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Modelling for fluid flow with Linear Characteristics in Rectangular Open-Channel

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Abstract:

Discharge measurement in an open channel within a pre-fixed degree of accuracy with least compromise on the head of flowing liquid is a challenging task. Sharp crested and broad crested weirs have been tried and investigated to the maximum extent and have not been popularly used in the field due to its intrusive nature which reduces the fluid head. Further, discharge measuring flumes like Venturi-flume, Standing-wave-flume have been successfully used with least disturbance in flow. However, the accuracy of flow depends on the fabrication. In addition, the change in bed levels may also induce slight changes in streamline flow inducing increased resistance to flow. Even a slight error in the fabrication to the designed profiles may induce large errors. Further, use of monograms or charts or computations with equations is mandatory to obtain the instant discharge in the flume at any instant. The discharge-depth relationships in regular channels have been rarely investigated to make it more useful flow measuring devices.

The authors, for the first time, have proposed a theoretical and experimental investigations for the flow in open rectangular channel and it is found that it is possible to get a near linear depth-discharge relationship. In this paper, the flow parameters are determined through a new general optimisation procedure presented. It is found that the near linear depth-discharge relationship is valid from $Y_A(b)$ to $Y_B(b)$, within a deviation of ±2 percent error, where b is the half base width of the channel. The proposed linear equation is given by

$Q_L = m\,(y - Q_c)C\sqrt{S}b^{3/2}, \quad Q_{la} = 0.6319Y - 0.0651,\ Q_{lt} = 0.6569Y - 0.0742.$

The significance of proposed research is that, the shift is from measurement of discharge through computations to direct reading of the discharge with a calibrated piezometer. Further, the medium of discharge conveyance, rectangular channel itself is used as a flow measuring device. Auto recordings can also be done using sensors or float devices, avoiding human interference.

Key Words: Open Channel Flow, Rectangular Channel, Linear Depth-discharge, Optimisation procedure, Geometrically Linear Flumes.

1. Introduction:

Flow measurement is a field in engineering which, of late, has assumed extreme importance, due to the improved awareness about water management. In most of the cases, for a predetermined discharge, the channel dimensions are designed. Even though, empirical and semi-empirical relationships have been developed, least investigative work is done on the reverse process of exploring measurement of discharge from the known channel dimensions. The discharge measurement is a much unpredictable task which depends on multiple factors. The major factor hindering the measurement is being the induced loss of head. Generally, the measuring flumes are designed by introducing a head loss between two sections. The cross-section of a channel may be closed or open at the top. The channels that have an open top are referred to as open channels while those with a closed top are referred to as closed conduits (Macharia Karimi.et.al., 2014)

The term natural channel denotes to all channels which have been developed by natural processes (also referred to as drainages) and have not been significantly improved by humans. Free surface at atmospheric pressure is an important characteristic of flow in open channel (Chow. V.T. 1959, Henderson 1967, Noor Aliza Ahmad.et.al, 2017, E.Eyo .et.al, 2007, Adarsh S.et.al. 2023).

Discharge Measurement in open channels is the main concerns in irrigation, environmental and hydraulic engineering field. Flow measuring structures, which are typically used to operate as a control in the channel, provide a special link between the flow discharge and up-stream head (Ismail Aydina.et.al, 2011, Mohamad Reza Madadi.et.al, 2013, 2014, Adarsh S.et.al. 2023).

In this paper, a theoretical and experimental investigation on the flow in open rectangular channel has been done; it is found that even in rectangular channel it is possible to get a near linear depth-discharge relationship. The major thrust in the paper is that, the shift is from measurement to direct reading of the discharge. Something similar to reading the head value we can read the discharge value (similar to rotameters in closed conduits).

2. Literature Survey

For the purpose of Optimisation technique, it is attempted to look into certain available research work on the above technique. It was Allen P. Cowgill (1944) who attempted on this technique to build a relationship between the weir profile and the head-discharge relationship. Later Keshava Murthy and Shesha Prakash (1995) improved and found new faster and better methods to get the linear, quadratic, logarithmic, exponential and any given power, thereby mastering the technique of optimization. They developed a new numerical and algebraic optimisation procedures to obtain the flow and weir parameters.

3. Formulation of Problem

Cowgill and Banks (Cowgill, 1944) proposed the relationship between the weir profile and the discharge-head relationship as given in Figs. 1 and 2 where the equations used are as below:

$y = f(x)$ (Weir geometry)

$Q = B * h^m$ (Flow relationship)

Q being the discharge, B a proportionality constant and h head above the weir crest

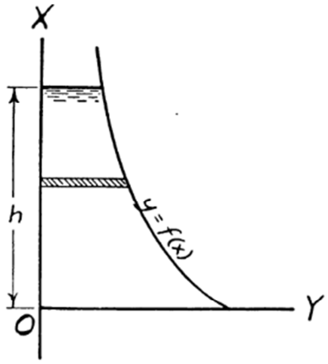

FIG. 1.

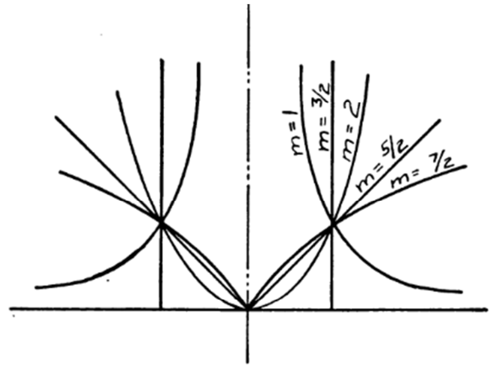

FIG. 2.

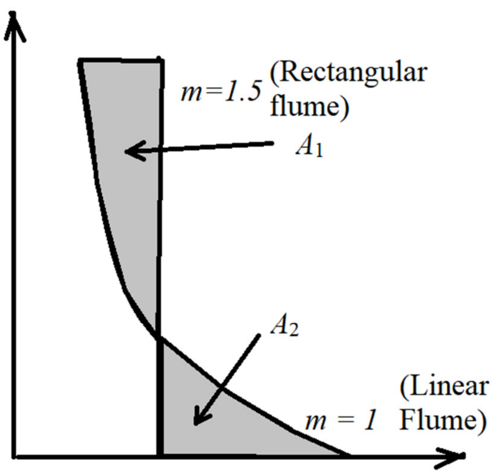

Fig 3: Definition Sketch

In the proposed research, the weir is considered to be kept at zero crest height and extending to the entire geometry of the channel. With this assumption, the theory of sharp-crested weirs can be extended to the channel.

Assuming that the area of flow in the shaded portion A_1 is the additional flow area being substituted by the flow area that is represented by the shaded portionsA_2. This assumption is similar to Stouts and Sutro weirs (Prat, 1914, Sutro, 1897, 1914) wherein the infinite crest width was substituted with the rectangular weir to match the flows between the two weirs.

For the first time, it was found that even in rectangular flume it is possible to get a near linear depth-discharge relationship. The flume can be considered to be similar to that of a compound proportional weir wherein the flow with desired head-discharge relationship is valid only in the complementary weir portion and in case of base weir flow the regular discharge equation is to valid. Extending the same argument for flumes, beyond a small portion of depth of flow from the bed of the channel the near linear depth-discharge equation will be valid. The initial depth where the proposed equation being not valid is ***threshold depth***. For flow in that portion of the threshold depth, normal rectangular flume depth-discharge equation is valid. An algebraic optimisation procedure on the lines of that developed by Shesha Prakash is derived and the same is proposed in the present research work.

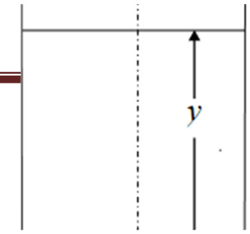

Fig. 4 Definition sketch of Rectangular flume

Consider the flow through the rectangular channel.

$$\text{cross}-\text{sectional area of flow} = \ a = b \times y$$

$$\text{wetted perimeter} = \ p = b + 2y$$

$$\text{Hydraulic mean radius} = \ R = \frac{a}{p} = \frac{by}{(b+2y)}$$

$$\text{From Chezy's equation, Discharge} = \ q = aC\sqrt{RS}$$

$$q = C\sqrt{S}\frac{a^{\frac{3}{2}}}{p^{\frac{1}{2}}} = C\sqrt{S}\frac{(by)^{\frac{3}{2}}}{(b+2y)^{\frac{1}{2}}}$$

$$q = C\sqrt{S}\frac{b^{\frac{3}{2}}\left(b\frac{y}{b}\right)^{\frac{3}{2}}}{b^{\frac{1}{2}}\left(1+2\frac{y}{b}\right)^{\frac{1}{2}}} = C\sqrt{S}\frac{b^{3}\left(\frac{y}{b}\right)^{\frac{3}{2}}}{b^{\frac{1}{2}}\left(1+2\frac{y}{b}\right)^{\frac{1}{2}}}$$

$$\text{Non}-\text{dimensionalising with } Y = \left(\frac{y}{b}\right);\ q = C\sqrt{S}\frac{b^{\frac{5}{2}}Y^{\frac{3}{2}}}{\sqrt{1+2Y}};$$

$$\boldsymbol{Q = \frac{q}{C\sqrt{S}b^{\frac{5}{2}}} = \frac{Y^{\frac{3}{2}}}{\sqrt{(1+2Y)}}}$$

4. Optimisation Procedure

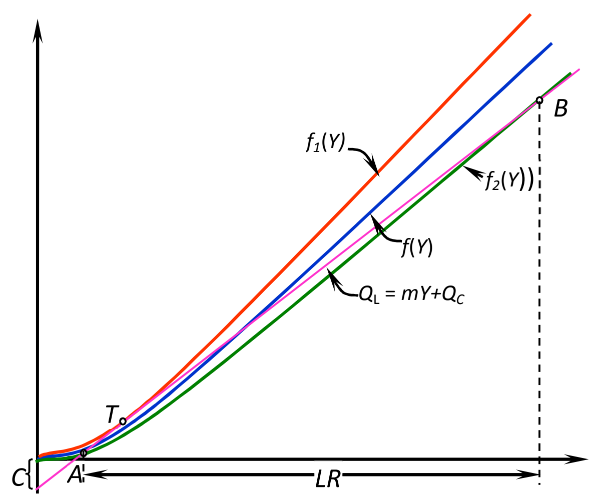

Fig 5: Optimization Procedure

To obtain a maximum straight-line between two bound curves for an ever increasing function between two parameters.

Let

$$Q_L = mY + Q_c \qquad \text{........ (1.01)}$$

Be the proposed optimal linear head-discharge relationship (where, m is the constant of proportionality and Q_c is the discharge intercept) to substitute the theoretical head-discharge relationship.

$Q = f(Y)$ ...... (1.02)

In a certain range. Letting $K_u = (1 + \frac{E}{100})$ and $K_d = (1 - \frac{E}{100})$ where E is the prefixed maximum permissible relative deviation of the proposed linear function and the theoretical head-discharge function. These defined two explicit curves $f_1(Y)$ and $f_2(Y)$ forming the lower and upper bounds for the linear function as shown in figure.

$f_1(Y) = K_u f(Y)$ ...... (1.03)

$f_2(Y) = K_d f(Y)$ ...... (1.04)

Following from 1.04, the solution can be obtained using the algorithm below.

- **Obtain the point of inflection on the curve for the discharge head**
- **Run linear regression between the two curves at positive and negative errors**
- **Obtain a common tangent to the straight-line section of the curves**
- **The limits of the tangent segment will be the linear operation region for the flow measurement**

Step 1: Find the point of inflection of the curve $Q = f(Y)$ given by Eq.(1.02)

$$\text{i.e } Q'' = f''(Y) = 0$$

This procedure is valid only when there is one point of inflection and the function is continuously increasing in 0 ≤ H ≤ ∞ which is always true for any discharge-head function. No real roots existing, hence no point of inflection. This means *H* is a continuously increasing curve.

Step 2: Now the objective is to find the maximum straight-line relationship within the error bound curves, Eqs. (1.03) and (1.04).

The flow parameters for flow through rectangular flume such as starting point (*A*) of the near linear flow equation (can be the threshold depth, below which the proposed equation is not valid), Ending point (*B*), beyond which the proposed equation is invalid and the linear flow equation itself in the form of Eq. (1.01) (for which *m* and Q_c are to be evaluated).

Following are the two considerations for an existing rectangular channel:

1. Pre-fix the threshold depth, only beyond which the flow equation will be valid. It can be fixed in terms of percentage of total non-dimensional depth with which the starting point *A* will be known and be can be computed.
2. With the existing channel height (excluding the free-board) being known point *B* could be pre fixed from which point A can be computed.
3. The range in which the linear flow equation is valid will be between *A* and *B*

This straight line to be maximum, it is proposed to be tangential to upper bound curve $f_1(Y)$ at point T. Let us assume that with a slight variation of 'm' we get a straight line longer than the one given by given by Eq.(1.01).

$Q_L = (m \pm \Delta m)Y + Qc$ .... (1.05)

But $(m + \Delta m)$ shifts the line beyond the boundary $f_1(Y)$ at T and $(m - \Delta m)$ for $f_2(Y)$ the end point will be shortened because the straight line intersects the bottom curve earlier due to the reduction in slope. Hence, the value of m is the optimum which yields the straight line of maximum length.

Now let us consider a small variation in "Q_c" as $(Q_c \pm \Delta Q_c)$ with which we get a longer straight line than the one given by Eq. (1.01).

i.e $Q_L = mY + (Q_c \pm \Delta Q_c)$ ...... (1.06)

But $(Q_c + \Delta Q_c)$ shifts the line beyond the boundary $f_1(Y)$ at T and $(Q_c - \Delta Q_c)$ for $f_2(Y)$ at B. Hence the value of Q_c is the optimum value along with m which yields the straight line of maximum length. Thus Eq. (1.01), gives us the straight line of maximum length hence the maximum linearity range.

To obtain the flow parameters for the present model,

Step 3: The non-dimensional flow equation through the rectangular channel is given by

$$Q = \frac{Y^{3/2}}{\sqrt{2Y+1}} \quad ...... (1.07)$$

Differentiating, w.r.t. Y

$$Q' = \frac{dQ}{dy} = \frac{\sqrt{Y}(4Y+3)}{2(2Y+1)^{3/2}} \quad ..... (1.08)$$

$$E = \frac{e}{100} = \text{ the maximum permissible and prefixed percentage error}$$

<u>At '*A*' starting point</u>

Point A can be found as explained in the previous steps.

$$(Q_L)_A = mY_A + Q_c \quad .... (1.09a)$$

$$(Q_D)_A = (1 - E)\frac{Y_A^{3/2}}{\sqrt{2Y_A+1}} \quad ...... (1.10a)$$

$$(Q_L)_A = (Q_D)_A \; or \; mY_A + Q_c = (1 - E)\frac{Y_A^{3/2}}{\sqrt{2Y_A+1}} \quad ...... (1.11a)$$

<u>At '*B*' starting point</u>

Point B can be found as explained in the previous steps.

$$(Q_L)_B = mY_B + Q_c \quad .... (1.09b)$$

$$(Q_D)_B = (1 - E)\frac{Y_B^{3/2}}{\sqrt{2Y_B+1}} \quad ...... (1.10b)$$

$$(Q_L)_B = (Q_D)_B \; or \; mY_B + Q_c = (1 - E)\frac{Y_B^{3/2}}{\sqrt{2Y_B+1}} \quad ...... (1.11b)$$

At '*T*' Tangent to upper curve

$$(Q_L)_T = mY_T + Q_c \qquad .....(1.12)$$

$$(Q_U)_T = (1+E)\frac{Y_T^{3/2}}{\sqrt{2Y_T+1}} \qquad ..... (1.13)$$

Differentiating, Eqs. (1.12) and (1.13) w.r.t. Y and from Eq. (1.08)

$$\left(\frac{dQ_L}{dY}\right)_T = m = (1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{3/2}} \qquad ..... (1.14)$$

Substituting for 'm' in Eqs. (1.12) and (1.13)

$$(1+E)\frac{Y_T^{3/2}(4Y_T+3)}{2(2Y_T+1)^{3/2}} + Q_c = (1+E)\frac{Y_T^{3/2}}{\sqrt{2Y_T+1}} \qquad ..... (1.15)$$

Stage 1 (By knowing Y_A)

Substituting for 'm' in Eq. 1.11a

$$(1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{3/2}}Y_A + Q_c = (1-E)\frac{Y_A^{3/2}}{\sqrt{2Y_A+1}}$$

$$Q_c = (1-E)\frac{Y_A^{3/2}}{\sqrt{2Y_A+1}} - (1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{3/2}}Y_A \qquad .... (1.16a)$$

Substituting for Q_c, from Eq. (1.16a) into (1.15) we get,

$$(1+E)\frac{Y_T^{\frac{3}{2}}(4Y_T+3)}{2(2Y_T+1)^{\frac{3}{2}}} + (1-E)\frac{Y_A^{\frac{3}{2}}}{\sqrt{2Y_A+1}} - (1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{\frac{3}{2}}}Y_A - (1+E)\frac{Y_T^{\frac{3}{2}}}{\sqrt{2Y_T+1}} = 0 \qquad .... (1.17a)$$

Stage 2 (By knowing Y_B)

Substituting for 'm' in Eq. 1.11b

$$(1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{3/2}}Y_B + Q_c = (1-E)\frac{Y_B^{3/2}}{\sqrt{2Y_B+1}}$$

$$Q_c = (1-E)\frac{Y_B^{3/2}}{\sqrt{2Y_B+1}} - (1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{3/2}}Y_B \qquad .... (1.16b)$$

Substituting for Q_c, from Eq. (1.16b) into (1.15) we get,

$$(1+E)\frac{Y_T^{\frac{3}{2}}(4Y_T+3)}{2(2Y_T+1)^{\frac{3}{2}}} + (1-E)\frac{Y_A^{\frac{3}{2}}}{\sqrt{2Y_A+1}} - (1+E)\frac{\sqrt{Y_T}(4Y_T+3)}{2(2Y_T+1)^{\frac{3}{2}}}Y_A - (1+E)\frac{Y_T^{\frac{3}{2}}}{\sqrt{2Y_T+1}} = 0 \qquad .... (1.17b)$$

Solving for Y_T from Eqs. (1.17a and 1.17b) and substituting in Eqs. (1.14) and (1.16), we can evaluate m and Q_c to get the linear depth-discharge equation for flow in rectangular channel. This equation is valid for flow depths Y_A to Y_B.

$$(Q_L)_B = (Q_D)_B or\ mY_B + Q_c = (1-E)\frac{Y_B^{3/2}}{\sqrt{2Y_B+1}} \qquad ...... (1.18)$$

and

$$(Q_L)_A = (Q_D)_A or\ mY_A + Q_c = (1-E)\frac{Y_B^{3/2}}{\sqrt{2Y_B+1}} \qquad ...... (1.19)$$

$$Q_L = mY + Q_c \qquad ......Y_A \leq Y \leq Y_B..... (1.20)$$

The above is the developed theorem to obtain the linear relationship, figure 6 depicts the plot showing values from know A to B, figure 7 depicts the plot showing values from know B to A which validates the theorem that has been proposed.

Validation through Graphical Method

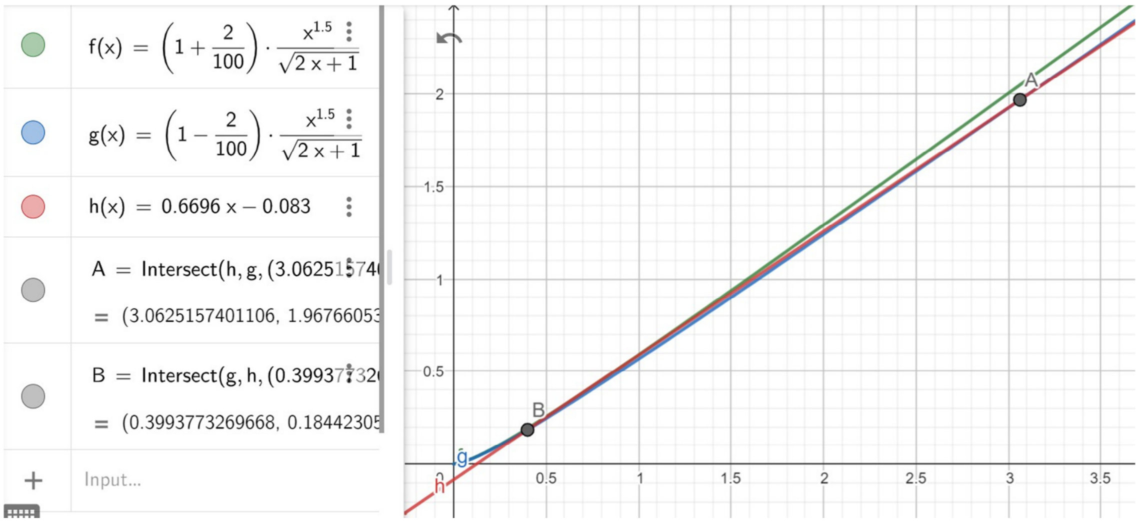

Fig 6: Plot showing values from known A to B

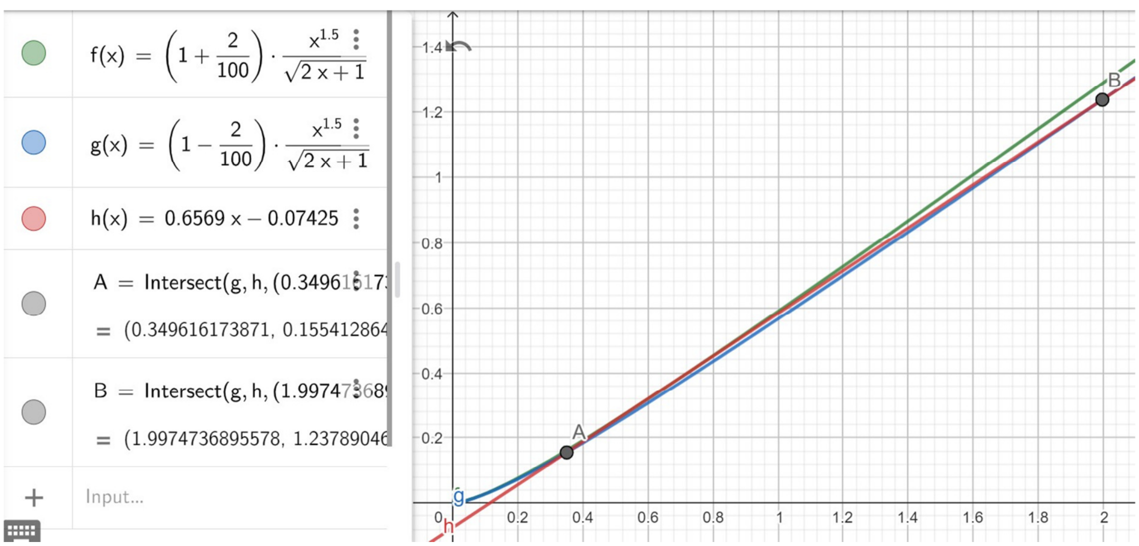

Fig 7: Plot showing values from known *B* to *A*

5. Analysis

The following 2 tables will provide the flow parameters based on the two conditions, viz. known threshold depth (*A*) and known channel depth (*B*)

Table 1: Flow parameters for known threshold depth (Y_A)

Y_A	Y_B	m	c		Y_A	Y_B	m	c
0.1	0.281129	0.48797	-0.02051		0.6	Infinity	0.698877	-0.11225

0.2	0.596683	0.579696	-0.04186		0.7	Infinity	0.706657	-0.12418
0.3	1.372236	0.640304	-0.06479		0.8	Infinity	0.711934	-0.13466
0.4	3.063444	0.669643	-0.08307		0.9	Infinity	0.71541	-0.14382
0.5	13.45666	0.68779	-0.0989		1	Infinity	0.718002	-0.1522

Table 2: Flow parameters for known End point (Height of the channel or known flood-depth ($\boldsymbol{Y_B}$)

Y_B	Y_A	m	Q_c		Y_B	Y_A	m	Q_c
2	0.344804	0.656933	-0.07425		1.5	0.316533	0.645276	-0.06773
1.9	0.346529	0.655276	-0.07354		1.4	0.3	0.641925	-0.06592
1.8	0.333	0.653172	-0.07225		1.3	0.3	0.638085	-0.06393
1.7	0.331385	0.65084	-0.07087		1.2	0.297	0.633645	-0.06173
1.6	0.324363	0.648226	-0.06937		1.1	0.272751	0.628453	-0.05927

Where $Q_L = mY + Q_c$ $\quad \ldots(Y_A \le Y \le Y_B)$

6. Methodology

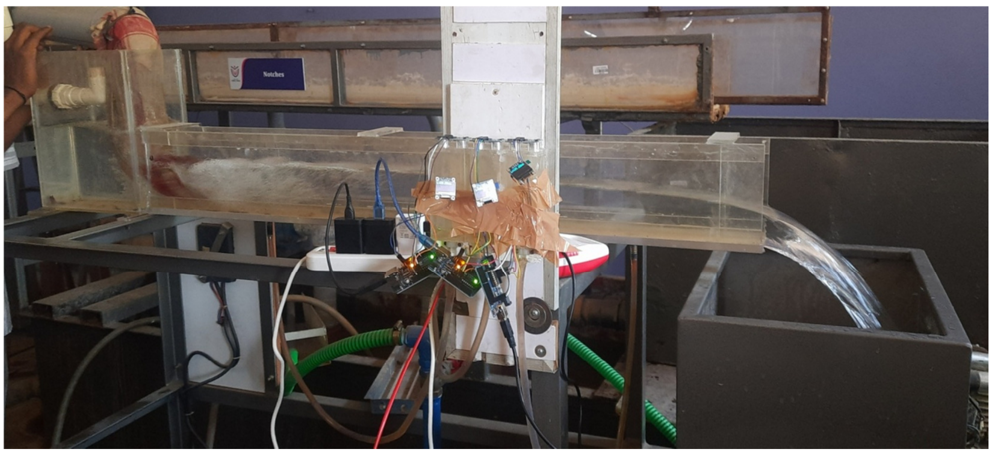

Plate 1: Experimental Setup

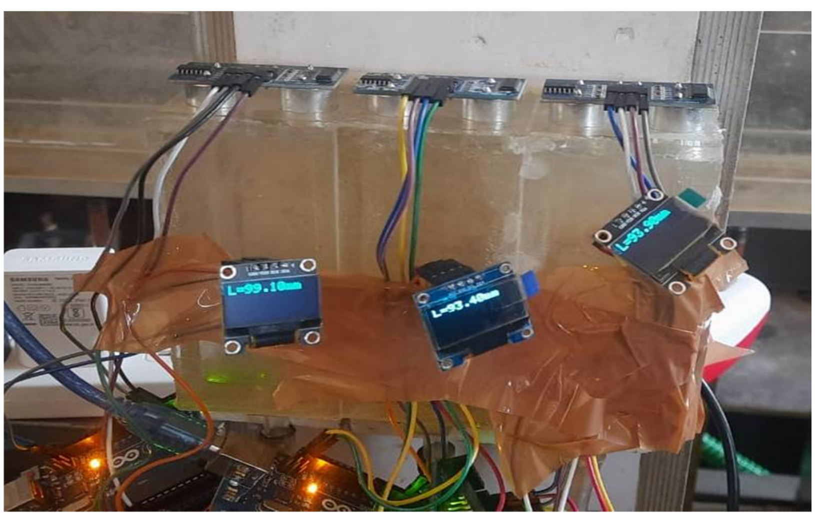

Plate 2: Ultrasonic Sensors used for Depth measurement

The experiments were carried out in the Hydraulics laboratory. The channel setup is as shown in plate 1. The experiments are conducted in open channels which are made of Perspex-glass. The test section of the channel is 1.2*0.075*0.15 m. The channel's straight length complies with IS criteria for the approach length necessary to achieve a constant, uniform flow. Experimental setup consists of an over-head tank of capacity 1000 litres (at the upstream) and measuring or collecting tank (on the downstream side) and the rectangular channel. To minimize the error and achieve accuracy, head readings are recorded with the ultrasonic sensors shown in plate 2 and readings are taken in three locations upstream, intermediate stream and downstream of the channel. The flow in the channel is collected in the collecting tank of size 0.5 *0.35*0.5m.

7. Results and Discussion

It can be observed from rectangular channel the proportionality between the flow depth and discharge is an increasing curve and there exist a linear relationship between flow depth and discharge. The actual experimental values co-insides with the theoretical values as shown in figure 8. The linearity range starts from 25.86 mm upto 150 mm of head. The actual and theoretical discharge equation is as follows $Q_{la} = 0.6319Y - 0.0651$, $Q_{lt} = 0.6569Y - 0.0742$. The datum is the reference line from which the flow depth is reckoned from the depth of flow recorded from the channel bed.

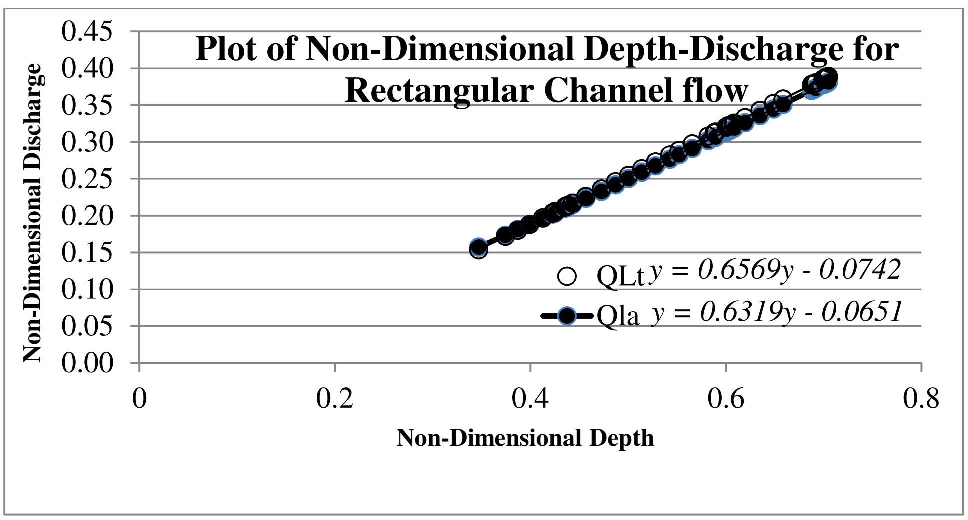

Fig 8: Actual and Theoretical Depth-Discharge Plot

8. Conclusion

The proposed linear discharge-depth relationship in rectangular channel (geometrically simple device), with least flow interference and near accurate measurement can be best alternative to the existing complicated measuring devices, either by construction or by calculations. In addition, no computations are required for measurement of discharges as it can be directly read on a scale which prompts even illiterate farmers to use such devices for effective cultivation and optimum usage of scarce resource, water. The simple linear discharge-depth equation that is proposed deviates less than 2% with the theoretical discharge. In addition, the threshold depth, beyond which the proposed linear depth-discharge relationship is valid, can be suitably designed as per the requirements. The linear relationship can be valid for either known or prefixed threshold depth or by knowing the height of the channel, the threshold depth can be fixed.

Further, the near linear depth-discharge relationship is valid from $Y_A(b)$ to $Y_B(b)$, within a deviation of ±2 percent error, where b is the half base width of the channel. The proposed linear equation is given by $Q_L = m\,(y - Q_c)C\sqrt{S}b^{3/2}$, $Q_{la} = 0.6319Y - 0.0651$, $Q_{lt} = 0.6569Y - 0.0742$, where Q_L is the discharge in the channel, y is the flow depth, C is Chezzy's Constant and S is the channel bed slope. Chezzy's C can also be substituted by Manning's n by the simple equation $C = \frac{1}{n}R^{1/6}$, where R the Hydraulic mean radius could be computed as $R = \frac{a}{P}$. a being the cross-sectional area of flow and P the wetted perimeter.

Further, as the discharge is linearly varying with the depth of flow, the discharges for various depths could be computed and the converted values of discharge printed on a linear scale on the piezometer attached in required units as litres per second or minute. The least count of the measurement decreases, increasing the sensitivity. The proposed measurement through the existing rectangular channels will be highly useful in practice in Irrigation, chemical and Hydraulic engineering, water and waste water engineering by providing least interference in flow. With the new proposed rectangular flume being used for flow measurement, it is proposed to be used as flow measuring device to directly read the discharge even in existing rectangular flumes. (Ex: Aqueducts can be converted as flow measuring devices). Experiments and graphical procedures are used to validate the mathematical models proposed and has been successful in validation. Depending on the required sensitivity of the measurement, flume design can be done.

Acknowledgements

The authors acknowledge the grants received from Visvesvaraya Technological University, Belagavi for setting up of the device to carry out the experiments. They are also thankful to the Management, Vidya Vikas Educational Society (R), Mysore for provision to install the device and conduct the experiments and their constant encouragement.

This research work is the most rear and new in the field of flow measurements which will be useful to the research community and also practically useful, when implemented. The field of flow measurements is being researched by a few people in the community and wish to get a request for reviewer reference. I can provide the reviewers who are working in this field.

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