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Experimental investigation of Slope Change Impact on Manning's n in a tilting bed flume

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***Abstract*—This paper presents the findings of laboratory investigations on a tilting bed flume to determine the impact of bed slope on Manning's roughness coefficient, n (Manning's n). Correct estimation of Manning's n is crucial in the relatively accurate approximations of velocity and discharge. While various studies have examined factors affecting Manning's n, limited research has assessed the direct impact of bed slope. In this study, a tilting bed flume with a uniform graded 12.5 mm gravel bed was used to investigate the variation of water depth along the flume length at various slopes. Using the discharge computed by the volumetric method at the collection container and water depth measured at three points within the flume, the cross-sectional area, hydraulic radius, velocity, and Manning's n were computed at three different slopes: 0.04, 0.09 and 0.13. It was found that the average water depth, cross-sectional area, and hydraulic radius decreased, whereas the velocity and discharge increased as the bed slope increased. The results revealed that Manning's n increases by 50% as the slope increases from 0.04 to 0.09. However, the value of Manning's n decreased when further increasing the slope to 0.13. These findings revealed conclusively that Manning's n is not independent of the bed slope. Therefore, a factor of slope should be incorporated alongside other aspects to determine a more accurate value of Manning's n.**

***Index Terms*—Manning's n, Tilting bed flume, Bed slope impacts.**

I. INTRODUCTION

OPEN channels are carriers of water in which water flows under gravity. In these channels, water is typically exposed to the atmosphere. Bed slope, bed roughness, channel geometry, velocity, and depth are the main factors that govern hydraulic behaviour in open-channel flow [1]. Open channels are important structures because of their use in irrigation (agriculture), stormwater drainage, and the flow of water in rivers and streams. Canals are among the most widely used waterways for irrigating crops worldwide. Many barren lands are turned into cultivated fields through the implementation of canal systems. For instance, in India, 1.8 million hectares of arid land. Land was turned into cultivable land [2]. Reportedly, there are about 3.8 million km of irrigation canals across about 95 countries [2], underscoring the dependence of agricultural systems on extensive canal networks. Hydraulic structures like weirs, barrages and canals are important because they are capable of transforming barren land into agriculturally rich territory. However, transporting the water with maximum efficiency and minimum losses is a challenge. Changing rainfall patterns under the impact of climate change require a renewed focus on modernising water management to provide a suitable adaptive solution [3]. Estimation of discharge and velocity in open channel is crucial in sustainable and integrated water resource planning and management.

A. Role of flow resistance determination in discharge estimation

Depth, velocity and discharge of water are influenced by the roughness of bed material. Estimating these flow parameters in open channels is crucial in flood routing. Since flood volume and time to peak can be computed using flood routing, accurate estimates of these parameters support flood risk management by improving early warning systems [4]. Correct estimates of bed roughness also assist in predicting flow rate and velocity in open channel flow, especially in storm water computations, sediment transport assessment and enhancing water delivery efficiency in the irrigation canals[5], [6] [7].

Despite many studies conducted in the past, there is no universally accepted theory of flow resistance [8]. Changes in flow resistance result in variations in velocity, discharge, energy loss, and water level in open channel flow. The factors causing this resistance include channel boundary, bed roughness, channel geometry and vegetation [5], [6], [8], [9], [10], [11].

Determining flow resistance is important because it helps estimate discharge and significantly affects the design efficiency of hydraulic structures [12]. It is relatively easy to determine resistance in pipe flow due to its confined nature. In contrast, it is comparatively difficult to estimate flow resistance in natural channels due to numerous variables, such as the morphodynamic nature of the riverbed geometry and sudden changes in flow direction [12]. The flow resistance directly affects channel discharge and water conveyance capacity, thereby disrupting the overall hydraulic efficiency of the canal system[7].

B. Manning's Equation and Concept of Roughness Coefficient (n)

Manning's equation is widely used to determine the discharge and velocity in rivers, canals and open channels [13]. Manning's equation remained popular due to its simplicity and practical application. In hydraulic engineering practices, Manning's n is commonly treated as a temporally constant parameter. However, studies have shown that it varies with flow conditions and hydraulic factors [14].

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

(where K is a unit conversion factor and K = 1 for SI units), therefore:

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

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

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

where,

V = mean flow velocity
Q = discharge
R = hydraulic radius
S = slope of energy grade line
A = flow area
n = Manning roughness coefficient

In (3), Manning's n itself contains slope; therefore, it may not be independent of slope.

Among all the parameters in Manning's equation, the coefficient n is an unresolved factor that plays an important role in estimating flow resistance. Manning's n, which is often assumed to be a constant factor in the equation, is one of the uncertain parameters in open channel hydraulic. This uncertainty affects accurate estimation of discharge. This uncertainty is because Manning's n is affected by a number of factors, including flow depth, slopes, bed roughness and vegetation conditions in the open channel [15], [16] .

C. Physical meaning and assumption of n

In engineering practice, Manning's n is treated as a temporally constant parameter, and its value is selected from standard tables. Manning's n play important role in river engineering, design and efficiency of hydraulic structures [17]. It is used for calculating the roughness of the channel bed [18]. There are multi-dimensional factors that affect Manning's n, including bed material, geometry, vegetation, slope, discharge and sediment load [17].

Noteworthy point is that Manning's n, despite being a constant value, is affected by many factors like slope, flow velocity, Reynolds number, Froude number and sediment load [19]. Where an accurate estimation of Manning's n is important for finding flow resistance in an open channel. However, despite decades of studies, the issue remains unresolved, particularly the effect of slope on Manning's n, which still requires further investigation.

Manning's n is a major source of uncertainty in open channel flow, errors in its estimation affect the calculation of discharge, flow velocity, water depth and energy dissipation [13], [20]. Although Manning's n is treated as a material property, there are certain other factors that affect its value.

D. Factor affecting Coefficient n

The author [17] has identified multiple factors that affect Manning's n. It is affected by multiple hydraulic and physical conditions [21], [22], such as:

1) Slope: One of the main findings of [17] is that there is a direct relationship between slope and n-value: as the slope becomes steeper, n increases, demonstrating that hydraulic resistance is affected by slope variability. According to Manning's equation, velocity increases with slope. However, changes in slope also affect Manning's n and affect the overall flow value.

2) Grain size: A study by [17] discussed that increase in flow resistance was observed upon increasing grain size of bed material, suggesting direct correlation between grain size and the Manning's n. The experimental observations revealed that when grain size was increased from 2 to 25mm, corresponding increase in the flow resistance was recorded [17].

3) Flow depth and submergence: Many studies have investigated the relation of Manning's n with flow depth. It has been reported that the depth of flow has inverse relation with Manning's n. As the depth of flow increase, decrease in the n-value was observed under controlled conditions in flume, however, other hydraulic and physical conditions also play role in it. These findings indicate that manning's n is also depended on flow depth. The roughness decreases upon increasing depth because the roughness element is deeply submerged; therefore, the flow of water on the upper surface confronts little to no resistance, which is submergence behaviour [17] [22].

4) Vegetation: The vegetation in the channel cause drag and resistance to flow. Studies have shown that the Manning's n increases with the presence of vegetation in the channel causing loss of momentum and results in energy dissipation [21]. A study by Arcement and Schneider [21] showed that hydraulic resistance in natural vegetative floodplain is affected by vegetation density, flow depth and obstruction effects because this phenomenon increase drag and flood plain flow resistance.

5) Discharge: Estimation of discharge in natural open channels like river and streams, is very difficult and complex due to high variability [19]. Hydraulic radius in Manning's equation is intended to account for the influence of discharge on Manning's n; however, such discharge independence is not shown [14]. In fact recent studies suggested that Manning' n may still vary with discharge and flow conditions [23].

6) Flow velocity: In Manning's equation there is a inverse relation between n and velocity, therefore, if Manning's n is uncertain as so far discussed, then there is high probability that we can get inaccurate values of discharge, flood level, and overall hydraulic performance [14]

E. Limitations of Manning's equation

Applying Manning's equation outside its original assumptions may produce uncertainty and confront calibration problems because of the following reasons:

1) Manning equation was originally intended to be used for uniform open channel flow, but currently it's been applied widely for unsteady flows, overland flow conditions and shallow water flows for which it was not originally designed. Therefore, Manning's n remained an unresolved element in these conditions [13].
2) Even though its stated that Manning's n is a roughness coefficient, it is pertinent to mention that the n-value is also influenced by geometry, terrain imbalances and vegetation [13]. Therefore, the n-value is an ambiguous parameter in Manning's equation.
3) Another limitation as per [13], is regarding the usage of standard values of Manning's n, taken from the tables, which according to him, may not be applicable for every case. For example, the selected n-values from the tables are used in the cases of river flow and artificial open channel flow including uniform flow but it may fail in the case of overland flow with very shallow depth [13]. Consequently, the value of Manning's n fetched from the respective tables cannot be generalized for all the cases and situations.
4) Yet another limitation of Manning's equation is rooted in the procedure of n-value determination. Since, there is no standard method for estimating Manning's n, consequently, it's often difficult to select appropriate n-value in different flow conditions [22].
5) The geometric dependency of Manning's n is another important factor because the value of n varies with geometric shape. Consequently, n is not a constant value and it changes with geometry. Therefore, Manning's n cannot be treated as just a material property [22].

These limitations revealed the gap in previous assumption regarding Manning's n by considering it to be a constant value, as recent studies have argued otherwise. As discussed, the value of Manning's n changes with hydraulic and geometric conditions such as flow depth, slope, vegetation and shape of channel. Additionally, a study by [24] explained that hydraulic resistance coefficient shows extreme variability due to sediment transport process, flow regime and turbulence interaction. Therefore the assumption that the resistance parameter is constant in open channel flow, is challengeable [24]. These arguments collectively suggest that Manning's n is not a purely material property rather it act as dynamic hydraulic resistance parameter.

$n \neq$ constant, Instead:

$n=f(y, S, R, Re, k_s, \nu)$

where:

- y = flow depth,
- S = slope,
- R = hydraulic radius,
- Re = Reynolds number,
- ks = roughness height,
- ν = viscosity.

F. Engineering Consequences of Roughness Uncertainty

Manning's roughness coefficient n along with uncertainty in geometry, wetted perimeter and slope, is a major source of uncertainty in the discharge calculation of open channel flow [25]. Analysis revealed that uncertainty of Manning's n can influence discharge estimation by approximately 3.5 times in comparison to other factors [25]. Furthermore, this study shows that even a 10% variation in Manning n can cause 5% change in total discharge estimation. Such uncertainty can affect high stakes hydraulic calculation such as flood discharge estimation and design of levee. Moreover, human subjectivity in the selection of Manning's n remains an uncertain factor [25]. However, despite having its limitation in selecting appropriate value of n, expert engineers are using their experience and field knowledge to make sound judgment [19].

Nonetheless, one of the biggest advantages of Manning's equation is embedded in its simplicity, because discharge can be measured by using limited parameters, such as flow area, hydraulic radius, slope, and Manning's roughness coefficient n. However, its simplicity is also one of its primary flaw because effects of channel roughness, flow conditions, sediment load and vegetation is represented by single empirical coefficient n (Manning's n), which is sensitive hydraulic condition and often uncertain [19]. A study by [26] mentioned that usage of unreliable values of Manning's n is a dangerous practice, adding risk of additional error in the estimation of flash floods. Wrong values of Manning's n could result in erroneous values of velocity, timing and magnitude of floods. Consequently, accurate evacuation warning cannot be given to the stakeholders for their safety. Another major drawback of wrong Manning's n estimation is inefficient / poor design of hydraulic structure.

Since, Manning's equation has been formed on empirical assumption [26], therefore, it lack theoretical soundness. Where, Manning's roughness coefficient n is continued to be unresolved element as it is not a constant roughness material property rather it is dependent upon multiple factors including slope, turbulences, vegetation and depth [26]. Since slope has an effect on Manning's n, therefore, it's possible that different slopes end up in different n-values.

G. Research Gap

Conventional methods of selecting Manning's n are based on empirical tables and calibration that focus on material of the riverbed, irregularity of the surface, variation in channel cross section, effect of obstructions, vegetation and degree of meandering [27]. It is pointed out by the previous studies that the roughness coefficient n changes with water depth, discharge, riverbed morphology, vegetation and local hydraulic conditions [28], [29]. However, limited experimental studies are conducted to evaluate the effect of slope on Manning's n with different grain sizes and discharges [30]. Therefore, this study aims to experimentally evaluate the effect of slope on Manning's n while keeping bed roughness constant.

II. METHODS AND MATERIAL

The effect of channel slope on Manning's roughness coefficient n is investigated under steady state conditions. The experimentation was conducted in the laboratory scale tilting flume to simulate controlled hydraulic conditions for flow resistance.

In order to investigate the changes in Manning's roughness coefficient with variation in slope, 15 cm thick bed comprising of uniform graded aggregates was used to simulate roughness of channel bed.

In each experimental run the slope is changed and the hydraulic parameter like flow depth and discharge is measured. The values of depth and discharge are subsequently used along with measured channel geometry to find the Manning's roughness coefficient n by using (3).

In each experimental run, average water depth is taken at three cross sections of the flume, subsequently, the wetted perimeter, cross sectional area, flow velocity and the Manning's coefficient n is calculated at each cross section. The values of water depth, wetted perimeter, cross sectional area, velocity and Manning's n at each selected cross section as well as the averages values of three cross sections, taken at each slope, were used for further analysis.

A. Experimental setup

Experimental investigation was conducted in the hydraulics laboratory. The rectangular tilting flume was made using commercial fabricated metal. The flume was 3.05 m long with a depth of 15 cm.

The rectangular flume was constructed with adjustable bed slope mechanism to simulate changing hydraulic gradient under controlled conditions. At each slope uniform grain size bed material was used. These uniform size aggregates were placed evenly at the flume bed and lightly compacted to ensure same boundary condition along the test section.

For smooth inlet of water, a water supply container was installed at upstream end of the flume. This arrangement provided stable and smooth inflows of water into the flume during experiments. During each experiment, water from the pump first entered into the water supply container and started filling it and upon exceeding the height of downstream wall that is separating the main flume from the water supply container, it overtopped it gradually and started to flow in the flume under gravity flow condition. This mechanism helped in minimizing turbulence. A water storage reservoir / container was placed at the end of flume length for the collection of water exited from the flume and measurement of discharge by volumetric method. Slopes were altered for each experimental run while keeping other hydraulic condition constant. The measurements of depth and discharge were taken for three different slopes against same bed material to check the impact of slope on the Manning's n.

Table1
Geometric Properties of Flume and bed material

Parameter	Symbol	Unit	Value
Flume length	(L)	M	3.05
Flume width	(B)	M	0.15
Flume depth	(H)	M	0.15
Channel geometry	—	—	Rectangular
Flume material	—	—	Metallic

B. Bed Material and bed condition

To simulate the roughness conditions, coarse aggregates retained on the standard sieve size = 12.5mm were used. The selected aggregate size was spread along the channel bed uniformly to create similar roughness conditions.

Table 2:
Properties and characteristics of bed material

Bed ID	Aggregate Size	Unit	Hydraulic Interpretation
BM-1	≥12.5	mm	Relatively moderate to high roughness

Variables in experiment

The experimental procedure was designed to investigate the slope change impact on Manning roughness coefficient n. The variable considered during the experiment are shown in Table 3 and the description of trial run is given in Table 4.

Table 3
Considered variables in experiment.

Variable Category	**Parameters**
Independent variables	Channel slope
Dependent variable	Manning's roughness coefficient (n)
Measured variables	Flow depth, discharge
Derived variables	Velocity, Hydraulic radius
Controlled variables	Flume geometry, grain size of the bed material water source, flow conditions,

Table 4:
Experimental Test Matrix

Run ID	Aggregate Size (Retained at Sieve)	Channel Slope	Trial Number
1	12.5 mm	0.04	1
2	12.5 mm	0.09	2
3	12.5 mm	0.13	3

C. Experimental Procedure

Each experimental process consisted of setting up slope using adjustable slope mechanism that raises the bed on the upstream end of the flume.

Secondly, uniform laying of selected aggregates was performed along the test section of channel flumes (Figure 1).

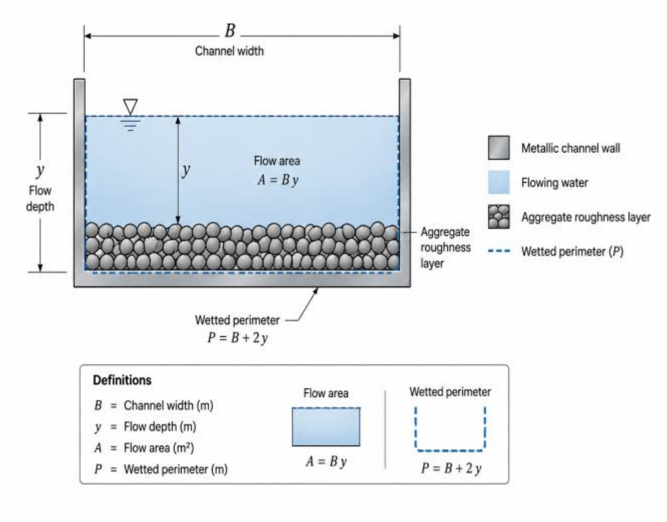

Figure 1: Cross section of the rectangular flume with aggregates bed.

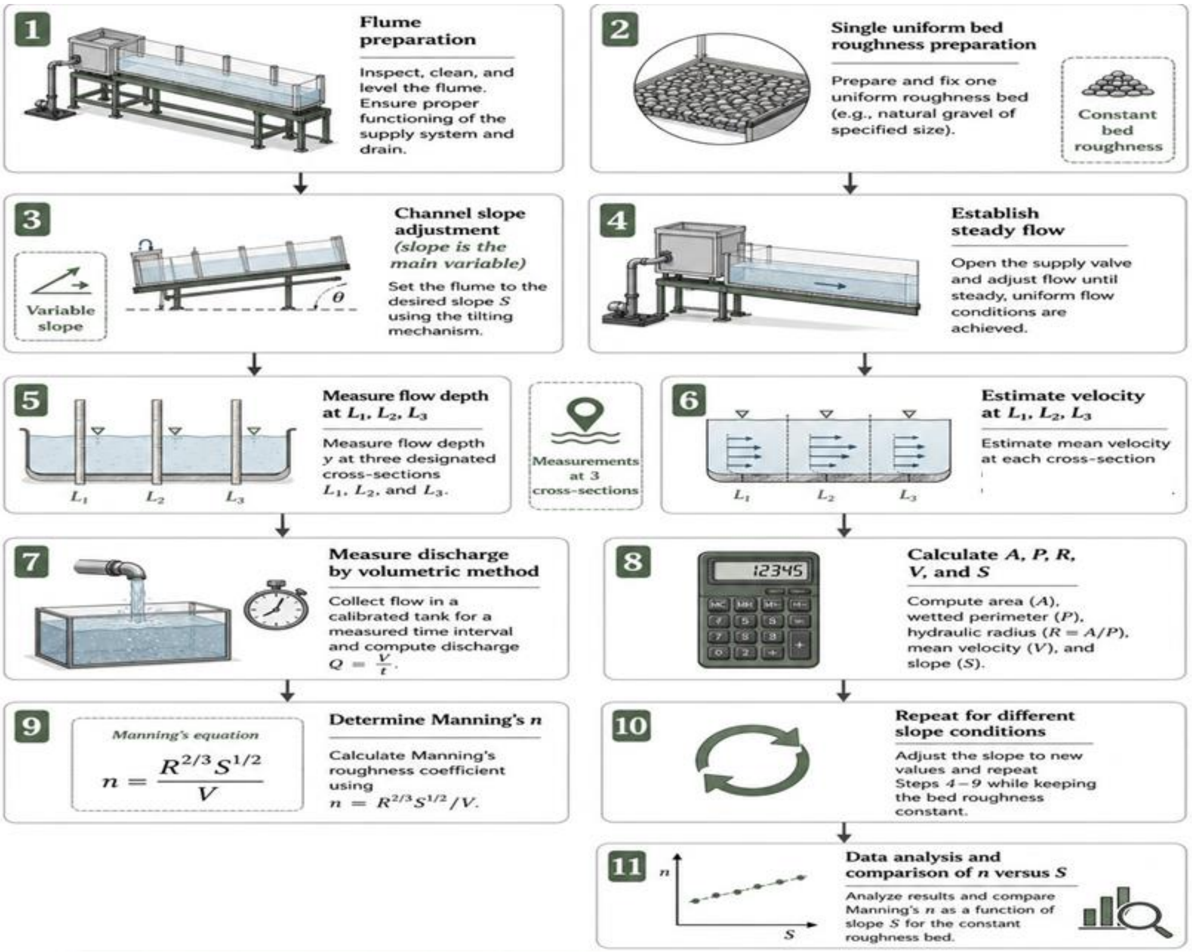

Figure 2: Flow chart of adopted methodology for lab investigations (This figure is for illustrative purpose only; actual apparatus may differ from it)

Steady state uniform water was introduced into the flume by maintaining constant discharge from the pump into the inlet chamber from which water entered the main flume in relatively turbulence free manner and then water is allowed to flow through the channel under controlled conditions. For each experiment trial, water flow was allowed to stabilized before any recording of measurement.

Three different points were selected: at the upstream (Point A), middle (Point B) and downstream (Point C) for measurement of flow depth along the flume length. Point A, B and C are located at the distance of 31 cm, 131 cm and 227 cm from the starting end of the flume with a total length of 305 cm. The cross sections taken at these points are named as L_1, L_2 and L_3 respectively. At each section, the water depths were taken at two points. Average of these measured depths was used to determine average flow depth at each cross section. By using volumetric method, the discharge was measured using the water collected in downstream container over measured interval of time. Using the collected data of volume and time, discharge was calculated.

Same steps were repeated for three bed slopes to analyze their effect on Manning's n.

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D. Measurement of hydraulic parameter

The parameters required for analysis of Manning's roughness coefficient n were acquired from experimental measured flow characteristics.

Discharge was calculated using equation:

$$Q = \frac{V}{t} \text{ ………………………………………………..(4)}$$

Where

Q = discharge,

V = collected water volume,

t = collection time.

The mean flow velocity was found using continuity equation.

$$V = \frac{Q}{A} \text{ ………………………………………………..(5)}$$

Where

A = cross sectional area

V = Average velocity

The slope of channel bed was calculated by

$$So = \frac{\Delta h}{L} \text{ ……………………………………………….(6)}$$

Where,

S_o = Bed slope

Δh = Difference in elevation of bed at the upstream and downstream end of the flume

L = Distance between horizontal measurement point.

To determine hydraulic radius, the following equation was used

$$R = \frac{A}{P} \text{ ………………………………………………..(7)}$$

Where

R = hydraulic radius

P = wetted perimeter

Table 5:
Hydraulic Parameters Used in the Study

Parameter	Symbol	Units used	Description
Discharge	(Q)	cm^3/s	Volumetric flow rate
Velocity	(V)	cm/s	Mean flow velocity
Flow area	(A)	cm^2	Cross-sectional flow area
Wetted perimeter	(P)	cm	Wetted boundary length
Hydraulic radius	(R)	cm	Ratio of area to wetted perimeter
Bed slope	(S)	—	Longitudinal channel slope
Manning coefficient	(n)	$s/cm^{1/3}$	Hydraulic resistance coefficient

E. Determination of Manning's Roughness Coefficient n

Manning's equation is rearranged for finding roughness coefficient n.

$$n = \frac{R^{2/3} S^{1/2}}{V} \text{ ………………. (3)}$$

(Roughness equation)

where

n = Manning's roughness coefficient

R = hydraulic radius

S = slope of energy grade line

(Assuming that the energy slope (S) was equal to the water surface slope (S_w) and the bed slope (S_o), owing to uniform flow conditions, bed slope was used in Equation 3 in place of energy slope)

V = average flow velocity

F. Uncertainty and reliability of experiment

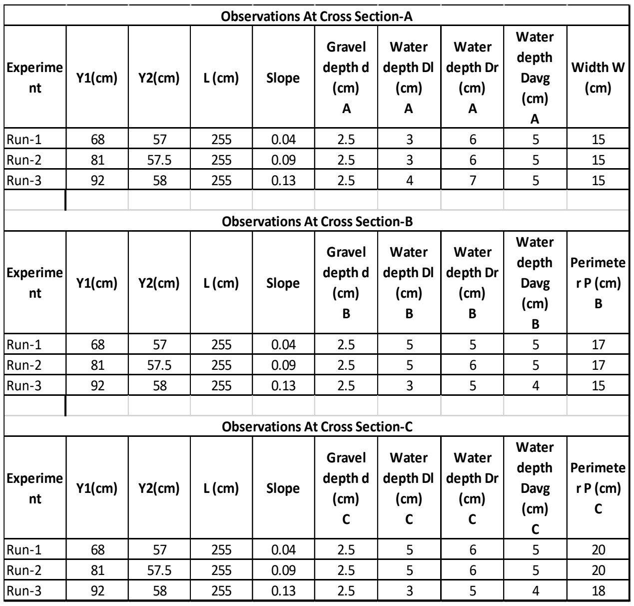
During experimentation, uncertainties could arise from the measurements of depths, discharges and slopes. The geometrical measurements were conducted with a scale having a least count of 1 mm, whereas stop watch with a least count of 0.01 second was used to measure time. However, the observation errors couldn't be ruled out, up to few mm and few seconds in the measurement of lengths (in horizontal and vertical direction) and time durations respectively.

Before each experimental run, steady flow conditions were established prior to any observation to minimize transient hydraulic effects. Aggregates were carefully placed on the bed with light compaction, for uniform leveling and roughness.

III. RESULTS & DISCUSSION

Water depth measurements were taken at three cross sections of the flume against, near the beginning (Point A), middle (Point B) and near the end (Point C) of the flume after which water discharged into the exit container.

Table 6:
Observations of Hydraulic Parameters During Experimentation on the flume



Observations At Cross Section-A

Experiment	Y1(cm)	Y2(cm)	L (cm)	Slope	Gravel depth d (cm) A	Water depth Dl (cm) A	Water depth Dr (cm) A	Water depth Davg (cm) A	Width W (cm)
Run-1	68	57	255	0.04	2.5	3	6	5	15
Run-2	81	57.5	255	0.09	2.5	3	6	5	15
Run-3	92	58	255	0.13	2.5	4	7	5	15

Observations At Cross Section-B

Experiment	Y1(cm)	Y2(cm)	L (cm)	Slope	Gravel depth d (cm) B	Water depth Dl (cm) B	Water depth Dr (cm) B	Water depth Davg (cm) B	Perimeter P (cm) B
Run-1	68	57	255	0.04	2.5	5	5	5	17
Run-2	81	57.5	255	0.09	2.5	5	6	5	17
Run-3	92	58	255	0.13	2.5	3	5	4	15

Observations At Cross Section-C

Experiment	Y1(cm)	Y2(cm)	L (cm)	Slope	Gravel depth d (cm) C	Water depth Dl (cm) C	Water depth Dr (cm) C	Water depth Davg (cm) C	Perimeter P (cm) C
Run-1	68	57	255	0.04	2.5	5	6	5	20
Run-2	81	57.5	255	0.09	2.5	5	6	5	20
Run-3	92	58	255	0.13	2.5	3	5	4	18

These measurements were repeated against three pre-selected slopes. Table 6 presents the observations recorded during lab experimentation at three different slopes at three points: A, B and C along the flume length. Where, these points were located at a distance of 31 cm, 131 cm and 227 cm from the starting end of the flume. At the beginning of experiment, the water entered into flume from the water supply container and as it moved forward the flow characteristics were controlled by the bed material, flume slope and geometry.

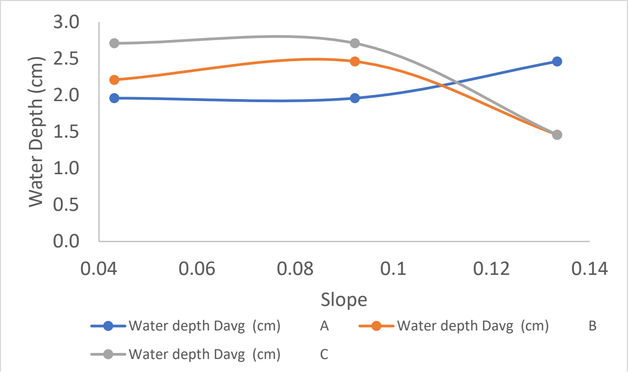


Figure 3: Variation of water depth with slope along the length of flume

Refer to Figure 3, at cross-section L_1 (Point A), the impact of slope change is not visible, rather slight rise in water depth has been noticed with increase in slope which is counterintuitive and could be because of observation bias. At cross section L_2 (Point B), the impact of controls of channel roughness, geometry and bed slope became visible and water depth decreased from 2.5 to 1.5 with increase in slope from 0.04 to 0.14. Similarly, the flow depth descended from 2.5 to 1.5 cm with slope increase from 0.04 to 0.013 at section L_3 (Point C). At the slopes of 0.04 and 0.09, water depth increased between A to C possibly because of bed roughness but it decreased from A to C at the comparatively steeper slope of 0.13. Evidently, the impact of steeper slope shadowed the frictional resistance of channel roughness and depth started to decrease markedly along the flume length

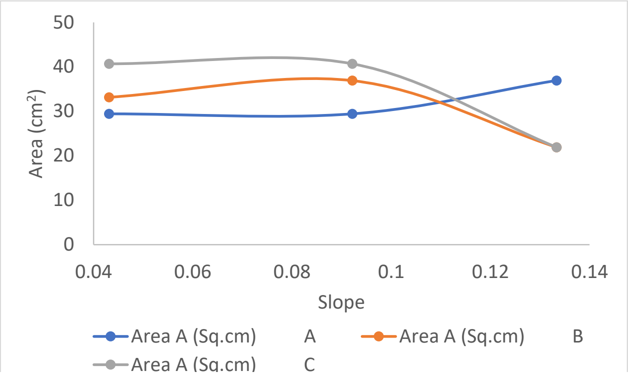


Figure 4: Variation of cross-sectional area with increasing slope along the flume length

The plots of cross-sectional area against slope are similar to depth vs slope curves because the width is uniform along the flume length (Figure 4). The cross-sectional area is decreased by increasing slope at all the section except at x-section L_1, where is flow is not fully developed due to short run length.

Since, both the areas and perimeters at various cross-sections are function of depth, consequently the hydraulic radius follows the trends (Figure 5) of depth and area as shown in Figure 3-4. However, the difference of hydraulic radius at section L_2 (Point B) and L_3 (Point C) is more pronounced in comparison to difference in the water depths and cross-sectional areas.

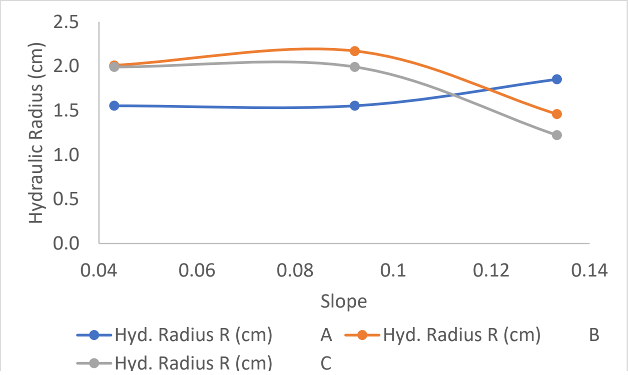


Figure 5: Variation of hydraulic radius with slope along the flume length

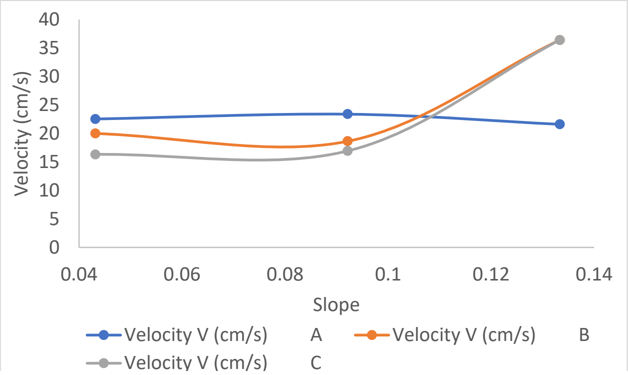


Figure 6: Variation of velocity with slope along the flume length

The discharge in the flume was computed at three different slopes by volumetric method, using Equation 4. The volumetric change in the end container was measured against time and discharge was calculated. Thereafter, velocity was calculated at three sections by using Equation 5. The plot of velocity against slope at three different cross-sections along the flume length is given in Figure 6. Since the discharge was assumed to be constant in the flume, the velocity became function of channel geometry and the bed roughness, provided the slope was kept constant. No appreciable change was noticed in velocity with change in slope at point A. Although, the velocity decreased from 23 cm/sec to 17 cm/sec along the flume length from point A to C at the slopes of 0.04 and 0.09. But the velocity increased with slope along the flume length at point B and C. Despite the same channel roughness along the flume length, the velocity has shown variation along the flume length. The velocity difference was more pronounced at the end of the flume in comparison to starting and middle sections.

Figure 7 present the variations of Manning's n with change in slope along the flume length. Interestingly, the n-value varied along the flume length from point A to C even at constant slope. At the slope of 0.04, the n-value varied from 0.01 to 0.02. Similarly, it increased along the flume from 0.02 to 0.03 at the slope of 0.09. Although variation was also observed at a slope of 0.13 (Figure 7), a reduction in the n-value occurred along the flume from point A to C, instead of the increase that was observed between points A and C at lower slopes. While, there was a variation in n-value at each slope but noteworthy point is that the n-value variation is comparatively larger from point A to B than from B to C probably because the boundary layer impact kicked in as the flow entered the flume near point A and moved towards point B.

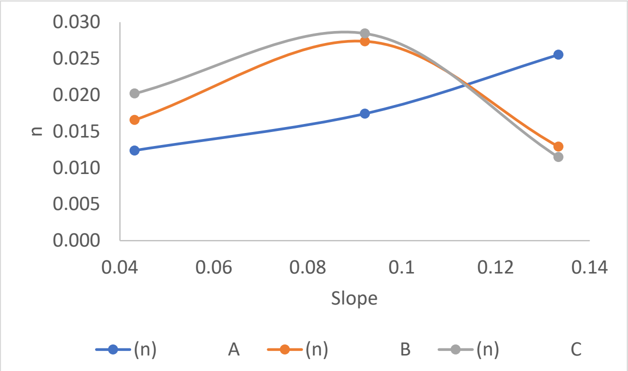


Figure 7: Variation of Manning's n with slope along the flume length

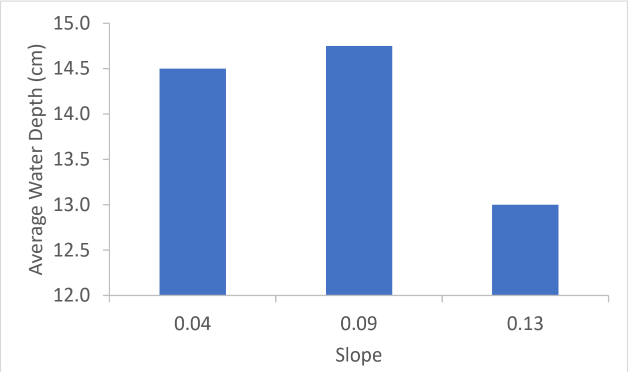


Figure 8: Variation of average water depth with slope

The average water depth across the three cross-sections of the flume increased slightly and then markedly decreased with an increase in slope, as shown in Figure 8. This reduction in flow depth occurs because an increasing slope accelerates the flow velocity; consequently, the depth decreases to satisfy the continuity equation in the prismatic channel.

The average cross-sectional area of water in the flume decreased with increase of slope as shown in Figure 9. Since the water depth decreased by increasing bed slope that has evidently reduced the cross-sectional area.

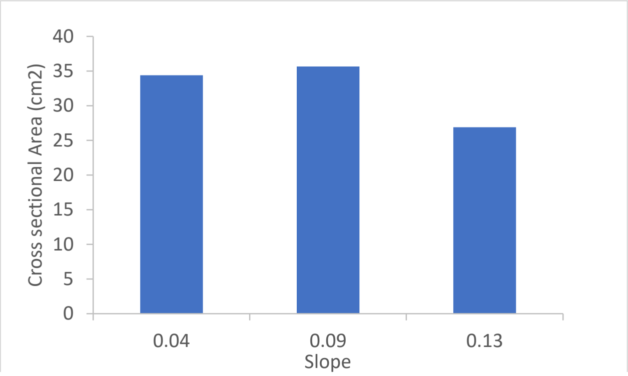


Figure 9: Variation of X-sectional area of the discharge with increasing slope

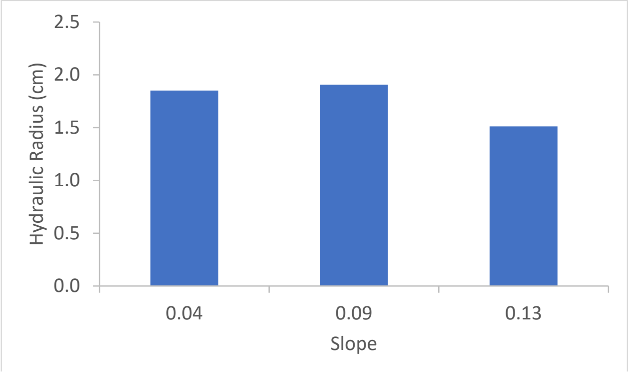


Figure 10: Variation of average hydraulic radius with slope

The average hydraulic radius of water taken at three cross sections of the flume decreased with increase in slope as shown in Figure 10. Since the hydraulic radius is directly proportional to water depth in the rectangular channels, therefore, hydraulic radius followed the trend of water depth as given in Figure 8 and thus it decreased by increasing bed slope.

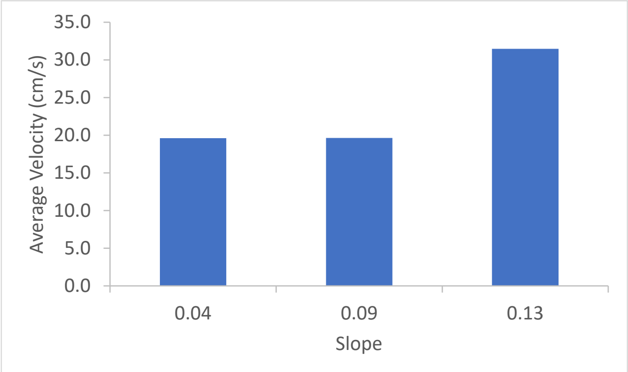


Figure 11: Variation of average velocity with slope

Evidently, both the velocity and discharge increase at comparatively steeper slopes as can be seen in Figure 11-12.

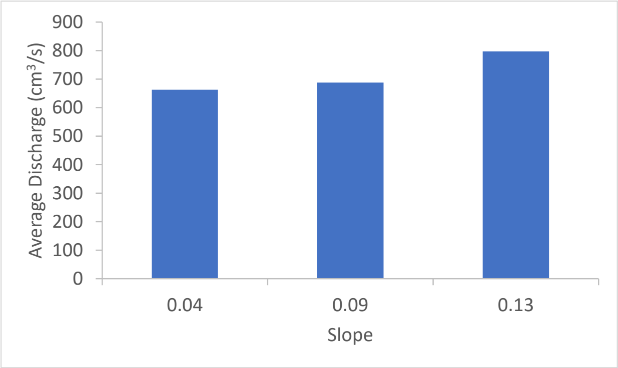


Figure 12: Variation of average discharge with slope

Since flow depth and velocity are inversely proportional under a constant discharge to satisfy the continuity equation, the increasing slope resulted in decreased average depths and increased velocities. Consequently, the total discharge increased from 693 to 798cms3/sec as the slope has been increased from 0.04 to 0.13.

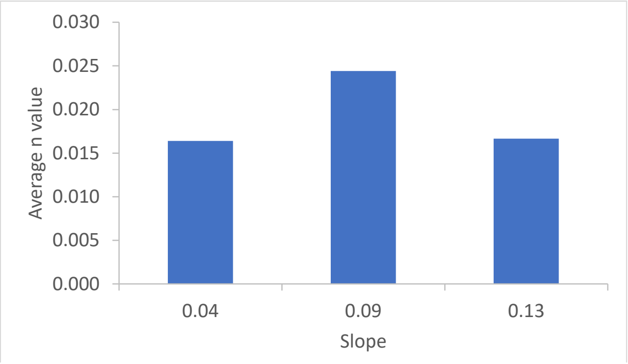


Figure 13: Variation of Manning's n with slope

The Manning's roughness coefficient n has increased from 0.016 to 0.024 and then decreased to 0.017 by increasing the slope from 0.04 to 0.09 and 0.09 to 0.13 respectively (Figure 13). This increase in Manning's n is more than 50% with reference to initial value as the slope changes from 0.04 to 0.09. These results endorsed the findings of [30], in which it is concluded that the roughness coefficient increases with slope in various trails at different discharges. However, the n-value decreases sharply as the slope is further increased to 0.13. In a nutshell, Manning's n is not independent of the slope.

This preliminary research is constrained by: 1) the investigations were performed on a laboratory flume having uniform bed materials (retained on 12.5 mm sieve), whereas the actual canals and rivers have greater variability in bed materials. 2) The relation between bed slope and Manning's n was investigated on limited data of three slopes ranges between 0.04 to 0.13.

Therefore, future investigations should include greater bed-material diversity and cover a wider slope range, spanning several gradients.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. Water depth observations were taken at three points (beginning, middle, and end) along the flume length. Whereas the discharge was calculated by the volumetric method. The experiment was repeated for three different bed slopes: 0.04, 0.09 and 0.13.
2. Water depth, cross-sectional area, and hydraulic radius decreased with an increasing slope from 0.04 to 0.13 at all sections along the flume length, except at the first measurement location (Point A) near the upstream end, which was likely due to boundary layer effects.
3. Flow velocity and discharge increased with an increasing flume slope. However, at each slope, the velocity decreased as the flow advanced from the upstream to the downstream end of the flume, because bed roughness slowed the flow**.** An exception occurred on steeper slopes, where the velocity observed at the midpoint (Point B) was approximately equal to that at the downstream end (Point C).
4. Manning's n, calculated from Manning's equation using the hydraulic parameters observed during the experiment, varied along the flume length at each slope and with changes in the bed slope."
5. It has been observed that Manning's n increases along the flume length except at the comparatively steeper slope of 0.13, where the n-value reduced along the channel length.
6. It has been found that the average depth, cross sectional area and hydraulic radius also decreased with increasing bed slope, however, the average velocity and discharge increased with increase in bed slope.
7. The average Manning's n-value of all the cross sections of the flume indicated that n-value is not constant, rather it varies with slope. It increased by 50% as the slope increased from 0.04 to 0.09, which is consistent with the findings on the accuracy of the approximation of velocity and discharge.
8. However, it is proposed to further investigate the impact of gravel size on Manning's n-value at various slopes. Moreover, longer tilting bed flumes with greater cross-sectional area may be used along with digital sensor to reduce the observation bias.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest to report regarding the present study.

AUTHOR CONTRIBUTIONS

Conceptualization, M.K.S.; methodology, M.K.S., I.R, M.J.K, M.R, S.H and A.D; software, M.K.S. and I.R; validation, M.J.K, I.R, M.R, S.H and A.D; writing—original draft preparation, M.K.S and M.W.H.R; writing—review and editing, M.K.S. and M.W.H.R.

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Data is available on reasonable request.

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