Flow measuring devices in surface irrigation for enhancing agricultural water productivity

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Judicious use of water plays a vital role in enhancing its productivity in agriculture. In India, surface irrigation covers about 88% of the irrigated area with application efficiency ranging from 30% to 40%. Therefore, it becomes imperative to improve water application efficiency of canal commands and other areas under surface irrigation. Water application efficiency can be improved by minimizing conveyance losses and by judicious irrigation scheduling pertaining to different crops, which can be accomplished by accurate measurement of irrigation water. Measurement of irrigation water supplied to farmlands not only assists in the saving of water but also enhances water productivity in agriculture. The most popular device for measuring irrigation water in field channels is the Parshall flume, which has undergone a series of modifications to simplify its construction, improve the accuracy of measurements and reduce its cost leading to its wider acceptance by the stakeholders. Thus, it becomes imperative to develop an accurate, low-cost and portable flow-measuring device for enhancing agricultural water productivity. Moreover, a review of the literature reveals limited availability of portable and digital flow-measuring devices for real-time measurement of surface irrigation through field channels. Nonetheless, it is established that the use of flow-measuring devices in surface irrigation will not only save water but also expand the area under irrigation, ensure its sustainability and improve agricultural water productivity.

Keywords: Agriculture, field channels, flow-measuring devices, surface irrigation, water productivity.

WATER is a valuable asset for agriculture and its judicious use plays an important role in enhancing agricultural water productivity. Globally, irrigation accounts for 70% of water abstraction. India receives an average of 4000 billion cubic metres (BCM) of precipitation per year, with an average river flow of 1869 km^3. The country's total utilizable water resource is about 1123 BCM, with 690 BCM contributed from surface water and 433 BCM from groundwater resources. Irrigation consumes about 80% of the available water resource which is expected to rise to 910 BCM by 2025 and 1072 BCM by 2050 (ref. 1). India currently occupies the world's highest irrigated land, comprising approximately 68.2 million hectares, with a major part of nearly 88% under surface irrigation. Surface irrigation systems in the country operate at 30%–40% efficiency, implying that at least 60% of the water supplied is lost at various points of the irrigation system. Nowadays, increasing water use in agriculture necessitates the use of water-measuring devices not only to supply measured quantities of water, but also to improve agricultural water productivity. Therefore, flow-measuring devices in surface irrigation methods would play a significant role in fulfilling the prime goal of the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) of the Government of India, by ensuring water supply to each farmland in the country. A good agricultural practice must incorporate both knowledge of crop water usage and technologies for effective irrigation management. Due to water scarcity in various regions, it also becomes imperative to supply a measured amount of water as desired by the crops at various growth stages.

Measurement of the amount of water delivered and received at each farmland of a canal command will ensure a more equitable allocation besides its conservation. Surface irrigation is generally considered a low water-efficient system owing to the difficulty of delivering water over long distances, lack of accurate water depth and flow-metering systems besides conveyance losses. According to Peter Drucker (an educator, philosopher and writer), i.e. 'what gets measured, gets managed', highlighting the importance of water measurement for its judicious management[2]. Therefore, real-time monitoring of irrigation water supply using digital water flow-measuring devices can assist farmers estimating irrigation efficiency and increasing water productivity. Furthermore, quantifying how much water is supplied to farms is required for the development of an effective on-farm water management plan. When too much water is applied, it overflows from the surface and percolates below the root zone of the crops, providing no further benefits to them. On the other hand, deficit water, particularly during important growth phases of the crops, might result in yield reduction. Therefore, accurate water measurement assists on-farm irrigation decision-makers for better allocation of irrigation water while minimizing its adverse environmental impacts. Moreover, irrigation water pricing necessitates the use of flow-measuring devices in irrigation channels. The amount of water applied to a field is determined by the time, flow rate and field area. The area to be irrigated and the time

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of irrigation water supply are simple to monitor, whereas measuring the flow rate in an open channel necessitates the use of appropriate instruments or methods. Even though the flow is not under pressure in an open-field channel, effective flow measurement can be difficult, and devices such as venturi, electromagnetic or strap-on transit-time flow meters used for piped flow are not feasible in open-channel flow.

Flow in an irrigation channel can be measured in a variety of ways, including the use of contact or non-contact sensor types and hydraulic structures[3]. Open-channel flow-measuring devices do not measure flow directly. Instead, some devices measure the flow velocity while others measure head or pressure variations. Weirs, flumes, current meters, propeller meters, orifices, electromagnetic meters, venturi meters, turbine meters, ultrasonic meters and pitot tubes are the most commonly used equipment for open-channel flow measurement[4]. Alternatively, it is possible to integrate a flow depth-sensing system using an ultrasonic sensor, pressure transducer or a shaft encoder. Non-contact flow meters are popular because of their portability, ease of installation and ease of use. However, due to the high cost of non-contact-type flow meters, their usage in on-farm irrigation water monitoring is limited.

Open-channel flow-measuring devices use the principle of either the weir or the orifice, and each device is customized to be used in specific situations. Furthermore, the ideal flow-measuring device must be low-cost, simple to operate, free of moving components, low-maintenance, accurate in measurement, unaffected by sand, silt or floating debris, and require minimal head loss in the channel. So, keeping these parameters in view, the Parshall flume and cut-throat flume, and trapezoidal flume are the most widely used devices, particularly in flat topography and with small channel gradients. Measured discharge through such devices is a function of the depth of flow at one location in the upstream section. However, such depth measurements are affected under submerged conditions, which would occur due to obstruction downstream or accumulation of silt or vegetation growth in the channel bed. The accuracy of the flow-measuring system is an important parameter for its wider adoption. Different flow-measuring devices are reported to operate with an accuracy of ±5% (refs 5 and 6). However, a few are capable of measuring flow with ±1% accuracy under laboratory settings[6]. However, under field conditions, it becomes difficult to achieve such accuracies, requiring more investment in their construction, besides periodic maintenance and recalibration. Overall, selecting a device not adhering to the site conditions would result in a nonstandard installation of reduced accuracy to the tune of ±10 (ref. 6).

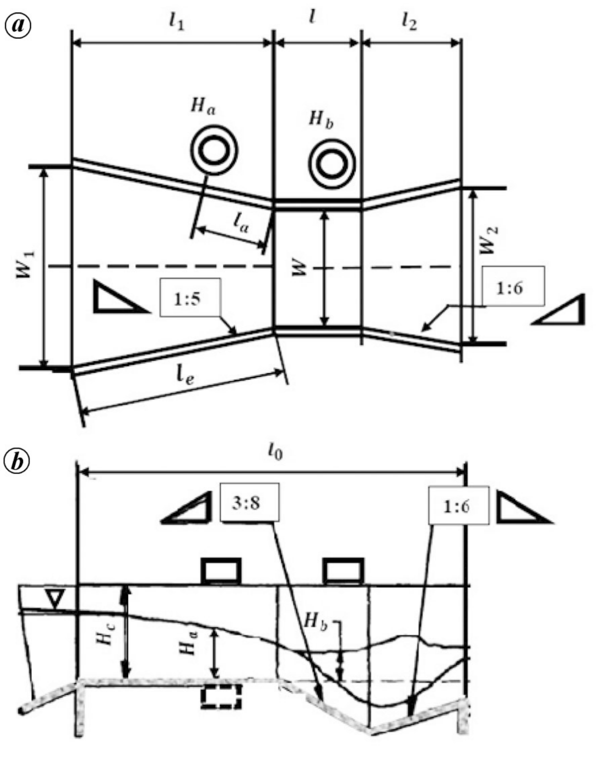

Figure 1. Parshall flume (IS 14371[9]): (***a***) plan and (***b***) sectional view.

Development chronology of flow-measuring devices for open channels

Cone[7] developed the fundamental plan and disseminated preliminary performance reports of a device called the 'venturi flume' for measuring water in an open channel. The formula for computing discharge through the venturi flume is given below.

$$Q = 6.68 H_{\mathrm{b}}^{2}[((H_{\mathrm{d}} - 0.14H_{\mathrm{a}} + 0.02)^{2} + 0.01H_{\mathrm{a}} + 0.56)]\frac{H_{\mathrm{b}}^{2}}{2} \times \sqrt{\frac{2gH_{\mathrm{d}}}{1 - \frac{H_{\mathrm{b}}^{4}}{(2_{3}^{2} + H_{\mathrm{a}})^{2} H_{\mathrm{a}}^{2}}}}, \quad (1)$$

where Q is the discharge (cubic feet per second (cfs)), H_{a} the head in upstream gauge (ft), H_{b} the head in throat gauge (ft) and H_{d} is the difference between these heads.

Subsequently, Parshall[7] modified the venturi flume developed by Cone[8] and introduced an 'improved venturi flume' by including converging and diverging sections with angles varying from 18.19° to 11.19° and 18.16° to 9.28° respectively. This flume was later named as the popular 'Parshall flume' (Figure 1). A general relationship for discharge under free-flow condition for 1 to 8-in throat sized is given by

$$Q = 4WH_{\mathrm{a}}^{1.55W^{0.026}}, \quad (2)$$

where Q is the discharge (cfs), W the throat width (ft) and H_{a} is the upstream head (ft).

Dimensions can be calculated using the following equations[9].

Width of the entrance cross-section of the flume (m)

$$W_1 = 1.2W + 0.48. \quad (3)$$

Axial length of the entrance section (m)

$$l_1 = 0.5W + 1.2. \quad (4)$$

Converging wall length (m)

$$l_e = 1.02 l_1. \quad (5)$$

Wall length between the crest and the head measurement section (m)

$$l_a = 2l_e/3. \quad (6)$$

Width of the exit cross-section of the flume (m)

$$W_2 = W + 0.30. \quad (7)$$

Side wall height in the entrance section (m)

$$H_c = H_{a\,max} + (0.15–0.20). \quad (8)$$

In the above equations, W is the throat width of the flume (m).

The axial length of the throat (l), exit cross-section (l_2) and other dimensions of the flume have been selected from table 1 of IS 14371 (ref. 9).

Parshall[10] suggested a detailed procedure for proper installation of the Parshall flume. These flumes were compared with various types of weirs and it was found that the loss of head required in the use of weir was approximately four times more than that needed for the Parshall flume. Equation (9) was used for discharge measurements under free-flow conditions for Parshall flume of size 1 ft (30.48 cm) to 8 ft (243.8 cm).

$$Q = (3.6875W + 205)H_a^{1.6}, \quad (9)$$

where Q is the discharge (cfs), W the throat width (ft) and H_a is the upstream head (ft).

The successful operation of the Parshall flume depends upon its proper installation. The setting of the crest at a proper elevation with reference to the bed of the channel assumes importance where sufficient fall is available. This setting may be determined with little difficulty, but if the fall or grade of the channel is minimal, care must be taken in fixing the height of the crest so that submergence is avoided. Robinson[11] standardized the design dimensions of small-sized Parshall flumes based on the calibration of 1, 2 and 3 inch flumes. A tolerance on the throat width and other dimensions was suggested to be ±1/16 inch and ±1/32 inch respectively. The head–discharge relationship for a 3 inch flume is

$$Q = 0.992 H_a^{1.55}, \quad (10)$$

where Q is the discharge (cfs) and H_a is the upstream head (ft).

It was also observed that presence or absence of the diverging section had no effect on the head discharge relationship of a flume. Skogerboe[12] developed a flume having levelled floor and zero–length throat section named as the 'Cut-throat flume'. Rectangular cut-throat flumes of size 1, 2, 3, 4 and 6 ft were studied and tested in the laboratory and a representative equation for discharge was given as follows

$$Q = 3.50W^{1.025} H_a^{1.56}, \quad (11)$$

where Q is the discharge (cfs), W the throat width (ft) and H_a is the upstream head (ft).

Hyatt[13] developed a 'trapezoidal flume' and suggested that the occurrence of critical depth in the throat section would indicate measurement of only upstream flow depth to determine the discharge. Under varying upstream depths, the flow remains independent of the downstream depth as long as it passes through the critical depth in the throat section. The equation under free-flow conditions is given as

$$Q = aH_a^{b}, \quad (12)$$

where H_a is the depth at upstream and a, b are constants.

For submerged flow conditions

$$Q = \frac{C_1 (H_a - H_b)^{n_1}}{\left(\log \frac{H_b}{H_a} + C_2\right)^{n_2}}, \quad (13)$$

where Q is the flow rate, H_a the depth at upstream, H_b the depth at downstream, n_1 the free-flow exponent, n_2 the submerged flow exponent and C_1 and C_2 are constants.

Bos *et al.*[14] developed several designs of modified, broad-crested weirs and their rating tables. The head–discharge relationship for a rectangular cross-section was given by

$$Q = C_d C_v (2/3)(2g/3)^{0.5} B_c h_1^{(1.5)}, \quad (14)$$

where Q, C_d, C_v, B_c and h_1 are the discharge, coefficient of discharge, approach velocity coefficient, width at critical section and the measured upstream head respectively. The value of C_d is closely related to the H_1/L ratio, where H_1 is the energy head corresponding to h_1 and L is the crest length in the direction of flow. Moreover, the range on H_1/L was observed to be $0.075 \leq H_1/L \geq 0.75$. Samani and Magallanez[15] developed a simple flume which combines the concept of circular and cut-throat flumes. Cross-sectional contraction was used to achieve critical flow in the flume using semi-circular cylinders affixed to the side walls of a rectangular channel with contractions of 40%, 54% and 60%. The theoretical discharge (Q) through the critical section (B_c) can be described by the following equations

$$Q = C_d B_c \sqrt{g\left(\frac{2H}{3}\right)^3}, \tag{15}$$

$$C_d = 1.33 - 0.44\frac{d}{B} + \sin\left(0.21\frac{H}{B_c}\right), \tag{16}$$

where Q is the flow rate (lps), H the upstream energy head (cm), C_d the discharge coefficient, B_c the throat width of the channel (cm), d the diameter of the cylinder (cm), B the bottom width of the channel (cm) and g is the acceleration due to gravity (9.81 m/s^2).

The Parshall flume has been modified in different respects to fit into particular field situations. Large-radius guide walls, modified profile along the canal and flume inverts have been used at the flume entrance. Whereas at the flume exit, the short rise had been replaced with longer concrete slopes or stilling basin. It was found that there was no effect on head-discharge relationship under free-flow conditions and hence the standard head–discharge relationship reported by US Bureau of Reclamation[6] may be used.

Design of the flow-measuring devices under free and submerged flow conditions

Singh *et al.*[16] proposed a stage–discharge relationship under free-flow conditions of the Parshall flumes of throat width 0.052, 0.076, 0.152 and 0.229 m as follows

$$Q = 2.72\,Wh^{1.55}, \tag{17}$$

where W is the width of the throat (cm) and h is the upstream flow depth (cm).

Das *et al.*[17] evaluated the performance of a cut-throat flume of throat width 0.127 m and length 0.918 m. The developed free flow and submerged flow equations are given below.

$$Q_{\text{free flow}} = 0.344 H_a^{1.695}. \tag{18}$$

$$Q_{\text{submerged flow}} = \frac{0.182(H_a - H_b)^{1.695}}{(-\log S)^{1.45}}, \tag{19}$$

where $Q_{\text{free flow}}$ is the free flow discharge (m^3/s), $Q_{\text{submerged flow}}$ the submerged flow discharge (m^3/s), H_a the flow depth at upstream (m), H_b the flow depth at downstream (m) and S is the submergence ratio (H_b/H_a).

Carollo *et al.*[18] proposed a head and discharge relationship based on the principle of the Bernoulli theorem and gradually varied flow conditions for the Samani, Magallanez, Baiamonte, Ferro (SMBF) horizontal flume.

$$Q = \frac{(B_c + \beta h) g^{1/2} h^{1/2}}{\left\{\frac{\alpha}{2} + \alpha\cos\left[\frac{1}{3}\arccos\left(1 - 2\frac{(B_c + \beta h)^2}{B^2\alpha^2}\right)\right]\right\}^{3/2}}, \tag{20}$$

where Q is the discharge (lps), B_c the throat width (cm), α a coefficient, β a coefficient depending on the assumed α value, g the acceleration due to gravity (m/s^2), h the upstream water depth (cm) and B is the channel width (cm).

Krupavati *et al.*[19] and Kolavani *et al.*[20] studied the flow characteristics of semi-circular flumes (simple flumes[12]). It was suggested that a single measurement of upstream depth can be used for discharge measurement in open channels, if the submergence conditions are below 80%. The location of critical depth moved towards the centre of the flume with increase in contraction from 40% to 60% and side contracted flumes were sensitive to higher submergence conditions. The contraction ratio and both positive and negative longitudinal slopes significantly affected the stage–discharge equation. Moreover, it was recommended that the proposed head and discharge relationship should be used only in the bed slope of channel range ±1%.

The flumes having contraction 2 : 1 (66.66%) width transition could be used more efficiently and effectively up to a higher submergence limit for measurement of water in open channels[21]. The calibrated equation of flumes was able to accurately determine the discharge with an error ranging from a minimum of 2% to a maximum of 10% in free-flow regimes[16–19].

When the tail water level downstream of a flume is raised sufficiently to alter the flow depths upstream, submerged flow conditions result, preventing critical depth within the flume. The discharge becomes a function of two flow depths (H_a and H_b) under such submerged flow conditions. A flow is said to be submerged if the degree or percentage of submergence, as represented by the ratio H_b/H_a is above the limits given in Table 1 (ref. 14).

Table 1. Free-flow limits

Width of throat (cm)	Free-flow limit (H_b/H_a)
2.5–7.5	0.6
15–22.5	0.6
30–240	0.7

Parshall[7] proposed the head–discharge relationship for the improved venturi flume under submerged flow conditions as follows

$$Q = 4WH_{\mathrm{a}}^{1.5422W^{0.026}} - \left\{ \left\{ \frac{H_{\mathrm{a}}}{\left\{\frac{1.5}{K}\right\}^{1.8} - 2.5} \right\}^{4.57-3.14K} + 0.093K \right\} W^{0.815}, \quad (21)$$

where K is the degree of submergence expressed as a decimal fraction, W the throat width (ft), Q the discharge (cfs) and H_{a} is the upstream head (ft).

When the ratio of upstream (H_{a}) and downstream (H_{b}) depth exceeds the free-flow limits, the discharge is reduced and is given by

$$Q_{\mathrm{S}} = Q - Q_{\mathrm{E}}, \quad (22)$$

where Q_{S} is the discharge under submerged flow conditions (cfs), Q the modular discharge (cfs) and Q_{E} is the reduction in modular discharge due to submergence (cfs).

Different rating curves have been developed by Bos[22] between Q_{E} and degree of submergence for different sized Parshall flumes. Robinson[23] analysed the available data pertaining to submerged flow in Parshall flumes and suggested the following simplified procedure. The discharge ratio Q/Q_0 was expressed as a function of percentage submergence $H_{\mathrm{b}}/H_{\mathrm{a}}$ for a different flume size.

A curve (Figure 2) between Q/Q_0 versus $h_{\mathrm{b}}/h_{\mathrm{a}}$ (%) was developed for different flume sizes. The ratio Q/Q_0 is actually a correction factor which can be applied to the indicated discharge in order to obtain the correct discharge value, i.e.

$$Q/Q_0 = \text{Correction factor at } h_{\mathrm{b}}/h_{\mathrm{a}}, \quad (23)$$

where Q is the actual discharge (cfs), Q_0 the free-flow discharge for a depth h_{a} (cfs), h_{a} the depth at upstream (inch) and h_{b} is the depth in the throat section (inch).

Hyatt *et al.*[24] developed a general form of the submerged flow equation using dimensional analysis pertaining to different sized Parshall flumes as follows

$$Q = \frac{C_1(H_{\mathrm{a}} - H_{\mathrm{b}})^{n_1}}{\left\{-\left(\log \frac{H_{\mathrm{b}}}{H_{\mathrm{a}}}\right)\right\}^{n_2}}, \quad (24)$$

where H_{a} is the upstream depth of flow, H_{b} the downstream depth of flow, C_1, C_2 are coefficients and n_1, n_2 are exponents.

Skogerboe *et al.*[25] proposed an equation for cut-throat flume under submerged flow conditions

$$Q = \frac{C_1(H_{\mathrm{a}} - H_{\mathrm{b}})^{n_1}}{(-\log S)^{n_2}}, \quad (25)$$

where Q is the discharge rate, C_1 the submerged flow coefficient, n_1 the free-flow exponent, n_2 the submerged flow exponent and S is the submergence.

Skogerboe *et al.*[26], developed a theoretical discharge equation for submerged flow for a flat-bottomed rectangular channel using momentum theory.

$$Q = \frac{g/2^{1/2} W (H_{\mathrm{a}} - H_{\mathrm{b}})^{3/2}}{\sqrt{\frac{(1-BS)(1-S)^2}{S(1+S)}}}, \quad (26)$$

where contraction ratio $B = W/b_{\mathrm{a}}$, submergence $S = H_{\mathrm{b}}/H_{\mathrm{a}}$, b_{a} is the width of the flume at the point of upstream flow depth H_{a} and W is the throat width of the flume.

Skogerboe *et al.*[27] proposed a general relationship of transition submergence situation in which the flow passes from free flow to submerged flow conditions or vice versa, and is expressed as follows

$$-\log S_{\mathrm{t}}^{n_2} = \frac{C_1}{C}(1 - S_{\mathrm{t}})^{n_1}, \quad (27)$$

where C is the free-flow coefficient, C_1 the submerged flow coefficient, n_1 the free-flow exponent, n_2 the submerged flow exponent and S_{t} is the transition submergence.

The reliability of flow measurements using cut-throat flumes in flat gradient channels under free-flow conditions had –2.2% to 8.6% error, while under submerged flow conditions, the error ranged from –3.2% to 14.6%. Therefore, cut-throat flumes cannot provide reasonably accurate flow measurements under submerged flow conditions[28].

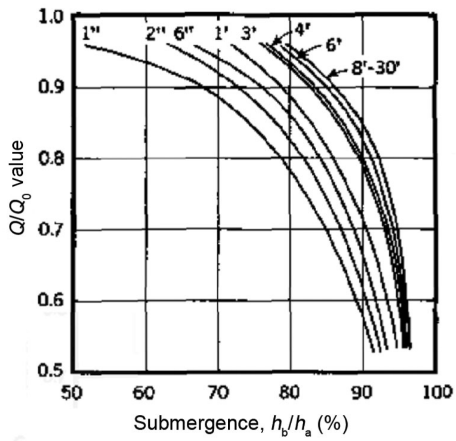

Figure 2. Effect of submergence on measurement of flow depth in a Parshall flume[23].

Structural modifications of a flow-measuring device

The design structure of open-channel flow-measuring devices is expected to influence the flow depth versus discharge relationship of a flume. The Parshall and cut-throat flumes are fabricated in metal for durability. However, due to weight of the flumes, soils in the periphery will get consolidated leading to some degree of settlement of the device. Further, as the flume and the adjacent channel are subjected to numerous wetting and drying cycles, the former is also prone to settlement which may lead to inaccurate measurement of flow.

The accuracy of a Parshall flume depends on the slope of the channel surface where the device has been installed or used[29]. The influence of longitudinal settlement under free-flow conditions using a 3 inch Parshall flume at slope values of 0%, +1.9%, +5.8%, +7.8%, +10.2%, –1.2%, –5.5%, –7.8%, –9.4% and –22.8% was examined. It was concluded that the flume had an error of 32% for ±10% change in longitudinal slope. Therefore, the equation for discharge measurement was modified using a discharge correction factor as follows

$$\mathrm{DCF} = 0.032S + 1.00, \tag{28}$$

$$Q = \mathrm{DCF} * a * H_{\mathrm{a}}^{\mathrm{b}}, \tag{29}$$

where Q is the discharge (cfs); S the longitudinal slope (%), DCF the discharge correction factor, H_{a} the upstream depth of flow (ft), a a coefficient and b is an exponent.

Similarly, lateral settlement also affects the accuracy of flow measurements under free-flow conditions of a Parshall flume[30]. The lateral flume crest slope values of 0%, +3.6%, +6.5%, +9.0%, +13.3%, –3.8%, –4.8%, –7.2% and –11.8% were tested. It was observed that the accuracy of the Parshall flume was sensitive to slope with about 7% error for a lateral slope of ±10% and the flow measurement included a correction factor of 0.75% adjustment for each 1% increase in the flume crest. The design parameters were also found to influence the head–discharge relationship of a Parshall flume[31]. An equation for correction factor (Y) based on upward slope (X_1) and downward slope (X_2) in diverging and throat sections for free-flow conditions has been proposed as follows

$$Y = 0.8323 + 0.5064X_1 - 0.3061X_2. \tag{30}$$

It has been suggested that during fabrication, a variation of 20°–25° in downward slope can be accepted with variation of upward slope from 3°16′42.6″ to 6°32′37.1″ to arrive at an accuracy level of ±5%.

Prasad[32] reported that a 5% increase in longitudinal settlement caused 17.2% variation in discharge, whereas similar change in transverse settlement caused only 5.7% variation. It was reported that with negative slope, the measured discharge was more than the observed discharge and vice versa for positive slope. Based on the experimental results, correction factors for longitudinal settlement, as well as both longitudinal and transverse settlement can be represented by the following equations.

For longitudinal settlement

$$C = 1.0267 + 0.0291S_{\mathrm{L}}. \tag{31}$$

For combined effect of longitudinal and transverse settlement

$$C = 1.0293 + 0.0299S_{\mathrm{L}} + 0.0088S_{\mathrm{T}}, \tag{32}$$

where C is the correction factor, S_{L} the longitudinal slope (%), S_{T} is the transverse slope (%).

Abt *et al.*[33] developed a method and an equation for adjusting discharge measurement for small Parshall flumes combining both lateral and longitudinal settlements. A regression analysis with multiple variables was carried out in which the ratio of the measured discharge (Q_{m}) to apparent discharge (Q_{a}) was correlated to the lateral correction (C_{LAT}), longitudinal correction (C_{LONG}), and actual flume throat width (C_{TW}). Therefore, the measured (actual) discharge for a small Parshall flume was estimated as

$$Q_{\mathrm{m}} = Q_{\mathrm{a}} \times C_{\mathrm{LAT}} \times C_{\mathrm{LONG}} \times C_{\mathrm{TW}}, \tag{33}$$

where

$$Q_{\mathrm{a}} = aH_{\mathrm{a}}^{\mathrm{b}}, \tag{34}$$

$$C_{\mathrm{LAT}} = -0.008S_{\mathrm{LAT}} + 1.0, \tag{35}$$

$$C_{\mathrm{LONG}} = -0.008S_{\mathrm{LONG}} + 1.0, \tag{36}$$

and

$$C_{\mathrm{WT}} = (\text{Throat width})^{0.35}, \tag{37}$$

In the above equations, S_{LAT} is the lateral slope across the throat, S_{LONG} the longitudinal slope (%), the throat width (in); a and b are coefficients dependent upon the flume geometry and H_{a} is the depth of flow at the downstream staff gauge (ft).

The effect of settlement on the accuracy of 30.5 and 61.0 cm Parshall flumes was studied by Genovez *et al.*[34]. The flumes were installed and evaluated for slope settlements on the lateral, longitudinal and combined lateral–longitudinal sides. The slope values of the flumes varied by ±7% and the experiments were carried out under free outfall circumstances. The findings also proved that the accuracy of a Parshall flume is slope-dependent. For longitudinal slope values of ±5%, the flume discharge error was found to be around 28%, while for lateral settling of ±5% it was around 10%.

According to Abt *et al.*[35], the accuracy of a Parshall flume is slope- and submergence-dependent. For lateral settlement of 2%, the error in discharge measurement by the flume under 70%, 80%, and 90% submergence was 3%, 5% and 11% respectively. As the cross-slope deviates from the horizontal, the accuracy of a Parshall flume decreases. A correction factor for submergence (C_K) was incorporated into the discharge rating equation, which is given as

$$Q_{\text{app}} = C_{\text{LAT}}(Q - C_K), \tag{38}$$

where the free-flow discharge Q is expressed as

$$Q = a * H_{\text{a}}^{\text{b}}, \tag{39}$$

and the correction factor for submergence C_K as

$$C_K = \left(\frac{H_{\text{a}}}{A}\right)^n + B, \tag{40}$$

where H_{a} is the upstream depth of flow, a and b are coefficients dependent upon the flume geometry, A and B are coefficients that depend on the degree of submergence K and n (an exponent).

Heiner[36] reported that errors of up to 60% could occur when the head is measured inaccurately. Additionally, standing waves followed by troughs develop in the flume when entry wingwalls diverge from the prescribed design, lowering the accuracy of flow measurements. Furthermore, a method was introduced to correct the misalignment of the staff gauge and various entrance wingwall configurations.

Radius wingwall

$$C_{\text{sw}} = -0.841\alpha^4 + 3.000\alpha^3 - 4.027\alpha^2 + 2.609\alpha + 0.259. \tag{41}$$

Radius wingwall with offset

$$C_{\text{sw}} = -0.808\alpha^4 + 2.889\alpha^3 - 3.921\alpha^2 + 2.580\alpha + 0.258. \tag{42}$$

45° Wingwall

$$C_{\text{sw}} = -1.038\alpha^4 + 3.509\alpha^3 - 4.457\alpha^2 + 2.745\alpha + 0.244. \tag{43}$$

45° Wingwall

$$C_{\text{sw}} = -0.841\alpha^4 + 3.000\alpha^3 - 4.027\alpha^2 + 2.609\alpha + 0.259. \tag{44}$$

45° Wingwall with offset

$$C_{\text{sw}} = 1.135\alpha^5 - 5.223\alpha^4 + 8.947\alpha^3 - 7.443\alpha^2 + 3.385\alpha + 0.208. \tag{45}$$

No wingwall or approach ramp,

$$C_{\text{sw}} = 1.691\alpha^5 - 7.052\alpha^4 + 11.01\alpha^3 - 8.444\alpha^2 + 3.571\alpha + 0.212. \tag{46}$$

In the above equations, C_{sw} is the correction factor for an inaccurate stilling well placement and α is the location ratio. In the case of varied wingwalls, the radius wingwall was recommended because it lowers the effects of standing waves and depressions, but it could not completely eradicate the problem at the maximum flow rate as advised by Parshall[37]. However, in the presence of 45° wingwalls or in the absence of wingwalls, the waves and depressions were unstable to precisely quantify the flow. However, the head measured by a staff gauge or ultrasonic methods is affected because of the migration of waves and troughs downstream as a result of the increase in flow rate. Due to this incorrect measurement of depth of flow, the Parshall flume recordings maybe inaccurate. It was shown that having no wingwalls or a 45° wingwall increased the errors even more. Due to these potential errors, it was suggested that the conventional Parshall flume rating equation be amended to incorporate a correction factor as follows.

$$Q_{\text{cor}} = \frac{Q_{\text{ind}}}{C_{\text{sw}}}, \tag{47}$$

where Q_{cor} is the corrected flow rate, C_{sw} is the correction factor and Q_{ind} is the flow from the standard Parshall rating (cfs) and is expressed as

$$Q_{\text{ind}} = a * H_{\text{a}}^{\text{b}}, \tag{48}$$

where a and b are size-specific coefficients and H_{a} is the upstream head measurement (ft).

Devices with digital sensing system for measurement of flow in open channels

A review of the literature pertaining to digital flow-measuring devices revealed that a few published works on such systems for flow measurements in pipes are available, but there is a dearth of papers pertaining to digital sensing systems in open-field channels. However, sensors working on ultrasonic and Doppler principles are available and used for measurement of flow depth in open channels, streams and rivers. However, there is a lacuna of sensing systems that are coupled or mounted with a portable flow-measuring device to provide information on both flow depth and cumulative discharge passing through the measuring unit on a real-time basis. Different manufacturers have developed digital flow meters based on the principle of rotating propeller, difference in pressure heads and the concept of orifice and nozzle flow. Presently, open-channel digital flow-measuring devices employing the concept of velocity area approach using mechanical, electromagnetic and acoustic principles are available in the market. However, they are expensive and used for *in situ* measurement of discharge and volume of water passing through rivers, streams and open channels. The discharge is calculated by multiplication of the real-time flow velocity with the wetted area of the cross-sectional profile of the channel[38,39]. Acoustic doppler current meters use the advanced acoustic doppler velocimeter (ADV) and acoustic doppler current profiler (ADCP) technologies to measure velocities in the channel and the wetted profile respectively, for real-time discharge rate[38]. Weaver[40] evaluated the performance of an uncalibrated Doppler flow meter at farmers' fields in Idaho, USA. It was observed that the output discharge rate had a measurement error of 15.5%. However, it was suggested that the acceptable measurement error in open channels should be ±10%. The digital presentation of the output data in terms of discharge rate and volume of flow was appreciated by the users. Vermeyen[41] evaluated the performance of Unidata's Starflow™ Doppler flowmeter and MGD Technologies' acoustic Doppler flow meter (ADFM) at the Water Resources Research Laboratory, United States. Bureau of Reclamation, Colorado, USA. It was observed that the average uncertainty in Starflow discharges was +26.20%, and the average uncertainty in ADFC was +1.30%. Besides, the Starflow™ system costs about INR 117,000 while the cost of the ADFM system varies from INR 1,170,000 to 1,377,000. Sood *et al.*[42] developed a low-cost automatic water flow meter for measurement of water in pipelines which supply only the required amount of water to the crops. The whole system comprised of a AT89S52 microcontroller, opto-coupler, G1/2 Hall effect water flow sensor, a water pump, relay, liquid crystal display, 5V supply, keypad and some passive components. The AT89S52 microcontroller is programmed in Keil development tool to supply measured water to different crops. However, the system does not have in-built irrigation scheduling information for different crops. Santhosh and Roy[4] proposed an intelligent flow measurement technique using an ultrasonic flow meter with optimized neural network. The system helped measure water flow in pipes of varying diameter, liquid density, and liquid temperature by an optimal artificial neural network architecture.

Limitations and scope of open-channel flow-measuring devices

Flow measurement in irrigation channels is an important step towards water conservation[42]. With the growing demand for water in agriculture, low-cost and precise flow-measurement instruments are preferred. Ever since the invention of the Parshall flume[7], its construction has been simplified to some extent with an aim to improve the accuracy and reduce the cost of open-channel flow-measuring devices. Three general strategies can be used to achieve critical flow in an open channel, viz. raising the channel bottom[14,43,44], contracting the flow cross-sectional area[15,26,27,43,45,46] and lowering the bottom elevation to establish a critical flow. One of the simplest methods of establishing critical flow for the purpose of measuring flow in an open channel is to contract the cross-section of the flow[15,43,45,46]. These efforts resulted in the development of the cut-throat flume[25,47] and the Replogle, Bos and Clemmens (RBC) flume[44]. Flow measurement is done by contracting the flow, which is the simplest and least expensive method because it does not necessitate complex inflow and outflow transitions[48]. The ideal condition for accurate discharge measurement is the throat section, which needs to be properly constricted to produce critical depth in the throat section. As a result, most of measurement structures employ the principle of permitting flow through the constricted throat to establish a critical depth, resulting in free-flow conditions in which the discharge is solely dependent on the upstream flow depth. However, in submerged flow conditions, the upstream flow depth is affected due to increase in the downstream flow depth of the diverging section. Therefore, the stage and discharge relationship developed for free-flow conditions does not hold good for the submerged condition[23]. Hence, the flow-measuring devices developed for open-channel irrigation systems should consider both flow conditions for accurate measurement leading to enhanced surface irrigation efficiency[49].

Different kinds of flumes, viz. Parshall flume, cut-throat and long-throated flume are being used in India and abroad for the measurement of flow in open channels. However, these flumes are associated with many known and unknown errors. The major lacunae in the use of the Parshall flume are difficulty in configuration of the throat section, its sloping floor and subsequently the field installation. Also, submergence owing to backwater effect is a primary source of inaccuracy in Parshall flumes. Besides this, the structural settlement of Parshall flumes causes errors in flow measurements[30,34,35,50–53]. The incorrect entrance geometry and gauge location also cause errors in flow measurements. Moreover, efforts have been made by researchers around the globe to modify the design of existing flumes and develop a flume that would overcome the limitations of the Parshall flume. In India, the Parshall and cut-throat flume structures are being constructed permanently in different types of canals.

Flow in an open channel can be monitored either instantaneously or continuously. Typical components of a continuous system are the primary flow-measurement device, sensor, transmitter, flow recorder and totalizer. The primary flow device, which is the core of a conventional continuous flow-measurement system, may be used to get instantaneous flow measurements. This device is designed to produce predictable hydraulic responses which are related to the discharge passing through the device. Weirs and flumes relate flow depth (head) to flow rate (discharge), magnetic flow meters relate induced electric voltage to flow, and venturi and orifice-type meters relate differential pressure to flow. These typical primary flow devices have proven to be accurate when installed and constructed according to established standards. Moreover, the flow depth sensor is required to monitor the depth of flow passing through the measuring device and transmits the information to the data logger. Such sensors are generally pressure transducers, ultrasonic transmitters, differential pressure cells, floats, capacitance probes, electromagnetic cells, etc. Sensor signal is often transformed into units of flow using mechanical, electromechanical or electronic mechanisms which are then recorded or communicated to the data logger. Flow totalizer is used in systems that display the total flow in real time. Continuous monitoring of the flow passing through an open channel should be considered while developing digital measuring devices for quantification of water supplied to the field during an irrigation event. Besides, the portable flow depth sensing system can be used in locations where permanent open channels are constructed. On the other hand, in the absence of permanent structures, the integrated flow-sensing system along with a portable water measuring device can be installed to provide continuous flow measurement.

It can be observed from the literature pertaining to flow measurement in open channels that there is limited availability of a low cost and portable flow-measuring device. Also, no such device has been integrated with sensing devices having a digital display unit for providing instant reading and measured quantity supplied during an irrigation event. Therefore, this study of open-channel flow-measuring devices would pave the way for the development of low-cost digital water measuring devices for open channels to obviate majority of the limitations pertaining to the use of weir, orifice, rating flume or other flow-measuring devices.

Conclusion

Accurate measurement of irrigation water plays a significant role in the saving of water and enhancing water productivity in agriculture. Indiscriminate use of water coupled with inaccurate scheduling of irrigation in agriculture is a hindrance to attainment of sustainability in irrigated agriculture. A plethora of agricultural water management practices are disseminated to farmers related to water conservation and enhancing water productivity. However, there is a need for a digital water measuring system in field channels for assisting the stakeholders in providing the desired amount of irrigation water according to the crop requirement. Water management technologies using micro-irrigation systems provide the highest water application efficiency to the tune of 90%, which covers only about 12% of the irrigated area in India, leaving the rest 88% to surface irrigation. The micro-irrigation technologies with higher water application efficiency generally use a pipe irrigation system equipped with pipe flow meters. However, in surface irrigation, the measurement of flow in open channels was primarily through different types of flumes, weirs and notches. Among these measuring devices, flumes with different designs are being used in open channels. Moreover, in canal commands adjustable proportionate modules are generally used to supply water to cropped land without any proper quantification mechanism. Hence, it is imperative to enhance water productivity of the canal commands and other regions using groundwater resources for surface irrigation. Besides this, PMKSY in operation since 2015 is mandated to provide irrigation water to all farmlands in the country. In order to fulfil the objectives of PMKSY, there is a need of low-cost and indigenous water measuring devices in the field channels of canal commands to supply measured amounts of water according to the crop water requirement. Such devices will ensure supply of the required quantity of water, thus prevailing of waterlogging and saving appreciable amounts of water, which can bring more area under irrigation in different reaches of a canal command.

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