Composite roughness for rough compound channels

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ABSTRACT: Accurate estimation of roughness in a compound channels is an important aspect in River hydraulics. Researchers have suggested equations for estimating composite roughness of an open channel flow which are good for simple channels and do not incorporate the interaction mechanisms that exist in a compound channel. An experimental investigation is performed to study the dependency of geometry, roughness and flow parameters for predicting composite roughness of non-homogeneous compound channels. Standard methods of predicting the composite roughness of compound channels are reviewed and applied to the new experimental rough compound channels for different flow conditions. Effectiveness of these methods is discussed and modification to the standard method is proposed. The new approach is found to give better results as compared to the other approaches when applied to the experimental data sets, large channel of FCF data sets and some natural river data sets.

Keywords: Compound Channels, Composite roughness, Stage-Discharge relationship, Non homogeneous compound channel, Different roughness.

1 INTRODUCTION

A major area of uncertainty in river channel analysis is that of accurately predicting the capability of river channels with floodplains, which are termed compound channels. Cross-sections of these compound channels are generally characterized by a deep main channel, bounded on one or both sides by a relatively shallow floodplain, which is rougher and has slower velocities than as compared to that of main channel. Due to interaction between the main channel and floodplains, there are bank of vertical vortices along the interface, which lead to extra resistance in terms of consumption a lot of energy. Due to this extra resistance, the prediction of stage-discharge curve become difficult and more difficult when there is large different roughness between the main channel and floodplain. Many studies have been carried out to provide an accurate estimation of resistance coefficient which is fit especially for inbank flow. However, none as yet has led to a general applicable method for a compound channel with different roughness that generally exists in a compound river sections. The need for accurate and preferably simple methods of discharge calculation in compound sections for both homogeneous and different roughness sections are thus very important. An experimental study was first carried out to apply the existing methods to predict composite roughness then attempt is made to modify it. The effectiveness is also tested in large channel facility of FCF and river data sets.

2 REVIEWS ON CHANNEL FLOW RESISTANCE

An important component in open channel flow is the estimation of flow resistance resulting from the viscous and pressure drag over the wetted perimeter. Such resistance is commonly represented by parameters such as Manning's roughness coefficient (*n*), the Darcy-Weisbach friction factor (*f*), or the Chezy's coefficient(*c*) as given below.

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

$$f = \frac{2gRS}{V^2} \quad (2)$$

$$c = \frac{V^2}{RS} \quad (3)$$

Some guidance is available for resistance coefficient estimation from a variety of sources, most accessibly in Chow (1959) and French (1985). Chow listed a series of tables presenting the values of Manning's *n* for a variety of rivers for varieties of surface conditions. These are supplemented by photographs of rivers for which resistance coefficients have been measured. French presented a more rational approach in the form of the US Soil Conservation Method, which involves identifying a basic '*n*' value depending on the bed and bank material of the river .Such approaches, however, are relevant to simple channel shapes, and may lead to serious error when extrapolated to overbank flow depths. The flow resistance of compound channels has also been studied by many researchers, such as Myers (1990), Shiono and Knight (1991), Nalluri and Adepoju (1985), Yang et al. (2005). Myers (1990) analyzed the influence of the width ratios of main channel to floodplain on the redistribution of flow resistance. Shiono and Knight (1991) discussed the variations of the Darcy–Weisbach friction factor, the dimensionless eddy viscosity and the secondary flow factor in smooth compound channels. Yang et al. (2005) described that when water in the main channel flows in an out-of-bank manner, the Manning coefficient on the flood plain (n_f) is decreased compared to that in a single trapezoidal channel, and the Manning coefficient in the main channel (n_m) increases. In adopting the cross sectional division method, since it fails to take account of the extra flow resistance due to momentum transfer from the main channel to the flood plains, the overall conveyance capacity of the compound channel is over-estimated. Looking these points in view an attempt has been made to investigate the flow resistance characteristics in compound channels with differential boundary roughnesses.

3 THEORITICAL ANALYSES

Since many rivers assumed a compound shape at flood flows; it is clearly of considerable importance to have reliable methods of channel analysis. In addition, situations where channel sections have the roughness varying laterally along the wetted perimeter are often encountered in design and laboratory experiments. Before the discharge estimation, it is necessary to develop a method to predict the composite roughness of a channel. In 1931, Pavlovskii's first proposed a formula for predicting the composite roughness of a channel. Since then, Lotter (1933), Einstein and Banks (1934), Krishnamurthy and Christensen (1972), Cox (1973) has proposed different formulae separately. Three major basic concepts are generally considered for derivation of any composite roughness approaches of a channel which are given as

a) Total discharge is sum of subarea discharges
b) Total cross sectional mean velocity equal to subarea mean velocity
c) Total resistance force is equal to sum of subarea resistance forces.

On the basis of these three concepts, there are many methods existing in literature to evaluate the composite roughness of channel are listed in Table.1.

Table-1 Equations for Equivalent Roughness for Compound Channel

Eq. No.	Equations for n_c	Assumptions	References
A	$n_c = \frac{\sum n_i A_i}{A}$	Total shear velocity is weighted sum of subarea velocity	Cox (1973)
B	$n_c = \left[\frac{\sum(n_i^{3/2} A_i)}{A}\right]^{2/3}$	Total cross sectional mean velocity equal to subarea mean velocity	Colebatch (1941)
C	$n_c = \left[\frac{1}{P}\sum(n_i^{3/2} P_i)\right]^{2/3}$	Total cross sectional mean velocity equal to subarea mean velocity	Horton (1933) Einstein (1934)
D	$n_c = \frac{P}{\sum(P_i/n_i)}$	Total discharge is sum of subarea discharges	Felkel (1960)
E	$n_c = \left[\frac{1}{P}\sum(n_i^2 P_i)\right]^{1/2}$	Total resistance force is equal to sum of subarea resistance force	Pavlovskii(1931)
F	$n_c = \frac{PR^{5/3}}{\sum \frac{P_i}{n_i} R_i^{5/3}}$	Total discharge is sum of subarea discharges	Lotter (1933)
G	$n_c = \frac{\sum P_i R_i^{5/3}}{\sum \frac{P_i}{n_i} R_i^{5/3}}$	Total discharge is sum of subarea discharges	Ida (1960) Engelund (1964)
H	$n_c = \frac{\sum(n_i P_i)}{P}$	Total shear velocity is weighted sum of subarea velocity	Yen 1(2002)
I	$n_c = \frac{\sum\left(\frac{n_i P_i}{R_i^{1/6}}\right)}{P/R^{1/6}}$	Total shear velocity is weighted sum of subarea velocity	Yen 2(2002)
J	$n_c = \frac{\sum(n_i P_i R_i^{1/3})}{PR^{1/3}}$	Total shear velocity is weighted sum of subarea velocity	Yen 3(2002)
K	$n_c = exp\left[\frac{\sum P_i h_i^{3/2} \ln n_i}{\sum P_i h_i^{3/2}}\right]$	Logarithm velocity distribution over depth h for wide channel	Krishnamurthy and Christensen (1972)

Since these methods (listed in Table-1) are seen to be valid for a channel of simple sections and giving poor results when applied to a compound channel section. So early investigations by Sellin [12], Wright and Carstens [13] have pointed to the existence of momentum transfer between the subsections, which is, in fact, more intense for small flow depths over the flood plain due to this a mixing shear layer is developed at the interaction region and apparent shear stresses appear. Wormleaton and Merret [14] and Khatua et al [15] proposed another empirical formula to estimate the apparent shear stress in straight compound channels. Posey [16] and Ackers [17] deduced a design formula for straight two stage channels by taking into account the interaction effects between floodplain and main channel.

4 EXPERIMENT APPARATUS AND PROCEDURE

For the present analysis we have chosen two experimental compound channel data sets. One is homogenous smooth compound channel and other is non-homogeneous rough compound channel having different roughness in floodplain and main channel sub sections of the channel. The channels were fabricated inside a tilting flume of dimension 15m long, 2m wide and 0.6m deep at the Hydraulics laboratory of National Institute of Technology, Rourkela in India shown in Figure 1.

Figure 1. Details of straight smooth and rough channel

At the beginning of the flume just after inlet and before head gate (called stilling chamber), a series of baffle walls were installed for energy dissipation purpose, i.e. to reduce turbulence and make water body still before passing over the channel. . Travelling bridges were there to carry measuring instruments. Tailgate was provided just before end point of the flume for bed slope measurement and maintaining uniform flow purposes.

The volumetric tank was reconstructed and a rectangular notch of 1.86m length and 0.1m height was newly installed at the end of the experimental flume for accurate discharge measurement of each run. For discharge measurement, the rectangular notch needed calibration. The area of the volumetric tank was measured properly thrice and average of it was found out to be $20.928784 m^2$. The discharge into the volumetric tank was measured by the time to rise method. Water surface slope measurement was carried out using a pointer gauge fitted to the traveling bridge operated manually having least count of 0.1 mm. The slope of the bed was found out by dividing the difference in depth of water at two ends of the test reach by the test reach length. From the measurement the bed slope of the flume was found out 0.001395. Depth of flow for all inbank series and overbank series at the test reach section was measured with the help of point gauge. The water is made to flow through the channels under gravity with the maximum discharge of $0.047 m^3/s$ and maintain a re-circulating system of flow through the flume to the large underground sump. One set of the whole channel was fabricated by using 5mm thick Perspex sheets of roughness $n = 0.01$ for main channel as well as flood plain. The compound channel used for investigation comprised a main trapezoidal channel of 120 mm wide at bottom, 280 mm wide at top having depth of 80 mm and side slopes of 1:1 along with symmetric floodplains of 805mm width, 120mm height and zero side slope, on both sides of the main channel.

Another set of the whole channel was fabricated by using 5mm thick Perspex sheets and roughened with gravel bed main channel with vegetative floodplain shown in Figure 1. The grain size of gravel particles had a median diameter (d_{50}) of 1.23 cm and the geometric standard deviation $\sigma_g = (d_{84}/d_{16})^{0.5}$ of particle size distribution was 1.35, where d_{84} and d_{16} are 84% and 16% finer particle diameters, respectively and the flood plains were covered with ribbed mat as rough surface of effective height of 1.5cm. The details of experiments can also be found in Sahu et al [24]. In order to evaluate the methods and check the validity of subsection divisions, a large number of laboratory and field data were also collected and applied to the present study. The data collected include 16 groups of the UK Flood Channel Facility (FCF), which is a large scale compound channel facility located at the laboratories of HR Wallingford Ltd. For the present analysis, two natural river sections have also been studied. The selected rivers are the River Batu which is located in Kuching, the capital city of Sarawak state, Malaysia almost straight and uniform in cross section. Extensive flood data from River Main in North Ireland was also obtained for comparison. Table 2 shows the geometrical properties and surface conditions of the rivers at the gauging stations.

Table -2 Detail of FCF Series (1&2), NIT Rourkela Channel (3), River Batu and River Main

Series No.	Main channel(mc)	Flood plain(fp)	Width of channel B(m)	Depth of mc h(m)	Slope	Width ratio(α=B/b)	SS
FCF Series 3	smooth	smooth	3.3	0.15	0.001	2.2	1:1
NIT Rourkela Channel (3)	Rough (wire mesh)	Rough (ribbed mat)	1.89	0.08	0.001395	15.833	1:1
River Batu	Rough (large boulder)	Rough (long vegetation)	5.15	1.544	0.0016	3.335	1:1
River Main	Rough (coarse gravel)	Rough (short vegetation)	13.7	0.95	0.00192	15.22	1:1

5 RESULTS AND DISCUSSIONS

5.1 *Stage -Discharge and Overbank Composite Roughness Relationship*

The stage discharge curve for 19 different discharges ranging from 0.005 to 0.047m^3/s is shown in Figure 3.1. Among these tests, 11 discharges are in an inbank condition. The notable feature of the relationship between stage and discharge is the discontinuity at the bankfull depth, and a reduction in discharge as the depth rises just above the bankfull value. This is due to the interaction between the main channel flow and the rough and shallow floodplain flow.

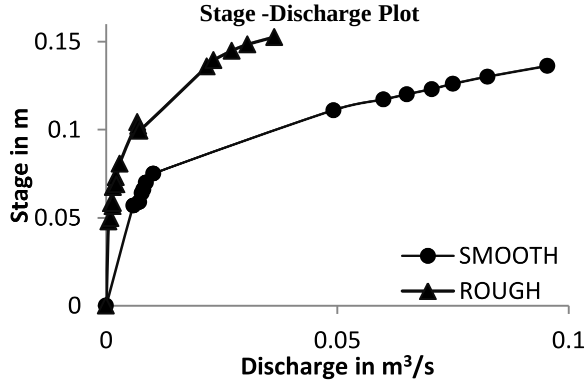


Figure 3.1 Stage-Discharge Curve for Compound Channel setup in NIT Rourkela

The interaction of flows results in the extra resistance, which increases the discharge on the floodplains and decreases that in the main channel. The extra resistance consumes lots of flow energy. As a result, the conveyance capacity of the whole cross section decreases. The composite flow resistance coefficients (shown in Figure 3.2) of the smooth compound channel are found to increase with overbank flow depth however in case of compound channel with rough floodplain the variation is peculiar i.e. at first the value increases with overbank flow depth and then found to decrease. This is due to combined effect of momentum transfer and different roughness between the floodplain and main channel. Henderson [25] points out that the Manning equation is strictly only applicable to flow in the rough turbulent zone of simple channels. The variation of Manning coefficient with flow depth, velocity and discharge are more significant in compound channel as compared to simple channels.

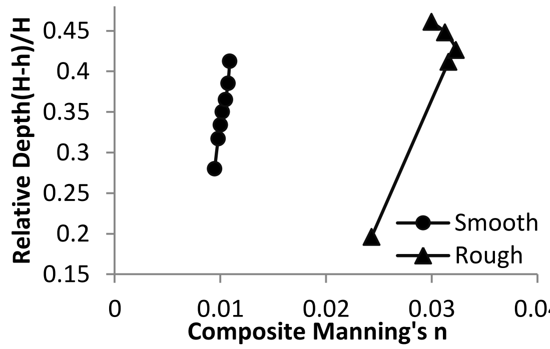
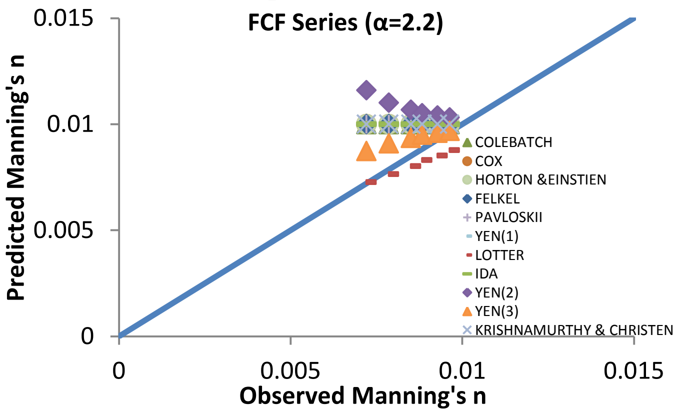


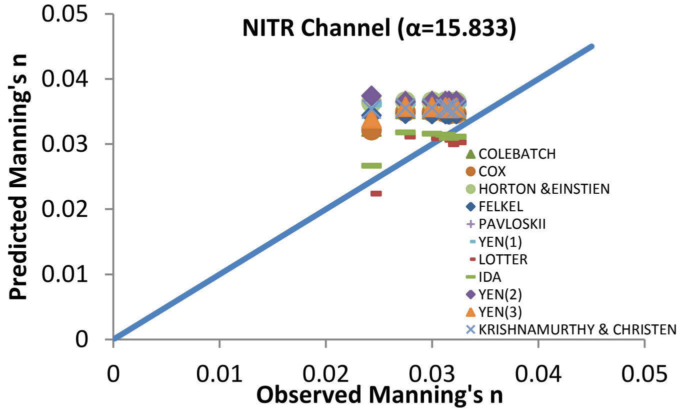
Figure 3.2 Overbank composite roughness results for the Experimental Compound Channels

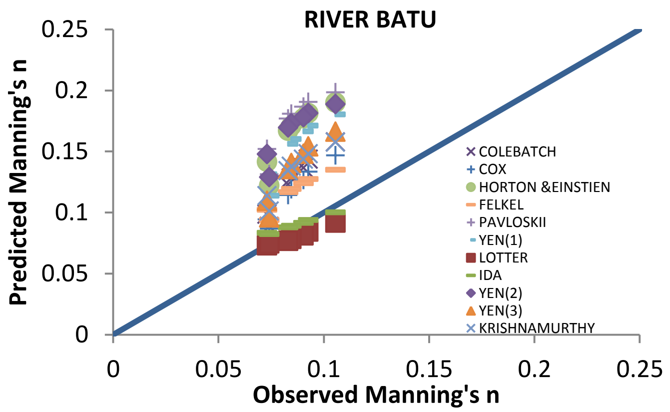
In addition, situations where channel sections have the different roughness varying laterally along the sub section wetted perimeter of a compound channel are often encountered in design and laboratory experiments. Figure 3.2 shows that the Composite Manning coefficients of the channel increase with the increasing ratio of the flood plain to the main channel depth.

5.2 *Prediction of composite roughness*

Yang [6] discussed that the diagonal division has the highest accuracy in predicting the composite roughness of a compound channel. But the main difficulty in using the diagonal division is how to find the positions of the division lines for all the shapes of the compound channel and the flow depths. So the vertical division is the appropriate sub sectional division method which could be applied to all methods for predicting composite roughness. To evaluate an accurate approach to estimate the composite roughness for both homogeneous and non-homogeneous roughness compound channels an attempt has been made to apply all these methods to the experimental data sets. Roughness of the river reach or floodplain is decided from the stage-roughness value obtained by inbank experimentations maintaining the same surfaces or the roughness value of the same surface may be obtained from standard books and articles (e.g. Chow (1959), French (1985)) With the known *'n'* value and other parameters of each subsection, and applying the equation (A) to (K), the composite roughness coefficient for the whole cross section was computed. The results from all these methods are listed in Table-1 and plotted in Figure 4. The methods result in higher error in assessing the composite roughness for the compound channels. The higher error is mainly due to non-inclusion of momentum transfer effect of compound channel instead followed some complementary assumptions which are meant for simple channels only. CM (Cox Method) assumed that the total shear force equals the sum of the constituent subsection shear force, the friction slope is the same for all subsections and the subsection velocities vary in proportion to the depth to a seven sixth power law. It is assumed in the EBM (Einstein and Bank Method) that the velocities are equal in all subsections, which are verified for a single channel by Knight and Macdonald's experiments (1979) that shows the ratio between the velocity in the bank region and that of cross section varies between 0.927–1.103.; but for the compound channels, the velocity in the main channel is larger than that on the floodplains.







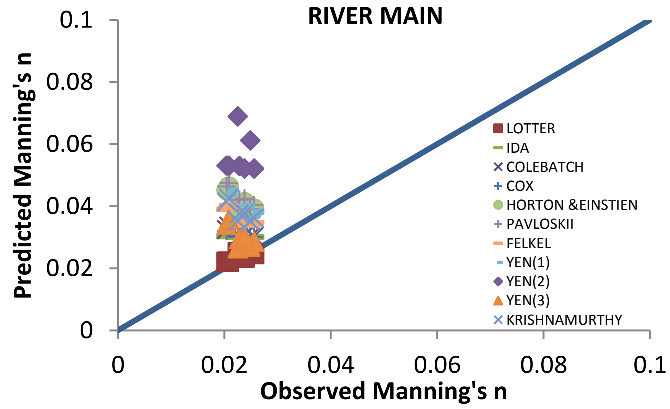


Figure.4 Comparison between Observed and Predicted Manning's *n* of all methods for FCF Series (3), NITR Channel (3), River Batu and River Main data

In the KCM (Krishnamurthy and Christensen), the assumption that there is no momentum exchange between the adjoining subsections is not correct for the compound channels. Large numbers of experimental results of SERC-FCF (Knight and Sellin [27], Ackers [17]) show that the flow velocities in the main channel and floodplains are much different, which causes a remarkable momentum exchange making the decrease in the velocity in main channel and increase in the floodplains even for the case of homogeneous roughness's. Due to these facts, the computed composite roughness by the approaches like CM, LM, EBM, and KCM etc are not providing good results for compound channels.

Among all the approaches, LM is found to give better results. However this method also fails when there is more interaction and for non-homogeneous roughness effects. Therefore an attempt has been further made to improve this method to incorporate the strong momentum transfer mechanism that exists in a compound channel.

6 A MODIFIED APPROACH

Lotter method is based on the assumption that the total discharge in a compound channel is the sum of subordinate discharge in that channel. These assumptions may be true for simple channel but for a compound channel this is not true because of strong interaction between its subsections. To incorporate the momentum transfer effect, the Lotter method needs to be improved. In the compound channel, the flood plain is giving a dragging force to the main channel sub section. Therefore, the wetted perimeter of the main channel needs to be increased to compensate the dragging force. So an amount of interface length (H-h) needs to be added to the perimeter of main channel so as to compensate the momentum transfer. This addition will take care of the extra resistance offered by floodplain to the main channel. Because for an over bank flow depth, the main channel compartment get an additional drag from the floodplain compartment along the interfaces. Therefore the perimeter of main channel needs to be increased. Because of large perimeter of floodplain, as compared to that of main channel, the need to change the perimeter of floodplain can be neglected. Consider a compound channel having its perimeter composed of M types of roughnesses viz. (P_1, P_2, P_3… P_i….P_m of roughness n_1, n_2, n_3……n_m respectively) in Fig.5.

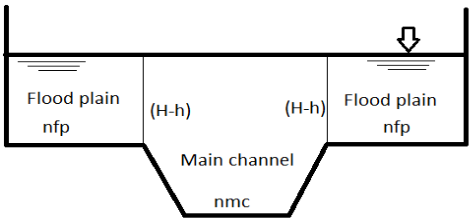


Figure 5 Different roughness units along the wetted perimeter of a compound channel

$$n_{c(LM)} = \frac{PR^{5/3}}{\sum \frac{P_i R_i^{5/3}}{n_i}} \quad (4)$$

The Lotter's equation (4) is modified with the change in perimeter of the main channel,

$$P_j = P_{mc} + 2(H - h) \quad (5)$$

Then the Equation (4) is revised using Equation (5) and given by

$$n_{c(MLM)} = \frac{PR^{\left(\frac{5}{3}\right)}}{\left[\left(\sum \frac{1}{n_f} P_i R_i^{5/3}\right) + \left(\frac{1}{nm} P_j R_j^{5/3}\right)\right]} \quad (6)$$

Where P, R and (H-h)/H are the total wetted perimeter, hydraulic radius and relative depth of the whole channel cross section of the compound channel. P_i and R_i are the wetted perimeter, hydraulic radius. n_{fp} and n_{mc} are the Manning's roughness coefficient of the flood plain and main channel, P_j and R_j Modified wetted perimeter and the hydraulic radius of main channel. $n_{c(LM)}$ and $n_{c(MLM)}$ are the composite roughness by Lotter method and Modified Lotter method(MLM).

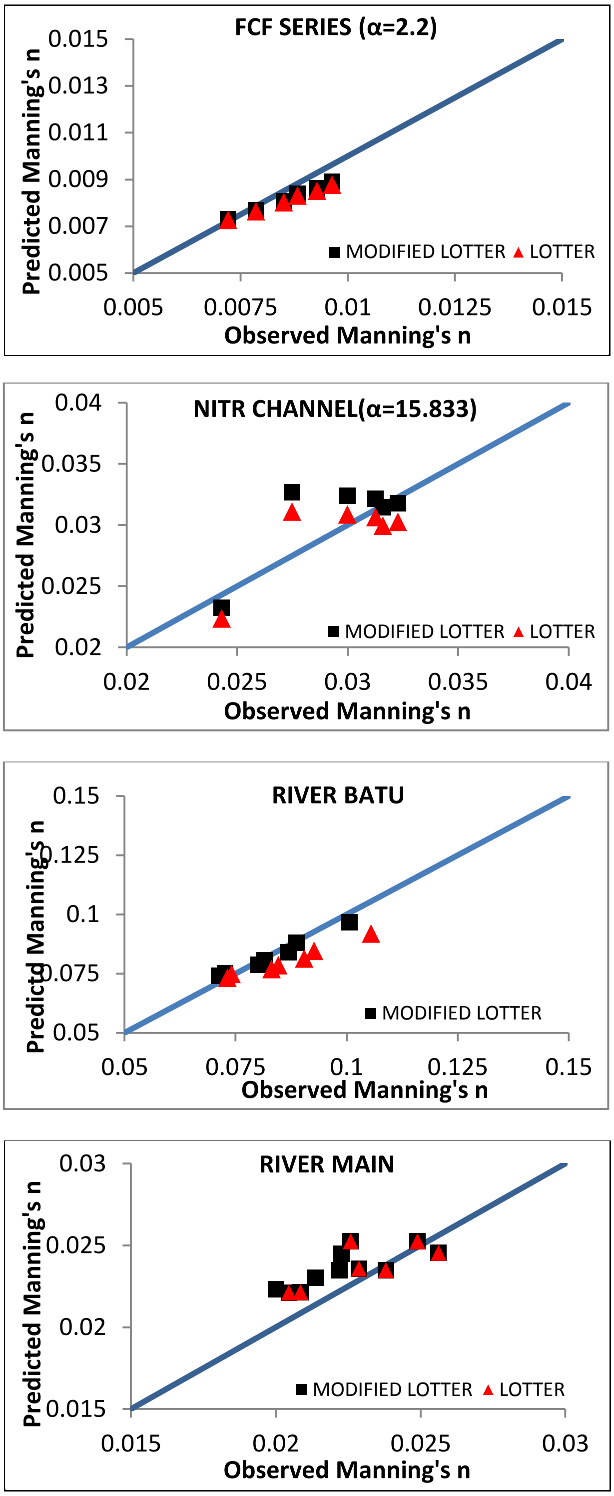


Figure.5 Observed Manning's n and Composite Manning's n by Modified Approach

Error statistics for each of the equations are also computed, given in Table 3. These include the mean of absolute and relative errors.It would also result in big errors, because the mean relative error of the composite roughness is as high as 97% as shown in Table 3. For correctly assessing the composite roughness, the lateral exchange of momentum must be taken into account. However, the composite roughness is distinct for the LM as compare to

MLM. The mean relative error for the MLM is only 0.5%. However it reaches 0.93% for the Lotter Method. The ML has the smallest errors (see Figure. 5; Table 3). So the ML has the highest accuracy.

Table -3 Errors in computation of composite *n* by different methods

METHODS	FCF SERIES 3		NITR- GRAVEL BED		RIVER MAIN		RIVER BATU	
	Mean Error (%)							
	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute
Cox	13.80	0.11	17.29	0.48	46.39	1.01	35.37	3.11
Colebatch	13.80	0.11	18.78	0.53	48.38	1.06	44.19	3.90
Horton &Einstein	13.80	0.11	24.80	0.70	97.13	2.13	90.46	7.81
Felkel	13.80	0.11	18.24	0.50	72.26	1.58	35.73	3.07
Pavloskii	13.80	0.11	25.69	0.72	102.24	2.25	101.64	8.76
Lotter	**-3.69**	**0.03**	**-0.93**	**0.03**	**5.41**	**0.11**	**-6.60**	**0.62**
Modified Lotter	**-1.29**	**0.02**	**1.02**	**0.04**	**3.42**	**0.056**	**-3.87**	**0.45**
Ida	13.80	0.11	4.17	0.11	36.42	0.80	4.77	0.35
Yen(1)	13.80	0.11	23.79	0.67	91.91	2.02	78.53	6.80
Yen(2)	20.21	0.16	25.59	0.72	145.89	3.25	93.75	8.06
Yen(3)	7.89	0.06	20.77	0.58	51.33	1.11	56.55	4.95
Krishnamurthy	13.80	0.11	21.33	0.59	81.62	1.79	54.87	4.75

7 CONCLUSIONS

Following conclusions are drawn from the present experimental and theoretical investigations

1. The composite flow resistance coefficients of the smooth compound channel are found to increase with overbank flow depth however in case of compound channel with rough floodplain the value first increases with overbank flow depth and then decreases. This is due to combined effect of momentum transfer and different roughness between the floodplain and main channel.
2. Different methods to predict the composite roughness are applied to the present smooth and rough compound channels. The representative methods are found to be unfit for the compound channels.
3. Out of all the discussed methods, the Lotter method is found to give better roughness results however the need of improvement of the method are suggested. Because the extra resistance produced due to flow interaction between main channel and flood plain in a compound channel has not been properly incorporated in Lotter method. That additional energy loss has now been compensated by increasing the hydraulic perimeter of main channel.
4. From the error analysis, the accuracy of the modified approach has been successfully tested to the experimental channel data, large channel FCF data sets and some natural river data sets.

8 ACKNOWLEDGEMENT

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