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CALIBRATION OF INCLINED RECTANGULAR WEIR WITH A NEW APPROACH

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Abstract: Thin plate weirs are the devices commonly used in channels for relatively accurate flow measurement. Researchers have attempted to improve the discharge coefficient of these weirs with fair degree of accuracy. Although these weirs have relatively better degree of accuracy, they are avoided in field measurements due to its major drawback in development of afflux. To reduce the afflux, researchers have attempted placing weirs inclined to the bed of the channel. This procedure of practice of the thin plate weirs of standard geometric shape has increased the discharging coefficient. However, the approach of finding a calibrated equation and the analysis has been ever improved with each attempt. This paper is concerned with the experimentation, analysis and development of discharge–head-inclination model to measure flow over inclined Rectangular weir with a new approach. The new method is simple and the error analysis shows that the estimated discharge is well within 2%. The research work is of considerable academic interest in showing that the head index is independent of weir inclination and depends on the shape of the weir opening. It is shown that the discharge coefficient increases with increase in weir angle with respect to normal (vertical) position, thereby reducing the afflux which may prompt field channel users to implement these weirs with simple head-discharge-inclination equation. The weir position of 75^o with respect to vertical plane along the flow direction has been experimented and analysed.

Keywords: Thin plate Weirs; Inclined weirs, Rectangular weirs, Discharge characteristics, Flow measurement, Afflux, Inclined-weir discharging index

Introduction

Sharp crested or thin plated weirs are most preferred flow measuring devices in open channel flows due to its simplicity in construction and accuracy. Many investigators have developed a large number of weir profiles for flow measurements with the main intention of increasing the discharging capacity and reducing the afflux to make it practically usable and acceptable weir profile. Since ages, the weirs have been fixed to be normal to the flow axis. However, sometimes, these weirs are also arranged oblique to flow axis known as oblique weir and side weirs to gain some benefits. Further, any flow measuring device is associated

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with discharge coefficient which is a measure of its discharging capacity. The literature in this paper is restricted to analysis of flow through the inclined weirs.

Nikou, et. al. (19) discussed on extraction of the Flow Rate Equation under Free and Submerged Flow Conditions in Pivot Weirs with Different Side Contractions.

Mojtabaet. al. (20) discussed about pivot weir used to regulate flow in conveyance channels inirrigation networks. A theoretical approach based on the Bernoulli and momentum equations were used to estimate overflow discharge and the discharge coefficient. The momentum and Bernoulli equations were applied to two successive sections upstream and downstream of a weir to obtain the overflow discharge and discharge coefficient. The Bernoulli equation is applicable only for free-flow conditions, but the momentum equation can be used for both free and submerged conditions.

Shesha Prakash and Shivapur (1, 2, 3, 4, 5, 6, 7, 8) have worked extensively on inclined weirs with different openings like Rectangular, triangular, trapezoidal and Inverted V-Notch (IVN). They have analysed the flow through weirs as a vector and resolved the flow through inclined weir as horizontal and vertical component and computed the discharge as sum of the two. They have proposed a coefficient β to be a function of weir inclination angle β to develop a general equation for flow through inclined sharp crested weirs. However there was no rational explanation for the use of coefficient β in the generalised discharge equation.

Shesha Prakash et.al (9, 10, 11, 12, 13, 14, 15, 16, 17, 18) have worked on flow through inclined weirs with different openings like Rectangular, triangular, trapezoidal and Inverted V-Notch (IVN). They have developed a mathematical model for the flow through weirs and a software to compute the head-discharge equation for the given type of weir and inclination.

In both the cases the results depended on the modeling and the both coefficients, viz., weir discharge coefficient and head index were developed on the basis of experimental values.

In the present study, a different approach is followed to obtain the weir discharge coefficient for flow through inclined rectangular weir.

Fig.1 shows the sketch of inclined rectangular weir and can be seen that the flow length along the plane of the weir increases with increase in inclination with the normal plane which increases the discharging capacity of the weir.

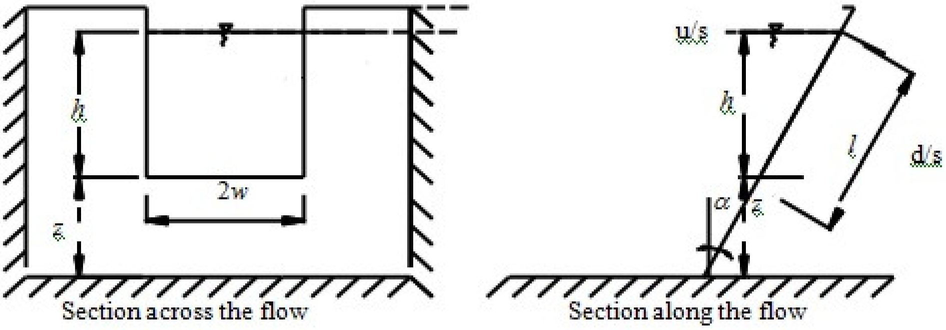

Fig. 1: Arrangement of Inclined Rectangular Weir.

Formulation of the Problem:

The discharge for flow through rectangular

weir, $\left(\frac{V^2}{2g}\right)$, the velocity of approach is very small it is ignored), is given by Darcy-Weisbach equation as

$$q = \frac{2}{3}\sqrt{2g}\,(2w)\,h^{\frac{3}{2}} \qquad (01)$$

Initially the obtained and computed values of Head and discharge were non-dimensionalised as below so that obtained equation will be more generic in nature.

Where q is the discharge through the weir in m^3/s, $2w$ is the crest width in m and h is the head over the crest in m.

Non-dimensionalising the above equation, we get

$$Q = \left(\frac{2}{3}\right) H^{\frac{3}{2}} \qquad (02)$$

Where $Q = \dfrac{q}{2\sqrt{2g}\,w^{\frac{5}{2}}}$; $H = \dfrac{h}{w}$

$\left(\frac{2}{3}\right)$ is retained in Non - dimensional head - discharge equation to preserve the identity of rectangular weir

Experiments

Experiments were carried on inclined rectangular notch fixed normal to the flow direction (0°), 15°, 30°, 45°, 60°,75° inclinations with respect to the normal plane (Vertical) along the flow axis. The experimental channel is rectangular in section and having dimensions 0.3m wide, 0.2m deep and of 4.6m length. The channel is constructed of Perspex sheet and has smooth walls and nearly horizontal bed to reduce the boundary frictional force. It is connected to a Head tank of capacity 750 liters. The inclined rectangular weir is made of 8mm stainless steel with a crest thickness of 1 mm and a 45° chamfer given on downstream side to get a springing nappe. The experimental set up is shown in Fig. 2.

Water is supplied to the channel by an inlet valve provided on supply pipe. Overhead tankis provided with overflow arrangement to maintain constant head. Smooth, undisturbed, steadyuniform flow was obtained by making the water to flow through graded aggregates and the surface waves were dampened by tying gunny bags at the surface near the tank. The head over the weir is measured using an electronic point gauge placed in piezometer located at a distance of about 1.40m on upstream of inclined rectangular notch. A collecting tank of size 1 m length, 0.6 m breadth, and of 0.6 m depth is provided with apiezometer. Water after running through the experimental setup is collected in a sump from which it is re-circulated by pump by lifting it back to the overhead tank.

Fig. 2: Experimental Setup

In the present study, the conventional method of volumetric discharge measurement is used, which increases the accuracy of the work. The measurements are done through electronic point gauge which automatically detects the water level and records the gauge reading. The volumetric measurement is done through self regulated timer for a fixed rise of water level automated through sensors. To eliminate the human error in piezometric readings in the collecting tank, time was auto recorded by an electronic timer, for the predefined interval of rise of water in the tank and averaged, by considering the cumulative volume and the accumulated time.

The present investigation was carried out on the range of variables shown in Table1.

Table-1: Range of variables studied.

Position of the weir	**Normal**	**Angle of inclination with vertical plane in degrees**				
	0	15	30	45	60	75
Head over the crest(m)	19.24	18.37	20.75	16.13	13.34	7.54
	78.17	18.37	69.19	55.07	40.42	20.12
Actual discharge	0.4362	0.4337	0.5824	0.4330	0.4090	0.2255
	3.4987	0.4337	3.5398	2.7270	2.1648	0.9856
No. of runs	43	38	34	37	22	26

Analysis of results

A plot of Non-dimensional discharge verses non-dimensional head for various positions of plane of rectangular weir have been shown in Fig.3. It shows that the discharge increases with increase in inclination angle α.

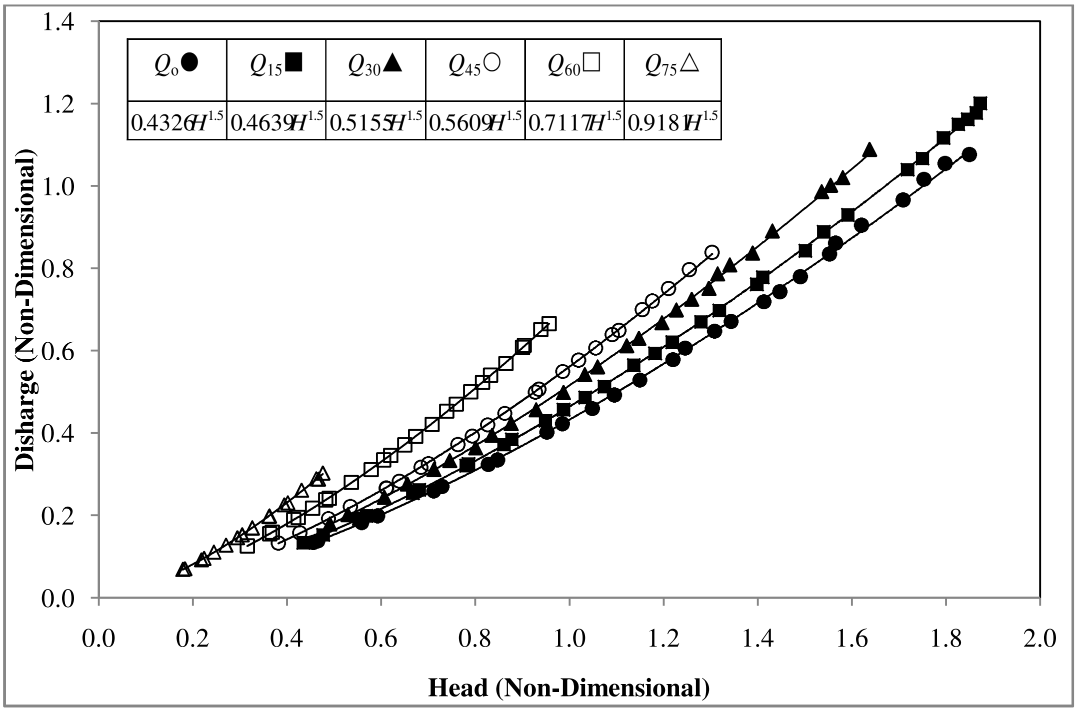

Fig. 3: Non-dimensional Head-discharge plot for various values of inclination α.

Hence, sharp-crested rectangular weir can be installed at a suitable inclination in the channel without any alteration to the conventional simple geometry of the weir so that the discharging capacity of the weir can be much higher, corresponding to the same head, as compared to conventional normal weir, which is evident from Fig. 3. This will help in reducing free board requirement on upstream of weir position. Further, it can also be used in the existing channels with least effect of afflux.

Mathematical Modeling:

Cowgill and Banks have shown that the head-discharge equation is a function of weir profile equation and proved that the profile equation for head-discharge equation of relationship $Q \alpha H^n$ will be given by $y \alpha x^{n-\frac{1}{2}}$. From Cowgill and Banks, for a rectangular weir with profile equation $y\ \alpha x$, the head-discharge equation will be $Q \alpha H^{(1+\frac{1}{2})} \Rightarrow \phi H^{\frac{3}{2}}$, where ϕ is the discharge coefficient for the weir and angle of inclination. With this it can be seen that the Head index is a function of weir profile and is assumed to be nearly constant at 1.5. Hence the discharge coefficient will be a function of weir inclination α.

i.e. $f(\alpha)$.

The discharge-head-inclination equation can be expressed as

$$Q = f(\alpha) H^{1.5} \tag{03}$$

This method reduces the complicated two dimensional variation of weir discharging index and head index to simple weir discharging index.

A programmable algorithm is used to obtain a second order polynomial to get the inclined-weir-discharging index as follows:

The modeling part is subdivided into two stages.

Initially the Actual and theoretical discharge values for corresponding weir inclinations are tabulated as Q_{ai} and Q_{ti}. The corresponding weir discharging index for given inclination is found by the following equation:

$$\phi_i = \frac{\Sigma Q_{ai}^2}{\Sigma Q_{ai} Q_{ti}}$$

The modeling consists of directly getting the inclined weir discharging index by performing regression analysis directly on non-dimensional, actual and theoretical discharges for corresponding inclinations.

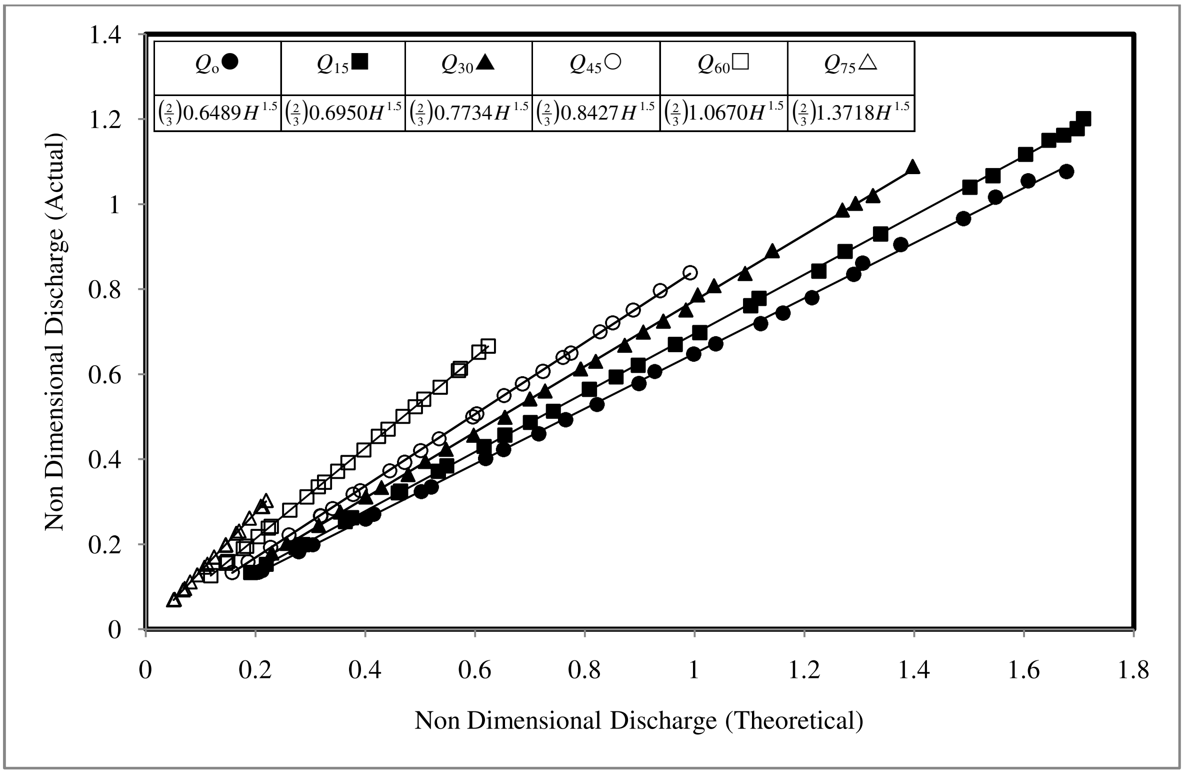

Fig. 4: Variation of Non-dimensional Actual and Theoretical Discharge for various weir inclinaions

Fig. 4 shows the variation Non-dimensional actual discharge with theoretical discharge for corresponding inclinations. As the theoretical discharge equation is derived for normal position of the weir, the coefficient will be obtained as an index of the corresponding inclined head-discharge equation with respect to normal position, thereby giving a better weir discharging index (ϕ). The retention of $(\frac{2}{3})$ in the derivation of non-dimensional head-discharge equation indicates that the concerned weir is rectangular weir and easily the obtained results can be compared with other sharp crested weirs.

$$\phi_i = \frac{(Q_a)_i}{(Q_t)_n}$$

The head-discharge equation for flow through any sharp crested weir is given by the relation

$$Q = \phi H^n$$

Table-2: Calibrated Head-discharge equations for various angles α.

Legend/Method	Q_o●	Q_{15}■	Q_{30}▲	Q_{45}○	Q_{60}□	Q_{75}△
SheshaPrakash et.al.	$0.4326H^{1.5}$	$0.4639H^{1.5}$	$0.5155H^{1.5}$	$0.5609H^{1.5}$	$0.7117H^{1.5}$	$0.9181H^{1.5}$
Presented Method	$(\frac{2}{3})0.6489H^{1.5}$	$(\frac{2}{3})0.6950H^{1.5}$	$(\frac{2}{3})0.7734H^{1.5}$	$(\frac{2}{3})0.8427H^{1.5}$	$(\frac{2}{3})1.0670H^{1.5}$	$(\frac{2}{3})1.3718H^{1.5}$

In the second phase the obtained 6 weir-discharging coefficients are listed against weir inclinations as radians relatively as y_i and x_i and arranged as matrix to develop the model for the present problem, 2ndorder polynomial curve can be fit to the data and simplifying the equations, we get the final general head-discharge-angle expression for any given rectangle, of and inclination as under:

$$\begin{bmatrix} 6 & \Sigma x_i & \Sigma x_i^2 \\ \Sigma x_i & \Sigma x_i^2 & \Sigma x_i^3 \\ \Sigma x_i^2 & \Sigma x_i^3 & \Sigma x_i^4 \end{bmatrix} = \begin{bmatrix} \Sigma y_i \\ \Sigma x_i y_i \\ \Sigma x_i^2 y_i \end{bmatrix}$$

Using the data obtained,

$\Sigma x_i = 3.927$	$\Sigma y_i = 5.399$
$\Sigma x_i^2 = 3.770$	$\Sigma x_i y_i = 4.162$
$\Sigma x_i^3 = 4.037$	$\Sigma x_i^2 y_i = 4.300$
$\Sigma x_i^4 = 4.599$	$n = 6$

Substituting the values, we get

$$\begin{bmatrix} 6 & 3.927 & 3.770 \\ 3.927 & 3.770 & 4.037 \\ 3.770 & 4.037 & 4.599 \end{bmatrix} \begin{bmatrix} \alpha^2 \\ \alpha \\ C \end{bmatrix} = \begin{bmatrix} 5.399 \\ 4.162 \\ 4.300 \end{bmatrix}$$

Solving by Gaussian elimination method, we get the quadratic equation as

$$\phi = 0.4891\alpha^2 - 0.1164\alpha + 0.6687$$

$$Q = \left(0.489\,\alpha^2 - 0.116\alpha + 0.668\right) H^{\left(\frac{3}{2}\right)}$$

Where $Q = \dfrac{q}{2\sqrt{2g}\,w^{\frac{5}{2}}}$; $H = \dfrac{h}{w}$ and α is in radians

The same is obtained as an Excel curve fit as shown in Fig. 5.

It can be seen that the equation developed by the model agrees with the one obtained by Excel and further, the regression coefficient in both the cases is exactly unity. This improves the credibility of the analysis and practical usage of the notch. Even though obtained discharge-head-inclination equation is complicated, it reduces to simple equation once the α values are substituted and simplified.

Error analysis:

Error analysis is carried out by computing the percentage deviation of the Computed discharge from the actual discharge for various inclinations for method developed by Shesha Prakashet. al and the presented method as shown in Table-3.

Table-3: Maximum absolute percentage deviation of Computed to Actual discharge.

Position of the weir/ Method	Normal	Angle of inclination with vertical plane in degrees				
	0	15	30	45	60	75
SheshaPrakash et al	1.7003	0.5959	1.5871	1.8818	0.9579	0.7316
Present research	1.5844	0.7907	1.7640	1.6521	1.0608	1.1500

Discharging capacity:

The discharging capacity of the inclined rectangular weir relative to normal position is shown in Fig. 6. ***Inclined weir discharging index*** is the ratio of the discharging capacity of an inclined weir to that of normal weir. ***Inclined weir discharging index*** for inclined rectangular weir for various inclinations with respect to normal position of rectangular weir are as plotted in Fig. 5.

$$C_{di} = 0.753\alpha^2 - 0.179\alpha + 0.030$$

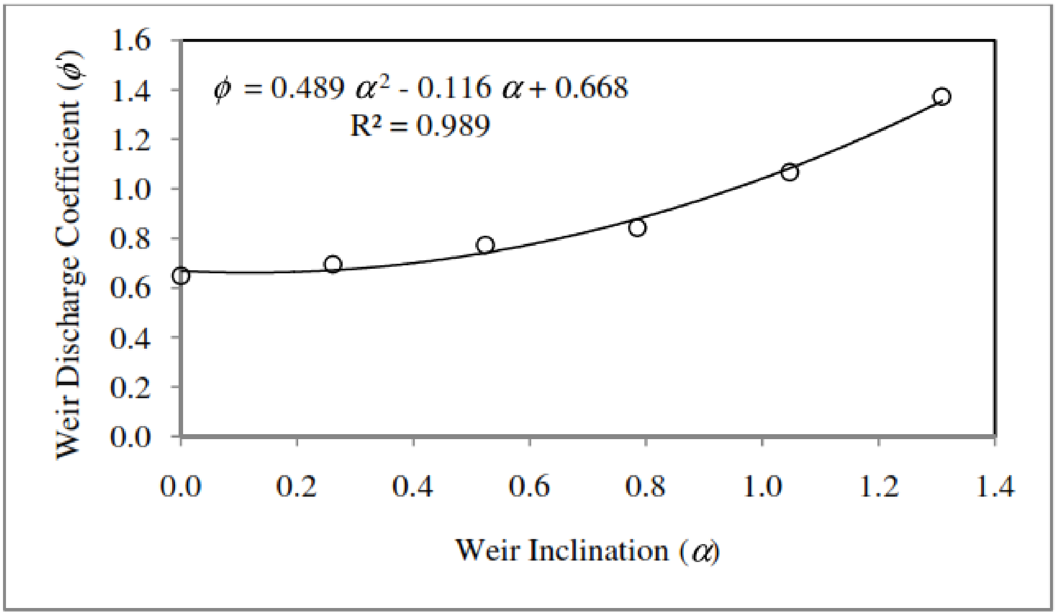

Fig. 5: Variation of weir discharge coefficient (ϕ) with weir inclination (α)

Analysis of afflux:

The Non Dimensional Head is computed for the Maximum Nondimensional Discharge for various inclinations of the rectangular notch as shown in Table4. It can be seen from Table 4 that the maximum reduction is with 75° inclination.

Table 4: Reduction in Afflux and increase in discharging capacity for various inclinations of Rectangular notch relative to its normal position

α		$Q_{\max}$ = 3.90E-03 LPS		$H = \left[\frac{Q}{\phi}\right]^{\frac{1}{n}}$	%ge Reduction in Afflux	Discharge per unit head	% increase in Q
Deg	Radians	ϕ	n				
0	0.00	0.649	1.5	0.033	0.0%	0.649	0.0%
15	0.26	0.675	1.5	0.032	3.0%	0.675	4.0%
30	0.52	0.763	1.5	0.03	9.1%	0.763	17.5%
45	0.79	0.892	1.5	0.027	18.2%	0.892	37.5%
60	1.05	1.090	1.5	0.023	30.3%	1.090	68.1%
75	1.31	1.371	1.5	0.02	39.4%	1.371	111.3%

Conclusions

Following conclusions were drawn based on the experimental investigation and the subsequent analysis by the authors.

- The discharging capacity of the weir increases with the increase in inclination of the plane of weir. In particular it is found to increase exponentially from 30° to 75°
- It is observed from Table3 that the percentage deviation of error in computation of discharge is well within 2% for all angles of inclination of the weir.
- Larger flow area is possible in the inclined weirs relative to the conventional normally positioned weirs. From Table4, it is seen that afflux is found to be about 39.4% with 75° inclination of rectangular weir relative to its normal position. The property of increase in ***Inclined weir discharging index*** with increase in inclination of weir plane can be explored to discharge more water quickly without increasing afflux on upstream side in predesigned canal structure during flood season, without changing the position of the preinstalled weir (which is practically very difficult). It is found to be 137% increase with 75° weir inclination relative to its normal position.
- In the presented analysis, the retention of fraction$\left(\frac{2}{3}\right)$ indicating the feature of head-discharge relation for rectangular weir will render the comparison of the obtained parametric values with other type of weirs more reasonable.

- Due to the simple geometry and ease of construction, inclined rectangular weirs find its applications as a simple measuring devices in irrigation, chemical and sanitary engineering for flow measurement and flow control.
- The Mathematical modeling results in a single head discharge inclination equation which can be used for any rectangular weir of any desired inclination.

Limitation:

The experiment can be done with larger discharge in larger channels and the Head Discharge Inclination equation can be improved by using the model.

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