INTERNATIONAL RESEARCH JOURNAL OF ENGINEERING AND TECHNOLOGY (IRJET) E-ISSN: 2395-0056
VOLUME: 07, SPECIAL ISSUE | JUNE 2020 WWW.IRJET.NET P-ISSN: 2395-0072
International Conference on Recent Trends in Science & Technology-2020 (ICRTST - 2020)
Organised by: ATME College of Engineering, Mysuru, INDIA

Flow Measurements in Open Channel- A Literature Review

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Abstract: Flow measurement is an exciting and interesting topic in fluid mechanics which is extremely important and of late is gaining much importance due to mismanagement and its over-usage. In particular, water is an important and irrecoverable and irreplaceable resource, practically and absolutely required for sustainability of all living beings. Even the ground water has been overused resulting in its scarcity and the available quantity of water needs to be managed resourcefully which implies that the fluid needs to be measured. Assuming water to be nearly an ideal fluid, most of the researchers have used various methods to measure water in closed conduits and open channels. Most of it to be accurate is intrusive like weirs; notches etc. and few are non-intrusive devices like measuring flumes like Partial-flumes, Venturi-flumes, standing-wave flumes etc. The energy loss in these flow measuring devices is also relatively less. This paper is based on review of essential literature based on flow measurements in open channel and documenting the significance of the proposed research so that it could be a repository in the present field for researchers.

Key words: Flow Measurement, Open channel flow, Flumes, Weirs.

Introduction

Open channel flow with free surface consist an interface between the moving fluid and asuperimposing fluid medium (usually air) with uniform pressure (usually atmospheric pressure). Further, channels are the devices which are used to convey water from source to destination. In Irrigation Engineering, Channels are like nervous system which carries water from stored place like reservoirs or tanks to the individual agricultural fields.

The ultimate goal of flow measurement is to preserve water through improving distribution techniques and optimal usage. Focusing towards measurement, management and maintenance will be advantageous to the farmers which will in-turn help prevent low yields and other crop damage caused by under or over usage of water. At present, irrigation consumes about 84% of total available water making the maximum, followed by Industrial and domestic sectors consuming about 12% and 4% respectively.

Flow measuring devices are commonly used to measure velocity and pressure or head. The head or velocity is measured first and then discharge is calculated through charts, tables, or equations. Generally, Water measuring devices use concept of pressure head h or pressure intensity p to determine discharge Q in flumes, weirs, orifices, and Venturi-meter. The point gauge or "weir sticks" are used to measure Q.Pressure or head is used with pipe flow meters such as venturi-meter. Devices including float and stopwatch, current-meter of propeller or cup & cone type and vane deflection meters are used to measure velocities, v. (**M.Y. El-Ansary.et.al. 2010).**

In open channels DischargeMeasurement ofwaterplays a major role from viewpoint of conserving water. Anexclusive relationship between discharge and upstream head can be measured throughproper discharge measurement which is mandatory to manage water resources efficiently.

Weirs, flumes and gates can be used to measure discharge in open channels for a long time (**Arun Goel 2006).** The basic concept of flow measurement is by inducing difference of pressure between two sections in closed conduits and difference in cross sectional area of flow (There by varying velocity in open channels Q = AV).

Properties of flow measuring weirs

Two important weir properties (Troskolonski, 1960) which depicts the measurements of discharge are 1) Relative error and 2) Sensitivity

Relative error in discharge is defined as the computational error in discharge dQ for an error in actual measurement of discharge Q.

$$\varepsilon_Q = \frac{dQ}{Q}$$

Table.1 Summary of Relative errors of Discharge for different weirs

No	Type of Weir	H-Q Relationship	Relative error of Q
1	Rectangular	$Q = KH^{3/2}$	$3/2$
2	Parabolic	$Q = KH^2$	2
3	Triangular	$Q = KH^{5/2}$	$5/2$
4	Linear Weirs like Sutro Weir	$Q = KH$	1

From the table 1,it can be seen that the computational error in discharge gets reduced with the indices of head in head-discharge relationship as the head-index reduces. Hence lowest head-index is most advisable for a flow measuring device. But simultaneously lower head-index also indicates the low discharging capacity of the device for a given flow depth.

Sensitivity is a measure of the accuracy of a measuring device for a larger variation of maximum and minimum discharge. i.e., for closer measurements of head, the computed discharge must be larger. Larger the sensitivity better is the flow measuring device for accurate measurement. It also indicates the slope of discharge-head curve.

It is the variation of discharge to the corresponding variation of head.

$$\Omega = \frac{dQ}{dH}$$

Since ages, the simplest ant accurate flow measuring devices are considered to be sharp crested weirs. These are mentioned by Hunter Rouse in his well-known book "History of Hydraulics" and dates back to sixteen century. The sharp crested weirs liketriangular, rectangular and parabolic weirs have been studied in great detail. Keshava Murthy gave a general theory of weirs incorporating the slope-discharge continuity equation which explains the uniqueness in the reference plane or the datum for every weir and the method of fixing the same. Since then a number of proportional weirs have been designed having different practical applications.

Troskolanski, in his well-known book of hydrometer, mentions about some geometrically simple weirs one of which is an inward trapezoidal weir. This weir was analysed by Keshava Murthy and Giridhar in detail with general theory of proportional weirs. Keshava Murthy and Pillai showed that weirs with discharge-head relationship $Q \alpha H^m$, $m \geq 3/2$, which do not require a base like conventional weirs, can also be designed with a base with advantages. Significantly, the geometrical simplicity of the conventional V-notch was retained by the new weir beyond a certain minimum depth, as the profile rapidly attains a near constant slope. Keshava Murthy designed proportional three-half power weirs and proportional parabolic weirs. Considerable work has been done on proportional weirs in the last four decades after the development of generalised theory on proportional weirs by Keshava Murthy. Keshava Murthy and Giridhar investigated theoretically and verified experimentally the linear characteristics of flow through the closed trapezoidal weir and termed it as 'Inverted V-notch (IVN)' with a near linear range of 72% from 0.22d to 0.94d. Further by adding a rectangular weir of dimensions (0.265W width at a depth of 0.735d above the weir crest), they enhanced the linearity range by over 200% and called it a "Chimney weir".

Keshava Murthy and Giridhar analysed the quadrant plate weirs (formed by two quadrant plates of radius *R,* placed back to back at a small distance *t*, by application of range of points method of optimization procedure. They showed that the flow through the above weir has linear characteristics. They further showed that the above weir can be improved with regard to its linearity range considerably by extending the tangents to the quadrants at the terminal points of the and called it Bell-mouth weir.

In Inverted V-notch and bell-mouth weirs, the base flow depths are in-built in the form of a small portion of 0.22*d* in the form of base weir. In other words, the base weir becomes an integral part of the whole weir itself and hence appropriately called 'Self Basing Linear Weirs (SBL Weirs). The main draw back in these types of weirs is that they have a restricted range, which inhibits their use in practice. Keshava Murthy and Giridhar gave a solution to the design of linear weirs by inverting a new class of Self Basing linear weirs for which the linear head-discharge relationship beyond a certain minimum head extends upto infinity with an increasing accuracy beyond the threshold depth. [22]

K. Keshava Murthy.et.al.1995 designed a straight line shapeand termed it as practical quadratic weir, with an inward slope of trapezoidal weir and has width 2w and vertex angle 2θ at the crest, where in the form of rectangular weir fixed at an optimum depth,p = 0.95d above the weir crest,$d$being the overall depth of the inward trapezoidal weir.Theyshowedthat, flow through such a weir is proportional to the square root of head $h$reckoned from the datum situated at 0.5d above the crest, in the range of $p \le h \le 2.95p$ within a maximum error deviation of ± 2% from the exact theoretical discharge. Parameters of the weir yielding a maximum quadratic head discharge relationship were optimised through numerical optimization procedure. Experiments shows exquisitecompliance with near constant average coefficient of discharge (C_d=0.61). The weir can be practically used for flow measurement in bypass in an open channel. Further the sensitivity of the weir is also highlighted.

Shesha Prakash.et.al 2003 presented anexperimental investigation and semi-theoretical analysis forflow through inclined sharp crested V-notchinstalled at an inclination with respect to the bed of the channel. Investigation showedimproved discharge coefficient by fixing the weir inclined towards downstream and the proposed calibrated head-discharge equation. The error variedfrom the estimated discharges to the actual discharges within ±6%. They showed that with thehigher discharge coefficient, there will be reduction in affluxthat helps to clear off the flood discharge at a relatively faster rate.

M. N. Shesha Prakash.et.al 2004 presented a study on flow over an inclined inverted V-notch (IIVN). With variation of inclination of weir plane with 0° (normal) and 15, 30, 45, and 60° weirs, aninclination-head-discharge equation is established. The linear head-discharge relationship for an inclined inverted V-notch (IIVN) is obtained through a new general algebraic optimization procedure which is relatively better than similar procedures developed earlier. Experimental analysis showed that the linear head-discharge relationship for flow through IIVN is independent of its inclination.The deviation of estimateddischarge computed with the calibrated equation from the actual discharge has been found to be well within 6.5% showing a good agreement with the developed analysis. Further, the significance of the IIVN to be used as a flow control and flow measuringdevice has been highlighted.

Anand V. Shivapur.et.al 2006 worked oninclined trapezoidal weir and presented a theoretical analysis and experimental investigation. They calibrated a general head-discharge equation for the inclined trapezoidal weir in terms of the angle of inclination of the plane of the weir with respect to vertical plane. Further, they have also emphasised the advantage of inclination in reducing the free board requirement on weir upstream in the channel. They showed thatfor flow through the inclined trapezoidal weir 'ITN' the established general-head discharge equation can estimate discharge within +9% and -6% error relative to the actual discharge. They also showed that the discharge through the inclined weir is 77% higher than that in the normal weir. This results in reduction of afflux and can be efficiently used in predesigned channels with fixed and limited free board so that the water will not spill out of the channel. ITW can also be used to measure denser and viscous fluids, which are more relevant in other engineering fields like environmental, chemical and irrigation engineering, with an advantage as the wedge of fluid above the inclined weir will discharge the fluid relatively at a faster rate.

M.Y. El-Ansary.et.al. 2010 tested and calibrated some water flow measurement devices, which were appropriate for on-farm management in Egypt. To fulfil this purpose, three of the common water- flow measurement devices (v-notch, rectangular weir and cutthroat flume) were calibrated in the Laboratory of Hydraulics Research Institute in Qanater City (Egypt). The calibration was carried out using an ultrasonic flow- meter. Results of this study showed that under low discharges, i.e. 5 and 10 Ls^{-1}, the most accurate device was the v-notch, under high discharges 15, 20, 25, 30 and 35 L s^{-1}, the most accurate one was the rectangular weir. Increasing discharge rate from 5 to 35 L s^{-1} resulted in increases in error percentage in the readings of the v-notch. On the other hand, the corresponding error percentages in readings of both the rectangular weir and the cutthroat flume were obviously decreased. As the increase in rate of discharge the error seems to be decreased. Effect of time interval on error percentage seemed to be irregular. From the aforementioned results, it could be deduced that the v-notch or weir is preferable to measure the discharge varying from 5 to 10 L s^{-1}, beyond which the rectangular weir, as well as the cutthroat flume, would be preferable.

Shesha Prakash.et.al 2011 to measure flow over inclined Rectangular weir a discharge–head-inclination model is developed. It was found that the discharging capacity is proportional to the inclination of the weir with respect to vertical plane. A new inclined-weir-discharging index is defined to indicate a measure of its discharging capacity with respect to normal position of the weir.

Anand V. Shivapur.et.al 2012 reportedon the usage of inclined compound notch-weir formed by two different side slopes of triangular weir.Through the analysis of the experimental data by semi analytical approach, the generalisedhead-discharge equation has been developed. Significant improvement in discharging rate compared to normal weir was reported. Exponential flows are occasionally obtained through the upper part of the weir while the lower triangular portion of the weir handles the lesser flows. Free board requirement for the channel is reduced with reduction in afflux and channel can be designed economically.They also showed that it can help in drawing suspended silt and in turn reducing the silting of upstream of notch-weir position when compared to the normal notch-weir especially in unlined channels.

Rasool Ghobadian.et.al 2012 presented a circular sharp-crested weir for discharge measurement in open channels, tanks and reservoirs. To measure the flow in open channels, these weirs are placed at bottom of straight-approach channels and perpendicular to the sides. Complex patterns of flow passing over circular sharp-crested weirs were considered, to extract the stage-discharge relationship for weirs an equation having experimental correlation coefficients is used. By solving two extracted non-linear equations by assuming critical flow over the weir crest, a theoretical stage-discharge relation is developed. A total of 58 experiments were carried out on six circular wires at different crest height and different diameters in a 30 cm wide flumeto obtain the theoretical stage-discharge relation. Analysis results showed that, the measured discharge above the weirsis less than the theoretically discharge for each stage, and this difference increased with the stage. A correction coefficient is developed as a function of the ratio of the upstream flow depth to the height of weir crest andthe theoretical stage-discharge relation is modified which ultimately resulted in good agreement with the measured results.

C. Di Stefano.et.al.2013with the help of incomplete self-similarity theory and dimensional analysisthe outflow process of a triangular in plan sharp-crested is calibrated. The measurements available in the literature the test is carried out and anew stage-discharge is theoretically deduced. Finally, he concluded that a power equation can be used for developing the stage-discharge equation, with anexponent and coefficient contingent on both the ratio between its heightand the side wall angle and crest length of the weir.

Jahanshir Mohammadzadeh-Habili.et.al.2013: Circular-crested weirs or overflow structures are used for a flow measurement and control in open channels and flood control in reservoirs. Using Newton's second law and Bernoulli's energy equation, a differential equation of velocity profile at crest section of circular-crested weir is developedto be used as discharge equation for a rectangular fluid particle on a convex streamline. Differential equation of velocity profile is used to derive Discharge coefficient, profile of crest velocity and crest pressure of the weir. A wide range (0.44 H/R 7.56) of existing experimental data of circular-crested weir is used for better validation and the results show good agreement with experimental data. Also, in comparison with Dressler and potential flow theories the proposed theory predicted that the crest velocity profile had highest precision.

S. Gharahjeh.et.al.2014 In general, energy consideration is used to derive head-discharge formula. Defining suitable assumptions, discharge coefficient fits into the experimental data. In this research, 'weir velocity' is function of the average velocity over the weir section, weir geometry and head over the weir. The unique behaviour of weir velocity versus the weir head for constant ratio of weir width to channel width is independent of the weir size and described in terms of weir parameters to calculate the discharge without involving a discharge coefficient. Combination of weir velocity data for different weir widths the discharge is computed as direct formulation. Weir velocity exhibits a simpler functional dependency on weir parameters in difference to the discharge coefficient.

A. Zahiri.et.al 2017: Compound rectangular sharp-crested in the form of side weirs can be used for flow discharge computation. Compound side weirs perform relatively better for accurate flow measurement and management in a wider range than that of side weirs. Rectangular compound side weir is one such a commonly used weir in which small rectangular weir in lower section is used for measuring low flow rates, and higher flows are measured by a wide rectangular section beside. Coefficient of discharge for such a compound side weir needs to be calibrated using a laboratory tests in a large set since determination of C_d for the same is difficult. Hence, based on the practical design method of May et al, a new approach was proposed for predicting flow discharge over compound side weirs that has been evaluated against experimental data in subcritical flow conditions which shows a very good agreement with the experimental data. The proposed method is independent of discharge coefficient for overflow rate computation and which in turn will provide a reliable and convenient tool for flow measurement of compound side weirs and their water surface profiles. The overall mean and absolute relative errors obtained through the experiment is found to be 1.6 and 7.8%, respectively.

Shesha Prakash.et.al 2018 presented a generalizedinclined head-discharge relationship for flow through triangular weir which is inclined with new approach. A weir is an obstruction put across a flow such that the head above the crest (level of fluid on the upstream side) is measured followed by estimation of flow quantity. Weirs are also flow control devices. The sharp crested weirs with its more accurate and consistent performance are usually used in laboratories rather in the field channels for flow measurements due to its major disadvantage in afflux development. In particular, Triangular weir has advantages about rectangular weirs. It can increase the discharge relatively better than rectangular weir with increased head. 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. This research is concerned with the experimentation, analysis and development of inclined head model to measure flow over inclined triangular weir with a new approach. The new method is simple and the error analysis shows that the estimated discharge is well within 2% and less than the previous methods of flow analysis. The research work is of considerable academic interest in showing that the head index is independent of weir inclination and depends on the opening in weir shape. It showed that coefficient of discharge 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 direction of flow has been experimented and analyzed.

Bhukya Ramakrishna.et.al 2018 presented a flow characteristic of sharp crested weirs. - Weirs are device which is commonly used in flow measurements. Sharp crested weirs are broadly used to measure discharge in, industries, laboratories and irrigation channels. The main objective of the study is to examine the flow behavior of different sharp crested weirs and to obtain the coefficient of discharge for different bed slope conditions (Horizontal, and 1in 400,1in 200). Head Measurement over the weir crest is the main aspect in analysis of discharge through sharp crested weirs. Weir opening width affects the dischargecoefficient and thereby affecting the discharge as well. Results showed that the average values of discharge coefficient for different thin plate weirs (i.e. Rectangular weir, V-notch weir, Trapezoidal weir, Sutro weir) 0.697, 0.798, 0.578, and 0.598 respectively.

As explained earlier weirs are found to be intrusive this reduces the flow energy of fluid which is undesirable, hence researchers also studied with non-intrusive devices like flumes.

Measuring Flumes

Measuring flumes are specially designed and shaped for flow measurement in open channels under free flow conditions.Flow may be categorized by a known relationship between the flow rate and head at specific location. The main concept of the measuring flumes is to alter the cross-sectional area of flow byvarying the bed width or raising the bottom floor or by combination of both. Flumes are open channels in which water may be conveyed depending upon the functional requirements and location which may be supported on or above the ground level. The head loss in flume is ¼ th of the weir for same width of weir, and velocity of approach is a part of the calibrated equation in the flume which is the main advantage of flume over a weir. Flumes may be classified as Venturi flumes, Cut throat and Parshall flumes, Standing wave flumes.Venturi flume was proposed by (V T Chow 1959, R L Parshall 1926, W H Hanger 1988). The calibration of Parshall flumes is not simplebut are best suited to be installed in the channel to allow sediments to pass through and without much of afflux. Parshall flumes of different sizes are of complex geometry and thedischarge can be estimated using corresponding monograms but it is to be noted that the submergence will also affect the discharge **(Arun Goel.et.al.2015).**

In 1917, Venturi flume was developed by Cone with either trapezoidal or rectangular in cross sectional area consisting of short throat with converging and diverging section. In 1928 an attempt was done by Parshall to improve Venturi flume and it is observed that with relatively slight head lossdue to enlarged velocity of the water in the flume it operates effectively and successfully in sand- or silt-laden streams. Thorntonet al (2009) carried out aresearchon flow through Parshall flume to determine the suitability of measuring supercritical flow. From the results the error was found to be within ±5 for both supercritical and sub critical flow regimes for a specified flow range using sameParshall flume. In 2013, Amanda et al conducted an experimental study on Parshall Flumefor Froude number range of 0.67–1.31 with discharge up to 0.854 m^3/sec and length 1.5 m. Experiment showed that with three zones on the basis of convergence ratio: (1) subcritical ($0 < Cr < 0.6$), (2) transition ($0.6 < Cr < 1.0$), and (3) supercritical ($Cr > 1.0$) On the basis of brief discussion of previous work it would be say that there is not much work attempt for small size flume**(Jalam Singh.et.al 2014).**

Zohrab Samani.et.al. 1993conducted Laboratory experimenton simple portable flume to determine the hydraulic characteristics. The flume comprises of a trapezoidal channel axially fittedwith pipe axially and side slopes of 1/1. The diameter of the pipe to channel bottom width ratio is approximately 90% or more. The cross section of the flow reducesby creating a critical-flow condition due to the existing of column. A gauge is installed to measure the depth of the water upstream of the critical-flow section. The gauge- reading is directly measure of the flow rate. Based on the parameters measured in the laboratory, a computer model is developed for calibration of this type of flume and validated in the field, which predicted the flow rates within an error of 5.1% and the measured maximum 81% submergence limit.

Zohrab Samani.et.al.2000 presented a flow measurement in open channelwith a simple flume. The choice of the measuring device depends on its accuracy, application and economy. Prefabricate the flume can be used to measure water in open drains to avoid the need for dewatering prior to installation. Cutthroat flumes have been used to ease of fabrication and installation in open drain systems or ditches. Major demerit in Cutthroat flumes is that they need to be specially transporteddue to the extended transitional length and width. A Venturi flume has several advantages over the traditional cutthroat flume. The advantages include ease of fabrication, economical, ease of transportation and less width requirements even for large flows can be measured.

Kaoru Yokoyama.et.al. 2004 presented a discharge measurement in an open channel by UVP (Ultrasonic Doppler Velocity Profiling). In comparison with industrial flowsEnvironmental flow is complex in structure. By several assumptions,velocity is measured at some points in space or the depth of the river to obtain Velocity distribution in order to understand the structure of environmental flow well. Because the existing velocity meters are used to measure velocity in space at a single point, which includes the time lag of measurement. Therefore, these methods must include some error in estimated velocity distribution. Discharge measurementin a pipe etc.has been done using UVPas it measures the instantaneous velocity distribution on a measurement line and has been certified as an accurate pipe flow measurement. From this feature, it is understood that UVP is suitable to measure environmental flow which is the main reason to use UVP in this study to estimate discharge in an open channel and in comparison, with quantitatively evaluated discharge in a pipe. Its adaptability to environmental fluid flow was evaluated. Discharge measurement in an open channel by UVP satisfies with that of a pipe, within an error of less than 10%.

Arun Goel 2006developed a flow meter that is simple device is easy to construct, operate and also maintain used to measure discharge in irrigation channels. Further, the flow meter finds its applications in the flow measurement in irrigation channels provided in small catchments and flow rate can be estimated for both free and submerged flow conditions. The proposed flow measuring device because of its simple geometry, is economical compared to other critical depth flumes.It is also shorter in length and bed slope which is not required in certain conditions. Proposed Flow meter is practically more useful due the conditions that the modular limit of flow meter is high i.e. S_l = 80%.

Arun Goel.et.al.2015 conductedexperimentsthe laboratory channels in the developed sharp-edged constricted flow meters using MS sheet installed in rectangular flume with four type width constraints viz. 2:1, 1.5:1, 1:1 and 90^o in the direction of flow. Discharges were varied from 2 lps to 30 lps and around 500 trials of upstream and downstream depths were recorded and plotted for both free and critical submergence. Curves were developed to calculate the discharge for each condition.The device which allows maximum critical submergence with contraction ratio 2:1 is considered has one of the most efficient devices.

Vishal B. Raskar 2017 developed a traditional technique for measuring discharge in open channel flow developed a new technique of discharge measurement by calibration of Venturi-flume, which will lead to efficient way and achieving economy and accuracy. The methodology is refined through preparing actual model and proposed model, by using the experimental observations analyzing them and preparing graphical output. From the study it is concluded that the proposed model is valid for design discharge of 0.005 m^3/sec and $2.5<b/Y_1<3.5$ with coefficient of discharge 4.00.

Zohrab Samani 2017in his research carried out design and calibration of three simple flumesfor open channel flow measurement. Principle of critical flow in open channels is used for the design of flumes. In an open channel the cylindrical columns are vertically installed to create a Critical flow through the contraction of the flow cross section. The flume models are calibrated by using model analysis. Using field scale flumes, the equations are validated, and for free flow conditionsa design example is provided.The designed three flumes can be used in prismatic (trapezoidal, rectangular, and circular) channels.

Conclusions

Different aspects presented by various authors on flow measurements in open channel are analysed. Flow measurement is a challenging task in water resources and hydraulic engineering projects. The actual measurement part is complicated both with weirs which are undesirable and flumes which needs technical knowledge. Hence it is still ineffective and the farmers who are mostly illiterate cannot understand the complex measurement & computation part and does nottrust the results. K. Subramanya (1986) has mentioned about Trapezoidal channels with negative side slopes and has even produced a graph to show the variation of non-dimensional parameters like depth of flow and discharge through the channel. He has used Manning's equation to find the depth-discharge relationship which is relatively more accepted equation by academicians and researchers (Chow. V.T. 1959, Henderson 1967). However, neither any analysis nor any suggestion as to how to exploit the linear relationship has been carried out therefore; there is a need for further research for improving flow measurements in open channel which should employ techniques yielding better result in a simple and accurate way.

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