

Simple Flow Measurement Devices for Open Channels



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Introduction

With increasing demands from agriculture, municipal needs, industry, and recreational use, there is a need for water users to conserve, use, and share water wisely. Measuring water in open channels is an important first step toward water conservation. The measurement of the amount of water delivered and received by users will help ensure that each gets their fair share and establish a more equitable distribution of available water and promote conservation. Ever since the development of Parshall Flume (Parshall, 1926), continuous improvements have been made to simplify, reduce cost, increase accuracy, and reduce head losses in open channel flumes (Hagar, 1988, Skogerboe, 1972, Replogle, 1975, Samani, 1992, 1993, 2000, USBR, 1985).

As we study the importance of water use and management, the importance of knowing not only the quality, but quantity of water becomes more apparent. Traditional flumes and weirs are practical in many scenarios, allowing for accurate flow measurement. However, with the low-gradient, high sediment channels found in many parts of the world coupled with the financial constraints and lack of technical expertise, there is a need for a simple, cost efficient way to measure discharge. Simple flumes do not require extensive upstream transition reducing the amount of materials needed and the cost for construction. They produce minimal head loss and are self flushing and do not accumulate sediment often found in weirs or even in traditional weirs in low-gradient conditions. Simple flumes have been found to be an attractive and accurate option to consider when measuring flow.

This manual is divided into two main chapters the first of which outlines the design characteristics of simple flow measurement devices which are typically easier and less expensive to produce. The second chapter investigates more traditional flow measurement devices while outlining the strengths and weaknesses of both types of flumes. Not all flow measuring devices are suitable for all conditions; the selection of a specific weir or flume often depends on the hydraulic conditions of the canal and the specific objectives of flow measurement.

Principles of Flow Measurements in Open Channels

To understand flow measurement it is necessary to understand how water flows. Water flow is based on principle of energy. Two types of energy govern flow in open channels, global and specific energy. According to the principle of specific energy, minimum energy occurs when the Froude number (Fr) is equal to 1.

$$Fr^2 = \frac{Q^2 T}{g(A^3)} = 1 \quad (1)$$

Where:

Q = flowrate

A = cross-sectional area

T = top width of the flow

g = acceleration of gravity

As shown in figure 1.

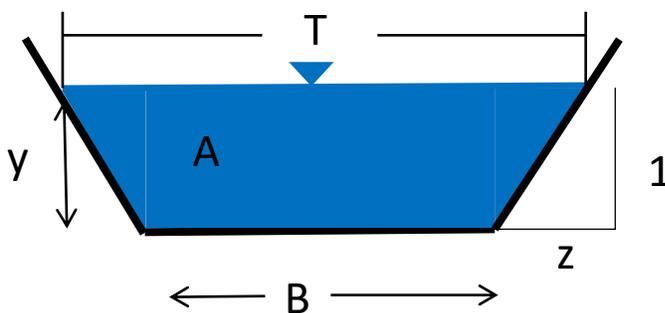


Figure 1. Typical channel dimensions shown in a channel cross-section.

This condition of minimum energy is also produces a specific flow called critical flow. As can be seen in equation 1 when critical flow occurs, the flow rate (Q) can be calculated through the cross-section area and top width of the flow. To accurately measure flow in open channel, it is

necessary to create a critical flow condition allowing flow to be measured by simply measuring the flow depth (yielding values for both T and A).

Critical flow in open channels can be created by three means: 1. Raising the bottom of the channel; 2. Lowering the bottom of the channel; 3. Contracting the flow cross-section (narrowing the channel). Flow measurement devices strive to achieve this critical flow for various conditions thus providing an accurate means of measurement.

Chapter 1: Simplified Flumes

Flumes are specially shaped open channel flow sections that are created to constrict flow in a canal or ditch and induce critical flow, allowing the flow rate to be determined. They are constructed of metal, concrete, wood, or fiberglass and can measure water over a wide variety of flow ranges. Larger flumes are constructed on site, while smaller flumes can be prefabricated and installed later on site.

Simple flumes require relatively little head loss, can operate in flat ditches, are relatively insensitive to approach velocity, and are self-cleaning due to the high velocity of water passing through. Flumes must be leveled and the flow entering the flume cannot contain waves or surges in order to provide accurate flow measurements.

Critical flow can be created by contracting the cross section of an existing canal without changing the existing canal dimensions. Simple flumes create a small section of critical flow before water returns to its previous energy state after a hydraulic jump has occurred. Minimal head loss is required and no extended inflow or outflow transition is needed. These flumes reduce the cost, calculations, and head loss while minimizing the required materials needed to measure flow. As canals come in various shapes and sizes, various short throated flumes have been developed to measure the flow in each respectively. The three simple flume types that have been developed are circular, rectangular (S-M), and trapezoidal flumes seen in figures 2, 11, and 20.

When the flow cross-section is contracted to create a critical flow, the discharge rate depends on the upstream energy (H), the width of the critical section (B_c), and the acceleration of gravity (g) as seen in figures 4 and 5. Therefore flow can be described as a function of H , B_c , and g as:

$$Q = \text{function}(H, B_c, g)$$

Gravity remains a constant, and the critical section (B_c) can be calculated for each channel type, leaving the upstream energy (H) as the only variable needed to calculate flow.

The function of Q was found to be (Samani, 2016):

$$Q = a(B_c^{2.5})(g^{0.5})\left(\frac{H}{B_c}\right)^b \quad (2)$$

Where:

Q = flowrate, ft³/s or m³/s

B_c = critical cross section width, ft or m

g = gravity, ft/s² or m/s²

H = upstream height of water at flume, ft or m

a and b are empirical coefficients that are determined experimentally using laboratory scale models shown in table 1 (Samani et al, 1991, 2000, 2003). These values are the same when using both imperial and metric measuring systems.

Table 1. Coefficients for various short throated flumes fitting the general equation (2).

| Flume Type | a | b |
|-------------------|----------|----------|
| Circular | 0.421 | 2.31 |
| Rectangular | 0.701 | 1.59 |
| Trapezoidal | 0.226 | 1.51 |

Once the dimensions of the channel and flume are known, B_c becomes a function of H, making the upstream height of water (H), the only variable needed to determine discharge.

Circular Flumes (Samani and Magallanez, 1992)

Pipes are often used to drain or convey water, and partially full pipes are considered open channels. The flume created in these circular channels consists of a vertical pipe installed inside a horizontal circular pipe to create critical flow. Cross-sectional and profile views of the circular flume are shown in figures 4 and 5. The head or height of the flow would be measured at the center of the upstream side of the vertical column as indicated by the ruler in figure 2.

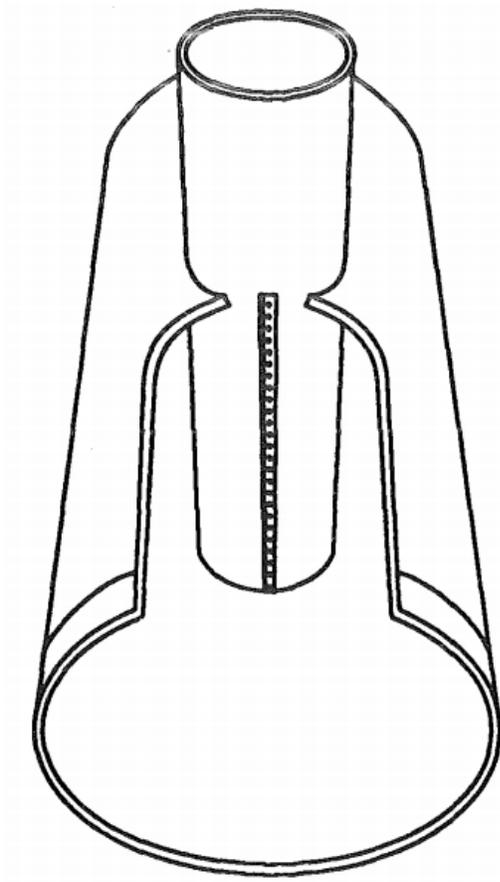


Figure 2. Cut out view of a circular flume from the upstream side (Samani, 1991).



Figure 3. Circular flume in southern New Mexico irrigation canal, located at GPS coordinates: 32.359167, 106.784722.

Inserting the coefficients for circular flumes from table 1 into equation 2, the equation for discharge using a circular flume is:

$$Q = 0.421 * B_c^{2.5} * g^{0.5} * \left(\frac{H}{B_c}\right)^{2.31} \quad (3)$$

Where:

Q = discharge, ft³/s or m³/s

H = head , ft or m

g = gravity, ft/s² or m/s²

B_c = width of channel at critical cross section in feet or meters, given by:

$$B_c = D - d \quad (4)$$

Where:

D = inside diameter of horizontal pipe (channel), ft or m

d = outside diameter of vertical pipe, ft or m

For the sake of simplicity, the critical width (B_c) of a channel is defined by $D - d$ with the coefficients (a,b) being used to correct for the change in critical width that occurs with the changing height in flow (Hagar, 1988). The parameters described in equations 3 and 4 are shown in figures 4 and 5.

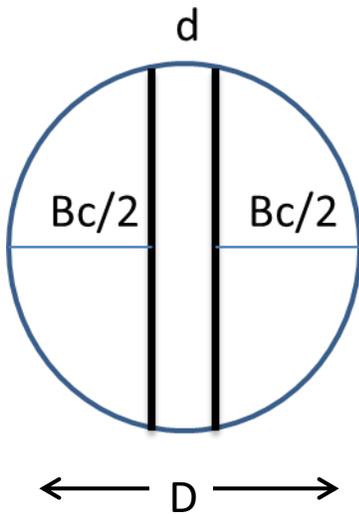


Figure 4. Cross sectional view of a circular flume.

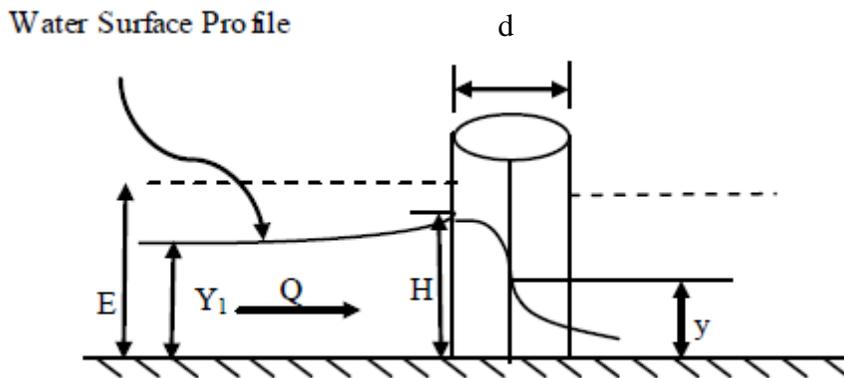


Figure 5. Profile view of circular flume and flow (Badar, 2012).

The principle limiting factors when designing simple flumes are: 1) the maximum submergence ratio (H_b/H_a), which is the height of water downstream (H_b) divided by the height of the water measured at the flume gage (H_a), 2) the ratio of the vertical column (d) to the diameter of the pipe (D), and 3) the entrance and exit lengths of the flume. Laboratory experiments (Samani, 1992) found the maximum submergence limit to be 0.80 (80%), the minimum ratio of d/D to be 0.25, the minimum entrance length to be equal to or greater than the maximum height of the water (entrance length $\geq H$), and the minimum exit length to be equal to or greater than one half the maximum height of the water (exit length $\geq \frac{1}{2} H$) as seen in figure 6.

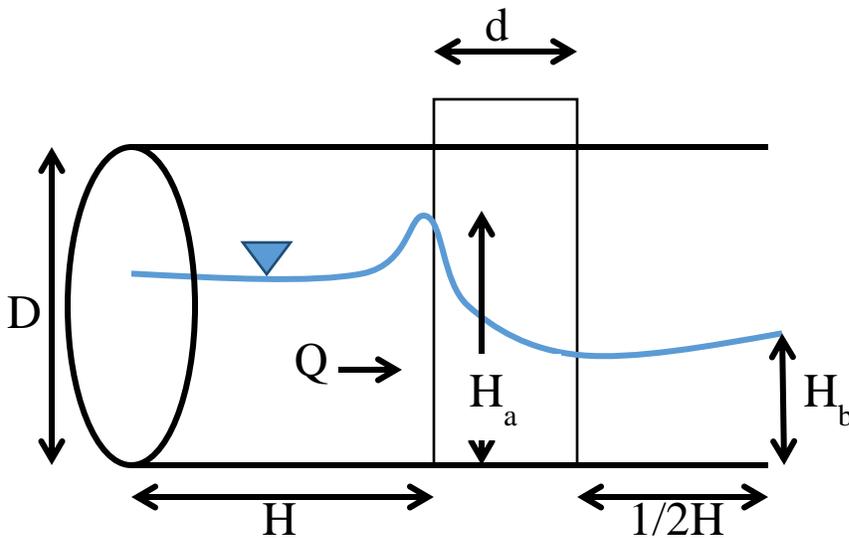


Figure 6. Diagram indicating critical design parameters, where $H_b/H_a \leq 0.8$ and $d/D \geq 0.25$.

One advantage to the circular flume is that it functions similar to v-notch, having a large exponent (2.31) thus being able to measure a large range of flow. This makes the circular flume ideal for variable flow conditions. The circular flume has been adopted for use in United States and various other countries. Some of their applications can be seen in figures 3, 7, 8, and 9.



Figure 7. Circular flume in North Dakota used to measure drainage discharge.



Figure 8. Circular flume in Canada used to measure flow in a canal (Ontkean, 2015).

Design Example of a Circular Flume

The following is an example of how to design and calibrate a circular flume for a given channel, known flow rate, and known normal maximum water depth.

Example:

Existing circular canal with a diameter: 1.2 ft

Maximum flow rate: $1.0 \text{ ft}^3/\text{s}$

Normal depth at maximum flow: 0.57 ft

We first assume a diameter of the interior vertical flume, generally in pipe sizes that are readily available. For this example we will start with the minimum allowable ratio of 0.3 ft ($d/D = 0.25$, $d = 0.25 * 1.2 \text{ ft}$).

$$B_c = D - d = 1.2 \text{ ft} - 0.3 \text{ ft} = 0.9 \text{ ft (equation 4)}$$

Using equation 3:

$$1.0 \text{ ft}^3/\text{s} = 0.421 * (0.9 \text{ ft})^{2.5} * \sqrt{32.2 \text{ ft}/\text{s}^2 * \left(\frac{H}{0.9 \text{ ft}}\right)^{2.31}}$$

$$H = 0.692 \text{ ft}$$

Submergence ratio: $0.57/0.692 = 0.824$, which exceeds the maximum submergence ratio of 0.8.

Therefore, we can increase the diameter of the column to $d = 0.60 \text{ ft}$, $D - d = 0.6 \text{ ft}$, and recalculate H.

$$H = 0.715 \text{ ft}$$

Submergence ratio: $0.57/0.715 = 0.80$ which meets the submergence requirement.

The entrance length would need to be at least 0.715 ft and the exit length would need to be at least 0.36 ft. This flume would require a vertical pipe of outside diameter 0.6 ft or greater and would measure flows up to 1.0 cfs (448.4 gpm).



Figure 9. Circular flume installed in a vineyard in Australia.

S-M flume (Samani and Magallanez, 2002)

Rectangular flumes can often be constructed and used in irregular channels. They are the easiest channel type to construct and calculate flow due to the constant width found throughout the verticality of the channel. Coupled with easier calculations, the contraction of a critical flow of water can be made to pass through the center of the channel making it ideal for flow with high sediment loads. This flume was first created, tested, and named by Samani and Magallanez and is named the S-M flume (Samani and Magallanez, 2000).

The contraction is made by cutting a pipe in half and placing a half on each side of the channel opposite each other with the gage set on the upstream side of the flume as seen in figure 11. This creates critical flow between the two half pipes and flushes sediment and debris through the flume.

Water Surface Profile

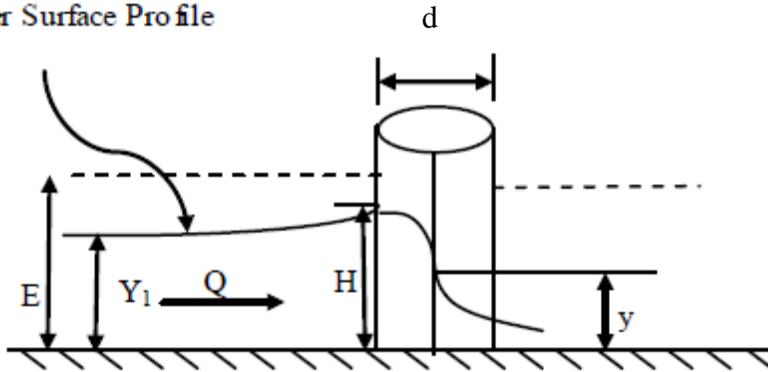


Figure 10. Profile view of S-M rectangular flume (Badar, 2012).

Inserting the coefficients from table 1 into equation 2, the discharge through the S-M flume is given by:

$$Q = 0.701 * B_c^{2.5} * g^{0.5} * \left(\frac{H}{B_c}\right)^{1.59} \quad (5)$$

Where:

Q = discharge, ft^3/s or m^3/s

H = height of water, ft or m

g = gravity, ft/s^2 or m/s^2

B_c = width of channel at critical cross section in feet or meters. Given by:

$$B_c = B - d \quad (6)$$

Where:

B = width of the base of the channel, ft or m

d = outside diameter of the half pipe, ft or m

The principle limiting factor when designing simple flumes is the maximum submergence ratio (H_b/H_a), which is the height of water downstream (H_b) divided by the height of the water measured at the flume gage (H_a). Laboratory experiments (Samani, 2000) found this maximum limit to be 0.80 (80%).

The ratio of the diameter of the pipe (d) to the width of the rectangular channel (B) is the contraction ratio. This ratio (d/B) should be greater than 0.40 (40%) or conversely $B_c/B \leq 0.6$ (60%), thus ensuring critical flow and allowing the discharge to be accurately measured (figure 11).

The minimum entrance length to be equal to or greater than the maximum height of the water (entrance length $\geq H$), and the minimum exit length to be equal to or greater than one half the maximum height of the water (exit length $\geq \frac{1}{2} H$) as seen in figure 12.

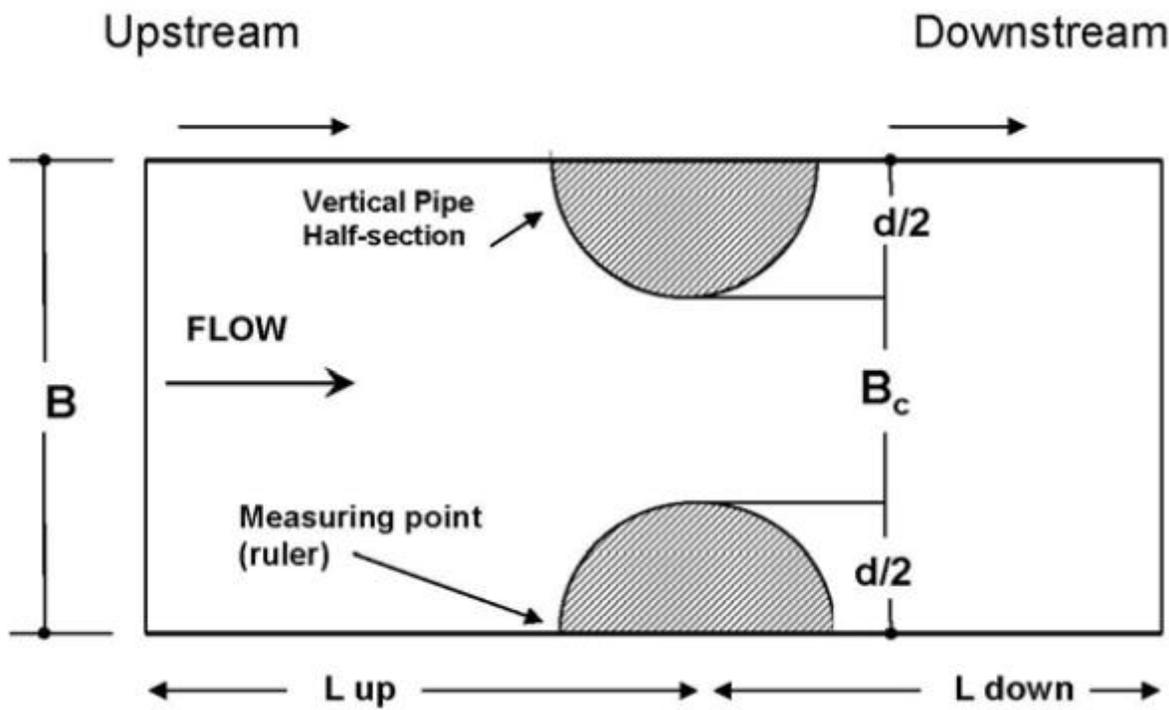


Figure 11. Plan view and common dimensions of S-M rectangular flume indicating the point of measurement with design parameter of $d/B \geq 0.4$ (Samani, 2005).

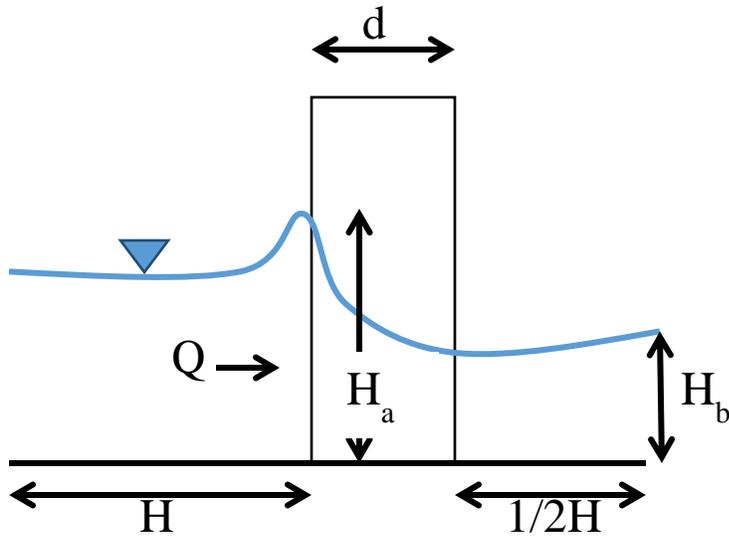


Figure 12. Diagram indicating critical design parameters, where $H_b/H_a \leq 0.8$.

Although rectangular in shape, S-M flumes are very universal and can easily be applied to irregular or trapezoidal shaped channels as shown in figure 13 by filling in the sides of the channel.

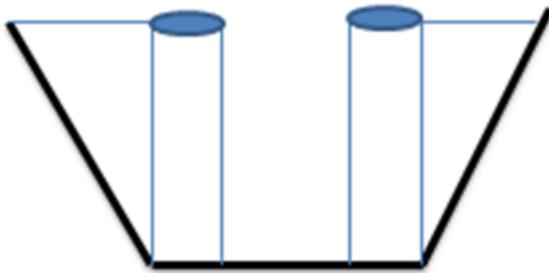


Figure 13. Cross-sectional view of S-M flume retrofitted into a trapezoidal channel.

The S-M flume can also be used to measure flow in parallel at varying heights and can be placed in high sediment or debris prone areas such as flood channels as seen in figure 14. This would allow the middle flume to measure discharge at low flowrates while allowing debris to pass through. At higher flowrates all three flumes would measure flow which could be added to

obtain the total flow. In these higher flow scenarios, the middle flume would act as a sluice gate, flushing sediment and debris through the flume.

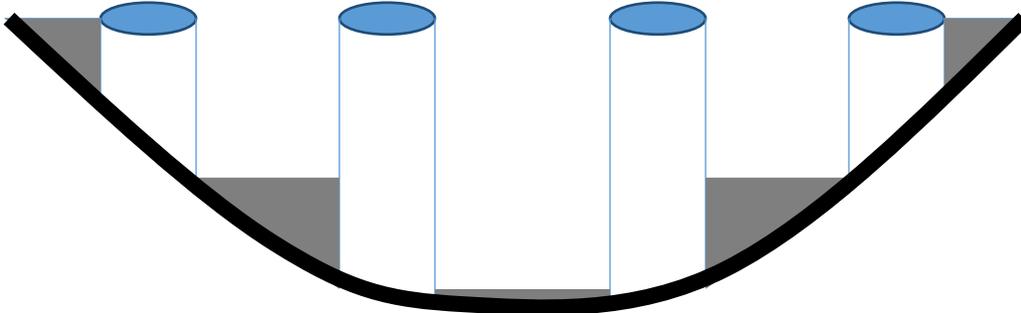


Figure 14. Multi-stage diagram of an S-M flume which could measure at both low and high discharge rates while allowing sediment to pass.

The S-M flume can also be installed at turnouts as shown in figure 15 and can function similar to a large turnout with a hydraulic jump induced due to the cross-sectional contraction and expansion, while being able to measure the flow at the same time.



Figure 15. An S-M flume installed in a turnout in a pecan farm in La Union, NM (Samani, 2005).

The pre-fabricated S-M flume can also be installed in unlined channels as shown in figure 16.



Figure 16. S-M flume installed in an acequia in Santa Fe, NM. (Samani, 2005).

Design Example of an S-M Flume

The following is an example of how to design and calibrate an S-M flume for a given rectangular channel, with known flow rate, and known normal maximum water depth. Additional solutions are provided in the case that a large enough pipe is not available. In this case the base of the flume could be elevated or the sides of the channel could be contracted.

Example:

Existing rectangular canal with base width: 1.2 ft

Maximum flow rate: $1.0 \text{ ft}^3/\text{s}$

Normal depth at maximum flow: 0.42 ft

We first assume a diameter of the interior vertical flume, generally in pipe sizes that are readily available. For S-M flumes we also need to meet the minimum contraction ratio of 0.40. For this example we will assume an outside diameter of 0.3 ft.

This gives a contraction ratio of $0.3/1.2 = 0.25$, which is below the minimum contraction ratio threshold.

Increasing d to 0.5 ft increases our contraction ratio to 0.42 which meets the requirement.

$$B - d = 1.2 \text{ ft} - 0.5 \text{ ft} = 0.7 \text{ ft (equation 6)}$$

Using equation 5:

$$1.0 \text{ ft}^3 / \text{s} = 0.701 * (0.7 \text{ ft})^{2.5} * \sqrt{32.2 \text{ ft} / \text{s}^2 * \left(\frac{H}{0.7 \text{ ft}}\right)^{1.59}}$$

$$H = 0.515 \text{ ft}$$

Submergence ratio: $0.42/0.515 = .815$, this still exceed the maximum submergence ratio of 0.8.

Therefore, we can increase the diameter of the pipe to $d = 0.6 \text{ ft}$, $D - d = 0.6 \text{ ft}$, and recalculate H .

$$H = 0.562 \text{ ft}$$

Submergence ratio: $0.42/0.562 = 0.75$ which meets the submergence requirement.

The entrance length would be a minimum of 0.562 feet, the exit length a minimum of 0.281 feet.

This flume would require a vertical pipe of outside diameter 0.6 ft or greater and would measure flows up to 1.0 cfs (448.4 gpm).

Alternate Solutions

Another solution would be to elevate the base of the channel slightly instead of increasing the pipe diameter from 0.3 ft to 0.6 ft.

Dividing the normal depth (0.42 ft) by the submergence limit (0.80), we obtain $0.42 \text{ ft}/0.80 = 0.525 \text{ ft}$.

The upstream height must be at least 0.525 ft.

Using the first pipe of 0.3 ft, we obtained an upstream height of 0.515 ft.

Subtracting the upstream height (0.515 ft) from the required height (0.525 ft); $0.525 \text{ ft} - 0.515 \text{ ft} = 0.010 \text{ ft}$.

By raising the base of the channel under the flume by 0.010 feet we would be able to use the vertical pipe diameter of 0.3 ft and meet the required submergence ratio.

An additional solution would be to further contract the sides of the channel to create a lower submergence ratio (figure 13).

Supposing that we only have a pipe of diameter 0.3 feet, we could instead fill in each side of channel with 0.3 feet of concrete or other material (figure 13).

This would create the same critical width (B_c) of 0.6 feet ($1.2 \text{ ft} - 0.6 \text{ ft}$), and give the same gage height of 0.562 feet found in the first solution which has been verified to work.



Figure 17. S-M rectangular flume installed in an unlined ditch in southern New Mexico.

Trapezoidal Flumes (Samani and Magallanez, 1993)

Most existing irrigation canals are trapezoidal in shape due to the high amount of water that can be conveyed through this shape and the natural shape the canals take due to erosion. As such, it becomes increasingly relevant and convenient to design a low-cost, easily installed flume that can be used to measure flow in trapezoidal canals. The flume was designed and installed similarly to how circular flumes are installed, with a vertical pipe in the middle of a channel as seen in figures 18 and 19.



Figure 18. Trapezoidal flume in southern New Mexico Irrigation canal located at GPS coordinates: 32.391389, 106.846111.



Figure 19. Close up (upstream side) of previous flume, with visible rust patterns indicating maximum water height and critical flow profile.

Inserting the coefficients from table 1 into equation 2, the equation for flow for this trapezoidal flume is:

$$Q = 0.226 * (B_c)^{2.5} * g^{0.5} * \left(\frac{H}{B_c}\right)^{1.51} \quad (7)$$

Where:

Q = discharge, ft³/s or m³/s

H = height of water, ft or m

g = gravity, ft/s² or m/s²

B_c = width of channel at critical cross section in feet or meters. Given by:

$$B_c = B + 2mH - d \quad (8)$$

Where:

B = width of the base of the channel, ft or m

m = side slope of channel, unitless (see figure 20)

H = height of water, ft or m

d = outside diameter of the vertical pipe, ft or m

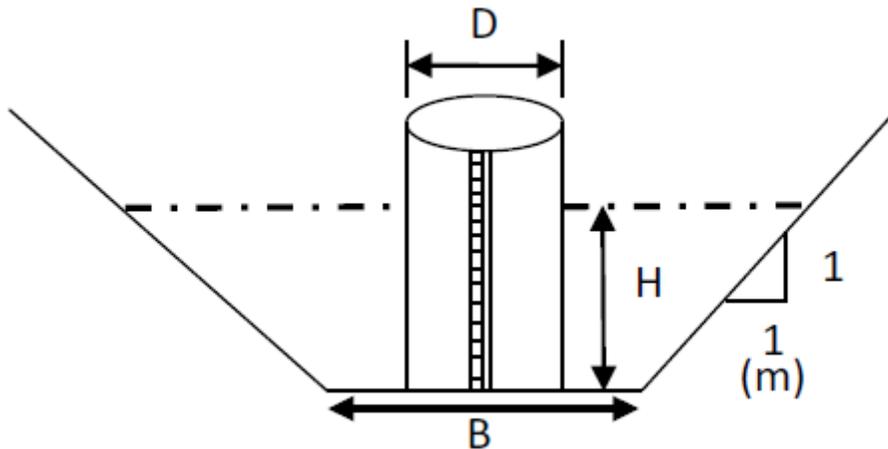


Figure 20. Cross sectional view of a trapezoidal flume with common dimensions (Badar, 2012).

The principle limiting factor when designing simple flumes is the maximum submergence ratio (H_b/H_a), which is the height of water downstream (H_b) divided by the height of the water measured at the flume gage (H_a). Laboratory experiments (Samani, 1993) found this maximum limit to be 0.80 (80%).

Laboratory experiments also shown that the ratio of the column diameter (d) to the canal bottom width (B), (d/B) should be 75% or more for critical flow to occur (figure 21).

The minimum entrance length to be equal to or greater than the maximum height of the water (entrance length $\geq H$), and the minimum exit length to be equal to or greater than one half the maximum height of the water (exit length $\geq \frac{1}{2} H$) as seen in figure 22.

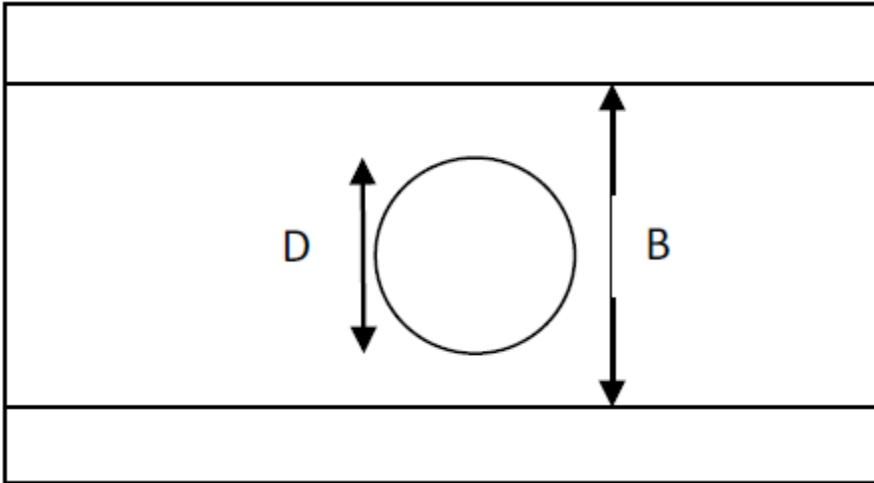


Figure 21. Plan view of a trapezoidal flume indicating D , diameter of flume and B , canal bottom width with design parameter $D/B \geq 0.75$ (Badar, 2012).

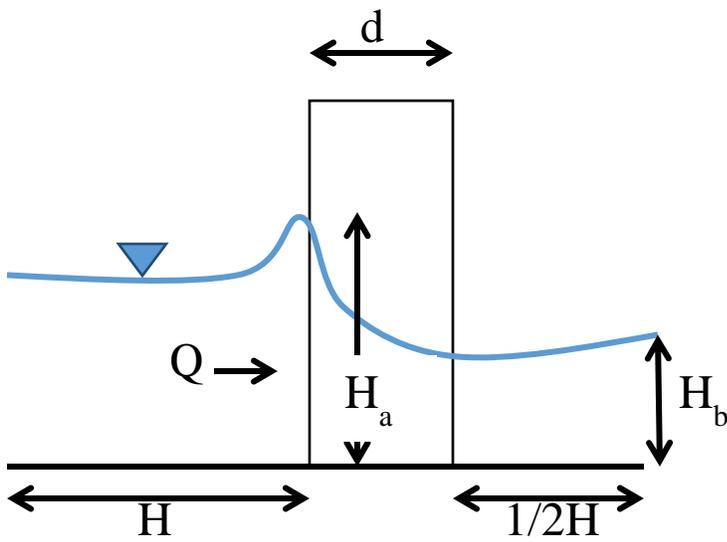


Figure 22. Diagram indicating critical design parameters, where $H_b/H_a \leq 0.8$.



Figure 23. Trapezoidal flume testing in the lab with critical flow.

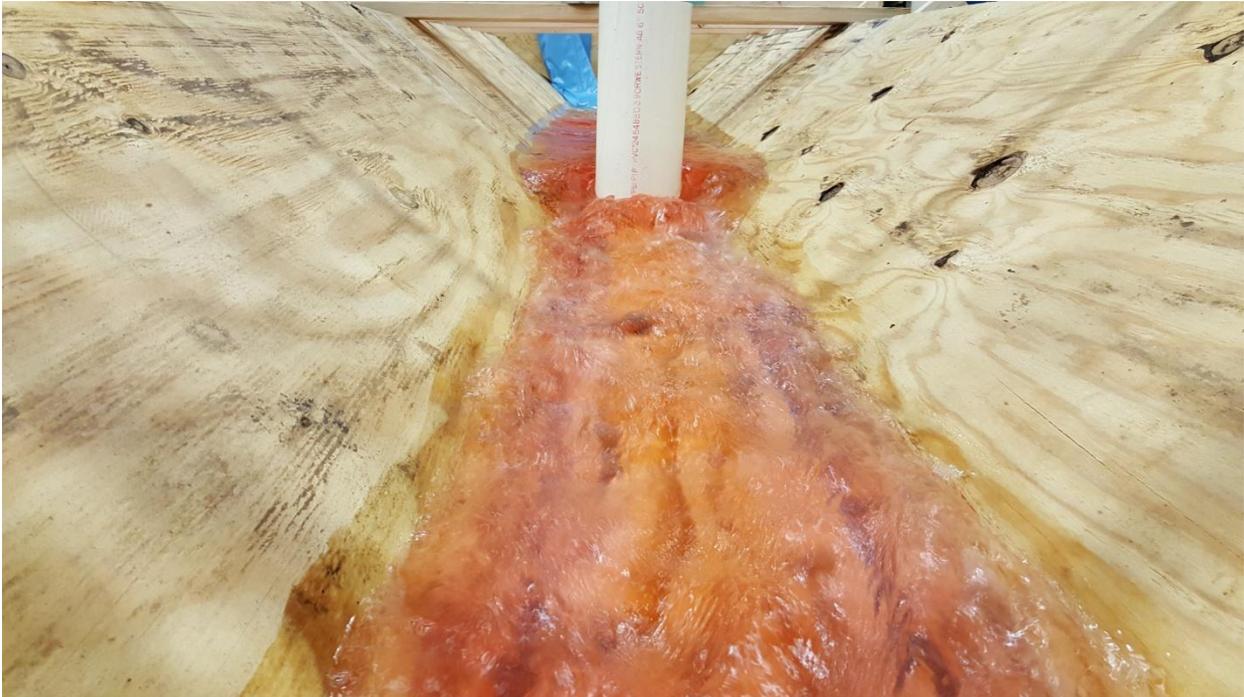


Figure 24. Trapezoidal flume as seen from downstream with both visible flow depths.

Design Example of a Trapezoidal Flume

The following is an example of how to design and calibrate a trapezoidal flume for a given channel, with known flow rate, and known normal maximum water depth. An additional solution is provided in the case that a large enough pipe is not available. In this case the base of the flume could be elevated.

Example:

Existing trapezoidal canal with base: 1.2 ft

Existing side slope: 1:1 (m:1)

Maximum flow rate: 1.0 ft³/s

Normal depth at maximum flow: 0.52 ft

We first assume a diameter of the vertical column, generally in readily available pipe sizes. We also need to meet the requirement of the column width being a minimum of 75% of the base of the channel. For this example we will assume an outside diameter of 0.9 ft.

$$B + 2*m*H - d = 1.2 \text{ ft} + (2 * 1 * H) - 0.9 \text{ ft} = 2H + 0.3 \text{ ft} \text{ (equation 8)}$$

Using equation 7:

$$1.0 \text{ ft}^3/\text{s} = 0.226 * (2H + 0.3 \text{ ft})^{2.5} * \sqrt{32.2 \text{ ft}/\text{s}^2 * \left(\frac{H}{2H + 0.3 \text{ ft}}\right)^{1.51}}$$

$$H = 0.632 \text{ ft}$$

Submergence ratio: 0.52/0.632 = 0.823, which exceeds the maximum submergence ratio of 0.8.

Therefore, we can increase the diameter of the column to d = 1.00 ft, $D - d + 2mH = 0.20 + 2H$ ft, and recalculate H.

$$H = 0.650 \text{ ft}$$

Submergence ratio: 0.52/0.650 = 0.80, which meets the submergence requirement.

The entrance length would be a minimum of 0.650 feet and the exit length would be a minimum of 0.325 feet. This flume would require a vertical pipe of outside diameter 1.0 ft or greater and would measure flows up to 1.0 cfs (448.4 gpm).

Alternate solution

Another solution would be to elevate the base of the channel slightly instead of increasing the pipe diameter from 0.9 ft to 1.0 ft.

Dividing the normal depth (0.52 ft) by the submergence limit (0.80), we obtain $0.52 \text{ ft} / 0.80 = 0.65 \text{ ft}$.

Meaning the upstream height must be at least 0.65 ft.

Using the first pipe of 0.9 ft, we obtained an upstream height of 0.632 ft.

Subtracting the upstream height (0.632 ft) from the required height (0.65 ft); $0.65 \text{ ft} - 0.632 \text{ ft} = 0.018 \text{ ft}$.

By raising the base of the channel under the flume by 0.018 feet we would be able to use the vertical pipe diameter of 0.9 ft and meet the required submergence ratio.



Figure 25. Trapezoidal flume in use in Dushanbeh, Tajikistan.

General Recommendations

- When designing a flume:
 - The length of the flume should be ≥ 1.5 times the maximum height of the flow.
 - The vertical column should be placed a minimum distance equal to the height of the water level from the entrance and $\frac{1}{2}$ the height of the water level from the exit (Samani, 2005).
- In all instances, the height of the water should be measured at the center of the upstream side of the vertical column.
- Often times, due to turbulence, the water level will be difficult to read, in such cases the water level should be taken as an average of the fluctuating height.
- A more desirable option to prevent the error caused by fluctuating water levels at the column would be to use the column as stilling well by drilling a hole in the base of the vertical column on the upstream side and measure the depth inside the. This will allow water to enter the column with little turbulence on the inside. The column must be sealed off preventing water from entering in other locations other than the most upstream side.
- Rating tables can easily be constructed once a flume is in place to prevent the need for continuous calculations.
 - For example: In a known rectangular channel of base 1.2 feet, with an installed S-M flume with half pipe diameters of 0.6 feet, equation 14 can be used to quickly create a rating table as seen in table 2.

Table 2. Rating table created for a rectangular channel with from known flume dimensions.

| Height of water (ft) | Flowrate (cfs) | Flowrate (gpm) |
|-----------------------------|-----------------------|-----------------------|
| 0.1 | 0.064 | 28.8 |
| 0.2 | 0.193 | 86.8 |
| 0.3 | 0.368 | 165.4 |
| 0.4 | 0.582 | 261.3 |
| 0.5 | 0.830 | 372.6 |
| 0.6 | 1.109 | 497.9 |
| 0.7 | 1.417 | 636.1 |
| 0.8 | 1.753 | 786.6 |
| 0.9 | 2.114 | 948.6 |
| 1.0 | 2.499 | 1121.6 |

- Data loggers equipped with pressure transducers are often used for the continuous recording of depth and calculation of instantaneous and cumulative flow.
- As seen in the design examples, flumes can be elevated or contracted when the required vertical pipe size is not available.
- Due to the short length of simple flumes, they remain more accurate and reliable than longer flumes when placed on a declining slope (Ontkean, 2015). However, flumes should always be installed on level terrain to provide accurate flow measurements.
- Maximum normal depth can be determined by looking at the high water mark in a channel or by using Manning's equation (Manning, 1981).

Chapter 2: Traditional Flow Measurement Devices

This Chapter discusses various traditional flow measurement devices including flumes, turnout valves, and weirs. The type of structure used to measure flow is often determined by the hydraulic conditions and the project objectives, with each type of structure having its benefits and limitations.

Circular Gate (Turnout) Flow Measurement

Irrigation systems often have circular gates installed to help control and divert flow. As many of Armco gates are already installed, the feasibility of using these gates as flow measuring devices was investigated (Cadena and Magallanez, 2005). The gates investigated in this report are Armco brand gates and this study is only relevant for them. It was found that flow could indeed be measured using a modified orifice flow equation given by:

$$Q = C_D(y, D)yD\sqrt{2gH} \quad (9)$$

Where:

Q = discharge, ft^3/s or m^3/s

y = vertical displacement of the gate (opening), ft or m

H = headloss through the opening, ft or m

g = acceleration of gravity, ft/s^2 or m/s^2

D = diameter of the gate, ft or m

$C_D(y, D)$ = a function of diameter and gate opening given by:

$$C_D(y, D) = b + m\frac{y}{D} \quad (10)$$

Where b and m are constants calculated by the following formulas:

Imperial

$$b = \frac{0.0859}{D^2} + 0.839$$

Metric

$$b = \frac{0.00798}{D^2} + 0.839 \quad (11)$$

And

$$m = \frac{-0.5994}{D} + \frac{1.013}{\sqrt{D}} - 0.7116 \quad m = \frac{-0.1827}{D} + \frac{0.5593}{\sqrt{D}} - 0.7116 \quad (12)$$

Where D is the diameter (feet or meters) of the gate in all cases.

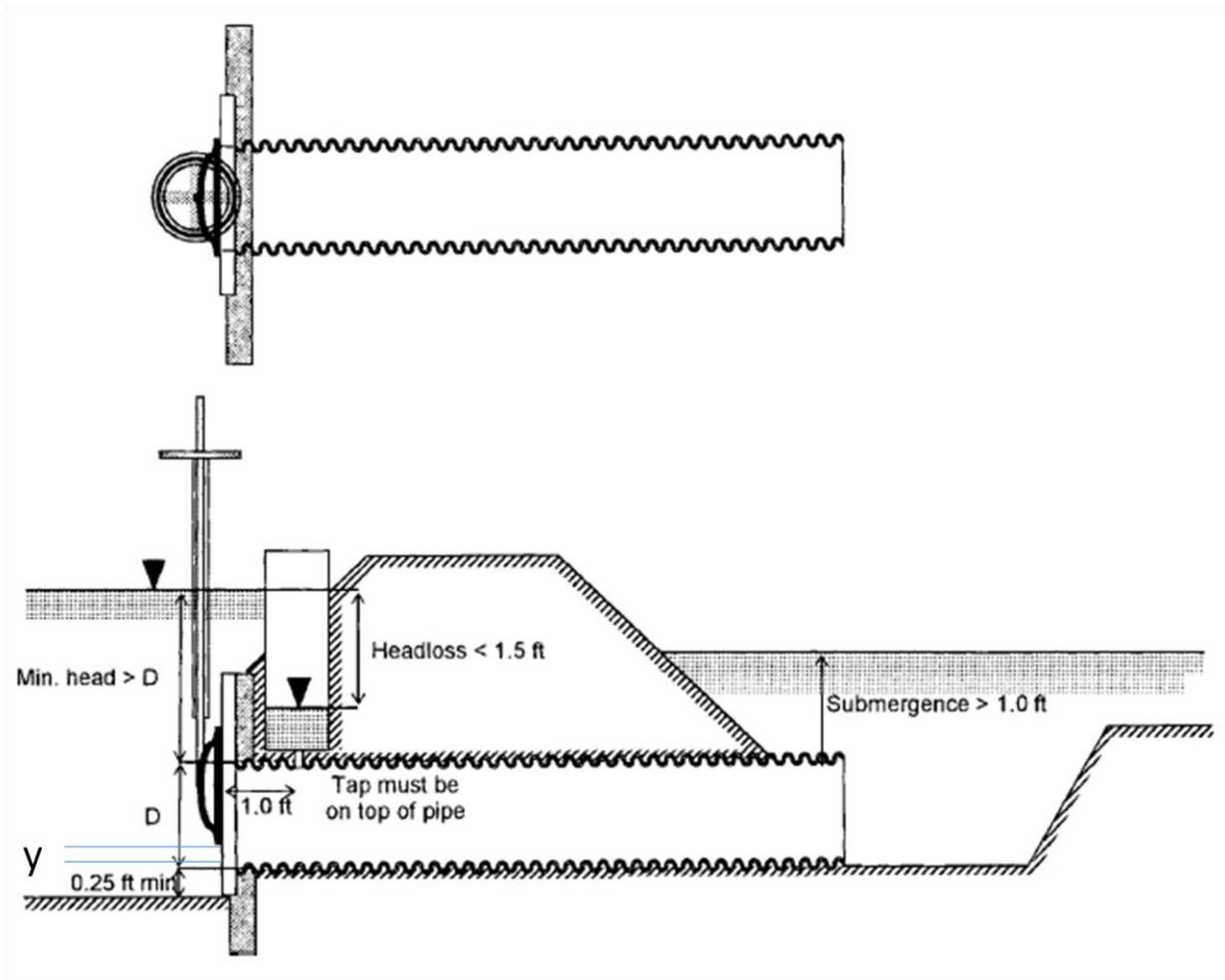


Figure 26. Example of an Armco circular gate turnout (Cadena, 2005).

As seen in figure 26 the head loss can be measured in a stilling well installed one foot beyond the opening of the gate. The diameter of the gate would remain constant, allowing the discharge through the gate to be measured by knowing how much of the gate was opened (y), and measuring the height of water in the stilling well.

Example Calculation of Flow through an Armco Circular Gate

The following is an example of how to calculate flow through an existing Armco circular gate with given diameter (D), headloss (H), and opening (y).

Example:

$$D = 2 \text{ feet}$$

$$y = 0.5 \text{ feet}$$

$$H = 1 \text{ foot}$$

Using equations 11 and 12 for imperial units we find that $b = 0.8605$ and $m = -0.2950$.

Substituting b and m into equation 10 yields: $C_d = 0.7867$.

Substituting C_d into equation 9 yields: 6.313 cfs.

Therefore, a circular gate of 2 foot diameter opened half a foot with a headloss of 1 foot has 6.313 cfs of discharge passing through it.

Traditional Flumes

Traditional flumes are excellent devices for monitoring the flow rate in open channels. They are constructed of metal, concrete, wood, or fiberglass and can measure water over a wide variety of flow ranges. Larger flumes are constructed on site, while smaller flumes can be prefabricated and installed later on site.

Flumes require relatively little head loss when compared to weirs, are relatively insensitive to approach velocity, and do not acquire as much sediment build up as found in weirs. Flumes must be leveled and the flow entering the flume cannot contain waves or surges in order to provide accurate flow measurements.

The construction of traditional flumes is a relatively expensive endeavor as considerable care must be taken when forming them to the correct shape and dimensions including raising or lowering the channel base. Professional installation is usually required to ensure that the converging section, throat width, and diverging section are the correct size and dimensions. While flumes can operate under submerged conditions, two measurements of water height are

required for accurate flow measurements under submerged conditions. Additionally, while approach velocity is incorporated in the calibration of the flumes, traditional flumes are designed to function parallel to the flow and will result in inaccurate measurement if located at right angles to flowing streams, such as turnouts.

Parshall Flumes

The Parshall flume is the oldest and most widely used flume, named after the engineer who originally designed it, Robert Parshall (Parshall, 1926). Critical flow in Parshall flumes is achieved by both contracting the flow and lowering the base of the channel, as seen in figure 27.

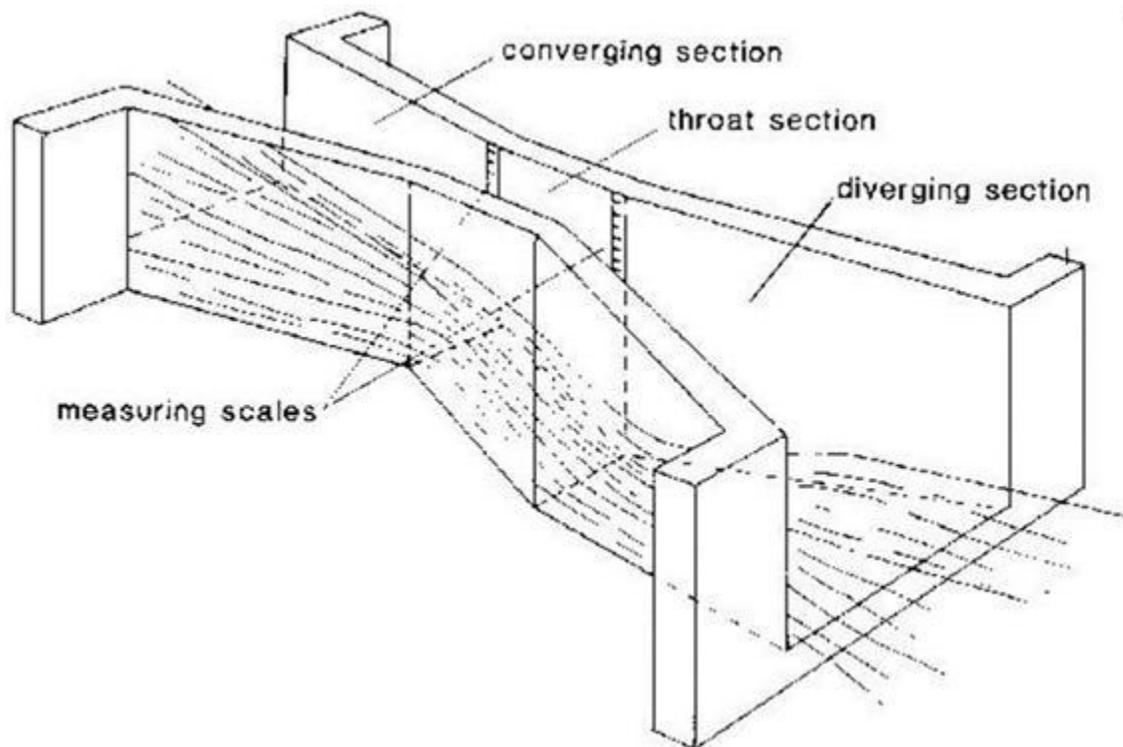


Figure 27. Parshall flume with converging, throat, and diverging sections.

Flume sizes are listed according to the throat width of the flume and range from 1 inch (2.54 cm) for discharges of 0.01 cubic feet per second (0.3 liters per second) up to 50 feet wide (15 m) for discharges as large as 3,000 cubic feet per second ($86 \text{ m}^3/\text{s}$). Parshall flumes must be constructed according to the dimensions outlined in Parshall flume tables (USBR, 1985) using one of the pre-

set sizes. The typical dimensions for a Parshall flume are shown in figure 28. Parshall flumes can operate in both unsubmerged (free-flow) and submerged conditions. However, additional measurements (upstream and downstream depth) are needed. In addition the calibration coefficients need to be recalculated when operating in submerged conditions.

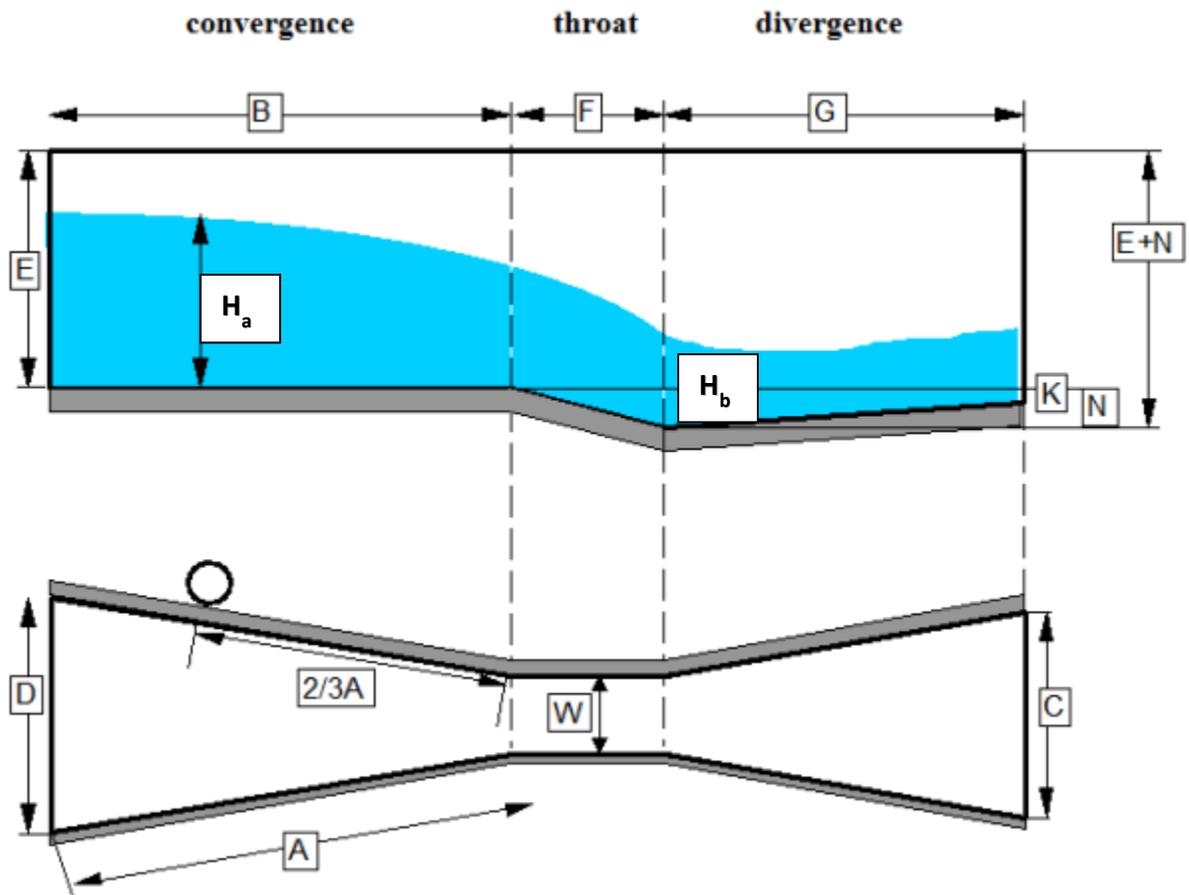


Figure 28. Plan and profile views of a Parshall flume.

The free-flow equation for discharge through smaller Parshall flumes (from 1 inch to 8 feet) is given by:

$$Q = C * H_a^n \quad (13)$$

Where:

Q = flowrate, cfs

H_a = head, ft

n = constant dependent on throat width (table 3)

C = constant dependent on throat width (table 3)

Flumes with a throat width of 8 feet or more have their discharge calculated by:

$$Q = (3.6875 * b + 2.5) * H_a^{1.6} \quad (14)$$

Where:

Q = flowrate, cfs

H_a = head, ft

b = throat width, ft

The degree of submergence is calculated by the ratio of the height of the water upstream of the throat to that of the height of the water downstream of the throat (H_a/H_b). Parshall flumes have different submergence ratios depending on the size of the flume as seen in table 3. If submergence is less than or equal to the values given on the table, the discharge is considered free-flow and can be calculated through direct application of these formulas. If the submergence is greater than the limit for specific throat widths, further calculations are required to determine the actual discharge. Guidelines and submergence curves for calculating flow can be found in The Water Measurement Manual (USBR, 1984).

Table 3. Submergence Limits for smaller sized Parshall flumes along with n and C values.

| Throat Width | Submergence Limit (H_b/H_a) | n | C |
|--------------|---------------------------------|------|-------|
| 1" | 0.50 | 1.55 | 0.388 |
| 2" | 0.50 | 1.55 | 0.676 |
| 3" | 0.50 | 1.55 | 0.992 |
| 6" | 0.60 | 1.60 | 2.06 |
| 9" | 0.60 | 1.53 | 3.07 |
| 1' | 0.70 | 1.52 | 4.00 |
| 1.5' | 0.70 | 1.54 | 6.00 |
| 2' | 0.70 | 1.55 | 8.00 |
| 3' | 0.70 | 1.56 | 12.00 |
| 4' | 0.70 | 1.57 | 16.00 |
| 5' | 0.70 | 1.58 | 20.00 |
| 6' | 0.70 | 1.59 | 24.00 |
| 7' | 0.70 | 1.60 | 28.00 |
| 8' | 0.70 | 1.60 | 32.00 |

Cutthroat Flumes

The cutthroat flume is a modified version of the Parshall flume and was first developed in 1972 by Skogerboe (Skogerboe, 1972), and it looked to improve upon the Parshall flume by eliminating the need to lower the bed of the channel. While still costly due to the amount of material needed and craftsmanship involved, cutthroat flumes are less costly and easier to install than Parshall flumes. The name cutthroat is derived from the lack of a throat section in the flume, consisting only of a converging and diverging section. Like the Parshall flume, the cutthroat flume can operate with much less headloss than weirs.

Cutthroat flumes utilize the existing channel bed and constrict the sides of the channel to create critical flow, allowing for the measurement of discharge. All cutthroat flumes converge at a ratio of three to one, have no throat length, and then diverge at a ratio of six to one. All other dimensions are based off of these values and the width of the channel as seen in figure 29.

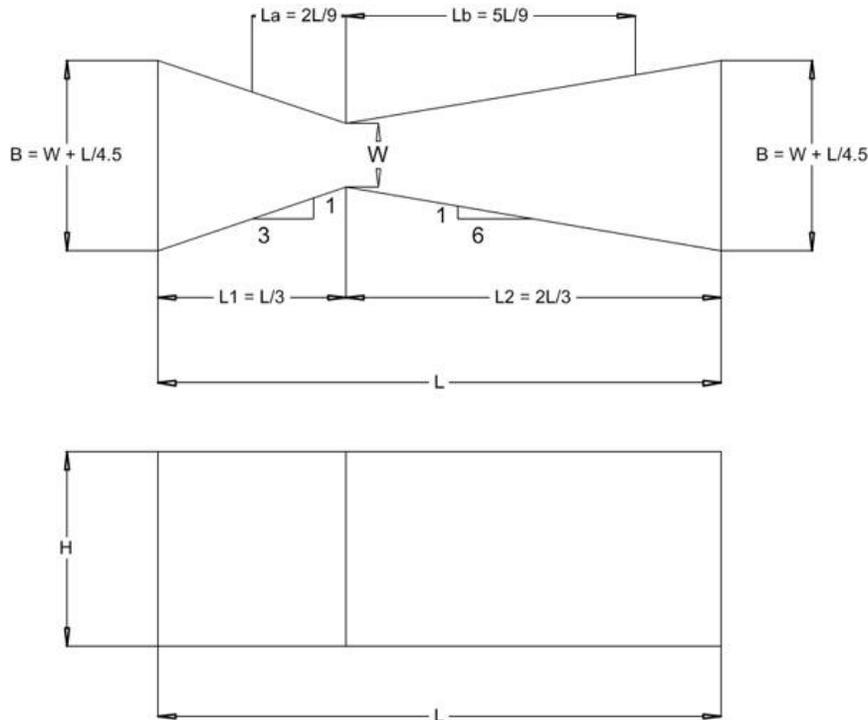


Figure 29. Plan and profile view of a cutthroat flume.

These flumes are easily constructed in rectangular channels, however the difficulty of on-site construction increases with trapezoidal channels when creating the proper contraction and divergence ratios. The governing equation for flow through a cutthroat flume for free flow condition (maximum submergence of 84%) is:

$$Q = C * H_a^{1.56} \quad (15)$$

Where:

Q = flowrate, cfs

H_a = upstream depth of water, ft

C = constant for each size flume using the equation:

$$C = 3.50 * W^{1.025} \quad (16)$$

Where W is the width at the most narrow section of the flume in feet.



Figure 30. Installed cutthroat flume.

Like the Parshall flume, the cutthroat flume can operate under submerged conditions, reaching submergence limits up to 84 percent (downstream head divided by upstream head). As the submergence ratio passes this value, accurate discharge values can still be calculated by measuring downstream depth and referencing submerged flow calibration curves found in *Design and Calibration of Submerged Open Channel Flow Measurement Structures: Part 3 – Cutthroat Flumes* (Skogerboe, 1967).

RBC Flumes

Replogle, Boss, Clemmens (RBC) flumes are a more recently implemented flume that utilizes a trapezoidal cross section instead of the rectangular cross section needed for Parshall flumes helping to reduce the cost of installation. Flow is contracted and forced into critical conditions by raising the elevation of the base of the channel allowing the discharge to be measured. An advantage of the RBC flume is that the flat floor used in RBC flumes allows it to be more easily retrofitted into existing channels. RBC flumes are calibrated by computer analysis (through the use of the free *WinFlume* computer program). Allowing for custom flume designs and rating tables to be easily created for non-standard dimensions.

One of the disadvantages the RBC flume has over the Parshall flume is that the base of the channel needs to be elevated which can allow sediment and debris to accumulate in low gradient conditions affecting the accuracy of discharge measurements.

The RBC flume is essentially a small broad-crested weir (Sturm, 2012), similar to previously mentioned weirs but with more flow-surface contact and discharge can then be calculated accordingly. The equation for the discharge of a rectangular broad crested weir when water passes through critical flow is:

$$Q = 1.6 * L * H^{2/3} \quad (17)$$

Where:

Q = Flowrate, cfs

L = Weir length (channel width), ft

H = Height of upstream water above weir, ft

As shown in the diagram below.

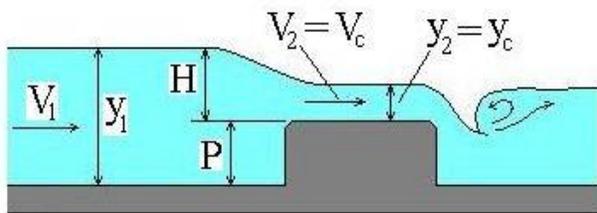


Figure 31. Profile view of a basic RBC flume or broad crested weir, critical flow is created by raising the bottom of the channel.

Generally, these flumes will have a ramp leading up to the throat section as shown in figure 32 to allow for an easier transition of water over the throat section.



Figure 32. An RBC flume ready to be installed.

These flumes are also often crafted on site by pouring concrete in an existing lined channel and forming it to the desired specifications as shown in figure 33.



Figure 33. Casting an RBC flume in an existing canal.

It is recommended when constructing or using RBC flumes to use the program WinFlume (http://www.usbr.gov/pmts/hydraulics_lab/winflume/) which creates rating tables and allows discharge to be calculated directly (Wahl, 2012).

Weirs

Weirs are one of the oldest, simplest, and most reliable structures that can be used to measure the flow of water in canals and ditches. Defined as a low dam built across a river or channel over which water can flow, weirs regulate the flow of water downstream, thus allowing it to be measured when properly constructed, installed, and maintained. Due to the simplicity of weirs, the most critical elements can easily be inspected allowing improper installations to be easily identified and quickly corrected. Weirs are accurate measuring devices once properly constructed and installed, as only one depth of water can exist in the upstream pool for a given discharge. Flowrates are determined by measuring the vertical distance from the crest of the weir to the upstream height of water at a distance upstream of the weir. For this height to properly determine the flow of water in a canal, the weir must have a regular shape, definite dimensions, and have a pool of adequate size allowing the system to perform in a standard manner.

Weirs require at least a 0.5 foot drop between the upstream and downstream water surfaces, a loss in head often not available in ditches with flat grades. Water must also approach the weir slowly, achieved by backing the water up in a weir pond created from the installation of the weir itself. Due to this reduction in water velocity, if the water is carrying sediment, it will settle out and fill the weir pond. As the pond fills, the velocity of the approaching water would increase, resulting in inaccurate flow measurement at the weir. Grass and weeds tend to thrive in slow water, leading to required maintenance of the weir pond to keep it free of sediment and weeds.

Weirs are generally divided into separate categories depending on the shape of the opening through which the water passes. These weir classifications are: rectangular, Cipolletti, and v-notch as shown in figures 36, 39, and 41 respectively. Rectangular weirs can be further divided into two classes. Weirs placed in a rectangular channel where the side walls act as the ends of the weir crest and do not contract are said to be suppressed rectangular weirs (figure 37), while weirs that do not have a crest that extends all the way to the sidewall are said to be contracted rectangular weirs (figure 34).

Contracted Rectangular Weirs

Contracted rectangular weirs is the more common type of rectangular weir and has the end of its crest and sidewalls so far removed so as to allow for full contraction of flow to develop. This contraction of flow is approximately the maximum contraction the flow would experience if there were no sidewalls at all. The flow through a contracted rectangular weir is given by:

$$Q = 3.33 * (L - 0.2H) * H^{3/2} \quad (18)$$

Where:

Q = flowrate, ft^3/s

L = crest length, ft

H = head, ft

As shown in figures 34 and 35.

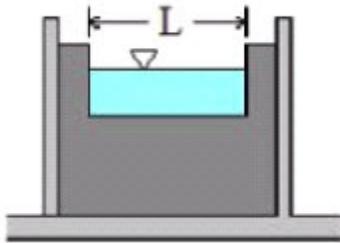


Figure 34. Cross section of contracted rectangular weir

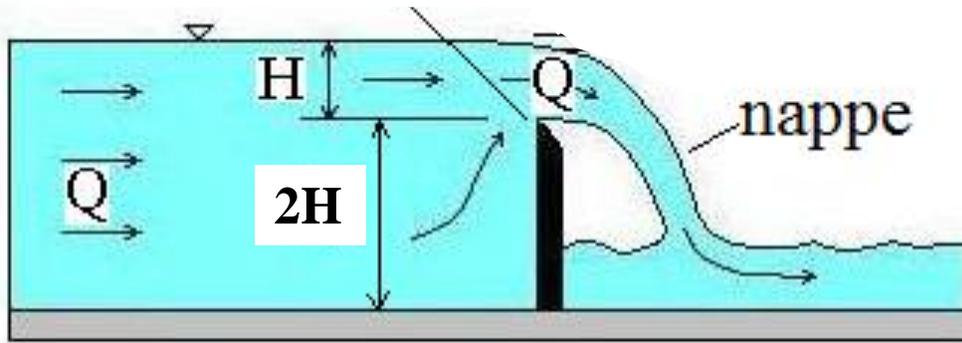


Figure 35. Profile view of a sharp crested weir.

The head of water is the height of water above the crest of the weir which can be measured with a ruler and the length of the weir would be a constant dimension making flowrate relatively easy to determine with one measurement. To be effective in measuring the flow of water, rectangular contracted weirs should be installed according to the following guidelines set forth by the United States Bureau of Reclamation (USBR). These guidelines are as follows:

1. The upstream face of the bulkhead should be smooth and in a vertical plane perpendicular to the axis of the channel.
2. The upstream face of the weir plate should be smooth, straight, and flush with the upstream face of the bulkhead.
3. The entire crest should be a level, plane surface which forms a sharp, right-angled edge where it intersects the upstream face. The thickness of the crest, measured in the direction of flow, should be between 0.03 and 0.08 inch (about 1 to 2 mm). Both side edges of rectangular weirs should be truly vertical and of the same thickness as the crest.
4. The upstream corners of the notch must be sharp. They should be machined or filed perpendicular to the upstream face, free of burrs or scratches, and not smoothed off with abrasive cloth or paper. Knife edges should be avoided because they are difficult to maintain.

5. The downstream edges of the notch should be relieved by chamfering if the plate is thicker than the prescribed crest width. This chamfer should be at an angle of 45° or more to the surface of the crest
6. The distance of the crest from the bottom of the approach channel (weir pool) should preferably be not less than twice the depth of water above the crest and in no case less than 1 foot.
7. The distance from the sides of the weir to the sides of the approach channel should preferably be no less than twice the depth of water above the crest and never less than 1 foot.
8. The overflow sheet (nappe) should touch only the upstream edges of the crest and sides.
9. Maximum downstream pool level should be 0.2 foot (6 cm) below the crest elevation.
10. The measurement of head on the weir should be taken as the difference in elevation between the crest and the water surface at a point upstream from the weir a distance four times the maximum head on the crest.
11. The cross-sectional area of the approach channel should be at least 8 times that of the overflow sheet at the crest for a distance upstream from 15 to 20 times the depth of the sheet.
12. If the weir pool is smaller than defined by the above criteria, the velocity of approach may be too high and the staff gage reading too low.

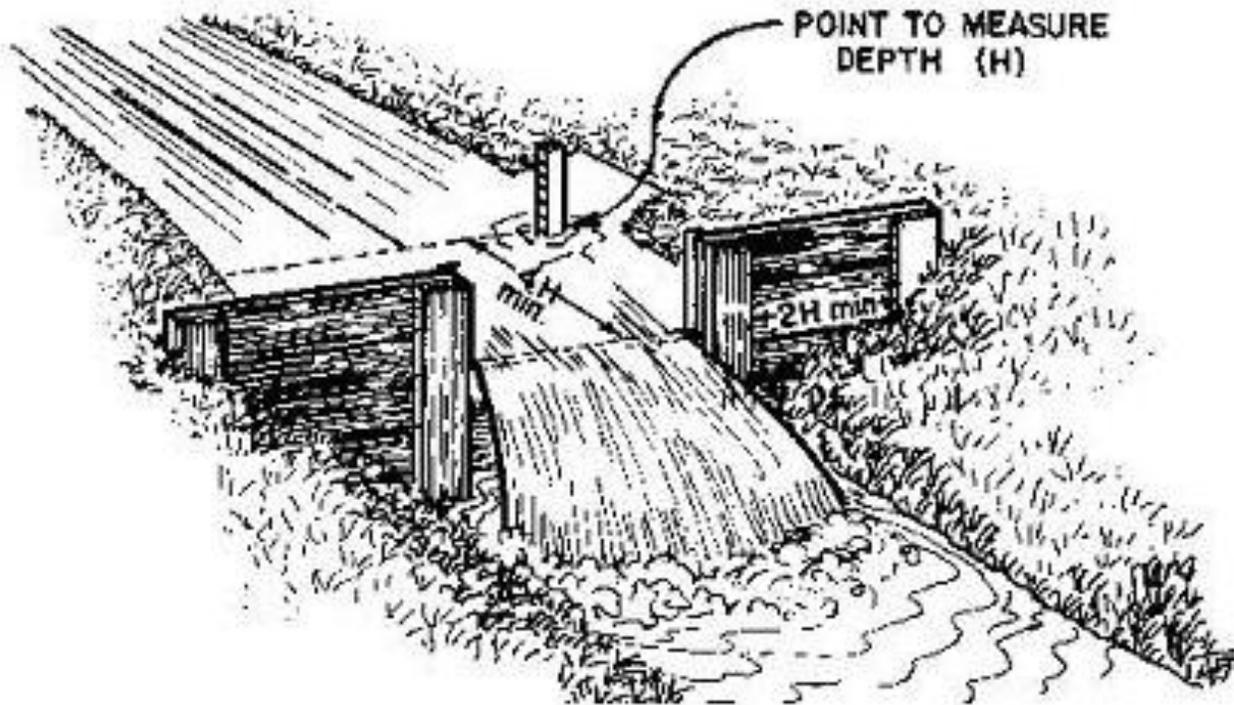


Figure 36. Typical rectangular weir.

Suppressed Rectangular Weirs

Suppressed rectangular weirs have a crest across the entire channel from sidewall to sidewall.

The flow through a suppressed rectangular weir is given by:

$$Q = 3.33 * L * H^{3/2} \quad (19)$$

Where the units are the same as those indicated above. The length of a suppressed rectangular weir would extend across the entire width of the channel as show in figure 37.

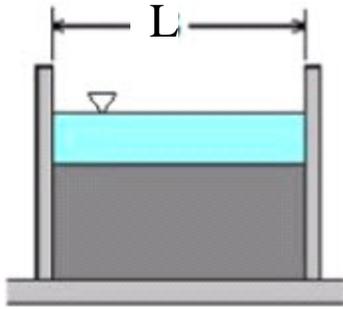


Figure 37. Cross sectional view of a suppressed rectangular weir.

Conditions for accuracy of measurement for this type of weir are exactly the same as those listed above for contracted weirs with the exception that the sidewalls should coincide with the edge of the crest and should extend beyond the crest to prevent lateral expansion of the nappe (water flowing over the weir).

Cipolletti Weirs

Trapezoidal weirs are often called Cipolletti weirs after the engineer who developed them as a way of eliminating the correction of the crest length needed for contracted rectangular weirs. They have sloping sides of 1 horizontal to 4 vertical. The flow over a Cipolletti weir is given by:

$$Q = 3.367 * L * H^{3/2} \quad (20)$$

Where the units are the same as those indicated above and as shown in figure 38.

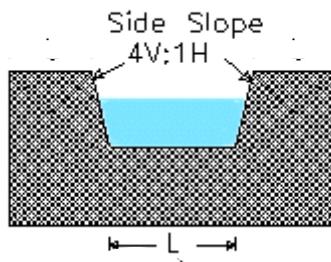


Figure 38. Cross section of Cipolletti Weir

Conditions for accuracy of measurement for this type of weir are the same as those for a contracted rectangular weir with the following additions. The weir should not be used for head less than about 0.2 foot, nor for heads greater than one-third the crest length.

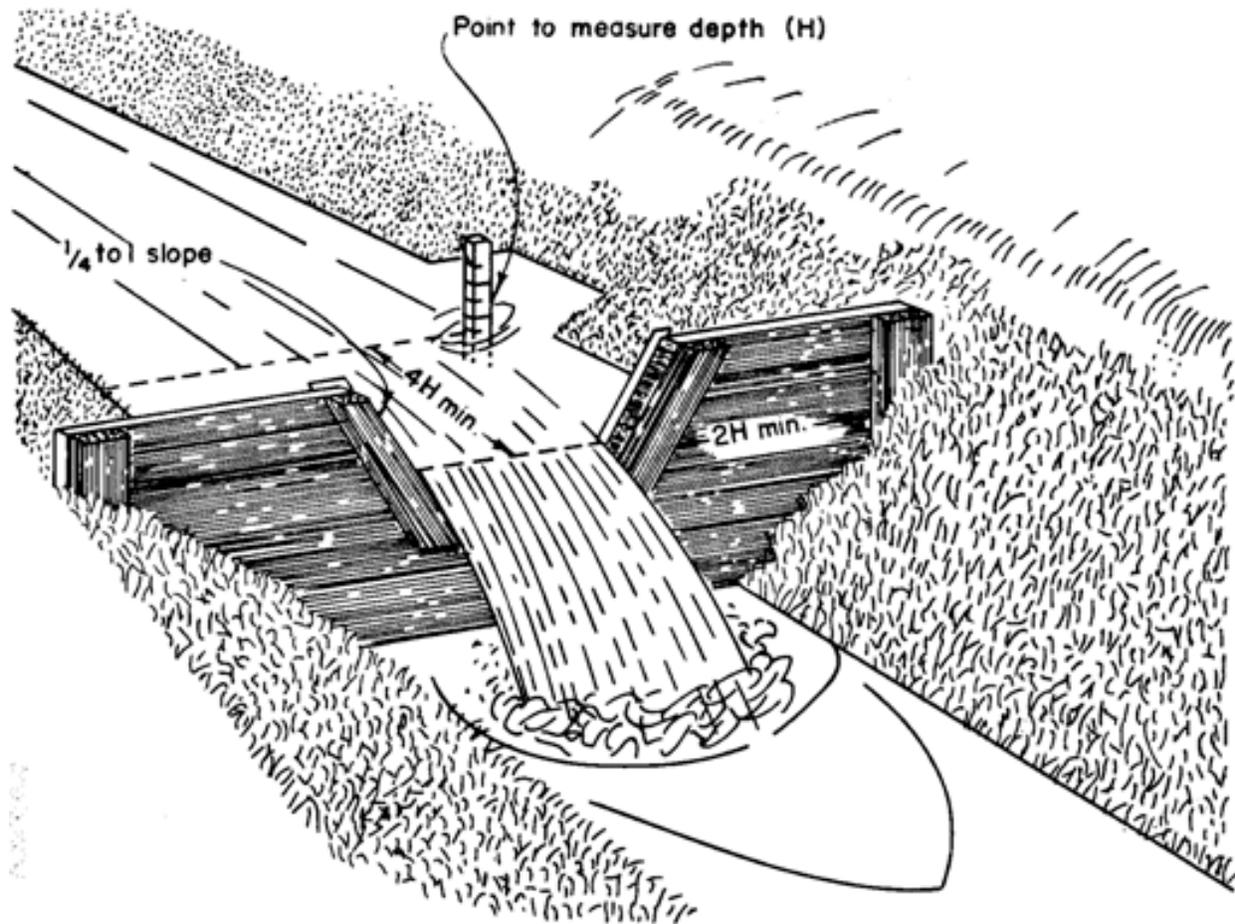


Figure 39. Typical Cipolletti weir.

V-notch Weirs

V-notch weirs are triangular weirs with the generally accepted standard being the 90° notch and is particularly adept at measuring small flows and can be used for flows which vary greatly. The flow over a v-notch weir is given by:

$$Q = 2.49 * H^{2.48} \quad (21)$$

Where the units are the same as those indicated above.

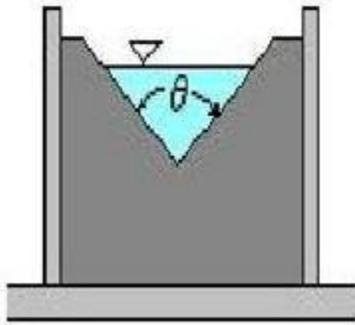


Figure 40. Cross sectional view of v-notch weir.

As seen in figure 40, the angle can be any that one chooses, however this angle is typically set at 90°. V-notch weirs are contracted weirs and can be built using the same guidelines listed for rectangular contracted weirs.

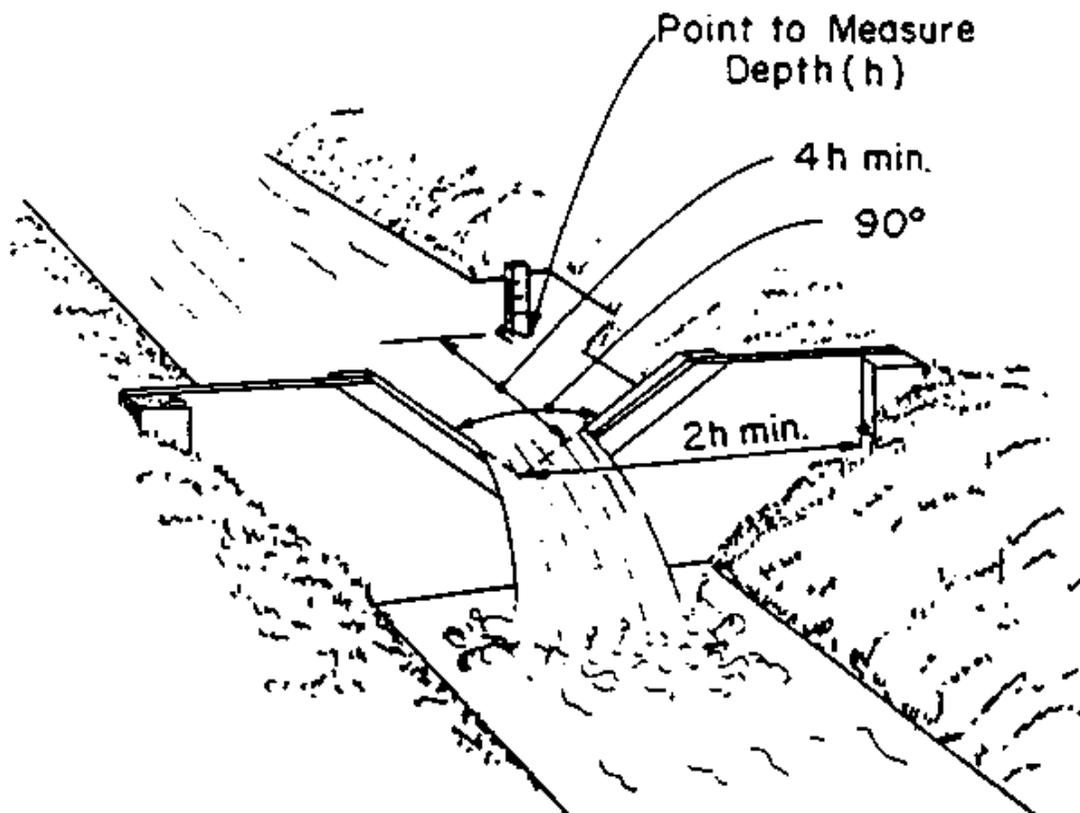


Figure 41. Typical v-notch weir.



Figure 42. V-notch weir.

The v-notch and rectangular weir can also be combined to provide an accurate flow measurement for both small and large flumes as demonstrated in figure 42. Once a certain discharge is obtained, water will flow over the top of the flat crest as well as through the v-notch.

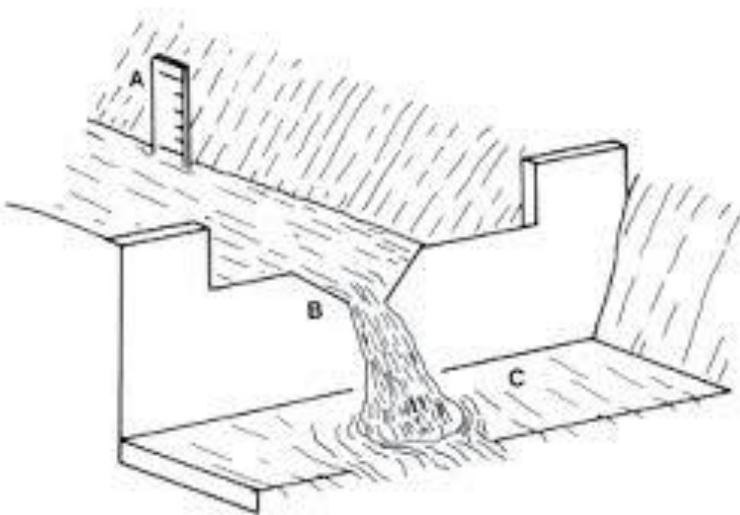


Figure 43. Combination V-notch and contracted rectangular weir.

References

- Badar A.M., Ghare A. D. 2012. Development of Discharge Prediction Model for Trapezoidal Canals using Simple Portable Flume. *International Journal of Hydraulic Engineering*, 1(5):37-42.
- Cadena, F., Magallanez, H. 2005. Analytical Solution for Circular Gates as Flow Metering Structures. *J. Irrig. Drain. Engr. ASCE*, 131(5), 451-456.
- Hagar, W. H. 1988. Mobile Flume for Circular Channel. *J. Irrig. Drain. Div. ASCE*, 114(3), 520-534.
- Manning, R. 1891. On the flow of water in open channels and pipes. *Transactions of the Institution of Civil Engineers of Ireland* 20: 161–20
- Ontkian, G. R., Healy, L. H. 2015. Impact of non-level operation of a circular flume on discharge measurements. *The Canadian Society for Bioengineering*. Paper No. CSBE15-120.
- Parshall, R. L. 1926 The Improved Venturi Flume. *Trans., ASCE*, 89, 841-880.
- Samani, Z., Magallanez, H., Skaggs, R. 2005. A Simple Flow Measuring Device for Farms. *Water Task Force. Report 3*.
- Samani, Z., Magallanez, H. 1992. Hydraulic Characteristics of a Circular Flume. *J. Irrig. Drain. Engr. ASCE*, 117(4), 559-567.
- Samani, Z., Magallanez H. 1993. Measuring Water in Trapezoidal Canals. *J. Irrig. Drain. Engr. ASCE*, 119(4), 181-186.
- Samani, Z., Magallanez H. 2000. Simple Flume for Flow Measurement in Open Channel. *J. Irrig. Drain. Engr. ASCE*, 126(2), 127-129.
- Samani, Z., 2016. Three Simple Flumes for Open Channel. Paper in progress.
- Stefano D. S., Piazza G. V. D., and Ferro, V. 2008. Field Testing of a Simple Flume (SMBF) for Flow Measurement in Open Channels. *J. Irrig. Drain. Engr.* 134(2), 235-240.
- Replogle, J.A. 1975. Critical Flow Flumes with Complex Cross Section. *Proc. ASCE Irrig. Drain. Div. Spec. Conf., ASCE*, Aug. 13-15, 336-338.
- Skogerboe, G.V., Bennet, R. S., and Walker, W. R. 1972. Generalized Discharge Relations for Cutthroat Flumes. *J. Irrig. Drain. Div., ASCE*, 98(4), 569-583.
- Skogerboe, G. V., Hyatt, M. L., Anderson, R. K., and Eggleston, K. O. 1967. Design and Calibration of Submerged Open Channel Flow Measurement Structures: Part 3 – Cutthroat Flumes. Report WG31-4. Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, UT.

Sturm, T. W., 2010. Open Channel Hydraulics, Second Edition. New York, NY.

United States Bureau of Reclamation (USBR). 1984. Water Measurement Manual. U.S. Dept. of Interior, Denver, CO.

Wahl, L. T., A. J. Clemmes, M. G. Bos, J. A. Replogle. 2012. The WinFlume Home Page, US Department of the Interior, USBR. http://www.usbr.gov/pmts/hydraulics_lab/winflume/