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Review of Methods of Measuring Streamflow Using Hydraulic Structures

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Abstract

The measurement of streamflow is very critical to hydraulic engineers and hydrologists as it provides vital information for environmental monitoring issues connected to water resources. The objective of this study is to examine various means of measuring streamflow specifically application of hydraulic structures installed across the direction of flow. Weirs are restricted to small rivers where the provision for sufficient head and constriction in the river is acceptable. Sharp-crested weir is easy to construct, and it is commonly used as a flow measuring device in an open channel. Flumes are self-cleaning due to the fact that the flow velocity through a flume is usually high. Traditionally, flume is used in measuring flow in agricultural systems, and it requires low maintenance cost. It has capacity to measure more flow rates than weir. Accurate streamflow measurement using flume is within $\pm 2\text{--}5\%$ while that of weir is $\pm 2\%$. Generally, flumes are employed to determine discharge where weirs are not useful.

Keywords: flumes, notch, orifices, streamflow, weirs

1. Introduction

Streamflow is very important in estimating hydrology cycle [1]. In practice, hydraulic structures are installed in open channels or rivers with a free water level to estimate discharge based on the measured upstream water level [2]. The main critical factors in constructing hydraulic structures across an open channel throughout the world are need for the reliable source of water supply, flood control, irrigation schemes, recreation activities and hydropower generation [3]. Technological interventions are needed for harnessing, conserving and proper management of water resources. Application of hydraulics structures in measuring streamflows in open channels is very important. Flumes and weirs are used in measuring streamflow in natural and artificial channels. Streamflow is manually or automatically measured.

Flumes and weirs are designed and constructed to change flow regime from one state to another. The parameters of flow measured in laboratory experiment of flume and models of weirs or spillways can be applied to an open channel prototype in real-life situation by manipulating the various scale models in the laboratory experiment [4].

Spillways are designed to safely convey flood to water course downstream from the dams and to prevent overtopping of the dams. The selection, design and construction of a particular type of spillway is carried on specific purpose of the project, hydrology of the area, topography, geologic conditions, dam safety and project economy. Provisions of hydraulically efficient and structurally strong spillway are vital for dam safety. In the olden days, many dams were operated with little hydrological information. Significant improvements made in meteorology and hydrology have updated control of flooding. The impact of this backwardness made many dams to have inadequate spillway capacities [5].

2. Methodology

The approach adopted in this work was reviewing and examining various hydraulic structures used in measuring streamflow in open channel structures and suggesting the most efficient one.

2.1 Streamflow measurement

Measurement of streamflow is essential in river basin planning, management and pollution mitigation. Several methods have been used for measuring streamflow. One of the methods used is the velocity area method which involves division of river into a number of segments. Flow in each segment is determined with the product of the area of the segment and the average velocity of stream at that location. The total discharge is then estimated by addition of the outcome for each segment of the river. The average velocity is measured using appropriate equipment such as water current metre. The corresponding area is computed through measurement of distances from a reference point on the riverbank.

Alternatively, streamflow is determined using hydraulic structures constructed across the river flow, and it requires establishing a good association between the head and the flow using empirical means as carried out in the laboratory. The two methods have certain limitations and are not applicable in all the circumstances. For example, velocity area method requires condition, which produces a stable depth discharge relationship, and the use of flume and weir is restricted to small rivers where there the provision for sufficient head and constriction in the river is acceptable.

Determination of flow in an experimental open channel was done by [6] using mean velocity equation. It was discovered that the proposed method was more accurate in estimating discharge, when compared with the conventional formulae.

2.1.1 Direct methods of streamflow measurement

Direct measurement of flow is achieved through several approaches; however, the use of any of such methods is based on some factors like size of the stream and the availability of equipment and expertise [7]. Generally, the section at which the discharge will be measured would be carefully selected so that the river reach is straight and is free of large obstacles that can impede the streamflow. Also, areas around or immediately downstream of existing hydraulic structures should be avoided so that the changes in flow conditions around these areas will not affect the streamflow measurement.

2.1.2 Volumetric method

Volumetric method is applied to measure small quantity of streamflow in ditches. In this method, the time taken to fill a containing vessel of known volume is measured, and the most accurate method of discharge measurement is to simply measure the time required to fill a container of known volume. This measurement can be taken repeatedly and the average streamflow can be estimated from the data [8].

2.1.3 Dilution method

In this method, a concentrated tracer solution like salt or dye of specific concentration is added to the river. This is followed by chemical analysis to determine its dilution after it has mixed completely with the stream and produced a uniform final output in the stream. The selection of the tracer to be used is based on meeting certain criteria. It should be easily detected and measured accurately. It should also be conservative. Salt and dye have exhibited these properties and have been in use for many years ago. Irrespective of the tracer selected, it is necessary to get required permission from relevant agency of government before addition of such tracer to body of water used for municipal water supply [8]. The expression used to determine the discharge using the dilution method is presented in Eq. (1):

$$Q = q \frac{(C_1 - C_2)}{(C_2 - C_o)} \quad (1)$$

where Q is the stream discharge (m^3/s), q is the tracer injection rate, C_1 is the tracer concentration in injection, C_2 is the final concentration of tracer in the stream and C_o is the background tracer concentration in the stream.

2.2 Indirect methods of streamflow measurement

These methods involve using various empirical formulae when it is impossible to measure discharge. Empirical formulae such as Chezy, Manning, and Strickler formulae are commonly used.

2.2.1 Chezy equation

One of the earlier formulas to evaluate the flow of water in river is Chezy equation. The formula was proposed in 1768 by a French engineer when designing a water supply canal in Paris [8]. Chezy coefficient depends on Reynolds number and boundary roughness. The Chezy expression for determining discharge in an open channel is given in Eq. (2):

$$Q = AC\sqrt{R S_o} \quad (2)$$

where Q is the stream discharge (m^3/s), A is the channel cross-sectional area (m^2), C is the Chezy coefficient (dimensionless), R is the hydraulic radius (m) and S_o is the channel bed slope (dimensionless).

2.2.2 Manning equation

The formula is named after an Irish engineer, Robert Manning, in 1889. The Manning equation is commonly used for the design of ditches carrying water. The Manning expression for calculating stream discharge in an open channel is presented in Eq. (3):

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

where Q is the stream discharge (m^3/s), A is the cross-sectional area of the channel (m^2), R is the hydraulic radius (m), S_o is the slope of the channel bed and n is the Manning roughness coefficient of the channel.

3. Flow measurement using hydraulic structures

Flow measurement using hydraulic structures involves the placement of a selected hydraulic structure such as weirs or flumes across a river channel. This is to generate flow properties that can be used to develop relationships between flow rate and water levels at certain section along the stream. This method uses a hydraulic structure constructed across a channel to produce flow properties that are characterized by relationships between the water level measurement at some location and the flow rate of the stream. The streamflow is estimated by taking measurement of the water surface level in or near the restriction of the hydraulic structure.

3.1 Weirs

Weirs are hydraulic structures which water flows over. They have advantage of being relatively lower in cost and relatively simple to construct. Weirs can be easily installed in open channels and a level of accuracy can be achieved when used appropriately. However, it is normally operated with a significant head loss, and its degree of accuracy can be affected by variation in approach velocity of water in flow channel [4]. A weir must be periodically cleaned to prevent sediment deposits at the upstream side of the weir, which will have adverse effect on the weir accuracy. Errors resulting from the approximations of discharge are corrected by means of a coefficient of discharge. Through experiment, the coefficient of discharge of a weir has been found to vary with the approach head; the results of the extensive tests with a V-notch weir produce results, which showed the variations [7].

3.1.1 Broad-crested weirs

Broad-crested weir is also known as long base weir. It is made up of an obstruction in the form of a raised portion of the bed, and it spans the full width of the channel with a crest sufficiently broad in the direction of flow for the surface of the liquid to become parallel to the crest of the weir [8, 9]. Broad-crested weirs are very robust structures and are generally constructed using reinforced concrete. The flow upstream is tranquil and conditions downstream allow a free fall over the weir. The flow characteristics of rectangular broad-crested weirs with sloped upstream face were studied by [10]. The results showed that decreasing upstream slopes from 90° to 10° resulted in increasing discharge coefficient values and dissipation of the separation zone. Flow was simulated over broad-crested weirs using 2D and 3D

computational fluid dynamic models. Results revealed that the 3D required more computation period than 2D [11].

Investigation on the effects of surface roughness sizes on the discharge coefficient for broad-crested weirs was carried out by [12]. Results showed that the logical negative effect of roughness increased with discharge for different lengths of the weir. The flow over a broad-crested weir in subcritical flow conditions was studied [13]. It was found that the discharge coefficient of a rectangular broad-crested weir was related to upstream total head above the crest, length of weir and channel breadth. Also, [14] studied the discharge relations for rectangular broad-crested weirs. Results showed that a discontinuity occurred in head-discharge ratings because the section width experienced a break in slope when the flow entered the outer section. Values of coefficient of discharge (C_d) obtained from the experiments on compound broad-crested weirs are lower than those of a broad-crested weir with a rectangular cross section. **Figure 1** illustrates flow pattern over a broad-crested weir. In broad-crested weir, the flow over the crest of the weir is critical so the discharge equation is not the same as that of the sharp-crested weir. The modified equation of the broad-crested weir is presented in Eq. (4). Rectangular broad-crested weirs are commonly employed to measure discharge in irrigation canals especially in developing countries [15]:

$$Q = C B \sqrt{g} \left(\frac{2}{3} H \right)^{3/2} \tag{4}$$

where Q is the discharge over the weir (m^3/s), B is the width of the weir (m), C is the discharge coefficient (dimensionless), H is the head of water over the weir model, upstream (m) and g is the acceleration of gravity = 9.81 m/s^2 .

3.1.2 Sharp-crested weir

Sharp-crested weir is regarded as the simplest form of flow measuring device over spillway in the measurement of flow in open channel. The characteristic of flow over the sharp-crested weir was recognised early in hydraulics engineering as the basis for design of round-crested overflow spillway. The shape of flow (nappe) over the sharp-crested weir can be represented by the principle of projectile. A sharp-crested weir is simple to instal and frequently used as a flow measuring device in an open channel. The determination of the discharge coefficient over sharp-crested weir was conducted by [16]. The results revealed that on the average, the coefficient of discharge was 0.7. Also, [17] determined the discharge coefficient

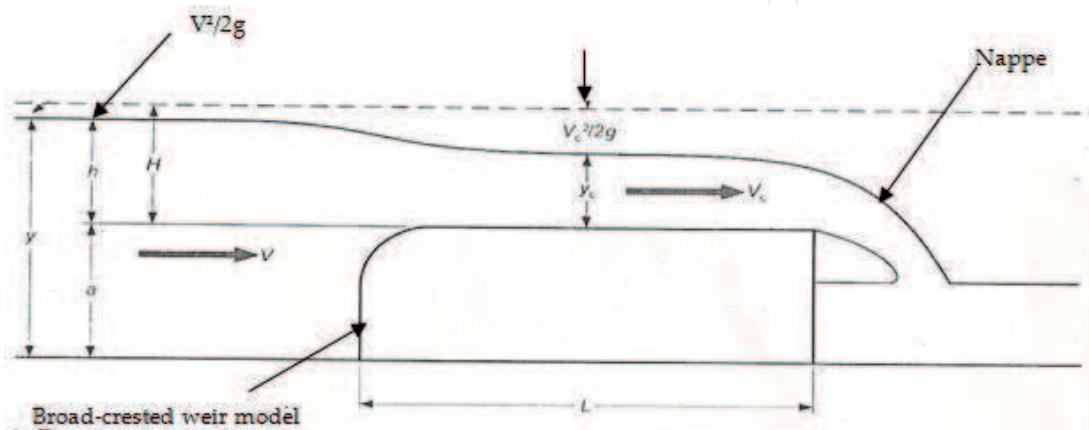


Figure 1.
Flow pattern over a broad-crested weir.

in an inclined rectangular sharp-crested weir using experimental and numerical simulation. Results revealed that the discharge coefficient of the weir increases with the increase in inclination of the weir plane. The discharge coefficient for a sharp-crested weir was investigated to vary between 0.61 and 0.73 [18].

A commonly used sharp-crested weir structure for measuring streamflow in irrigation and drainage channels is rectangular in shape [19]. In the sharp-crested experiment, the relationship between water level over the weir crest and discharge can be established; also the coefficient of the discharge for the weir can be determined. At the upstream of the sharp-crested weir, the velocity of all moving water elements is nearly uniform and parallel to the channel bed [19]. **Figure 2** shows flow pattern over a sharp-crested weir. The nappe usually traps a certain amount of air between the lowest nappe surface and the downstream side of the weir. When the downstream water level rises over the weir, the weir is said to be submerged. Eq. (5) is used for estimating the specific energy of water over the sharp-crested weir:

$$E = a + H + \frac{V^2}{2g} \quad (5)$$

where g is the acceleration of gravity = 9.81 m/s^2 , a is the height of the weir above the channel bed (m), H is the height of the water surface above the weir crest (m), V is the upstream flow velocity (m/s) and E is the specific energy (m).

Considering a streamline from a point in the upstream flow to a point in the plane of weir on the assumption of uniform velocity in the upstream of flow, the relationship between discharge and water level over sharp-crested weir is presented in Eq. (6):

$$Q = \frac{2}{3} C_d B \sqrt{2g} h^{3/2} \quad (6)$$

where Q is the flow discharge (m^3/s), C_d is the discharge coefficient, B is the width of weir and h is the head over the weir (m).

3.1.3 V-notch sharp-crested weir

V-notch sharp-crested weir is an upright tinning structure placed perpendicular to the base of a horizontal channel. The weir is a common discharge measuring

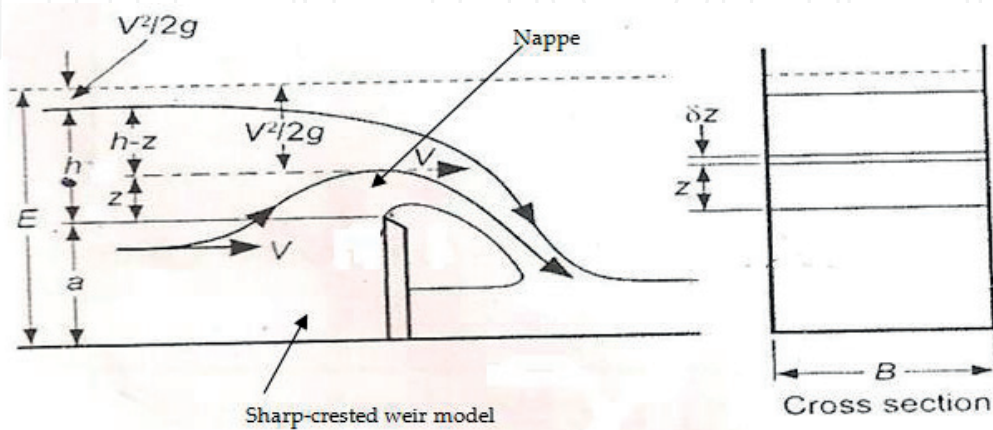


Figure 2.

Flow pattern over a sharp crested weir, where a is the height of the weir crest above the flume channel bed (m); L is the length of the weir (m); V is the velocity of moving water (m/s); y is the depth of water before the critical stage (m); y_c is the critical depth (m); V_c is the critical velocity (m/s); H is the head of water above the weir (m); and h is the head of water above the weir at upstream of weir section (m).

device applicable to a various degree of streamflow. Globally, the weir is also known as Thompson weir. The flow regimes that are observed in the weir are:

- Partially contracted weir in which the contraction at the sides of the weir is partly noticed because of closeness to the walls and bed of the channel.
- Fully contracted weir is a channel whose bed and sides are at far distance from the edges of the weir to give enough approach velocity parallel to surface of the weir. Expression to determine discharge over the weir is presented in Eq. (7):

$$Q = \frac{8}{15} \sqrt{2g} \tan \frac{\theta}{2} h^{\frac{5}{2}} \quad (7)$$

where Q is the flow discharge (m^3/s), g is the acceleration of gravity = 9.81 m/s^2 , h is the water head above the weir vertex (m) and θ is the vertex angle ($^\circ$).

3.1.4 Trapezoidal-shaped (Cipoletti) weir

Modification of fully contracted sharp-crested weir with a trapezoidal control section is known as Cipoletti weir. The weir crest slopes outward with 1:4 horizontal to vertical inclination. Cipoletti in 1886 observed that an increase in side contraction with corresponding increase in head results in reduction of discharge over the weir. The discharge reduction would be taken over by the control section. This will permit the use of head-discharge equation of a full-width rectangular weir. The equation for the determination of discharge over Cipoletti weir is shown in Eq. (8):

$$Q = 3.367 C_d L H^{\frac{3}{2}} \quad (8)$$

where Q is the discharge (m^3/s), C_d is the discharge coefficient, L is the effective length (m) and H is the depth of flow of water over the weir base (m).

3.1.5 Short-crested weir

Short-crested weirs have characteristics similar to broad-crested and sharp-crested weirs. Streamlines above the crest of short-crested weirs are curved. Some typical examples of the weirs are weir sill with rectangular control section, V-notch weir sill, triangular profile weir (Crump weir), the flat V-weir, cylindrical-crested weir, streamlined triangular profile weirs and flap gates.

3.1.6 Crump weir

In 1952, Crump published details of a weir with a triangular profile which had been developed at the Hydraulic Research Station. This was claimed to give a wide modular range and also to give a more predictable performance under submerged conditions than other long-based weirs [7].

Crump proposed upstream and downstream slopes of 1:2 and 1:5, respectively, which were based on sound principle. The upstream slope was designed so that sediment build-up would not reach the crest. The downstream slope was shallow enough to permit a hydraulic jump to form on the weir under modular flow condition, thus providing an integral energy dissipater; also under submerged conditions, losses are not too high and the afflux is minimized. The equation for the determination of discharge over Crump weir is shown in Eq. (9):

$$Q = C_d B g^{1/2} h^{3/2} \quad (9)$$

where Q is the flow discharge (m^3/s), C_d is the coefficient of discharge, B is the width of weir (m), g is the acceleration of gravity (m/s^2) and h is the head above the weir (m).

3.1.7 Ogee weir

This is a special type of weir, generally used as a spillway of a dam [20]. The crest of an Ogee weir rises up to a height of $0.115 H$ and falls in a parabolic form. The shape of water over an Ogee weir is similar to the shape of the lower of a sharp-crested weir. The expression for determining discharge over an Ogee weir is presented in Eq. (10). An Ogee spillway with a fixed-width curvature can pass more flow. Hence, under low hydraulic heads, it is considered as an economical viable structure [21]:

$$Q = \frac{2}{3} C_d L \sqrt{2g} H^{3/2} \quad (10)$$

where Q is the discharge (m^3/s), C_d is the discharge coefficient, L is the length of the weir (m) and H is the depth of flow of water above the weir crest on the upstream side (m).

3.2 Flumes

Flume is a hydraulic device that can be used to constrict flow scenarios in an open channel for the purpose of measurement. In a broad meaning, a flume can be described as an artificial prismatic open channel in the laboratory. It can be used to simulate various hydraulic parameters in an open channel flow such as: depth and corresponding discharge [4]. Flumes can be generally described as hydraulic structure which water flows through. They can be tailored to a greater range of flows and require less head loss.

The traditional flume is used to measure discharge in agricultural systems. Flumes are designed in order to produce a critical depth in the flume throat and thereby creating a direct relationship between water depth and flow rate. In practice, test data or derivation of empirical relationship based on field research is usually employed in determining the relationship between the water depth and the flow rate.

3.2.1 Accuracy and advantages of the flume

Flumes are self-cleaning due to the fact that the velocity of flow through a flume is usually high and also the absence of no obstruction across the channel. It is also possible to operate with a very smaller head loss which cannot be achieved with a similar weir structure, and this makes flume to be adopted in many areas where the available head is limited. Traditionally, flume is used in measuring flow in agricultural systems and it requires low maintenance cost [22]. It has capacity to measure higher flow rates than a comparably sized weir.

In terms of accuracy, it is possible to obtain an accuracy within $\pm 2-5\%$ (for the flume itself) with overall system accuracy for a typical installation being $\pm 10\%$ when all factors are considered [22].

3.2.2 Classifications of flumes

Flumes are generally classified into two major categories. These are long-throated and short-throated flumes. Examples of long-throated flumes are rectangular (Venturi), trapezoidal and U-shaped flume. Examples of short-throated flumes are Parshall flumes and H-flumes, throatless flume with rounded transition and throatless flume with broken plane transition (cutthroat flumes). When compared with weirs, long-throated flumes are similar to broad-crested weirs (parallel streamlines), while short-throated flumes behave like short-crested weirs (curved streamlines).

3.2.3 Discharge measurement using flumes

Flumes are specially configured open channel structures which control the velocity, resulting in flow changes and in water level. The streamflow through a flume is estimated by measuring depth of water in the flume at a specified location, based on the flume configuration. Generally, flumes are employed to determine discharge where weirs are not useful. They are commonly useful in measuring field runoff when streamflows during storms can be channelled and conveyed across the device. Flumes are very suitable in measuring streamflows containing sediment because the increased velocity through the flume tends to make itself cleaning [7]. The discharge over a flume is determined using Eq. (11):

$$Q = kH_a^n \quad (11)$$

where Q is the flow rate (m^3/s), k is the flume discharge constant (varies according to flume size), H_a is the depth at the site of measurement (m) and n is the discharge exponent (depends on flume size).

3.3 Orifices

Orifice is a small opening provided at the side or bottom of a tank through which liquid flows out. It is used to measure the flow of a fluid from a tank or reservoir. The cross section of the opening may be square, rectangular, triangular or circular. The stream or liquid coming out of an orifice is called a jet. The difference between orifice and notch is size; orifice is smaller than the notch. The quantity of flow measures by orifice is smaller than the notch [22]. Orifices are classified based on size, shape, discharge conditions and shape of the upstream edge. The expression for estimating the amount of flow through an orifice is shown in Eq. (12):

$$Q = AC_d\sqrt{2gh} \quad (12)$$

where Q is the discharge (m^3/s), C_d is the discharge coefficient, A is the area of orifice (m^2), h is the depth of flow of water over an orifice (m) and g is the gravitational acceleration = 9.81 m/s^2 .

3.3.1 Rectangular notch

A notch is an opening in the side of a tank or a vessel in such a way that the liquid surface is below the top edge of the opening. It is a device used to measure the rate of flow of liquid through a tank or a small channel. Notch is a thin structure, usually made of a metallic plate [20]. Flow pattern over a rectangular notch is

similar to flow over rectangular and Ogee weirs. The expression for calculating flow through a rectangular notch is presented in Eq. (13):

$$Q = \frac{2}{3} C_d L \sqrt{2g} H^{3/2} \quad (13)$$

where Q is the discharge (m^3/s), C_d is the discharge coefficient, L is the length of the weir (m) and H is the depth of flow of water in the notch (m).

4. Conclusion

Selecting the most appropriate hydraulic structure and the optimal design of its dimension is very critical to the accuracy and quality of streamflow measurement. Therefore, it is incumbent on the designer to balance its choice based on the characteristics of the structures, field constraints and human factors as dictated by the water management in the area. The characteristics of different hydraulic structures for streamflow measurement are embedded in a number of properties such as:

- i. Range of measurement is determined by the shape and width of the crest.
- ii. Head loss required by hydraulic structures with a high discharge capacity usually has a high coefficient of discharge and vice versa.
- iii. Accuracy of measurement is determined by reliability of the calibration. Sharp-crested weir (V-notch) has the highest accuracy ($\pm 2\%$) when measuring small discharge in an open channel.
- iv. Possibilities of regulating discharge over hydraulic devices have been developed to perform more than one function such as streamflow measurement and flood regulation. Other structures such as flumes are designed exclusively to have a fixed crest.

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