Prediction of energy loss in compound channels having enlarging floodplains

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ABSTRACT: In this paper, energy loss in non-prismatic compound channels of different geometry and flow conditions are analysed. Two types of diverging compound channels are considered. Those are a) compound channel with diverging floodplain originating from compound channel with prismatic flood plain with angle 5.93° b) compound channel with diverging flood plain of 3.81°, 5.7° and 11.3° angle originating from simple main channel. Due to non-uniformity of flow in such cases the prediction of flow parameters is much complex as compared to that in a prismatic compound channels. Investigators need an accurate value of energy slope for prediction of flow in such cases. Due to limited data sets available in literatures, application of CFD using ANSYS has been made to produce more datasets for non-prismatic compound channels. The results of discharges for different diverging angles are found to give satisfactory results when verified with the available experimental datasets. Energy slope of the non-prismatic compound channels are found to be function of non-dimensional geometric and hydraulic parameters like width ratio (α), relative depth (β), relative distance (Xr) and diverging angle (θ) of the channel. An expression to predict the energy slope is developed which will be helpful for accurate prediction of flow in such cases. The model is verified well with present experimental channels and with the data of other researchers.

1 INTRODUCTION

In natural rivers, due to changes in the cross-sectional area, the state of the flow may be changed from uniform to non-uniform. Under such conditions, the hydraulic analysis will be more complicated compared to simple uniform flow. Rivers when get flooded, they usually instigate transition reaches by varying the width of floodplains. Additional energy losses occur during interaction between main channel and floodplains as well as due to non-uniformity of flow occurring during movement through non-prismatic reaches.The interaction between the flow in the main channel and the flow in the floodplain is investigated, e.g. by Knight and Demetriou (1983), Shiono and Knight (1991) Khatua and Patra (2008), Khatua et al (2012) etc. showed that three sources of energy losses coexist under uniform flow conditions: bed friction, momentum flux due to both turbulent exchange and secondary currents across the total cross-section. Three other flow configurations in non-prismatic geometry with constant overall channel width were also well investigated by Elliot & Sellin (1990), Chlebek & Knight (2008) flow in meandering two-stage channels, Shiono & Muto (1998) or flow in a doubly meandering compound channel, Islam et al. (2008). Proust et al. (2010) estimated the energy losses in straight, skewed, divergent, and convergent compound channels. Their results showed that the slope of energy line equals the head loss gradient at the total cross-section. Distribution of energy in an overflow bank section of a non-prismatic compound channel is a vital aspect that needs to be identified properly. When the flow is non-uniform and the total width of the channel is constant, a common characteristic between the various experiments was identified: mass transfer between the main channel and the floodplains generate low variation in flow depth along the longitudinal direction. The stream-wise variation in flow depth was even found to be negligible for a few flow configurations. On the other hand, when the width of the overall channel is varying, the flow depths markedly vary. This was observed for flows in symmetrically diverging or converging floodplains. In this case the mass transfer between main channel and floodplain exhibits different characteristic, as they are produced by both stream-wise changes in total width of the channel and in water depth and consequently become stronger than when the overall channel width is constant.

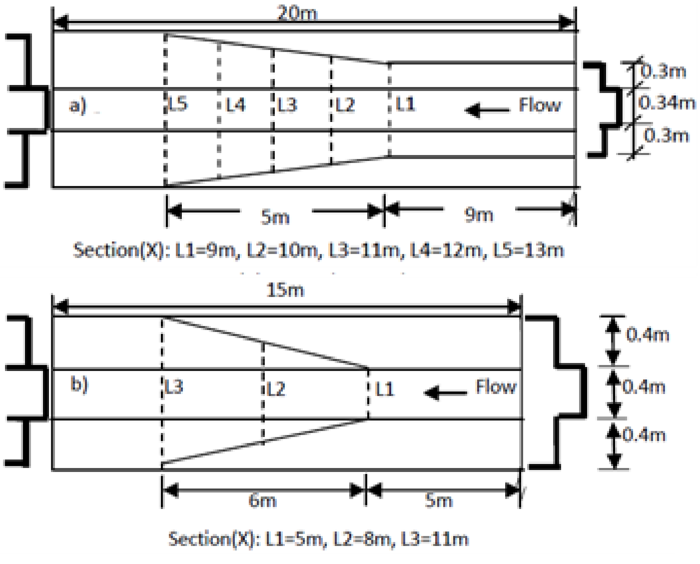


Figure 1. Schematic view of the non-prismatic compound channel a) Dv5.93-having diverging floodplain with angle 5.93°(NIT Rourkela) b) Dv3.81-diverging flood plain with angle 3.81°(Yonesi et al.,2013)

Usually Chezy's, Manning's or Darcy-Weisbach equations are used to calculate the velocity of flow in an open channel. Due to its popularity, the field engineers mostly use Manning's equation to estimate discharge in non-uniform flow.

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

Where Q= discharge in channel m^3/s, A= cross sectional area in m^2, R = hydraulic radius, in meters, S_e= slope of energy grade line, in meters per meter. n = Manning's roughness coefficient. An effort here has been made to develop an expression to predict the energy slope of compound channel with diverging floodplains. Multiple Linear regression analysis has been applied to the non-dimensional dependent and most influencing independent parameters.

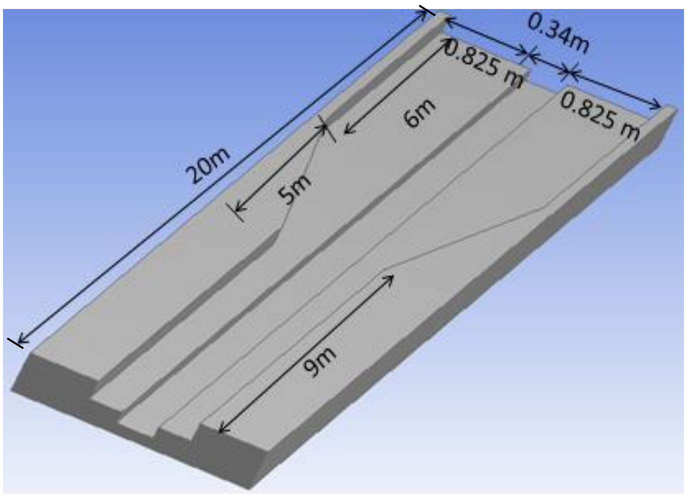
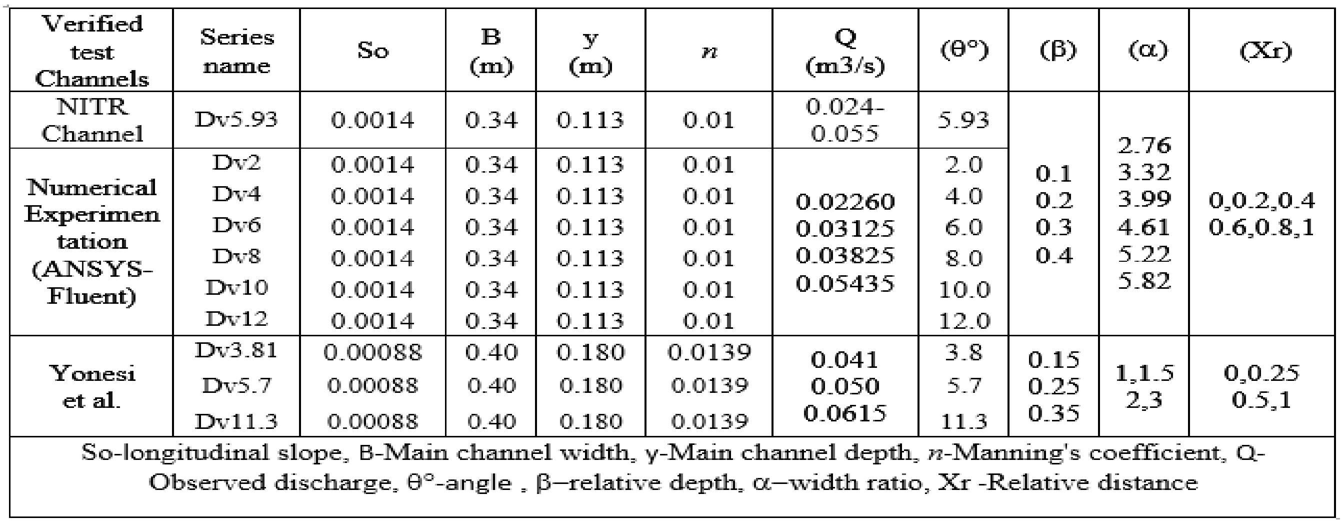


Figure 2. Oblique view of 5m diverging compound channel, Dv5 (5.93° angle from the flood plain) located at National Institute of Technology, Rourkela, India (using ANSYS Fluent)

2 EXPERIMENTAL INVESTIGATION AND RESULTS

In this present work to find the depth of flow of a diverging compound channels and to study it's variation of flow with its geometrical and hydraulic parameters, numerical experimentations using ANSYS-Fluent for all different geometry for diverging compound channel and laboratory experimentations for diverging compound channel (5.93° angle) had been conducted in the hydraulic engineering laboratory at National Institute of Technology, Rourkela, India. The flume dimension is 22m longx2m widthx0.5m. The experiments have been carried out in the glass flume made up of Perspex sheet, MS bars, plates and angles, fitted with all accessories. The roughness of the flood plain and main channel are kept same and estimated to be 0.01. Water was supplied through three numbers of centrifugal pumps (each 15 hp capacity) discharging into a large RCC overhead tank. The water is made to flow to the stilling basin of flume from the overhead tank by regulating valves. Baffle walls arrangement have been made inside the stilling basin to reduce the turbulence. Water is made to flow under gravity from the head gate end to the tail gate of the flume. At the downstream end there is a measuring volumetric tank followed by a large underground sump which feed the water to the overhead tank through pumping. This is an arrangement of complete recirculation system of water for the experimental channels. For first 11m the channel is compound with prismatic floodplain and then it is made diverged for 5m. The main channel width is 340mm having symmetrical flood plains width of 300mm on both sides making diverging angle of 5.93° (i.e. flood plain width is increased from 300mm to 820mm). The longitudinal bed slope is found to be 0.0014 maintaining subcritical flow conditions everywhere. Five different sections are chosen for the study i.e. at x=9m, x=10m, x=11m, x=12m, x=14m as shown in Figure 1(a). In this paper we considered three more channel data for development of a model to predict energy loss. Those are from University of Tehran, Iran, diverging compound channel, 1) Dv3.81 representing 3.81° angle 2) Dv5.7 for 5.7° angle and 3) Dv11.3 for 11.3° diverging angle (Yonesi et.al, 2013).

Table 1. Geometric and hydraulic parameter for experimental channel dataset from literature and experimental work.



Verified test Channels	Series name	So	B (m)	y (m)	n	Q (m3/s)	(θ°)	(β)	(α)	(Xr)
NITR Channel	Dv5.93	0.0014	0.34	0.113	0.01	0.024-0.055	5.93	0.1 0.2 0.3 0.4	2.76 3.32 3.99 4.61 5.22 5.82	0,0.2,0.4 0.6,0.8,1
Numerical Experimentation (ANSYS-Fluent)	Dv2	0.0014	0.34	0.113	0.01	0.02260 0.03125 0.03825 0.05435	2.0			
	Dv4	0.0014	0.34	0.113	0.01		4.0			
	Dv6	0.0014	0.34	0.113	0.01		6.0			
	Dv8	0.0014	0.34	0.113	0.01		8.0			
	Dv10	0.0014	0.34	0.113	0.01		10.0			
	Dv12	0.0014	0.34	0.113	0.01		12.0			
Yonesi et al.	Dv3.81	0.00088	0.40	0.180	0.0139	0.041 0.050 0.0615	3.8	0.15 0.25 0.35	1,1.5 2,3	0,0.25 0.5,1
	Dv5.7	0.00088	0.40	0.180	0.0139		5.7			
	Dv11.3	0.00088	0.40	0.180	0.0139		11.3			
So-longitudinal slope, B-Main channel width, y-Main channel depth, n-Manning's coefficient, Q-Observed discharge, θ°-angle , β–relative depth, α–width ratio, Xr -Relative distance										

Figure 3. Schematic 3D of non-prismatic compound channel and the diverging compound channel (θ=5.93°) located at National Institute of Technology, Rourkela, India

2.1 *Experimental Results*

Due to limited data sets available in literatures, application of CFD using ANSYS has been made to produce more datasets for non-prismatic compound channels. The flow depth along the longitudinal distance for diverging compound channel of NITR (Dv5.93) is shown in Figure 4. The numerical flow depth obtained from the ANSYS fluent for Dv6 channel having 6° diverging angle are found nearly equal to the flow depth measured from the experiment for the same discharge. Adopting the similar procedures more datasets on compound channel with diverging floodplains have been extracted from the ANSYS fluent model.

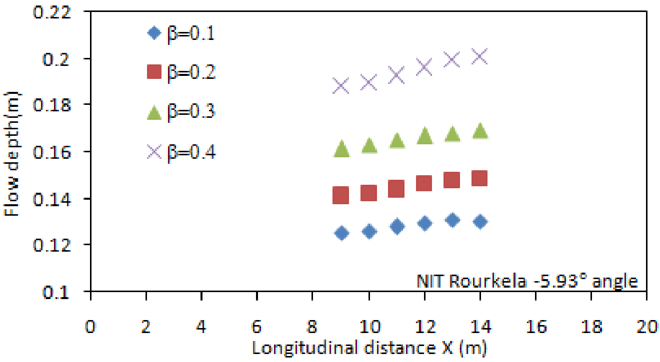


Figure 4. Flow depths along the longitudinal direction at non-prismatic reach for the compound channel having floodplains with 5.93° diverging angle at NIT Rourkela.

2.2 *Numerical Experimentations*

For finding out the more data sets of compound channel having diverging floodplains, ANSYS Fluent is used. Six different angles are chosen viz. 2°, 4°, 6°, 8°, 10° and 12° maintaining same width ratio for the first 9m prismatic portion i.e. 2.76. The main channel width is 0.34m and floodplain is 0.3m either side of the main channel upto 9m (Figure 2). Then the flood plain is diverged making the angle as aforementioned above. In ANSYS fluent, k-ε model is used to predict the depth at different section of diverging portion of the channel. For the development of the model, the flow depth are chosen for such sections that having same width ratio for all six different angle. For the current study the width ratios are selected as 2.76, 3.380, 3.99, 4.61, 5.22 and 5.82. The detailed results of water surface profile for all these channels obtained are used for finding out the energy slope.

3 ANALYSIS OF ENERGY LOSS AND INFLUENCING PARAMETER

The resistance to flow of a channel can be significantly increased or decreased by the presence of contractions or expansions of floodplain. For accounting the additional resistance, various methods exist which are generally for simple channels or meandering channels. It has been confirmed that ignoring contraction and expansion losses due to converging and diverging cross section can introduce significant error in the channel conveyance estimation. Here we consider the effect on estimation of conveyance due to enlarging of floodplain width.

Consider a prismatic compound channel having total width B and main channel width b. Let the flood plain has been expanded from width B at Section 1 to 6 as shown in Figure 5. Here the total diverging part of the channel is divided into six arbitrary sect--ions where the corresponding average flow depths say Y_1, Y_2, Y_3, Y_4, Y_5 and Y_6 respectively are occurring. The energy loss between the two consecutive sections is calculated from the equation of conservation of energy between those sections. For calculating the energy E, let the datum may be taken as bottom of the extreme downstream end of the enlarging part of the channel i.e. here the channel bottom at section 6. The total energy with non-uniform flow can be considered as the sum of macroscopic Kinetic energy, potential energy of the gravity force and the internal energy Proust et al.(2010). The change in internal energy between two consecutive sections is very less as compared to the corresponding potential and kinetic energies. Therefore the contribution of internal energy here is not considered while applying the conservation of energy principle for any two sections i.e. section 1 and section 2.

$$E_1 = Z_1 + Y_1 + \frac{\eta_1 V_1^2}{2g} \qquad (3.1)$$

$$E_2 = Z_2 + Y_2 + \frac{\eta_2 V_2^2}{2g} \qquad (3.2)$$

where *E* = total energy head at any section, *Z* the bottom elevation of the respective section above the datum, *Y* the flow depth, *V* the mean velocity at that section and η_1 and η_2 are the velocity head correction factor at that consecutive sections taken as one for this case. Considering $h_l$the total energy loss between those two sections, we can write.

$$Z_1 + Y_1 + \frac{\eta_1 V_1^2}{2g} = Z_2 + Y_2 + \frac{\eta_2 V_2^2}{2g} + h_l \qquad (3.3)$$

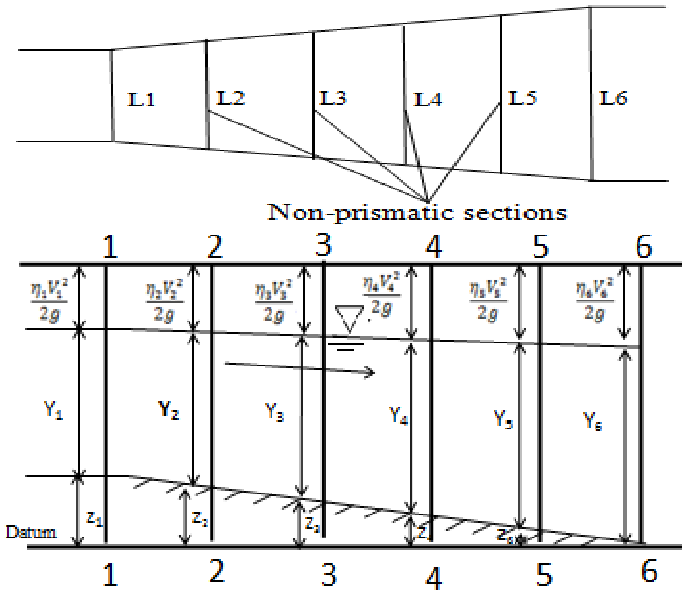


Figure 5. Sketch of energy profile for diverging compound channel.

It may be noted that the energy loss (h_l) may not be linearly varying between sections to sections. It mainly depends on the channel geometry, converging or diverging angle, and surface and flow conditions (Naik and Khatua 2014, Rezaei 2006). Knowing the energy loss between two sections, the energy slope (S_e) between those sections can be calculated by

$$S_e = \frac{h_l}{L} = \frac{E_1 - E_2}{L} \qquad (3.4)$$

where $h_l = E_1 - E_2$and L is distance between two consecutive sections. Calculation of this energy slope is helpful for correct estimation of flow or average velocity in any part of the non-prismatic sections. This is further helpful for drawing the energy gradient and energy slope.

4 SELECTION OF GEOMETRIC AND HYDRAULIC PARAMETERS

Flow hydraulics and momentum exchange in diverging compound channels are significantly influenced by both geometrical and hydraulic variables. The computation of flow variables in a diverging compound channel is more complex than that for simple compound channel. The geometrical and flow factors responsible for the estimation of energy losses at different reaches of a compound channel having enlarging floodplain are

i. Relative flow depth (β) = (*H*-*h*)/*H*. where *H* = height of water at a particular section and, *h* = height of water in main channel
ii. Diverging angle denoted (θ)
iii. Width ratio (α) i.e. ratio of width of floodplain (B) to width of main channel (*b*)
iv. Relative distance (*Xr*) from a reference or origin i.e. The distance of the arbitrary reach or section in longitudinal direction of the channel/total length of the non-prismatic channel. Total five flow variables were chosen as input parameters and energy loss as output parameter.

Due to flow interaction between the main channel and floodplain, the flow in a compound section consumes more energy than a channel with simple section carrying the same flow and having the same type of channel surface and geometry. The energy loss is manifested due to the compiling effect of width ratio (α), relative distance (*Xr*), relative depth (β) of flow, diverging angles (θ) of the channel.

$$S_e = \frac{dH}{dx} = f(\alpha, \beta, Xr, \theta) \qquad (4)$$

5 RESULTS AND DISCUSSIONS

5.1 *Dependency of energy loss on different parameters*

The dependency of energy loss in terms of energy slope S_e with their best functional relationships has been found out from different plots. The variation of energy loss in terms of energy slope S_e with relative depth (β), width ratio(α), diverging angle(θ) and relative distance (Xr) is plotted in Figure 6(a-d) respectively. For each change of independent parameters like $\alpha, \beta, Xr, \theta$ it has been clearly noticed that there is an increase of dependent parameter energy slope S_e with increase of the independent parameters. From the Regression analysis, the best functional relationship between dependent parameter S_e and independent parameter $\alpha, \beta, Xr, \theta$ are found as follows. The best functional relationship between S_e and β, is exponential and between S_e and α is logarithmic in nature with high regression coefficient (R^2) value as 0.946, and 0.935 respectively whereas the best functional relationship for $S_e$with both θ and Xr are power function having regression coefficient R^2 value as 0.891 and 0.954 respectively.

6 MODEL DEVELOPMENT

In this present work, the MS-Excel data analysis regression model tool is used for formulation of the mathematical model to predict the energy slope in terms of width ratio (α), relative distance (*Xr*), relative depth (β) of flow and diverging angles (θ) of the compound channels. The Multiple Linear Regression (MLR) is applied where the dependencies of energy slope on different geometrical and hydraulic parameters are related. Therefore all the variables are divided into two categories i.e. dependent and independent variables.

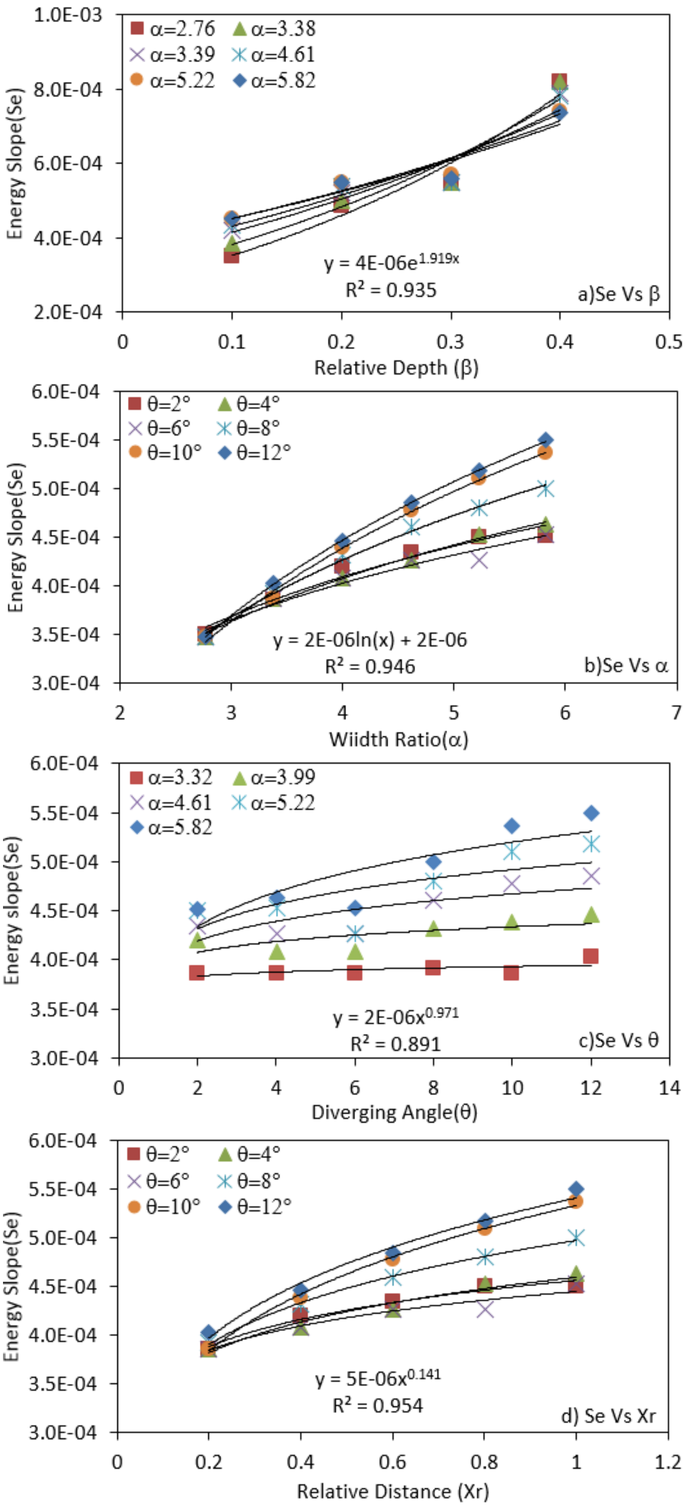


Figure 5 (a-d). Comparison of energy slope for subsequent hydraulic and geometric parameter

At first the variation of non-dimensional variables in relation to energy slope are plotted and the best fit curved are obtained. The functional relationships which are providing the maximum coefficient of determination (R^2) are fixed for each dependency parameter with energy slope. The dependency of energy slope and the best functional relationships have found out from different plots from numerical experimentation data sets as well as the from the global datasets exist in the literature. The functional relationship for energy slope can be written as

$$S_e = f(\alpha, \beta, Xr, \theta) \qquad (6.1)$$

By analyzed the above plots, corresponding functional relationships of energy slope with different geometric and hydraulic parameters are found out are represented as f_1, f_2, f_3, f_4 respectively. The best functional relationships obtained areα

$$S_e = f(\beta)$$

$$f_1 = A_1(\beta)^{1.919}c_1 \qquad (6.2)$$

$$S_e = f(\alpha)$$

$$f_2 = A_2 ln(\alpha) + c_2 \qquad (6.3)$$

$$S_e = f(X_r)$$

$$f_3 = A_2(X_r)^{0.141}c_3 \qquad (6.4)$$

$$S_e = f(\theta)$$

$$f_4 = A_2(X_r)^{0.141}c_4 \qquad (6.5)$$

Where$A_1, A_2, A_3, A_4, c_1, c_2, c_3$and c_4 are proportionality coefficient. From the above graph it is shown that the R2 value for all relationships are very high and varies from 0.89 to 0.95. By using the above relationships we develop the equation for predicting energy slope S_e. All the dependent variables taken in Y-axis and observed energy slope value which is obtained from the independent variables are taken in X-axis. After applying the Multiple Linear Regression analysis using data analysis of MS-Excel, the unstandardized coefficients are found out and tabulated in Table 3.

Table2. Unstandardized coefficients from regression analysis.

Model	Unstandardized coefficients	
	A	Standard Error
Intercept (Constant)	-1.25208E-06	6.40371E-07
θ	0.013743500	5.81021E-07
β	0.910878030	0.029799024
α	0.130013147	0.151667588
Xr	0.053864115	0.044427138

As described previously the functional relationship for energy slope S_e with all independent variables are written as

$$S_e = f(f_1, f_2, f_3, f_4) \qquad (6.6)$$

After diverting in separate functional group for each non-dimensional parameter, the equation for energy slope is presented as

$$S_e = -1.25208\text{E} - 06 + 0.911f_1 + 0.13f_2$$
$$+0.054f_3 + 0.0137f_4 \qquad (6.7)$$

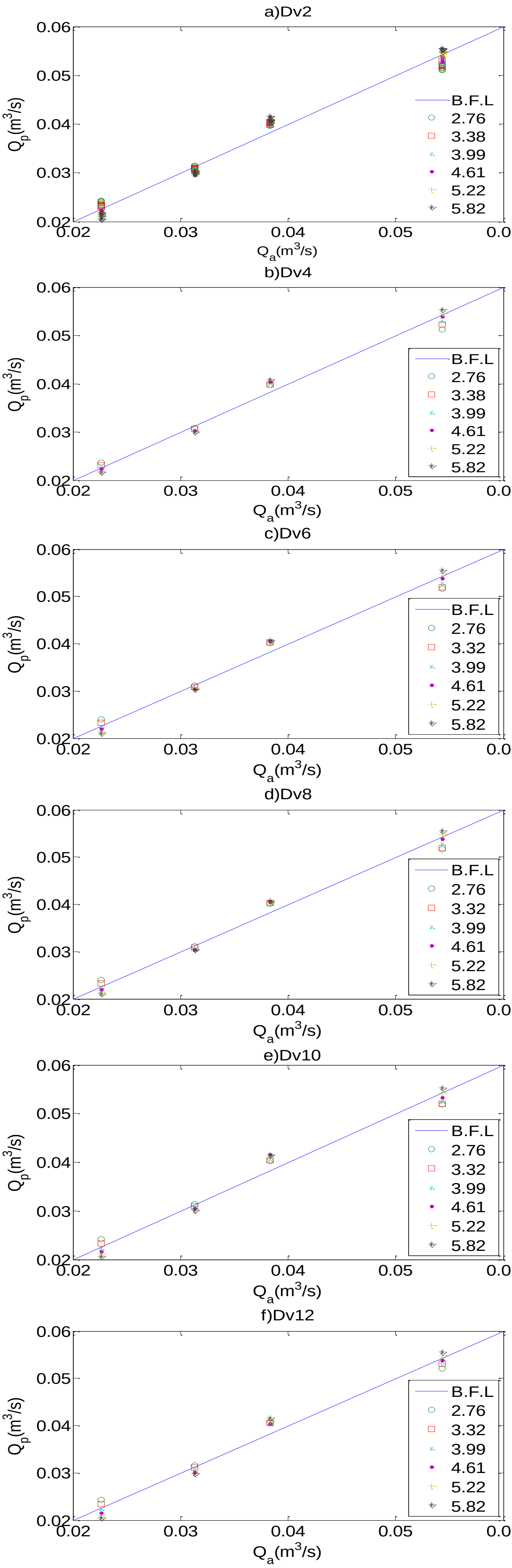


Figure 6 (a-f). Validation occurs in between actual discharge (Q_a) and predicted discharge (Q_p) for diverging compound channel (numerically experimented channel by ANSYS Fluent) with six different angle.

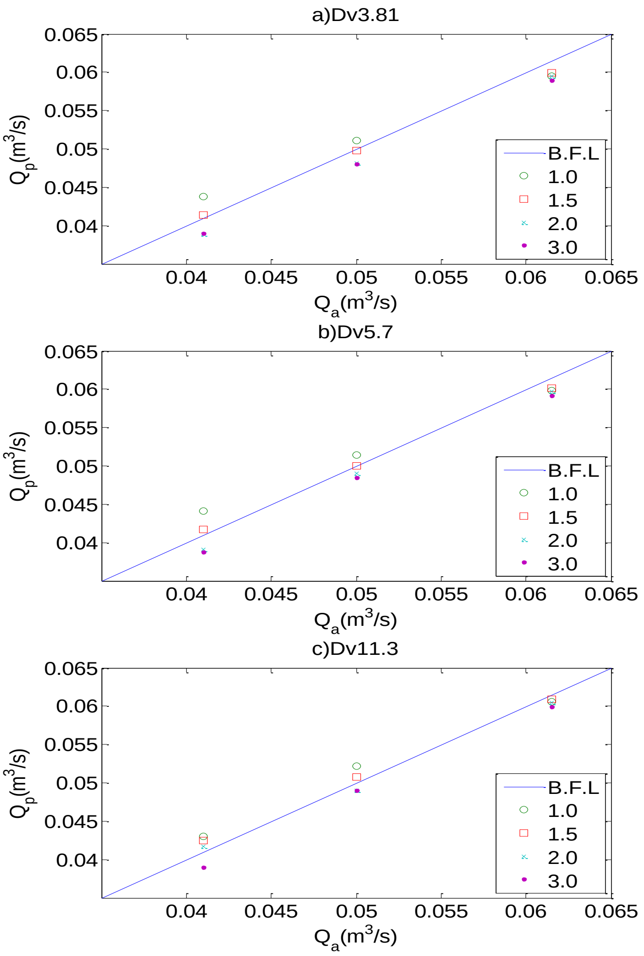


Figure 7(a,b,c). Validation occurs in between actual discharge(Q_a) and predicted discharge (Q_p) for diverging compound channel for three different diverging angle 3.81°,5.7° and 11.3° (Yonesi et al.,2013)

Now putting the individual values of functions f_1, f_2, f_3 and f_4 from equations (6.2 to 6.5), equation (6.6) is now modified and the final expression is given by

$$S_e = 1E - 05(-9.9205 + 36.4e^{1.919\beta} + 2.6\ln(\alpha) + 0.3161(\theta)^{0.971} + 2.69(X_r)^{0.141}) \qquad (6.8)$$

After formulation of the new mathematical model equation (6.8), an attempt has been taken to predict the discharge using this energy slope by Manning's equation (1) and to validate with the present experimental channel datasets and the discharge data of other investigators. Figure 6(a-f) shows the variation of predicted verses actual discharge with best fit line (B.F.L) for the experimental channels. Similarly the plots for diverging compound channels of other investigators are also plotted for comparison in Figure 7(a-c). (Datasets of Yonesi et al. (2013)).

The present mathematical model predicts the energy slope accurately. This has been demonstrated the between the observed discharges and predicted discharges. In all the channels the results of the present approach matches well with the observed value showing the good agreement between observed value and predicted value through the best fit line (B.F.L).

Table 3. Statistical results of empirical equation in predicting energy slope.

Error Calculation	Energy slope
MAE	0.00054660
MAPE	0.054660
MSE	0.000085861
RMSE	0.009266129

The energy slope of a compound channel having diverging flood plain with varying angle can easily be evaluated by using the proposed model. Though the model performed well for the present diverging compound channel and the diverging compound channel of other datasets but the range of validity should be trusted for smooth, rectangular main channel and compound channel having enlarging floodplain with angle ranging from 2° to12° only.

7 CONCLUSIONS AND FUTURE WORK

- Prediction of energy loss for non-prismatic compound channel is a very important issue for the river hydraulics. Experimental investigation has been done to study the effect of geometric and hydraulic parameter of a diverging compound channel on prediction of energy slope due to non-uniformity of the flow.
- The dependency of hydraulic and geometrical non-dimensional parameters (width ratio, relative depth, diverging angle and relative distance) on energy slope is presented. The energy slope is found to increase with relative depth exponentially, increase with angle and relative distance by power function and increase with width ratio logarithmically.
- A multilinear regression analysis has been performed to predict the energy slope on the basis of width ratio, relative depth, diverging angle and relative distance.
- The strength of the present expression has been checked with MAE, MAPE, MSE, RMSE and regression coefficient, the present expression provides less MAE, MAPE, MSE and RMSE with higher value of R2. This is believed that the present model can be applied successfully to compound channel having diverging flood plain for uniform roughness only.
- The energy slope model will be helpful to predict the discharge in non-prismatic compound channel more accurately as compared to the traditional energy slope approaches. Improvements to the equation can be made by analyzing the non-uniform roughness channels and obtaining more datasets.

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