STAGE–DISCHARGE PREDICTION FOR MEANDERING CHANNELS

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ABSTRACT
Accurate estimation of discharge in any open channel depends on the suitable accounting of the resistance coefficients. The energy loss is influenced by the channel geometry and flow parameters, which are assumed to be lumped into a single value manifested in the form of resistance coefficients in terms of Manning's *n*, Chezy's *C*, and Darcy–Weisbach *f*. The flow structure for meandering channels is more complex as compared to that of straight channels due to its three-dimensional motion. Consequently, the use of design methods based on straight channels is inappropriate when applied to meandering channels and results in large errors when estimating the discharge. A series of experimental results are presented concerning stage–discharge–resistance relationships for meandering channels with rigid and smooth boundaries. Investigation concerning the loss of energy of flows for meandering channels in terms of variation of Chezy's *C* due to variation of sinuosity, geometry, and longitudinal slope are studied. A discharge predictive method for meandering channel is proposed that accounts for the variation of roughness with depth of flow in the channel. The performance of the model is evaluated and is found to compare well with other available models.
Keywords: Aspect ratio, bed slope, boundary shear, dimensional analysis, flow resistance, meandering channel, sinuosity, stage–discharge relationship.

1 INTRODUCTION

Prediction of flow, velocity, and energy loss in a meandering river is an important topic in river hydraulics that needs to be investigated from a practical point of view in relation to flood prediction, the bank protection, navigation, water intakes, and sediment transport-depositional patterns, etc. These are influenced by many factors, notably the shape of the cross-section, the longitudinal variation in plan form geometry represented by meandering, longitudinal and vertical distribution of wall roughness, etc. These factors are assumed to be lumped into a single value of resistance coefficient manifested in the form of energy loss. Shiono *et al*. [1], Patra and Kar [2], Patra and Khatua [3], Khatua [4], and others have shown that the structure of the flow is surprisingly more complex for meandering channels as compared to that of straight channels. Consequently, the use of design methods based on straight channels is inappropriate when applied to meandering channels. Chezy was the first to consider the wetted perimeter of channels as an analog to boundary resistance. The equation proposed by Chezy (1769), Darcy–Weisbach (1857), or Manning (1891) is used to compute the section mean velocity. While using these equations, selection of a suitable value of roughness coefficient in terms of Manning's *n*, Chezy's *C*, or Darcy–Weisbach friction factor *f* is the single most important parameter for the proper estimation of discharge in an open channel. The Soil Conservation Service [5] method for selecting roughness coefficient values for channels account for meander losses that are discontinuous at the limits of the defined sinuosity ranges, with consequent ambiguity and uncertainty. To overcome the problem, the relationship was linearized, known as the Linearized SCS (LSCS) method. Visual estimation of *n* values can be made at each site using Barnes [6] guideline and Chow [7]. Chang [8, 9] investigated energy expenditure and proposed an analytical model for obtaining the energy gradient, based on fully developed secondary circulation for wide rectangular sections. Jarrett [10]

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developed a model to determine Manning's n for natural high gradient channels having stable bed and in-bank flow without meandering coefficient and having stable bed and bank materials (boulders). It was intended for channel gradients from 0.002 to 0.04 and hydraulic radii from 0.15 to 2.1m, although Jarrett [10] noted that extrapolation to large flows should not be too much. Arcement and Schneider [11] modified Cowan [12] method and were designed specifically to account for selecting n values for natural channels and flood plains resistance. Shiono *et al.* [1] reported the effect of bed slope and sinuosity on discharge of meandering channel. Pang [13] has shown that roughness coefficients not only denote the roughness characteristics of a channel but also the energy loss of the flow. James [14] reviewed the various methods for bend loss in meandering channel and proposed suitable modifications for it.

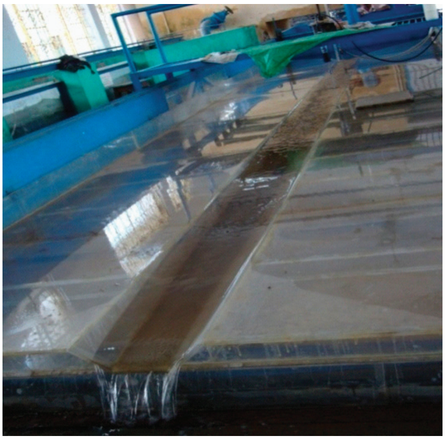
Maria and Silva [15] expressed the friction factor of rough turbulent meandering flows as the function of sinuosity and position (which is determined by, among other factors, the local channel curvature). They validated the expression by the laboratory data for two meandering channels of different sinuosity. The expression was found to yield the computed vertically averaged flows that were in agreement with the flow pictures measured for both large and small values of sinuosity. Lai Sai Hin *et al.* [16] expressed that estimation of discharge capacity in river channels was complicated by variations in geometry and boundary roughness.

The review shows the importance of study of effect of parameters, such as the bed slope, aspect ratio, sinuosity, roughness coefficients, flow depth, etc., on the discharge estimation in a meandering channel. Experiments are conducted to investigate the loss of energy of meandering and straight channels of different sinuosity, geometry, slope, and flow depth in terms of variation of Chezy's C. The study is primarily a step in understanding the flow processes in prediction of roughness in an experimental channel. Using dimensional analysis, a model for roughness coefficients in terms of Chezy's C is developed. The work is supported by data observed from four sets of experimental channels of different geometry, slope, aspect ratio, and sinuosity. The results of the present model compares well with approach of Shiono *et al.* [1], LSCS method proposed by James and Wark [17], Toebes and Sooky [18] method, and others.

2 EXPERIMENTAL SETUP

The present research uses both meandering and straight experimental channel data recorded from the tilting flumes in the Fluid Mechanics and Hydraulics Engineering Laboratory of the Civil Engineering Department, at the National Institute of Technology Rourkela, India. Observation are made from two straight channels (Type-I has rectangular cross-section and Type-II has trapezoidal cross-section. The other two meandering channels are named as Type-III and Type-IV, respectively. The tilting flumes are made out of metal frame with glass walls at the test reach. The flumes are made tilting by hydraulic jack arrangement. Inside each flume, separate meandering/straight channels are cast using 10 mm thick perspex sheets. Photo graphs of Type-II and Type III channels with measuring equipments taken from the downstream side are shown in Photo-1(a, b) and the sectional plan views are shown in Figs 1(a) and 1(b), respectively.

Water is supplied to the experimental setup by a recirculating system. Two parallel pumps are used to pump water from an underground sump to the overhead tank. From the overhead tank, water is led to a stilling tank located at the upstream of the channel. A series of baffle walls between the stilling tank and channels are kept to reduce turbulence of the incoming water. At the end of the experimental channel, water is allowed to flow through a tailgate and is collected in a masonry volumetric tank from where it is allowed to flow back to the underground sump. From the sump, water is pumped back to the overhead tank, thus setting a



(a)

(b)

Photo 1. View of Type-II and Type-III channels with the measuring equipments.

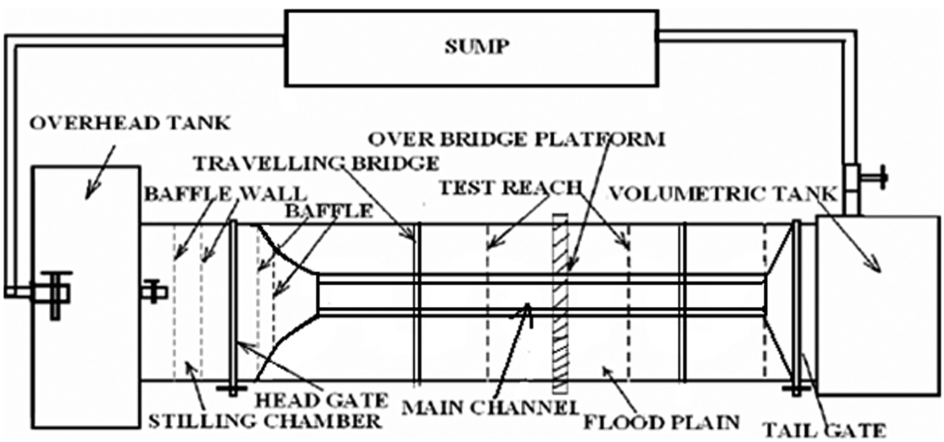


Figure 1: (a) Plan view of Type-II channel with measuring equipments.

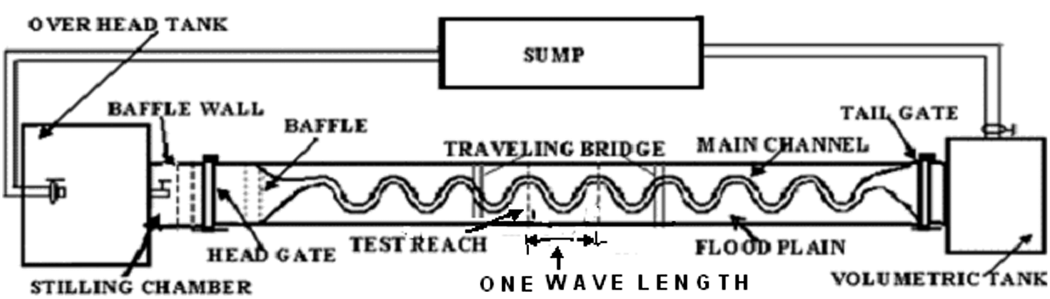


Figure 1: (b) plan view of Type-III meandering channel with measuring equipments.

complete recirculating system of water supply for the experimental channel. The tailgate helps to establish uniform flow in the channel.

Water surface slope measurement is carried out using a pointer gauge fitted to the travelling bridge operated manually having least count of 0.1 mm. Point velocities are measured using a 16-Mhz Micro *ADV* (Acoustic Doppler Velocity-meter) at a number of locations across the predefined channel section. Guide rails are provided at the top of the experimental flume on which a travelling bridge is moved in the longitudinal direction of the entire experimental channel. The point gauge and the micro-*ADV* attached to the travelling bridge can also move in both longitudinal and the transverse direction of the experimental channel at the bridge position. The micro-*ADV* readings are recorded in a computer placed besides the bridge. As the *ADV* is unable to read the data of upper-most layer (up to 5 cm from free surface), a micro-Pitot tube of 4 mm external diameter in conjunction with suitable inclined manometer are used to measure velocity and its direction of flow at the pre-defined points of the flow grid. A flow direction finder is also used to get the direction of maximum velocity with respect to the longitudinal flow direction.

The Pitot tube is physically rotated normal to the main stream direction till it gives maximum deflection of manometer reading. The angle of limb of Pitot tube with longitudinal direction of the channel is noted by the circular scale and pointer arrangements attached to the flow direction meter. Discharge in the channel is measured by the time-rise method in the measuring tanks located at the downstream end of the experimental channel. All observations are recorded in the central test reach for straight channel of Type-I and Type-II and at the central bend apex of Type-III and Type-IV meandering channels. The overall geometrical parameters and hydraulic details of the experimental runs are given in Table 1.

3 RESULTS AND DISCUSSIONS

3.1 Stage-discharge variations for meandering channels

In the present investigation, achieving a steady and uniform flow has been difficult due to the effect of curvature and the influence of the geometrical parameters. However, for the purpose of present work, an overall uniform flow is tried to be achieved in the channels. Flow depths in the experimental channel runs are so maintained that the water surface slope becomes parallel to the valley slope. At this stage, the energy losses are taken as equal to potential energy input. This has become a standard whereby the conveyance capacity of a meandering channel configuration can be assessed (Shiono *et al.* [1]). Under such conditions, the depths of flow at the channel centerline separated by one wavelength distance must be the same, where wavelength of a sinusoidal meandering channel is the distance over which the wave's shape repeats (Fig. 1b) (http://en.wikipedia.org/wiki/Wavelength - cite_note-hecht-0). In all the experimental runs, this simplified approach has been tried to achieve. This stage of flow is taken as normal depth, which can carry a particular flow only under steady and uniform conditions. The stage discharge curves plotted for different bed slopes for particular sinuosity of channel are shown in Fig. 2.

For both straight and meandering channels, discharge is found to increase with stage and longitudinal slope. For the similar geometry, the increase in discharge with flow depth for meandering channels is found to be less as compared to that for straight channels. The drop in discharge is more for channels of higher sinuosity (Type-IV channel) than that from low sinuosity (Type-III channel).

Table 1: Geometrical parameters and hydraulic details of the experimental runs.

Sl no	*Item description*	*Type-I*	*Type-II*	*Type-III*	*Type-IV*
1	*Channel type and nature of surface of bed*	*Straight-rectangular*	*Straight trapezoidal (side slope 1:1)*	*Meandering rectangular*	*Meandering trapezoidal (side slope 1:1)*
2	*Channel width (b)*	*120 mm*	*120 mm at bottom and 280 mm at top*	*120 mm*	*120 mm at bottom and 280 mm at top*
3	*Bank full depth*	*120 mm*	*80 mm*	*120 mm*	*80 mm*
4	*Bed slope*	*0.0019*	*0.003*	*0.0031*	*Varying (slopes – 0.003, 0.0042, 0.0053, 0.008, 0.013, 0.015, 0.021)*
5	*Sinuosity*	*1.00*	*1.00*	*1.44*	*1.91*
6	*Number of runs for stage–discharge data*	*11*	*5*	*15*	*55*
7	*Discharge (cm^3/s)*	*1061, 1280, 2148, 2307, 2902, 3249, 4117, 4548, 5058, 5947, 6312*	*4766, 6961, 8147, 8961, 9739*	*316, 426, 1347 1669, 2200, 2357, 2619, 2757, 2946, 3338, 3698, 4191, 4656, 5596, 5680*	*Slope-0.003 (1479, 2605, 3101, 3717, 4097, 4563, 5994)* *Slope-0.0042 (4798, 5329, 5899, 7210, 7809, 8636)* *Slope-0.0053 (294, 484, 987, 1742, 2048, 2757, 3224, 3338, 3698, 4191, 4656, 5515, 6396, 7545)* *Slope-0.008 (904, 1416, 2165, 4863, 5492, 6768, 8473)* *Slope-0.013 (2357, 4877, 5410, 5991, 7181, 8157, 9480)* *Slope-0.015 (1319, 2742, 4497, 4884, 6209, 8112, 8397)* *Slope-0.021 (1286, 2150, 3346, 4070, 5451, 6123, 9223)*
8	*Depth of flow (cm) corresponding to flow discharge of runs*	*3.02, 3.44, 4.98, 5.24, 6.21, 6.80, 8.15, 8.82, 9.55, 10.92, 11.48*	*5.2, 6.4, 7.0, 7.4, 7.8*	*1.29, 1.57, 3.44, 4.05, 4.98, 5.31, 5.78, 6.08, 6.41, 7.11, 7.7, 8.55, 9.34,10.9, 11.01*	*Slope-0.003 (1479, 2605, 3101, 3717, 4097, 4563, 5994)* *Slope-0.0042 (4798, 5329, 5899, 7210, 7809, 8636)* *Slope-0.0053 (294, 484, 987, 1742, 2048, 2757, 3224, 3338, 3698, 4191, 4656, 5515, 6396, 7545)* *Slope-0.008 (904, 1416, 2165, 4863, 5492, 6768, 8473)* *Slope-0.013 (2357, 4877,5410,5991, 7181, 8157, 9480)* *Slope-0.015 (1319,2742, 4497 4884, 6209, 8112, 8397)* *Slope-0.021 (1286,2150,3346, 4070, 5451, 6123, 9223)*

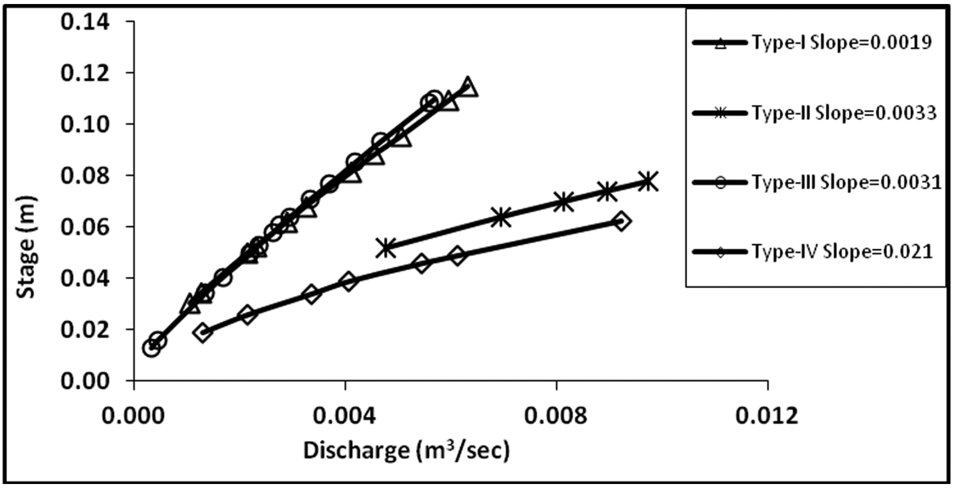


Figure 2: Stage discharge variations in open channel flow.

3.2 Variation of reach averaged longitudinal velocity with depth of flow

Plots between the reach averaged velocity and flow depth for all the experimental channels are shown in Fig. 3. From the figure, it can be seen that for all the channels, the increase in reach averaged longitudinal velocity of flow is nearly in accordance with the increase in depth of flow. The rate of increase of reach averaged velocity with flow depth is more for straight Type-I and Type-II channels than Type-III and Type-IV meandering channels. This is because the meandering channels offer more resistance to flow. Further due to spreading of water to a wider trapezoidal section for Type-IV channel than Type-I and Type-III channel sections (Sinuosity $[S_r] = 1$ for Type-I and Type-II, $S_r = 1.44$ for Type-III, and $S_r = 1.91$ for Type-IV), resulting additional resistance to flow. For all flow conditions, the rate of increase of velocity with flow depth is higher for the sinus channel of Type-IV and lower for straight channel of Type-I. This is mainly due to their large differences in the longitudinal bed slopes. The slope of the channel is an important parameter influencing the desired driving force. As for higher slopes (Type-IV, slope = 0.021) in a particular channel, there is increase in the rate of velocity with flow depth.

3.3 Roughness coefficients in meandering channel flow

Flow resistance is usually represented by the resistance coefficient of the boundary, such as the Chezy's coefficient C, Manning's roughness n, and Darcy–Weisbach friction factor f. Assuming the flow to be uniform and neglecting all non-friction losses, the energy gradient slope can be considered equal to the average longitudinal bed slope S of a channel. Under steady and uniform flow conditions, we use the equations proposed by say Chezy to compute the section mean velocity of a channel section as

Chezy's equation $$U = C\sqrt{\mathrm{RS}} \quad (1)$$

where S = the longitudinal slope of the channel, R = the hydraulic mean radius of the channel section, and C = Chezy's channel coefficient representing the average channel resistance to

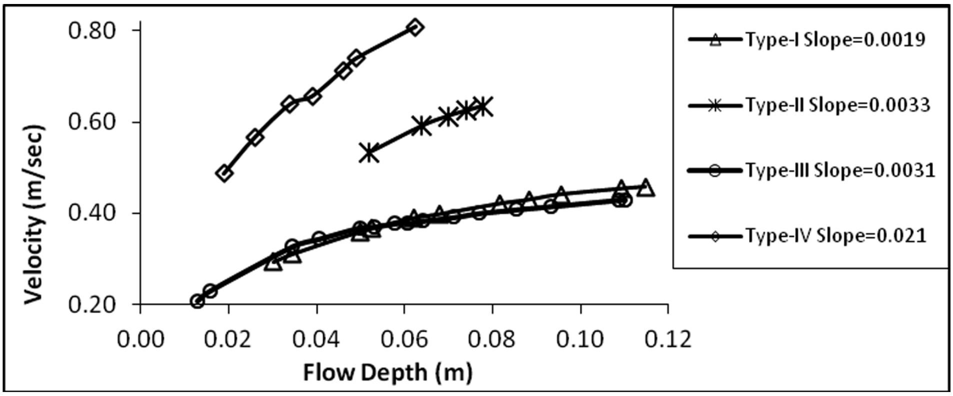


Figure 3: Variations of velocity with flow depth in open channel flow.

the fluid flow in a channel. These roughness values are given in many standard books and publications for straight reach sections. Due to continuous stream wise variation of radius of curvature, flow geometry in meander channel is in the state of either development or decay or both. Sinuosity and slope have significant influences for the evaluation of channel discharge which needs to be addressed properly. The variations of resistance coefficients for the experimental meandering channels are also found to vary with depth, aspect ratio, slope, and sinuosity. Variations of these are all linked to the stage–discharge relationships which are modeled in the next section of the paper. The results of roughness coefficients with discharge and flow depth are given in Table 2(a). For the highly meandering channel of Type-IV, the variations of roughness coefficients with depth of flow for more longitudinal slope conditions are presented in Table 2(b).

3.3.1 Variation of Chezy's c with depth of flow in open channel

Variation of Chezy's C with the non-dimensional parameter of flow depth/channel width for the channels investigated is shown in Fig. 4. Type-I and Type-II channels are straight and have the same base width. However, the nature of the curve for Type-II shows that at higher flow depths, there is lesser increase of values of Chezy's C due to the effect of wetted perimeter of two trapezoidal channels (Type-II) than rectangular channels (Type-I). The nature of curve for meandering channels of Type-III and Type-IV are similar. The rate of increase of Chezy's C for meandering channels is lesser at higher depths due to increased resistance at these depths. It can be seen from the figure that meandering channels exhibit a steady increase in the value of C with depth of flow. Chezy's C is found to decrease with increase of aspect ratio indicating that the meander channel consumes more energy as the depth of flow increases. For a channel with increase in slope, the Chezy's C is less for a particular stage.

4 DIMENSIONAL ANALYSIS

Dimensional analysis offers a method for reducing complex physical problems to the simplest form prior to obtaining a quantitative answer. The important variables affecting the stage–discharge relationship are considered to be velocity U, hydraulic radius R, viscosity ν, gravitational acceleration g, bed slope S, sinuosity S_r (defined as the ratio of the length of the

Table 2(a): Experimental results showing variations of C with flow depth.

Channel type	Run no	Discharge Q (m^3/s)	Flow depth h (m)	Channel width b (m)	Average velocity (m/s)	$\sqrt{S}/n$	Chezy's C
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Type-I	SR1	0.00106	0.030	0.12	0.293	3.96	47.389
Straight	SR2	0.00128	0.034	0.12	0.310	3.97	48.109
rectangular	SR3	0.00215	0.050	0.12	0.359	3.97	49.987
channel slope	SR4	0.00231	0.052	0.12	0.367	3.98	50.327
= 0.0019	SR5	0.00290	0.062	0.12	0.389	3.99	51.143
	SR6	0.00325	0.068	0.12	0.398	3.96	51.163
	SR7	0.00412	0.082	0.12	0.421	3.97	51.950
	SR8	0.00455	0.088	0.12	0.430	3.96	52.168
	SR9	0.00506	0.096	0.12	0.441	3.99	52.748
	SR10	0.00595	0.109	0.12	0.454	3.97	52.909
	SR11	0.00631	0.115	0.12	0.458	3.96	52.953
Type-II	ST1	0.00477	0.052	0.12	0.533	5.13	50.692
Straight	ST2	0.00696	0.064	0.12	0.591	5.13	52.023
trapezoidal	ST3	0.00815	0.070	0.12	0.613	5.08	52.140
channel slope	ST4	0.00896	0.074	0.12	0.624	5.04	52.041
= 0.0033	ST5	0.00974	0.078	0.12	0.634	5.00	51.903
Type-III	MR1	0.00032	0.013	0.12	0.207	5.14	43.279
Meandering	MR2	0.00043	0.016	0.12	0.229	5.11	44.203
rectangular	MR3	0.00135	0.034	0.12	0.326	5.01	47.561
channel slope	MR4	0.00167	0.041	0.12	0.343	4.93	47.594
= 0.0031	MR5	0.00220	0.050	0.12	0.368	4.88	48.099
	MR6	0.00236	0.053	0.12	0.370	4.79	47.504
	MR7	0.00262	0.058	0.12	0.378	4.75	47.433
	MR8	0.00276	0.061	0.12	0.378	4.68	46.865
	MR9	0.00295	0.064	0.12	0.383	4.66	46.897
	MR10	0.00334	0.071	0.12	0.391	4.61	46.739
	MR11	0.00370	0.077	0.12	0.400	4.60	46.966
	MR12	0.00419	0.086	0.12	0.408	4.56	46.881
Type-IV	MT1	0.00148	0.031	0.12	0.316	5.47	53.10
Meandering	MT2	0.00261	0.045	0.12	0.351	5.02	51.09
trapezoidal	MT3	0.00310	0.050	0.12	0.364	4.94	50.96
channel slope	MT4	0.00372	0.056	0.12	0.377	4.83	50.57
= 0.003	MT5	0.00410	0.059	0.12	0.388	4.84	51.01
	MT6	0.00456	0.063	0.12	0.396	4.78	50.78
	MT7	0.00599	0.074	0.12	0.418	4.66	50.45

Table 2b: Experimental results for Type-IV channel with longitudinal slopes.

Different slopes of highly meandering channel	Run no	Discharge Q (m^3/sec)	Flow depth h (m)	Channel width b (m)	Average velocity (Q/A) (m/sec)	$\sqrt{S}/n$	Chezy's C
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Slope = 0.0042	MT8	0.00480	0.057	0.12	0.476	6.04	53.54
	MT9	0.00533	0.061	0.12	0.483	5.93	52.98
	MT10	0.00590	0.065	0.12	0.491	5.84	52.59
	MT11	0.00721	0.072	0.12	0.522	5.90	53.81
	MT12	0.00781	0.075	0.12	0.534	5.92	54.26
	MT13	0.00864	0.078	0.12	0.559	6.08	56.00
Slope = 0.0053	MT14	0.00029	0.011	0.12	0.215	6.78	42.57
	MT15	0.00048	0.014	0.12	0.250	6.58	43.26
	MT16	0.00099	0.022	0.12	0.313	6.47	45.18
	MT17	0.00174	0.031	0.12	0.368	6.34	46.34
	MT18	0.00205	0.034	0.12	0.386	6.33	46.81
	MT19	0.00276	0.041	0.12	0.418	6.26	47.40
	MT20	0.00322	0.046	0.12	0.428	6.09	46.70
	MT21	0.00334	0.047	0.12	0.431	6.07	46.64
	MT22	0.00370	0.049	0.12	0.443	6.05	46.89
	MT23	0.00419	0.053	0.12	0.457	6.02	47.07
	MT24	0.00466	0.056	0.12	0.470	6.02	47.37
Slope = 0.008	MT28	0.00090	0.019	0.12	0.342	7.71	42.90
	MT29	0.00142	0.025	0.12	0.391	7.58	43.78
	MT30	0.00217	0.033	0.12	0.437	7.38	44.14
	MT31	0.00486	0.051	0.12	0.558	7.49	47.43
	MT32	0.00549	0.056	0.12	0.564	7.26	46.45
	MT33	0.00677	0.062	0.12	0.600	7.31	47.41
	MT34	0.00847	0.070	0.12	0.637	7.31	48.13
Slope = 0.013	MT35	0.00236	0.031	0.12	0.504	8.72	40.65
	MT36	0.00488	0.048	0.12	0.613	8.53	42.01
	MT37	0.00541	0.051	0.12	0.620	8.33	41.39
	MT38	0.00599	0.054	0.12	0.638	8.32	41.64
	MT39	0.00718	0.060	0.12	0.665	8.23	41.74
	MT40	0.00816	0.064	0.12	0.693	8.31	42.45
	MT41	0.00948	0.070	0.12	0.713	8.18	42.24
Slope = 0.015	MT42	0.00132	0.021	0.12	0.445	9.50	39.12
	MT43	0.00274	0.033	0.12	0.543	9.10	39.83
	MT44	0.00450	0.044	0.12	0.623	9.02	40.92
	MT45	0.00488	0.046	0.12	0.640	9.05	41.30
	MT46	0.00621	0.053	0.12	0.677	8.92	41.46
	MT47	0.00811	0.062	0.12	0.727	8.89	42.08
	MT48	0.00840	0.063	0.12	0.728	8.80	41.79
Slope = 0.021	MT49	0.00129	0.019	0.12	0.487	10.97	37.67
	MT50	0.00215	0.026	0.12	0.566	10.76	38.57
	MT51	0.00335	0.034	0.12	0.639	10.55	39.15
	MT52	0.00407	0.039	0.12	0.656	10.10	38.15
	MT53	0.00545	0.046	0.12	0.714	10.10	38.96
	MT54	0.00612	0.049	0.12	0.739	10.13	39.40

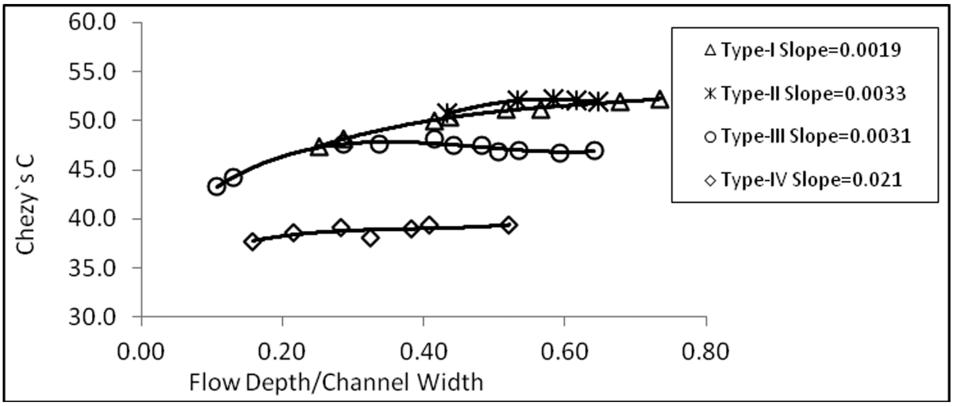


Figure 4: Variation of Chezy's C with flow depth/channel width.

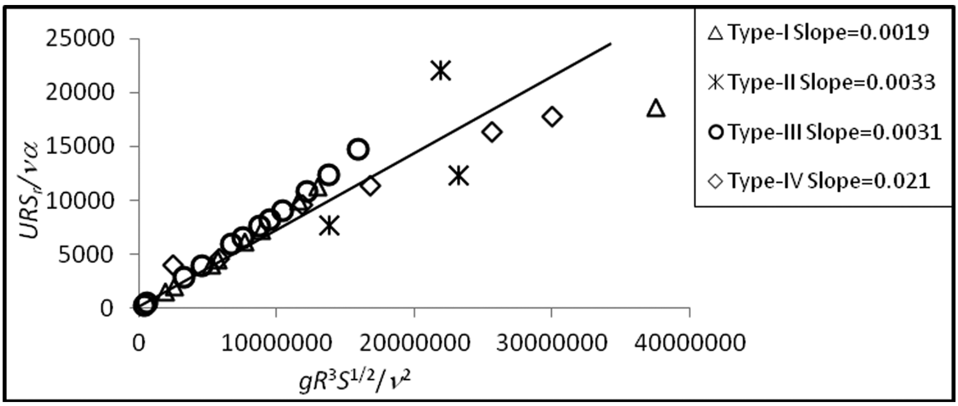


Figure 5: Calibration equation for $\left\{\frac{gR^3S^{1/2}}{\nu^2}\right\}$ and $\left\{\frac{URS_r}{\nu\alpha}\right\}$ for derivation of Chezy's C.

thalweg, i.e. path of deepest flow to the length of the valley) and aspect ratio (width b to flow depth h ratio) α. Now all these dimensionless parameters can be related functionally as

$$\varphi\{U, S, S_r, \alpha, g, R, \nu\} \tag{2}$$

Sinuosity (S_r) is inversely related to the velocity. Chezy's C is dimensionally non-homogenous. Therefore, the dimensional group $\left(g.R^3/\nu^2\right)$ is used because of its similarity to the traditional Chezy's equation for one-dimensional flow in a prismatic channel and is expressed as

$$\frac{UR}{\nu} = \varphi\left[\frac{1}{S_r}, S, \alpha, \left(\frac{gR^3}{\nu^2}\right)\right] \tag{3}$$

In an attempt to find a simple relationship between the dimensionless groups for meandering channel shapes under different hydraulic conditions, the values between $\left\{\frac{gR^3S^{1/2}}{\nu^2}\right\}$ and

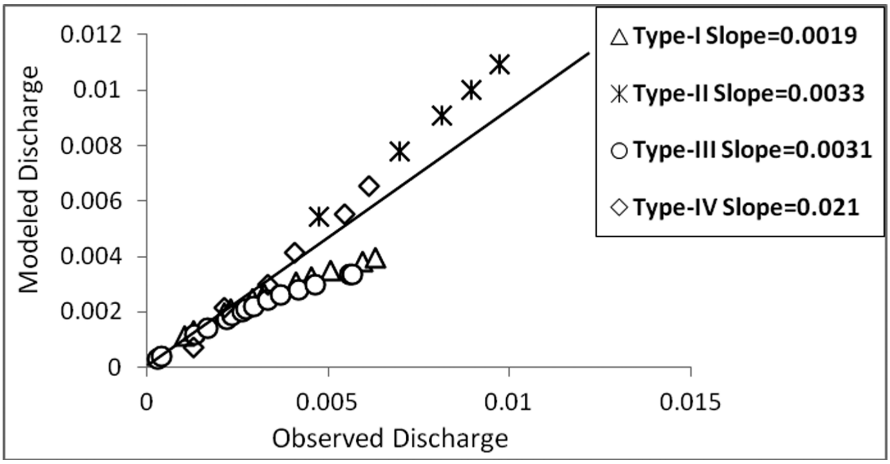


Figure 6: Variation of observed and modeled discharge using Chezy's *C*.

$\left\{\frac{URS_r}{va}\right\}$ is plotted in Fig. 5 using the experimental data together with data previously collected for meandering channel for different slopes. From the plot between dimensionless parameters, the best possible fit is found to be in the form of power equation having a regression correlation of 0.97. The relationship is expressed as

$$\left\{\frac{URS_r}{va}\right\} = k \times \left\{\frac{gR^3S^{1/2}}{v^2}\right\}^{0.86} \tag{4}$$

Using the relation obtained from eqns (3) and (4), the newly developed relationship for Chezy's *C* in a meandering channel is expressed as

Chezy's *C*
$$C = k \times \frac{g^{0.95}R^{1.35}a}{S^{0.02}v^{0.9}S_r} \tag{5}$$

where k is a constant of value 0.001 found from the experiments, where Manning's n and Chezy's C are related as $C = \frac{R^{\frac{1}{6}}}{n}$.

5 DISCHARGE ESTIMATION USING THE PRESENT APPROACH

Using eqn (5) the Chezy's *C* are evaluated and then the velocity from the channels are obtained from eqn (1). Plot between observed and calculated discharge is shown in Fig. 6. The calculated (modeled) discharge using the newly developed equations of Chezy's *C* is in good agreement with the observed values. The calculated discharge for the meandering channels of Type-III and Type-IV are more close to the observed value.

6 APPLICATIONS OF OTHER METHODS TO THE PRESENT CHANNEL

If Q_c represents the calculated discharge and Q_m the measured discharge, the percentage of standard error for each series of experimental runs are computed using equations given as

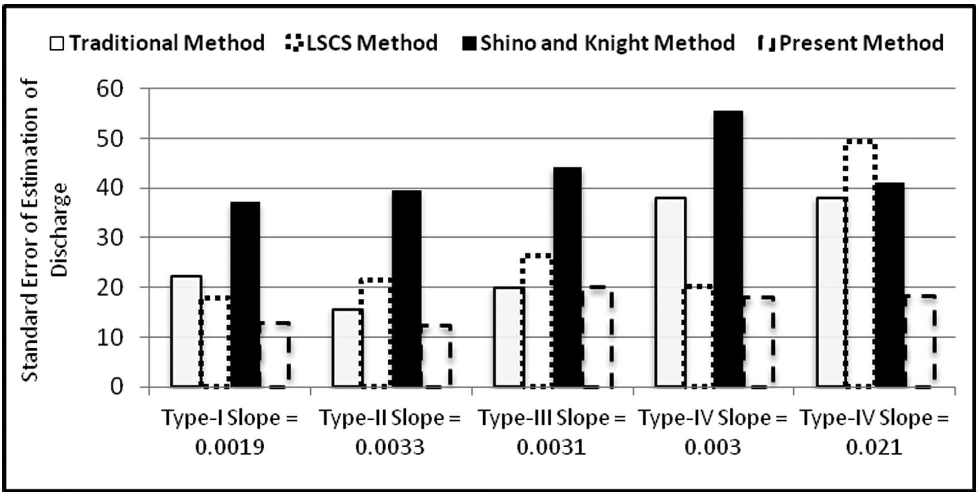


Figure 7: Comparison of standard error of estimate of discharge with present approach.

$$\sqrt{\frac{\sum\left[\frac{(Q_c - Q_m)}{Q_m}\times 100\right]^2}{N}} \tag{6}$$

where N = number of overbank flow observations for each compound channel geometry. The standard error of estimate of discharge by the present approach compares well with other investigators (Fig. 7). The overall percentage of standard error of discharge from the proposed method is 18.08, while it is 28.5 for *LSCS* method and is closely followed by the traditional method with standard error of 31.32. The overall standard error of discharge using Shiono *et al.* method [1] is also found to be of 46.9. Figure 7 shows that the proposed approach gives better discharge results as compared to other approaches for the present experimental channels.

7 CONCLUSIONS

1. Experiments are carried out to examine the effect of channel sinuosity and geometry on the variation of roughness coefficients in a meandering channel. The study is also extended to a meandering channel of higher sinuosity (S_r = 1.91). The flow resistance in terms of Chezy's C changes with flow depth for meandering channels. The resistance coefficient not only denotes the roughness characteristics of a channel but also the energy loss of flow. The assumption of an average value of flow resistance coefficient in terms of Chezy's C for all depths of flow results in significant errors in discharge estimation.
2. Dimensional analysis carried out to predict the resistance coefficients in a meandering channel shows that roughness coefficients are dependent on four dimensionless parameters namely, the sinuosity, aspect ratio, longitudinal slope of the channel, and Reynolds number of the flow. Using the proposed equation for roughness coefficient, stage–discharge relationship in a meandering channel can be adequately predicted. The present equation is found to give better discharge results as compared to the other established methods.

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