Parshall Flumes: A Review

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Abstract: The Parshall flume was developed to measure discharge accurately in irrigation channels, municipal sewers, dam discharge, industrial effluent, and many more e.g. landfill leachate, etc. The principal advantages of Parshall flume include low head loss, self-cleaning capability and their ability to withstand relatively high degrees of submergence without affecting the rate of flow. An inspection of the original rating equation for Parshall Flumes indicated that the equation was not valid for the discharges as low as is currently recommended for the flumes' use. Also, the original equation did not take into account the various changes produced in the flume due to changes in climatic conditions. These changes include settlement and submergence of the flume. Hence, this review focusses on all the corrections made by various researchers across the world. New and improvised equations were written for various ranges of discharges, with correction coefficients being introduced for each anomaly.

Keywords: Parshall flume; Settlement; Correction coefficient; Degree of submergence

1. Introduction

It is of primary importance for a hydraulic engineer to measure the irrigation water as it is delivered to the farmers from the main canals and ditches (Parshall,1950). Faulty measurements lead to restriction of the farmer's water supply to such an extent that it seriously interferes with his crops' maturity. However, if accurate measurements are made, the value of crops would be more than enough to pay for the expenditure of the installment and measurement of a practical and good measuring device (Parshall,1928).

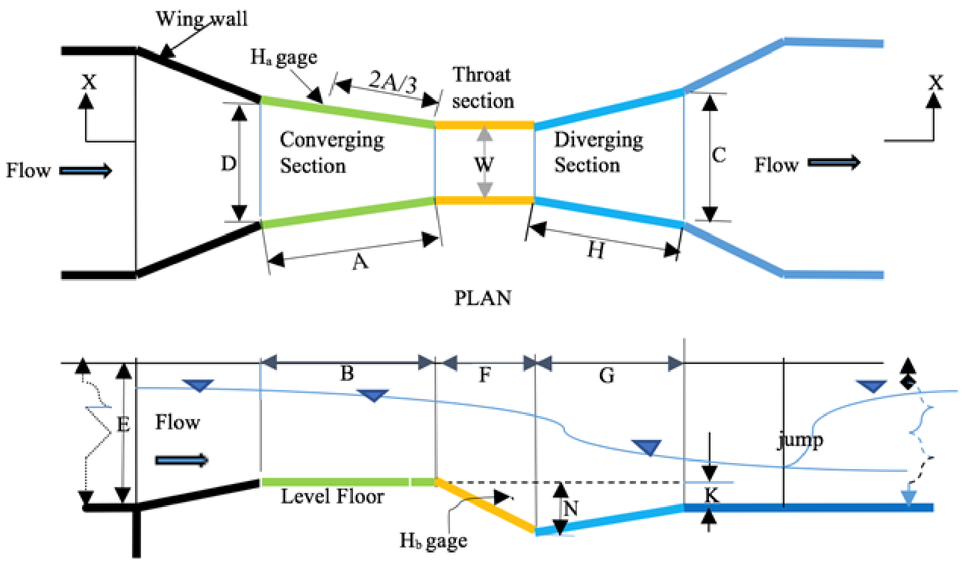
One of the earliest instruments to be used for the measurement of irrigation water was weir. A weir is accurately able to measure the flow if it is maintained properly. However, high head losses, as well as choking of weirs with debris, posed a problem in its usage for the measurement of water flow (https://www.openchannelflow.com/flumes).

To get rid of these problems, another device was created, which is now commonly known as the rating flumes. A rating flume is a simple hydraulic structure that commonly consists of a converging section, a throat, and a diverging section (https://www.openchannelflow.com/flumes).

One of the most commonly used flumes which can accurately measure the water flow is Parshall Flumes, created by Parshall (1928). The Parshall Flume originally referred to as the "Improved Venturi Flume", differs from the Venturi Flume created by Cone (1917) in the following ways (Parshall,1928):

a) The Angle of convergence was reduced from 18°26’ to 11°19’.
b) The throat was lengthened from 1ft to 2 ft.
c) The angle of divergence was reduced from 18°26' to 9°28', and
d) A drop was introduced through the throat of the flume.

It should be noted that the above angles and dimensions were for Parshall Flumes with throat widths 1 ft.to 8 ft, which were the initial focus of the study of Parshall (1928). However, with time, this study was extended by building flumes with throat widths 3-inch,6-inch and 9- inch by Parshall (1950). Later flumes with throat widths extending from 10 feet to 50 feet were built (Parshall, 1953). Finally, Parshall Flumes possessing small throat widths of 1-inch,2-inch, and 3-inch were calibrated by Robinson (1957). The definition sketch of the Parshall Flume has been shown in Fig. 1:



W-Throat width; A= Converging side wall length; F- Throat length; K- Sill height; B- Length of converging section; C-Downstream end width; D-Upstream end width; H- Diverging sidewall length; G- Length of diverging section; E=Flume depth; N=Depth of Throat depression

ELEVATION AT SECTION X-X

Fig. 1: Definition sketch of Parshall Flume

1.1 Conditions of Flow

Two types of flow conditions are encountered during the flow analysis of Parshall Flumes (https://www.openchannelflow.com/blog/parshall-flumes-free-and-submerged-flow):

a. Free Flow: When the water surface downstream of the flume is not high enough to reduce the flow through the flume, then free-flow occurs in the flume. In such a case only a single reading at the primary point of measurement (H_a) is needed so as calculate the discharge through the flume. It should also be noticed that a hydraulic jump (standing wave) is created at the downstream end of the flume in case of free-flow conditions.

b. Submerged Flow: When the elevation of the water surface downstream of the flume is high enough to reduce the velocity of flow, increase the upstream depth of water and hence create a backwater effect, then submerged flow conditions are said to have occurred in the flume. In this case, the resistance to the flow is high enough that discharge through the flume is decreased. Here two gauge readings, H_a and H_b are required to calculate the flow through the flume.

1.2 Rating Equations

The rating equations for the calculation of free flow and submerged flow through flumes of different sizes were given by the respective researchers as follows:

- For flume widths 1 ft.- 8 ft. free-flow (Parshall, 1928):

  $$Q = 4WH_a^{1.522W^{0.026}}$$

  where Q is the discharge rate in cubic feet per second, W is the throat width and H_a is the upper head measurement in feet.

For flume widths 1 ft.-8 ft. submerged flow (Parshall,1928):

$$Q = 4WH_a^{1.522W^{0.026}} - \left\{\left(\frac{H_a}{\left\{\frac{1.8}{K}\right\}^{1.8} - 2.45}\right)^{4.57-3.14K} + 0.093K\right\} W^{0.815}$$

Where; K=Degree of submergence H_b/H_a as a fraction; H_a, H_b =Primary and secondary staff gauge readings in feet.

For flume widths 10 feet-40 feet free flow (Parshall,1953):

- $Q = (3.6875W + 2.5)H_A^{1.6}$

where Q is the discharge rate in cubic feet per second (cusec), W is the throat width, and H_A is the upper head measurement in feet.

For flume widths 10 feet-40 feet submerged flow Parshall (1953):

To find submerged flow, Parshall (1953) provided a correction curve relating to upper gauge H_A, degree of submergence (%) and correction discharge. The correction discharge so found is deducted from the value of free-flow discharge at corresponding H_A to get the submerged flow discharge.

For flume widths 1-inch,2-inch and 3-inch free flow (Robinson,1957):

$$Q = 0.338H_a^{1.55} \quad \textit{(For 1-inch flume)}$$

$$Q = 0.676H_a^{1.55} \quad \textit{(For 2-inch flume)}$$

$$Q = 0.992H_a^{1.55} \quad \textit{(For 3-inch flume)}$$

In the above formulae, Q = discharge rate in cubic feet per second, H_a = upper head measurement in feet.

For flume widths 1-inch,2-inch and 3-inch submerged flow:

To find submerged flow rate, separate curves were provided by Robinson (1957) relating upper head H_a and degree of submergence (%) with the submerged flow discharge for 1,2 and 3-inch flumes, respectively.

However, none of the above-mentioned formulae took into account the various changes produced in the flume flow due to changes in climatic conditions and human errors. These include lateral and longitudinal settlement of flume as well as incorrect staff gauge location and entrance wing wall configurations. Hence, corrections were made by various researchers across the world. New and improvised equations were written, with correction coefficients being introduced for each anomaly.

2. Objective

This paper aims to act as a ready reference guide for researchers and field engineers in enhancing their knowledge and understanding in the context of discharge rating through Parshall flumes. Further, the objective of this review is to guide future developments in the correction coefficients for various anomalies caused by human errors and natural forces, as well as future improvisations in the empirical relationships developed for the determination of discharge through the flume.

3. Discussion

a. Flow corrections for submerged flow in Parshall Flumes

Robinson (1965) provided a simplified way to find outflow through a Parshall Flume in case of submerged flow conditions. Robinson created a graph in which the discharge ratio Q/Q_o was created as a function of the degree of submergence h_b/h_a, in percentage.

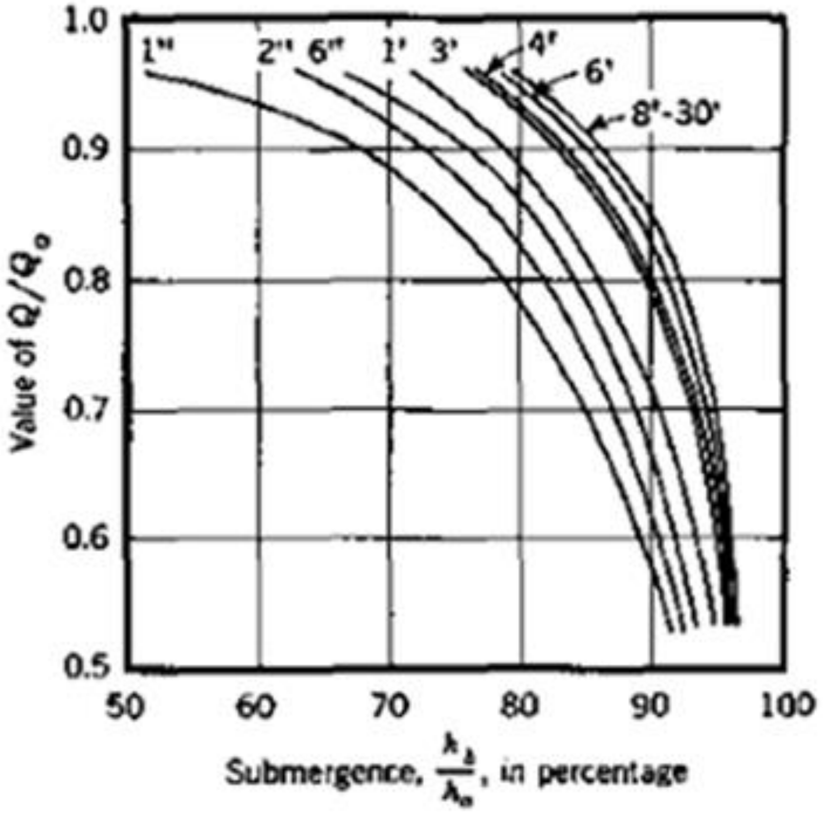


Fig. 2 Graph relating the ratio Q/Q_o and the degree of submergence h_b/h_a, in per cent with flumes of given different widths (Robinson,1965)

Here Q_o is the free flow discharge at the given value of h_a, which can be seen from Parshall (1950,1953).

Hence to find the value of submerged flow at given values of h_a and h_b:

i. Firstly, the degree of submergence, $\{(h_b/h_a) \times 100\}$would be computed.
ii. After this, from Parshall (1950, 1953), the value of Q_o would be found by looking at the value of free-flow discharge at the given value of h_a.
iii. Then, from the graph shown above, for the given throat width and degree of submergence, the value of Q/Q_o would be found.
iv. Finally, this value would be multiplied by Q_o (found in step ii) to get the value of submerged flow Q.

The maximum deviation with the observed data is equal to ±7%.

b. Flow corrections for settlement in Parshall Flumes

i. Abt et al., (1989), studied the flow in a 3 inch Parshall Flume installed in a channel at varying slopes of 0,+1.9,+5.8,+7.8,+10.2,-2.3,-5.5,-7.8,-9.4 and -11.8%. Free flow conditions were allowed to occur. At each slope, about 6-14 tests were carried out. During each test, the flow depth H_a was recorded with the help of stilling well and point gauge. Using this reading, the value of measured discharge was found using the rating equation of the manufacturer. This value was compared with the actual discharge flowing through the channel, recorded with the help of a calibrated orifice reading. An attempt was done to relate the actual and measured discharge values with the help linear regression. It was found that the Discharge Correction Factor (DCF) in case of longitudinal settlement (slopes) is:

$$\mathrm{DCF} = 0.032\mathrm{S} + 1.00$$

where S is the slope of the flume in percent

Hence, the correct formula to determine the free flow discharge in a flume having longitudinal settlement is:

$$\mathrm{Q} = \mathrm{C_{DCF}aH_a^b}$$

where: Q=Discharge in cusec., H_a=Staff gauge reading in feet, a,b=Coefficients. It should, however, be noted that the above equation is valid only for free flow in a 3-inch Parshall flume having slopes up to ±11.8%.

ii. Abt and Staker (1990) studied the effects of lateral settlement (tilting) of Parshall flume on the measurement of flow under free-flow conditions. This was done by installing a 3-inch Parshall flume in a recirculating channel, with the flume being at the lateral slopes of 0.0,3.6,6.5,9.0,13.3,-3.8,-4.8,-7.2 and -11.8%. At each transverse slope, flow depth H_a was recorded in a stilling well with the help of point gages located on both sides of the flume. This value was used to find out the apparent discharge. The measured i.e., the actual discharge was found with the help of a calibrated orifice meter.

The sign convention of a transverse slope is defined by looking in the direction of flow. If the right side of the crest of the flume, when looking in the direction of flow, is lower than the centreline of the flume floor, then the lateral slope is termed to be negative. If, however, the left side of the crest of the flume is lower than the centreline of the flume floor, then the lateral slope is termed to be positive.

After recording measured and apparent discharges at different lateral slopes, an attempt was made to relate the two quantities with the help of a linear regression technique. Hence a Discharge Correction Factor (DCF) was found to be:

$$C_{DCF} = \pm 0.008S + 1.00$$

where S=Transverse slope in percent

It should be noted that positive sign is used in the equation if the gage is present on the left side, with the flume having a negative transverse slope or the gage is present on the right side with the flume having a positive transverse slope. Similarly, negative sign convention is used if the gage is present on the right side, with the flume having a negative transverse slope or the gage is present on the left side with the flume having a positive transverse slope.

Hence, the correct formula to determine the free flow discharge in a flume having lateral settlement is:

$$Q = C_{DCF} a H_a^b$$

Where:

Q=Discharge in cusec., H_a=Staff gauge reading in feet.a,b=Coefficients.

It should, however, be noted that the above equation is valid only for free flow in a 3-inch Parshall flume having slopes up to ±13.3%.

iii. Abt et al., (1992) conducted studies on 1-inch,2-inch, and 3-inch Parshall flumes so as prove the fact that the methodology used by Abt and Staker(1990); Abt et al.,(1989) to find the corrections for lateral and longitudinal settlements for a 3-inch Parshall flume can, in fact, be applied to smaller Parshall Flumes too. This was done by individually installing 1-inch,2-inch and 3-inch Parshall flumes in a recirculating channel. Further, with each flume, tests were first done by varying longitudinal slopes, then by varying transverse slopes and by variation of the combined lateral-longitudinal slope. Free flow conditions were allowed to occur.

In each case, the apparent discharge was found by recording the value of H_a with the help of a stilling well, while the measured (actual) discharge was recorded with the help of a calibrated orifice meter.

The relation between apparent and measured discharge was found with the help of a linear regression technique to study the individual effects of lateral flume settlement and longitudinal flume settlement. The Discharge Correction Factors C_{LAT} (for lateral slope effect)and C_{LONG} (for longitudinal slope effect) were found to be the same as developed by Abt et al. (1989) for a 3-inch flume, thus proving that the same coefficients can be used for smaller Parshall Flumes too.

Finally, multiple variable regression analysis was conducted to study the effect of combined lateral-longitudinal flume settlement. The relation between measured(actual) and apparent discharge was found to be:

$$Q_m = Q_a \times C_{LAT} \times C_{LONG} \times C_{TW}$$

where

Q_a=Apparent Discharge=aH_a^b

H_a=Staff gauge reading in feet.

a and b =Coefficients

Q_m=Measured Discharge

$$C_{LAT} = -0.008 S_{LAT} + 1.0$$
$$C_{LONG} = 0.032 S_{LONG} + 1.0$$
$$C_{TW} = (throat\ width)^{0.035}$$

In the above relations:

S_{LAT}= Transverse slope of the flume in percent

S_{LONG}= Longitudinal slope of the flume in percent

Throat width is expressed in inches.

iv. Genovez et al.,(1993) conducted studies on 1 ft. and 2 ft. flumes to find out the individual effects and further combined effects of lateral and longitudinal slopes. This was done by individually placing the two flumes in a recirculating channel, with the flumes present at varying lateral, longitudinal and combined lateral-longitudinal slopes. Free flow conditions were allowed to occur. Finally, after finding the apparent discharges by recording the values of H_a gauge and obtaining measured (actual) discharge values with the help of calibrated orifice, linear regression analysis was applied to find out the value of Discharge Correction Factor for longitudinal slope (C_{long}) and lateral slope (C_{lat}). These values were found to be:

$$C_{long} = 0.056S_{long} + 1.00$$

$$C_{lat} = -0.020S_{lat} + 1.00$$

where S_{long} and S_{lat} are the longitudinal and lateral slopes in percent. Lastly, using multiple variable regression analysis, the relation between apparent and measured discharge was found in case of combined lateral-longitudinal settlement The relation is as follows:

$$Q_m = Q_a \times C_{lat} \times C_{long} \times C_{TW}$$

where

Q_a=Apparent Discharge=aH_a^b

H_a=Staff gauge reading

a and b =Coefficients

Q_m=Measured Discharge

$$C_{TW} = (throat\ width)^{0.010}$$

Throat width is expressed in centimeters.

v. Abt et al.,(1994) studied the effects of transverse slope on Parshall flumes under submerged conditions. This was done by conducting 11 experiments on Parshall flumes of throat width 1-ft. The flume was installed in a recirculation channel with a transverse slope varying from -3% to +3%. It was found that the accuracy of Parshall is dependent on the slope as well as the degree of submergence. Hence, the formula for submerged flow discharge measurement was modified. The improved formula is as follows:

$$Q_{app} = C_{LAT}(Q - C_K)$$

Where Q=Free flow discharge given by:

$$Q = aH_a^b$$

And C_K is the submergence correction factor given by:

$$C_K = \left(\frac{H_a}{A}\right)^n + B$$

Where H_a=upstream flow depth, a and b are coefficients dependent on flume geometry, A and B are coefficients dependent on submergence degree, n is an exponent whose value depends on K for a specific geometry and C_{LAT} is the lateral correction factor.

The values of a,b, A, B,n, and C_{LAT} can be seen from the following table.

Table 1: Coefficient and Discharge Correction Data (Abt et al., 1994)

Degree of Submergence K (%)	Discharge Correction (C_{LAT})	a	b	A	B	n
60	-0.020	4.00	1.522			
70	-0.016	4.00	1.522	3.024	0.065	2.372

80	-0.022	4.00	1.522	1.855	0.074	2.058
90	-0.053	4.00	1.522	1.032	0.084	1.744

vi. Abt et al.,(1995) studied the effects of combined transverse-longitudinal settlement on the Parshall flumes in case of submerged flow conditions. This was done by conducting 383 experiments on Parshall flumes of throat widths 1-inch,2-inch,3-inch,1-ft. and 2-ft respectively. Each of these flumes was installed in a recirculating channel on a one by one basis. Each experiment consisted of 8-13 measurements of H_a (primary gauge reading), which were readily read at the stilling well. With the help of this reading, the apparent discharge was obtained using the manufacturers'rating formula. The measured (actual) discharge was obtained with the help of a calibrated orifice.The transverse slopes were varied from -11.6% to +11.6%,while the longitudinal slopes were varied from -10.5% to +10.5%.

Results indicated that significant errors creep in the value of apparent discharge due to the presence of a transverse-longitudinal slope combination. Henceforth, equations were developed to obtain a correct discharge. They are as follows:

The correct i.e., the measured discharge can be found from the formula:

$$Q_m = Q_a \times C_{lat} \times C_{long} \times C_{TW}$$

Where Q_m is the measured discharge; Q_a is the apparent discharge given by:

$$Q_a = aH_a^b$$

C_{lat} is the coefficient of lateral correction given by:

$$C_{lat} = C_{dlat}S_{lat} + 1.0$$

C_{long} is the coefficient of longitudinal correction given by:

$$C_{long} = C_{dlong}S_{long} + 1.0$$

For free flow situations:

$$C_{dlat} = -0.0003TW - 0.006$$

$$C_{dlong} = 0.011log(TW) + 0.015$$

And for Submerged flow conditions:

$$C_{dlat} = (-0.0003TW - 0.0006) + [(-0.0003TW - 0.006)(28 - 97K + 103K^2 - 31K^3)]$$

$$C_{dlong} = [0.011log(TW) + 0.015] + [0.011log(TW) + 0.015](-24 + 105K - 152K^2 + 74K^3)$$

Here TW is in centimeters in the above equations. It should be noted that the flow is corrected up to ±3% of the actual discharge for cases with a degree of submergence lower than 90 per cent, while the flow is corrected up to ±5% of the actual discharge for cases with a degree of submergence greater or equal to 90%.

c. Flow corrections in case of incorrect staff gauge location and entrance wing wall configurations.

Heiner et al., (2011) conducted tests on a 2 ft. acrylic Parshall flume to determine the sensitivity on flow rate due to incorrectly located staff gauges as well as varying entrance conditions to the flume. For this, head measurements were taken at 55 locations within the upstream section of the flume, including the location recommended by Parshall i.e., twothirds upstream the crest of the flume. Also, varying entrance conditions such as radius wingwall,45° wingwall, and no wingwall were inducted on the flume, and each condition was individually tested.

It was found that the flow rating differs significantly for incorrect staff gauge installment as well as each wing wall configuration. Hence, correction factor C_{sw} were determined for every case:

Radius wingwall:

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

Radius wingwall along with offset:

$$C_{sw} = -0.805\alpha^4 + 2.889\alpha^3 - 3.921\alpha^2 + 2.580\alpha + 0.258$$

45° wingwall:

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

45° wingwall along with offset:

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

No wingwall or approach ramp:

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

Where C_{sw}=Correction factor for incorrect stilling well installment
α=Location ratio. It is a ratio of the distance of head measurement location from the crest divided by the design head measurement location (2A/3).

Finally, the corrected value of discharge from the formula:

$$Q_{cor} = \frac{Q_{ind}}{C_{sw}}$$

Where Q_{cor}=corrected flow discharge
C_{sw}=correction factor
Q_{ind}=Flow indicated by standard Parshall flume rating in cusec.
$Q_{ind}=aH_a^b$
a and b are coefficients
H_a is the staff gauge reading in feet.

It should be noticed that the above study is valid only for 2-ft Parshall flumes.

3. Conclusion

In this paper, a comprehensive review of the state-of-the-art research on the subject of correction coefficients is presented. Based on recent analytical and empirical findings, the following conclusions have been drawn:

- The flow ratings of Parshall Flumes is sensitive to
    i. Submerged flow conditions
    ii. Lateral settlements
    iii. Longitudinal settlements
    iv. Combined lateral-longitudinal settlements
    v. Incorrect staff gauge locations, and
    vi. Varying entrance conditions.
- The original rating equations did not take these factors into account while computing the discharge. Hence, corrected equations should be used in the presence of an anomaly. The use of these equations would significantly increase flow-measurement accuracy.

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