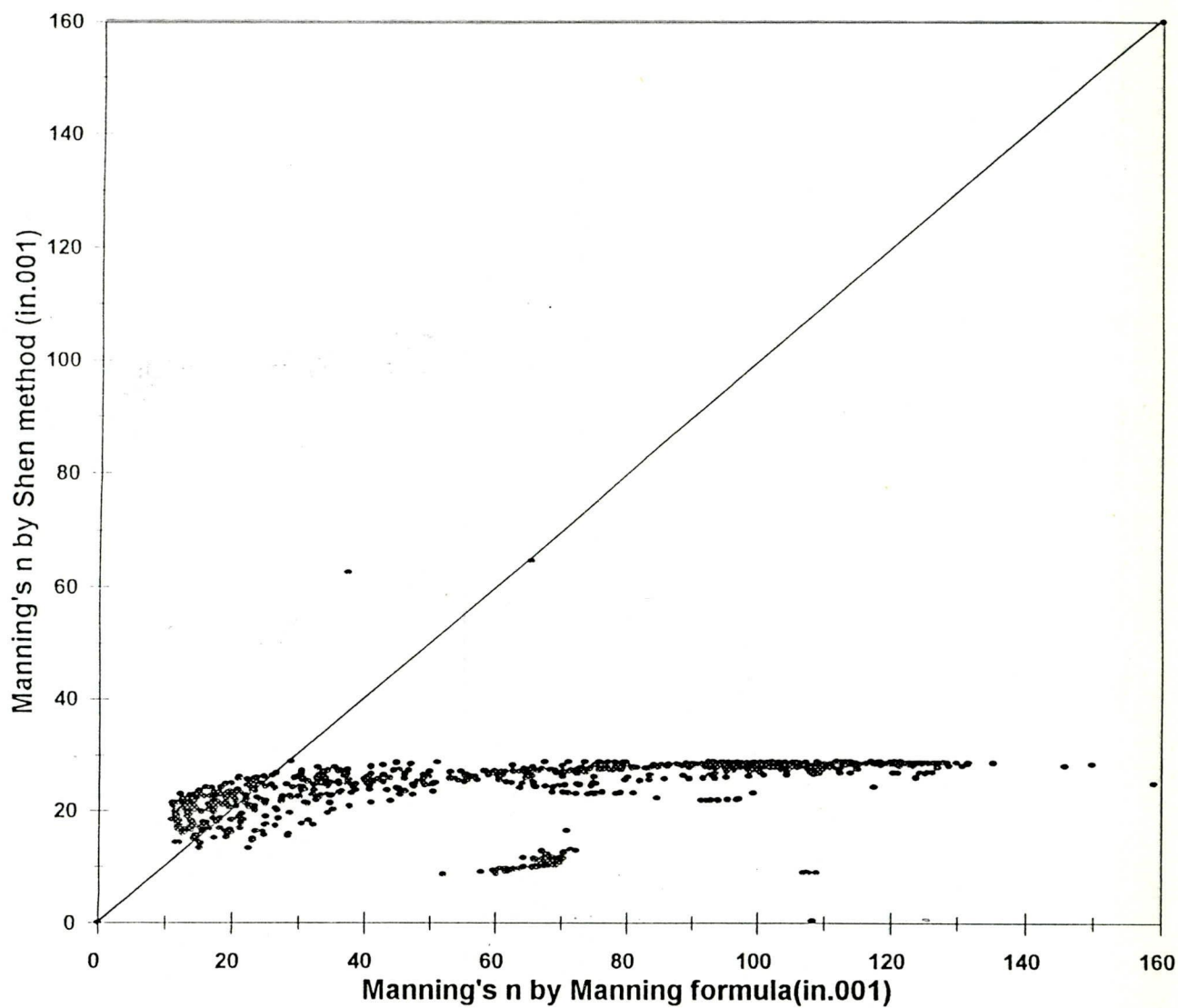


Fig. B.35 Comparison between the values of Manning's n computed by Manning formula and Shen et al. (1990) method with bed form dimensions by Vajda (1990) at Hardinge Bridge

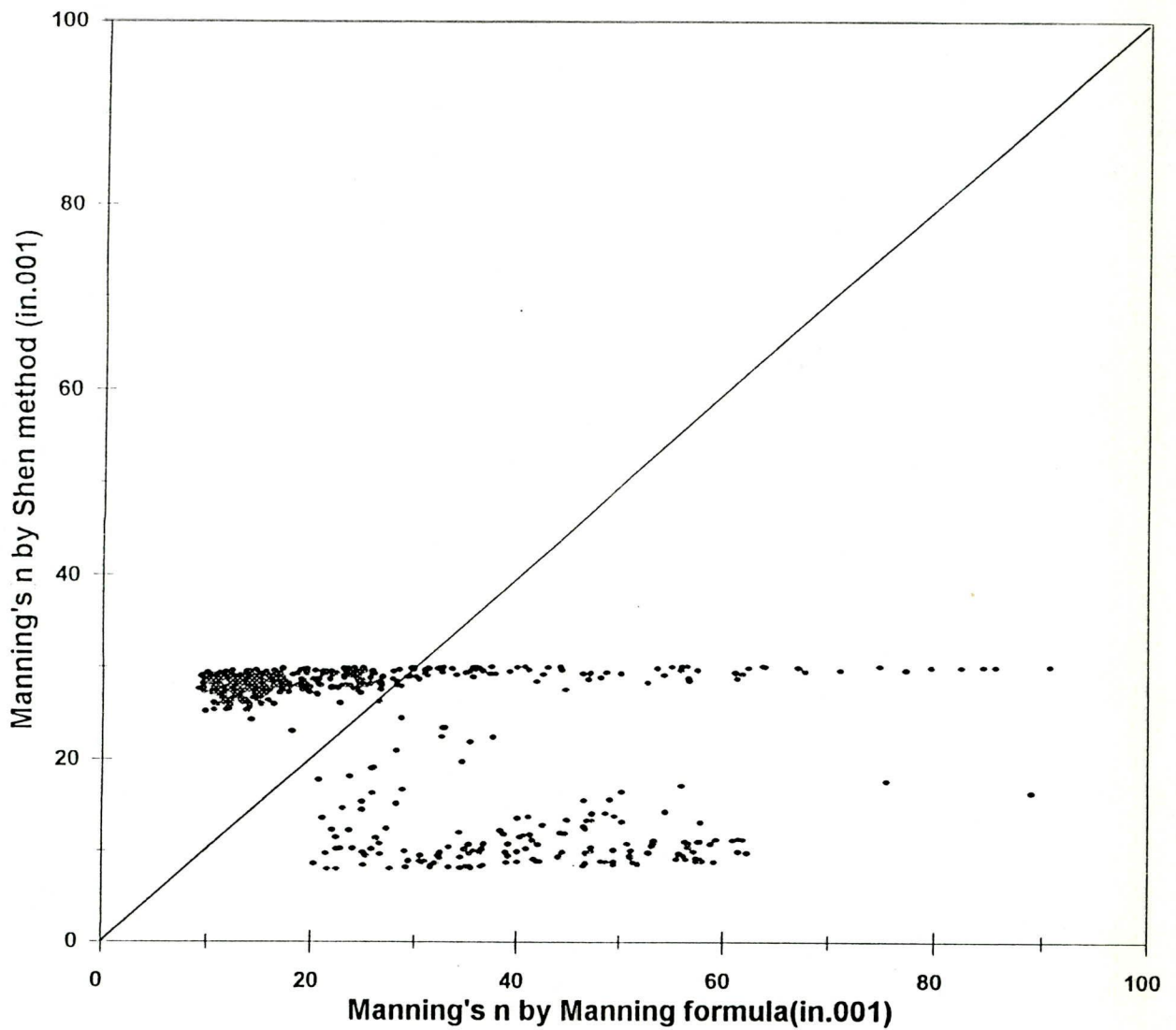


Fig. B.36 Comparison between the values of Manning's n computed by Manning formula and Shen et al. (1990) method with bed form dimensions by Vajda (1990) at Baruria

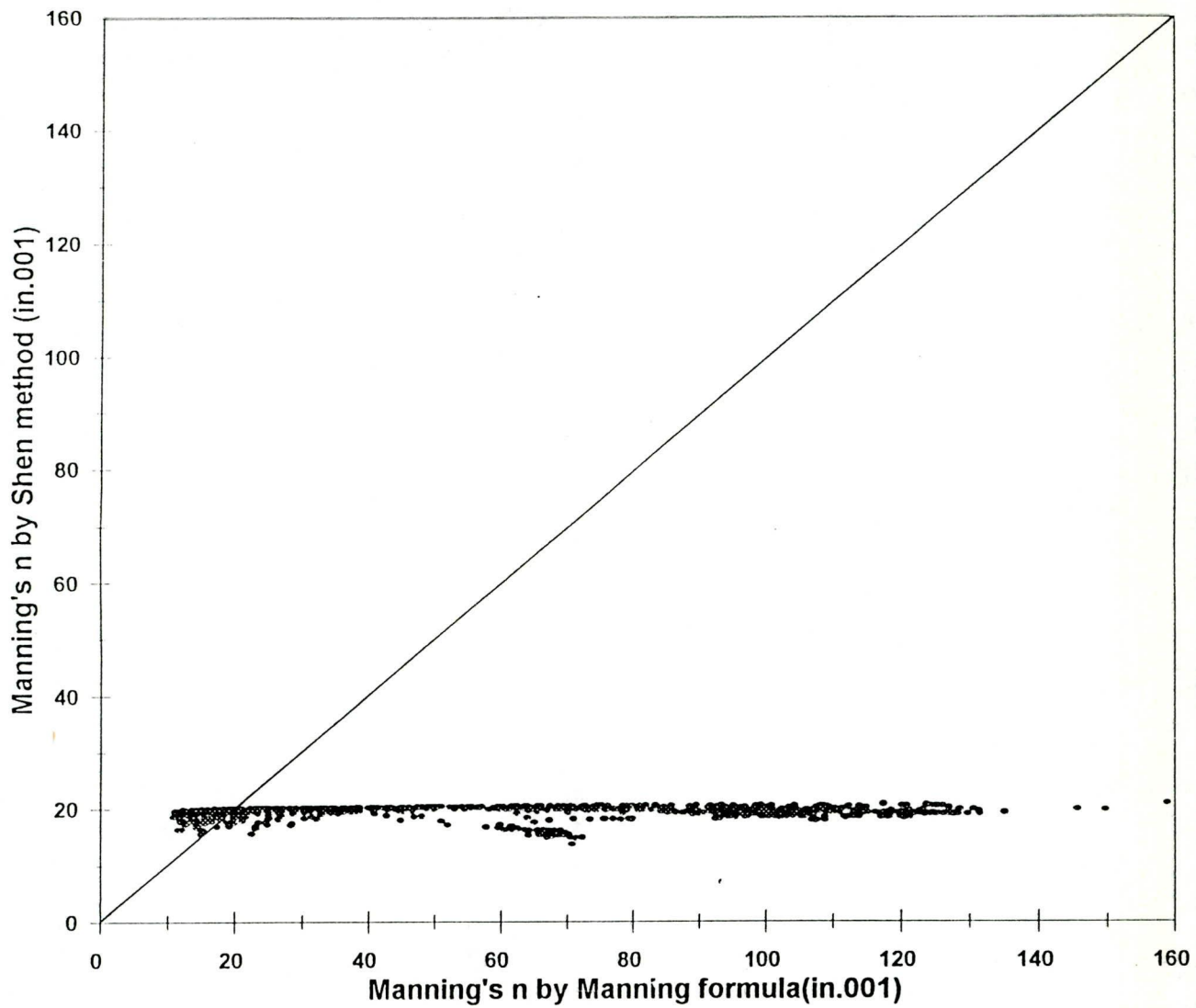


Fig. B.37 Comparison between the values of Manning's n computed by Manning formula and Shen et al. (1990) method with bed form dimensions by Yalin (1992) at Hardinge Bridge

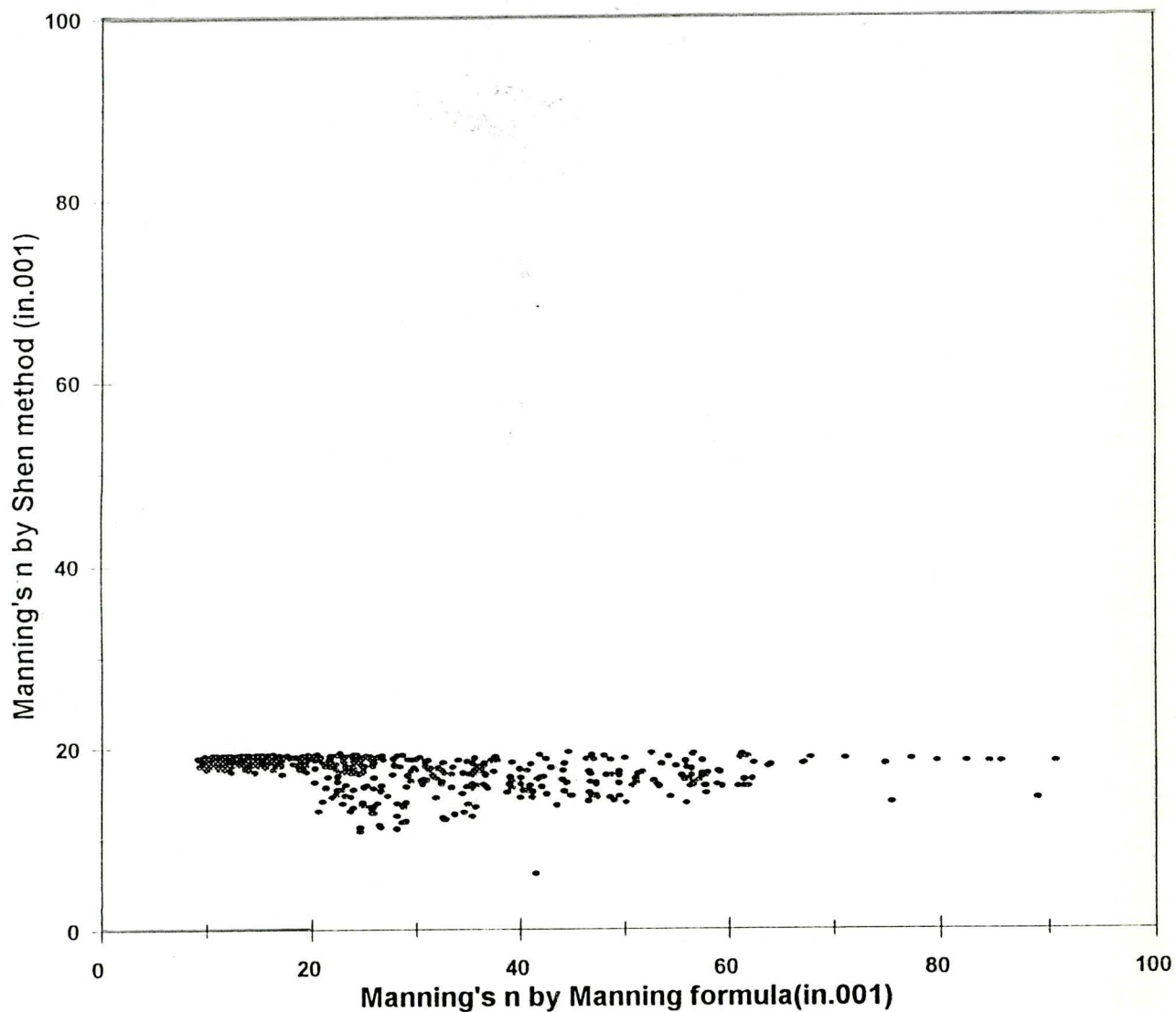


Fig. B.38 Comparison between the values of Manning's n computed by Manning formula and Shen et al. (1990) method with bed form dimensions by Yalin (1992) at Baruria

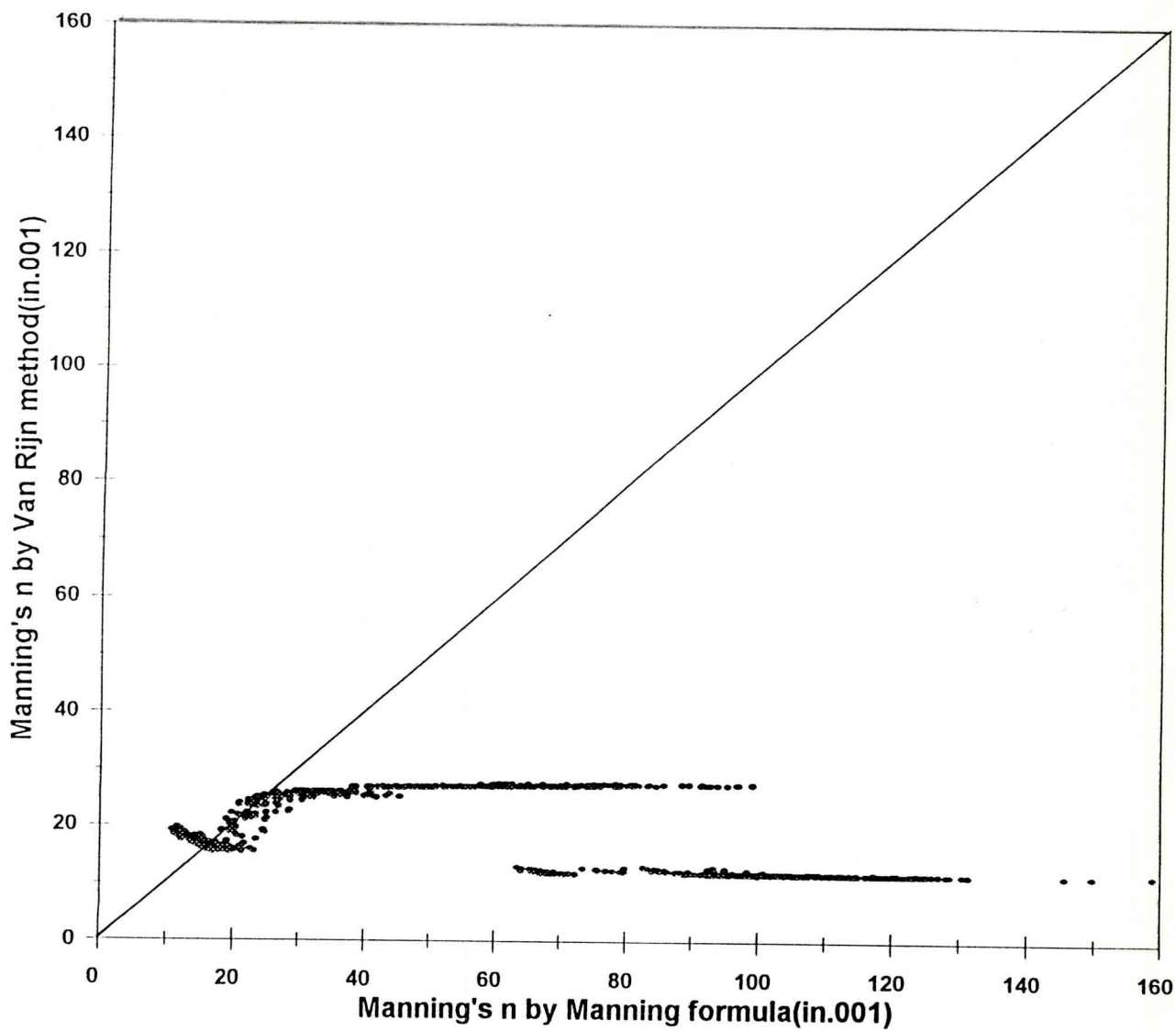


Fig. B.39 Comparison between the values of Manning's n computed by Manning formula and Van Rijn (1993) method at Hardinge Bridge

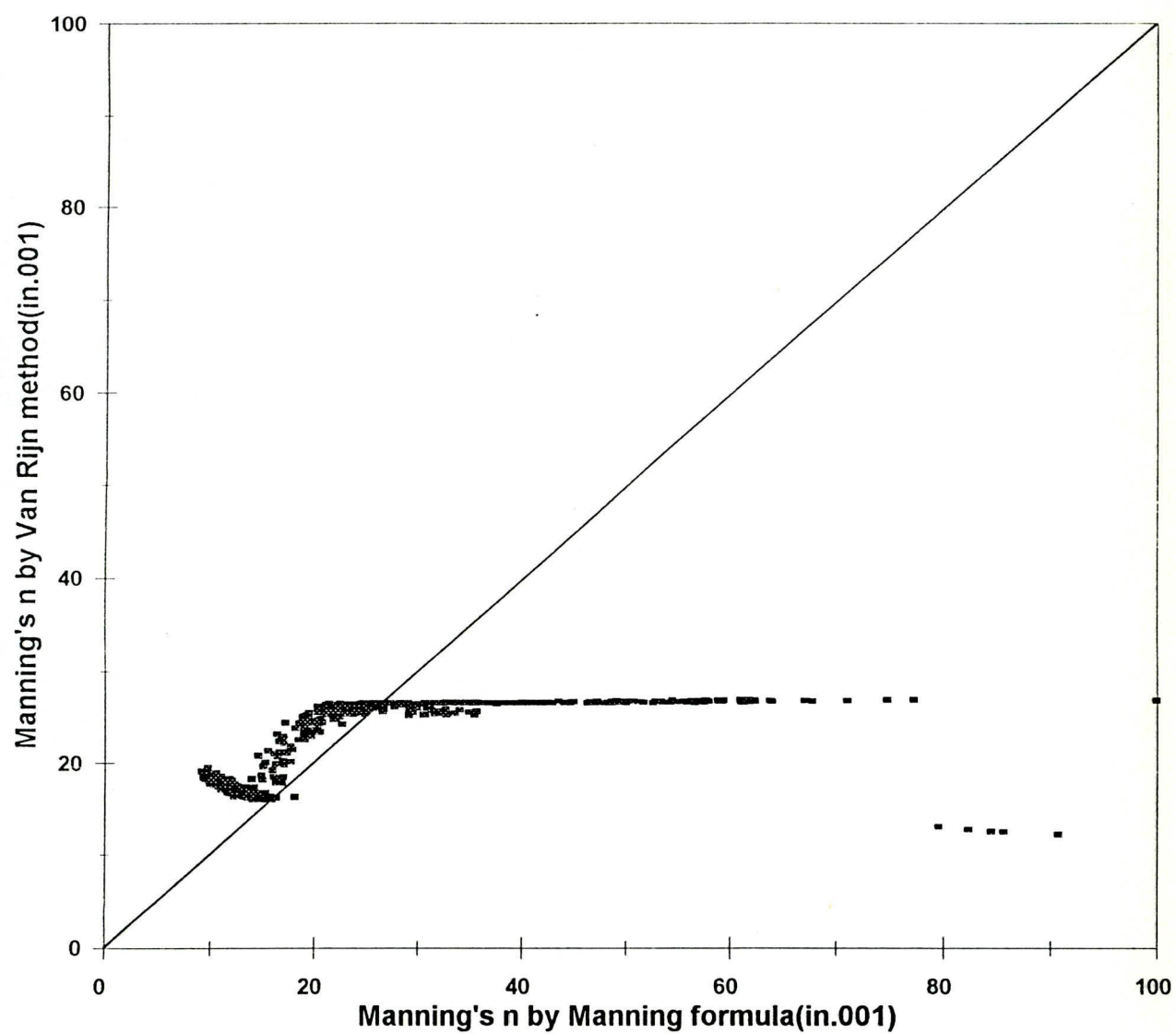


Fig. B.40 Comparison between the values of Manning's n computed by Manning formula and Van Rijn (1993) method at Baruria

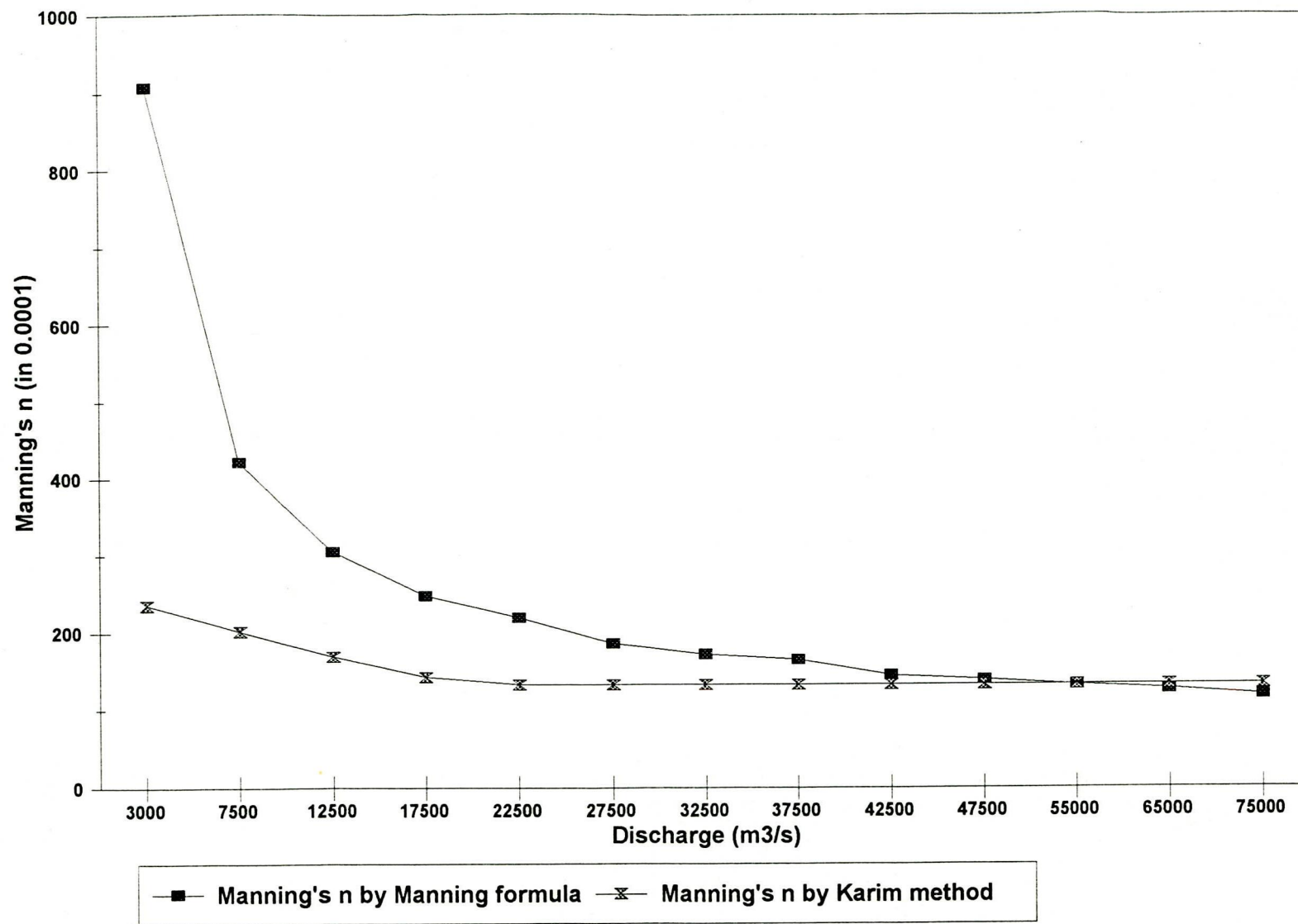


Fig. B.41 Variation of Manning's n predicted by Karim (1995) method with discharge at Hardinge Bridge

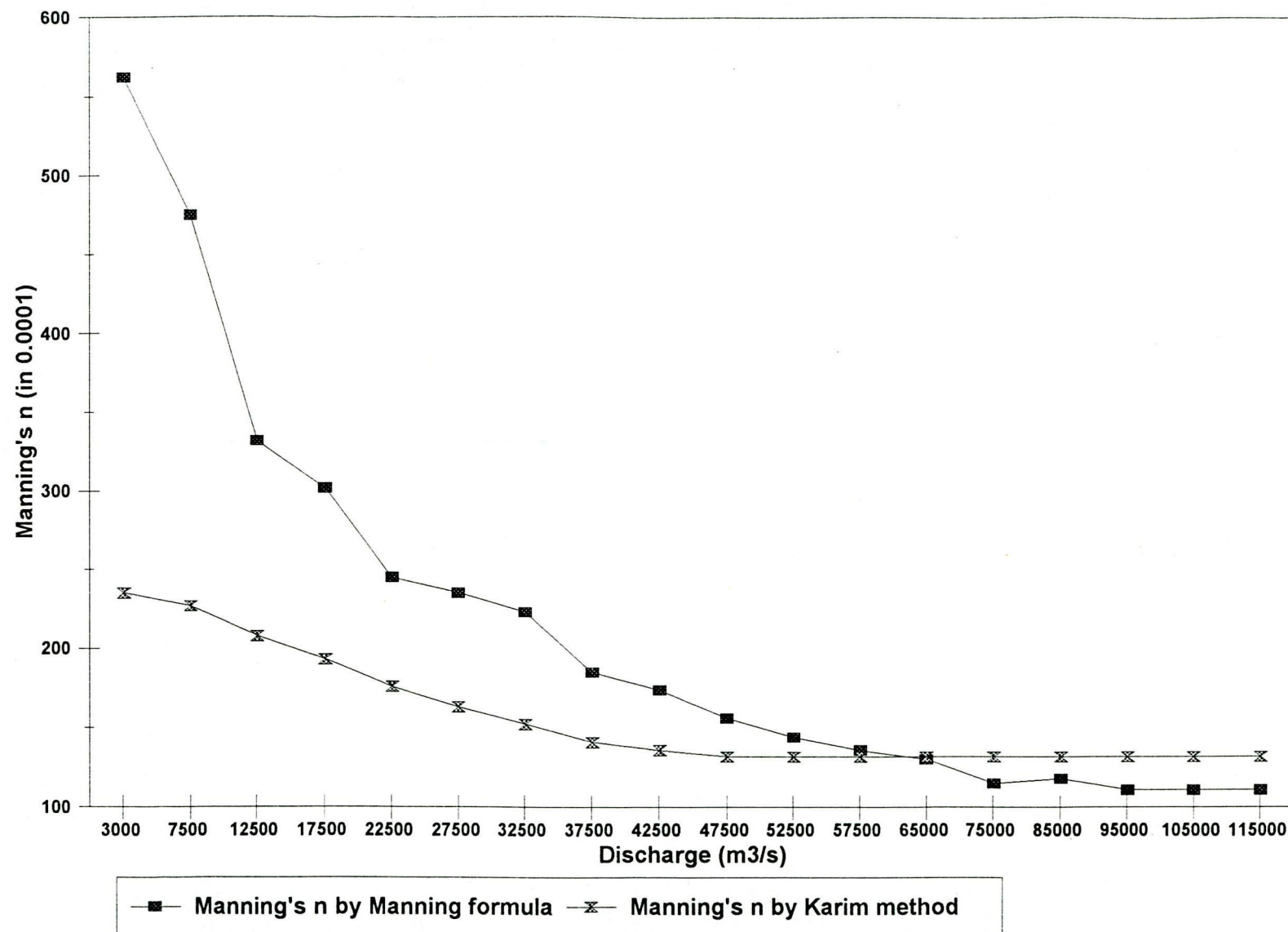


Fig. B.42 Variation of Manning's n predicted by Karim (1995) method with discharge at Baruria

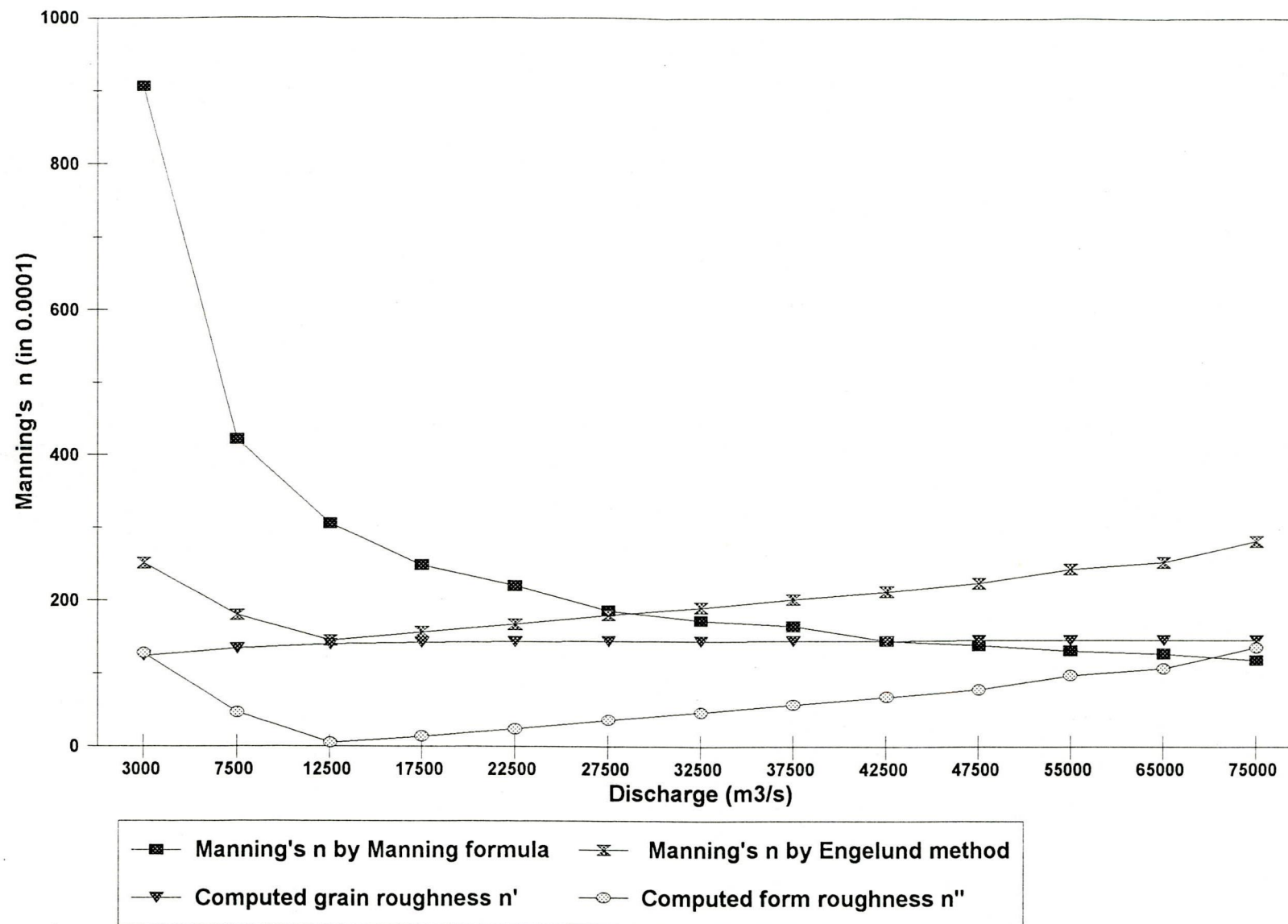


Fig. B.43 Variation of Manning's n predicted by Engelund-Hansen (1967) method with discharge at Hardinge Bridge

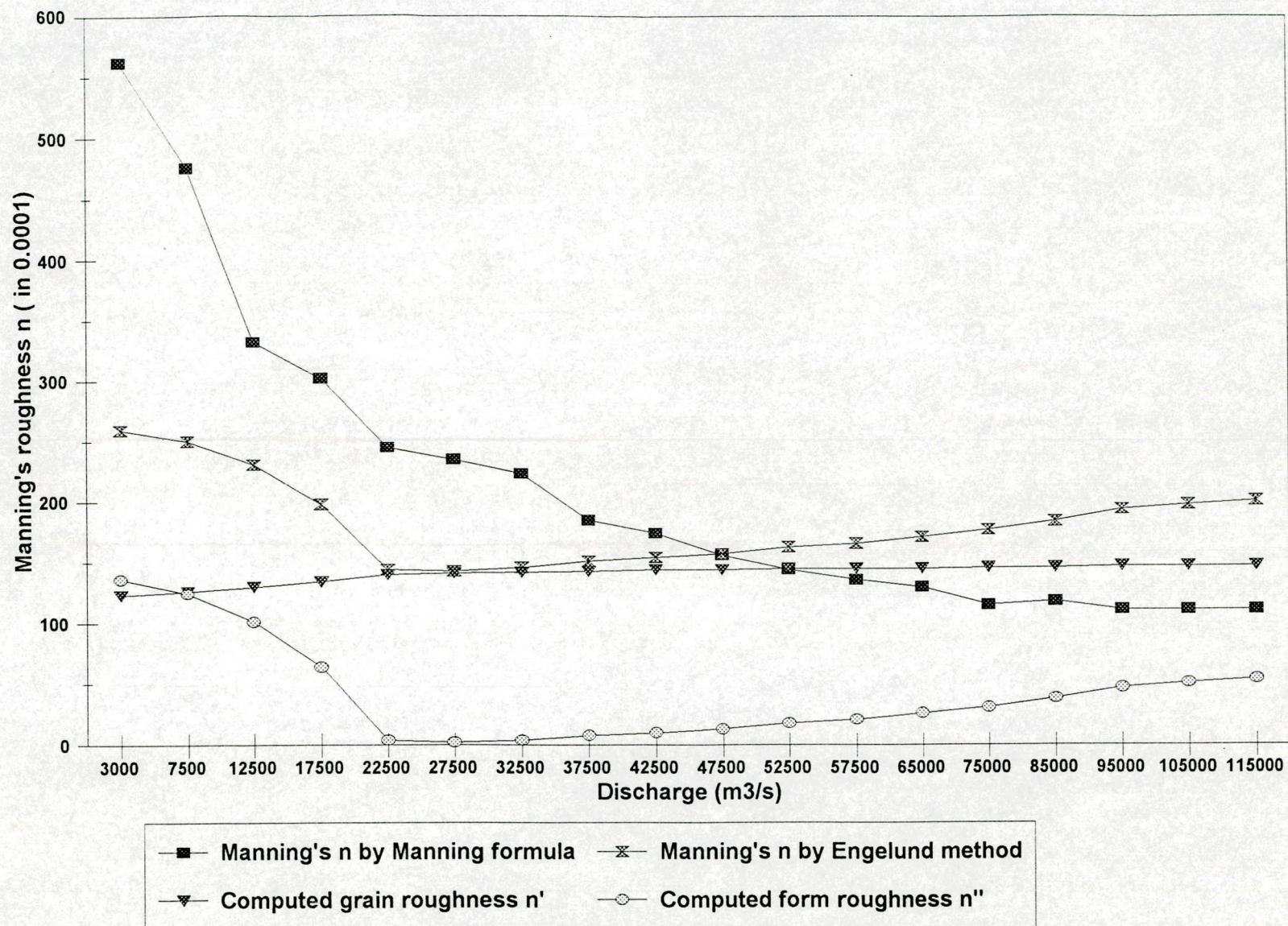


Fig. B.44 Variation of Manning's n predicted by Engelund-Hansen (1967) method with discharge at Baruria

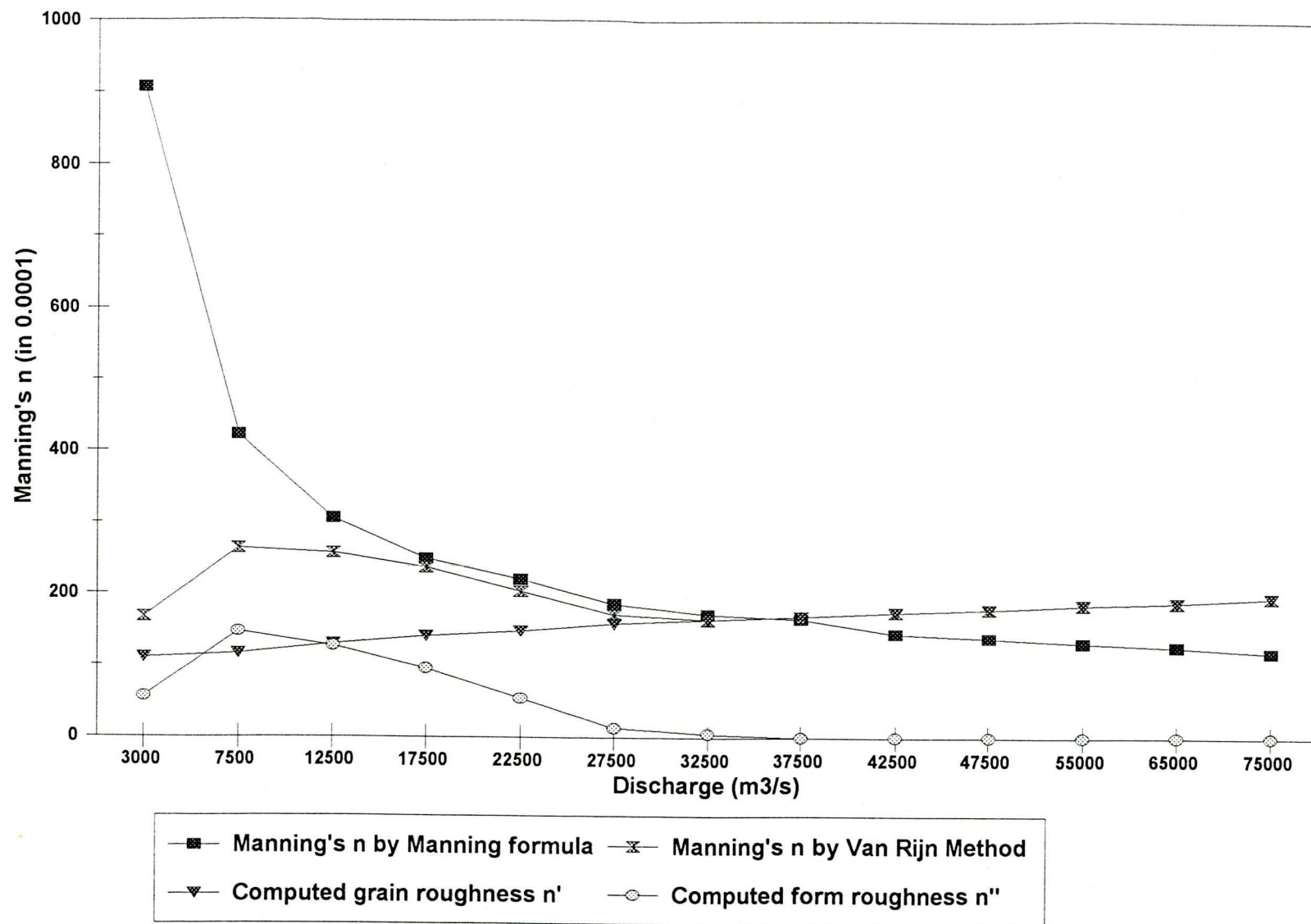


Fig. B.45 Variation of Manning's n predicted by Van Rijn (1993) method with discharge at Hardinge Bridge

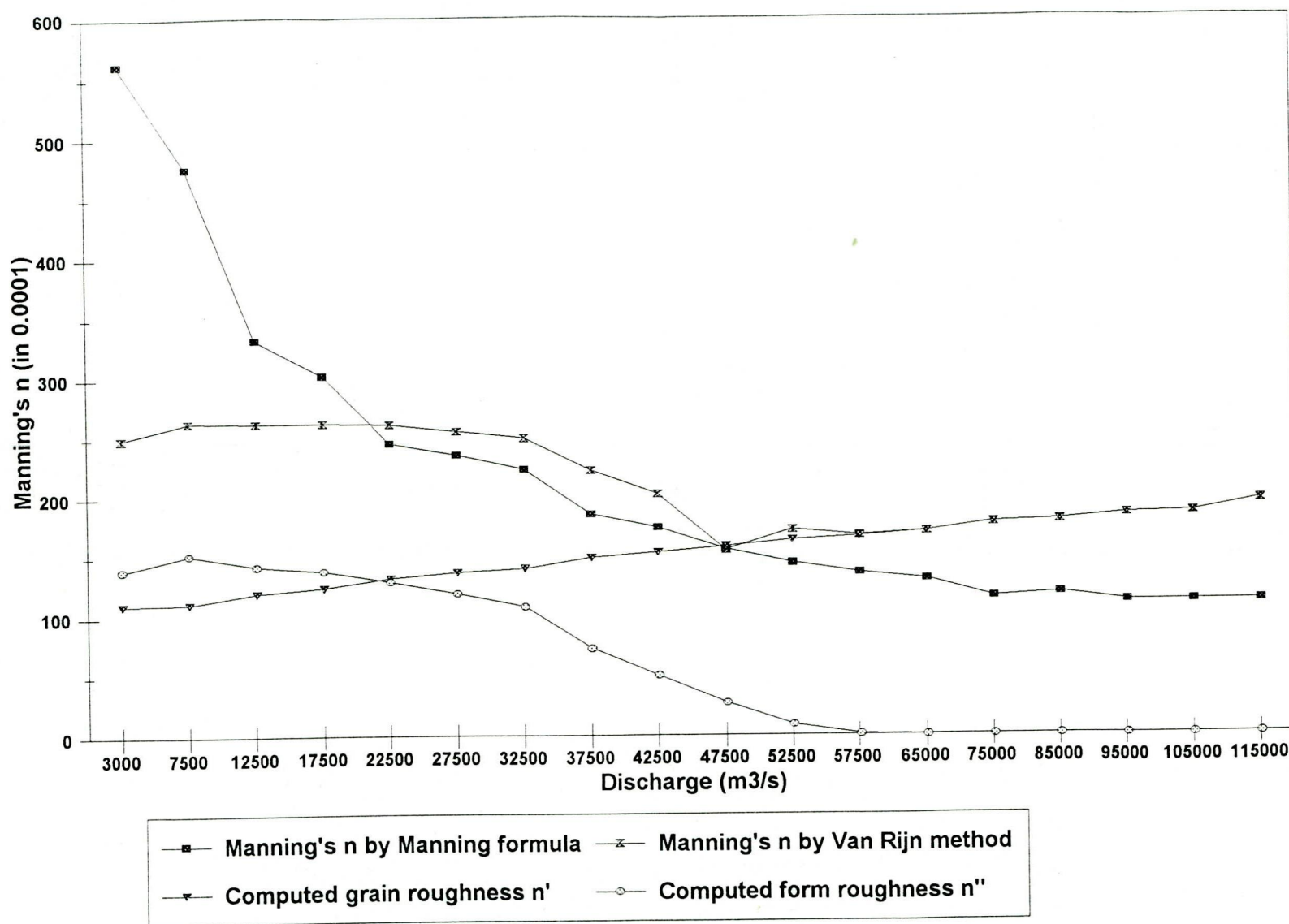


Fig. B.46 Variation of Manning's n predicted by Van Rijn (1993) method with discharge at Baruria

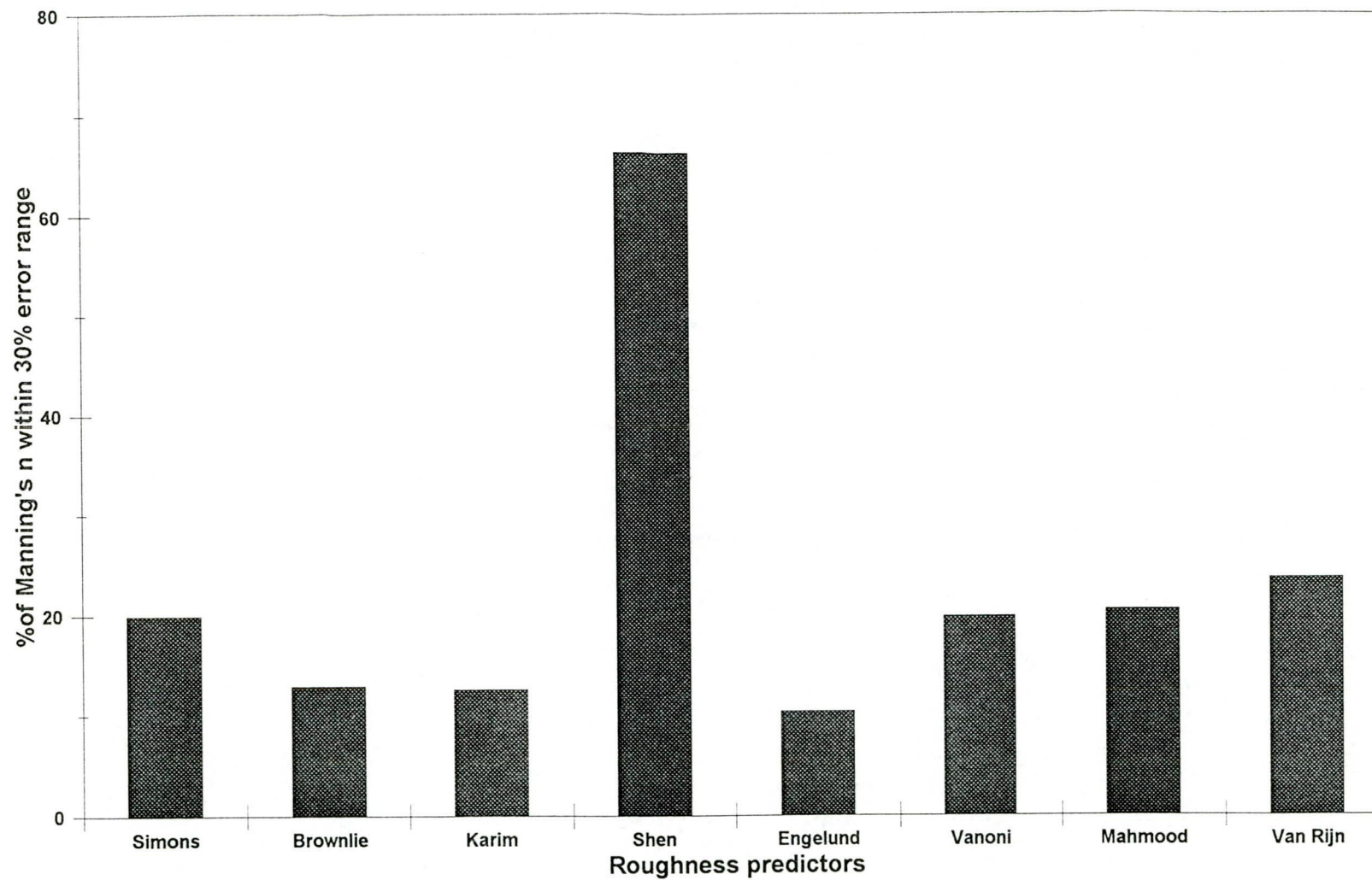


Fig. B.47 Percentage of Manning's n lying within $\pm 30\%$ error ranges predicted by different roughness predictors at Hardinge Bridge

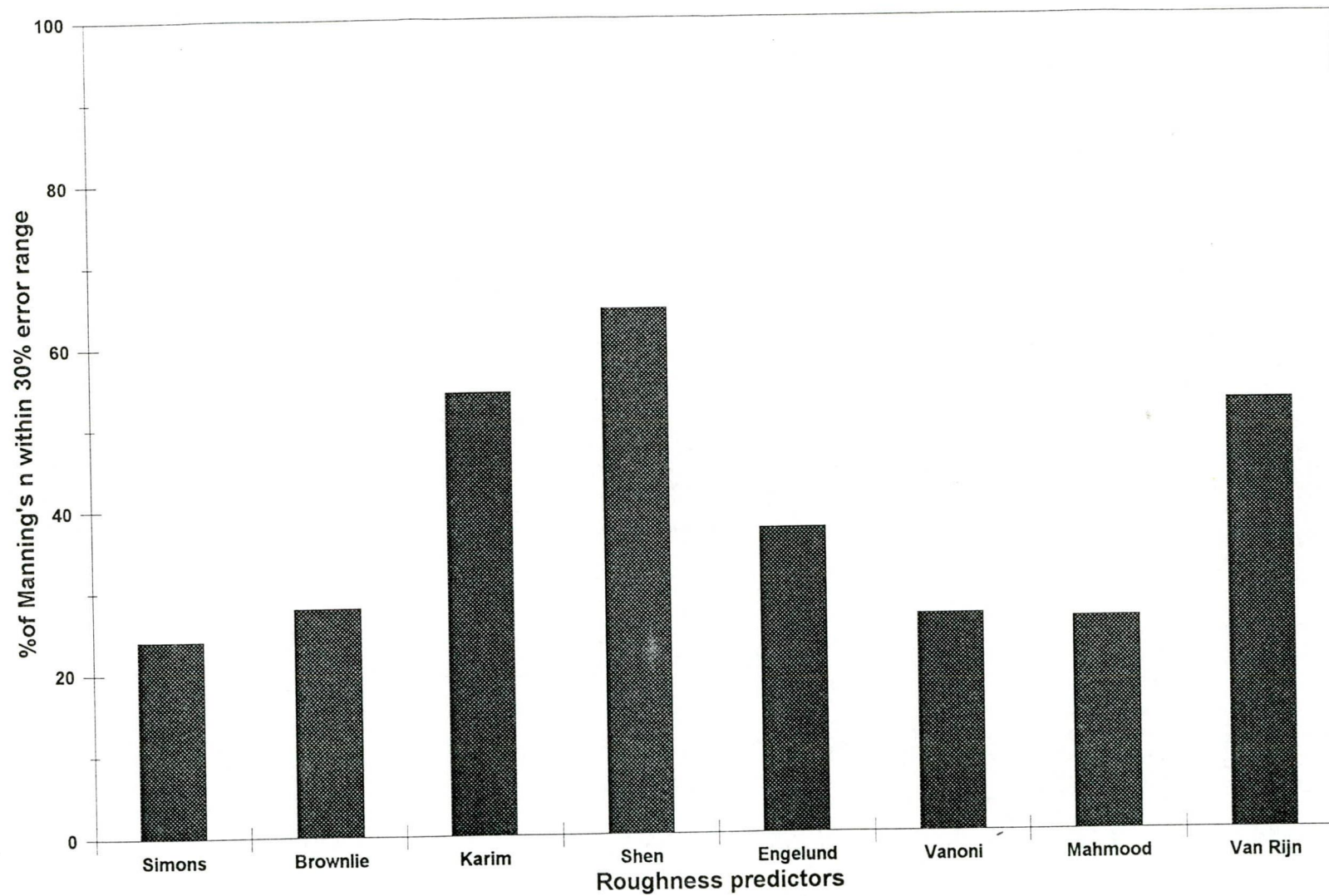


Fig. B.48 Percentage of Manning's n lying within $\pm 30\%$ error ranges predicted by different roughness predictors at Baruria

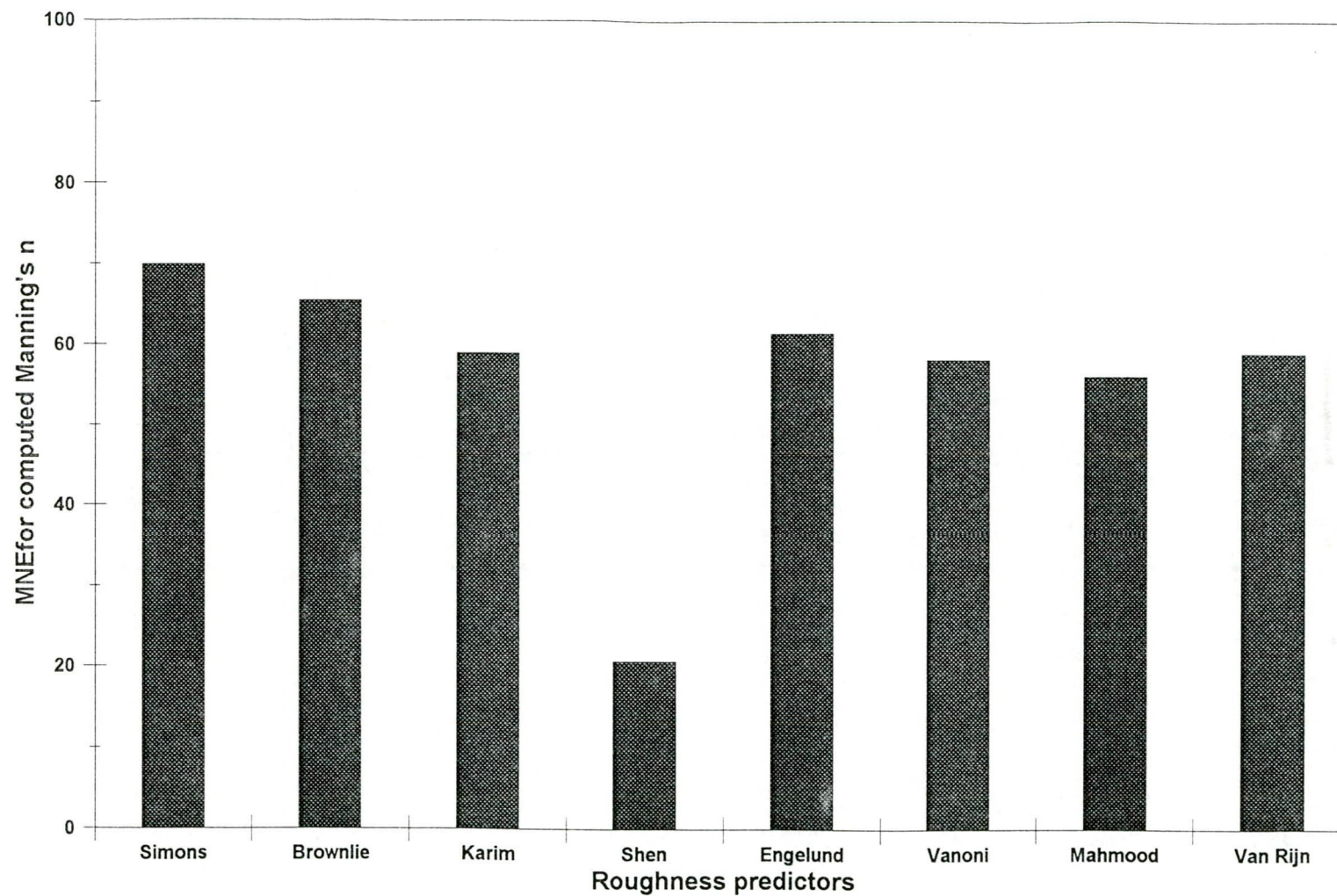


Fig. B.49 The MNE for predicted Manning's n by different roughness predictors at Hardinge Bridge

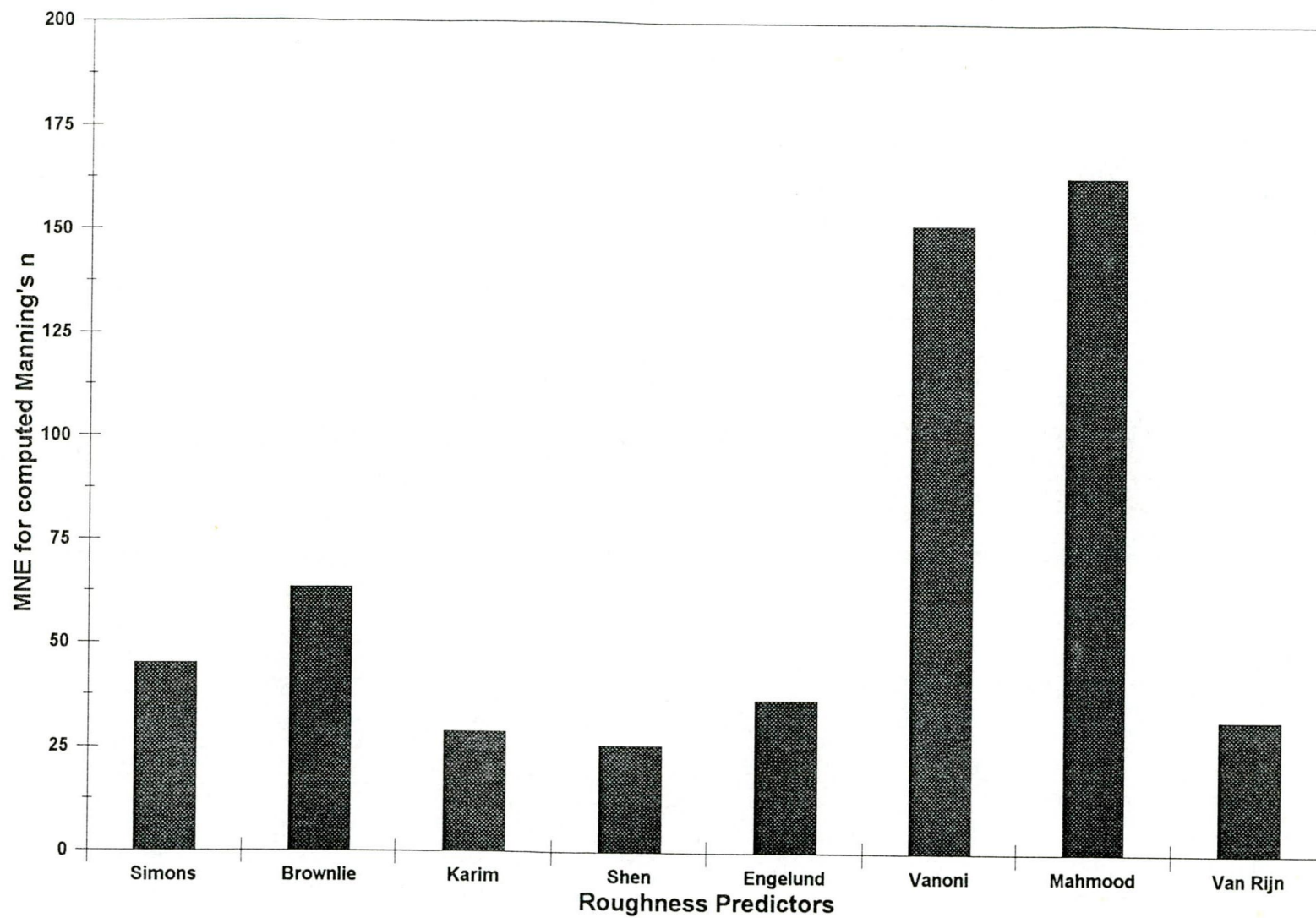


Fig. B.50 The MNE for predicted Manning's n by different roughness predictors at Baruria

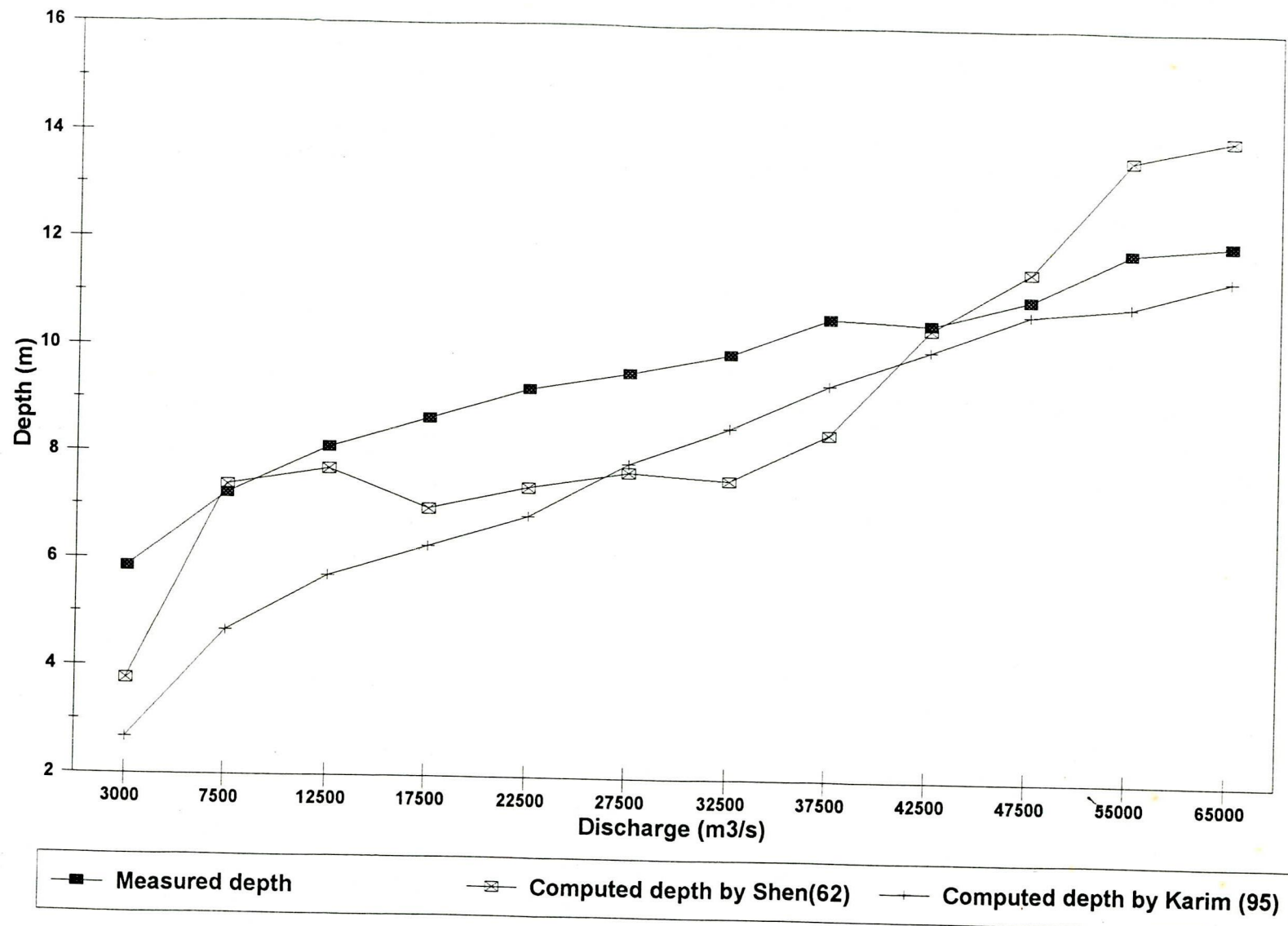


Fig. B.51 Variation of depth predicted by Shen (1962) and Karim (1995) methods with discharges at Hardinge Bridge

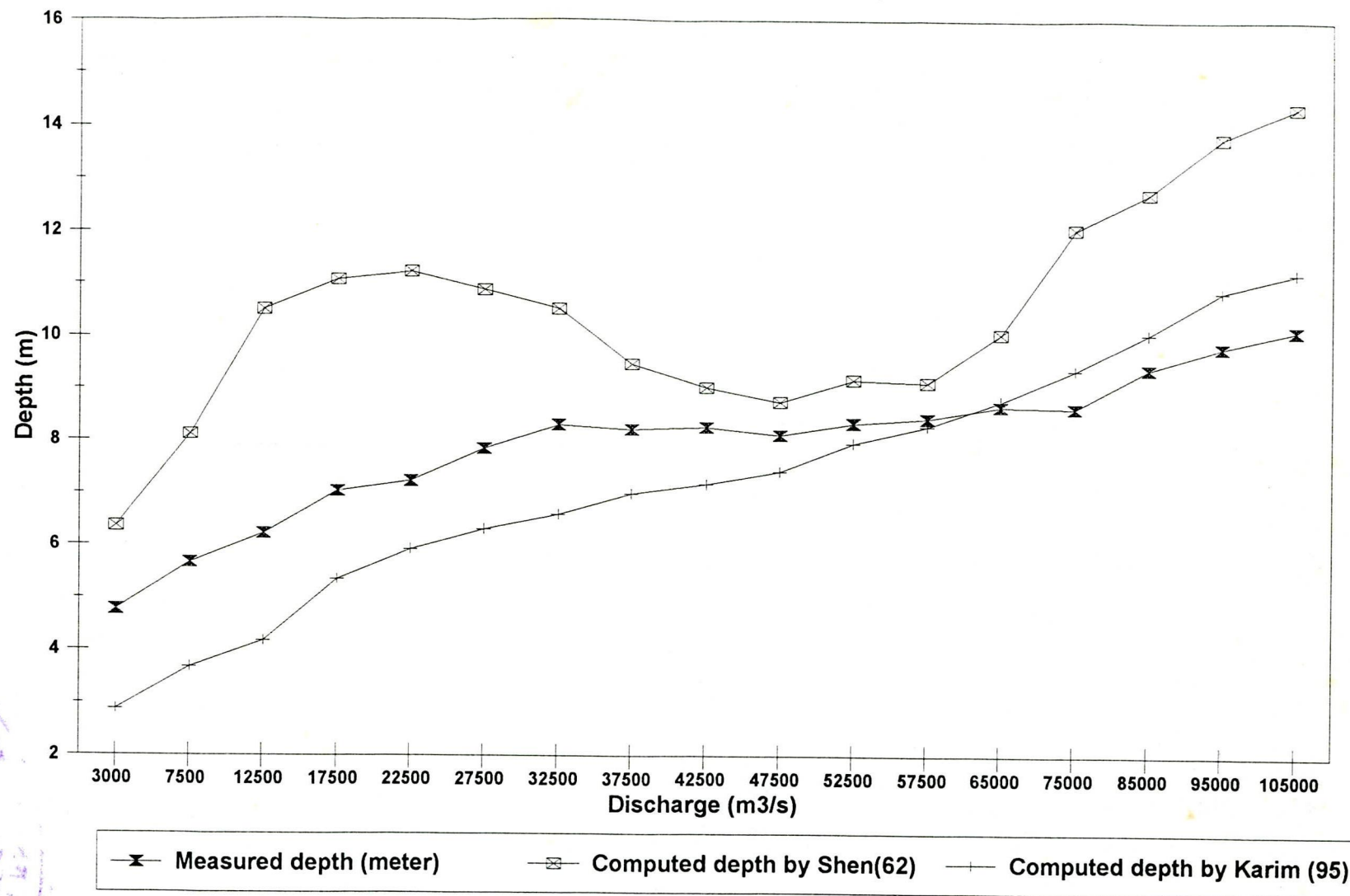


Fig. B.52 Variation of depth predicted by Shen (1962) and Karim (1995) methods with discharges at Baruria

