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REVIEW OF HYDRAULIC PERFORMANCE OF OPEN-CHANNEL FLOW-MEASURING FLUMES

PREGLED HIDRAVLIČNIH RAZMER PRI KORITIH ZA MERJENJE PRETOKA V VODOTOKIH

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Abstract

The review explored various flumes used for open channel flow measurement and provided insight into operational concepts, discharge measurement, range of flow, head loss requirements, degree of accuracy and submergence, advantages, and limitations for use. The reviewed flumes included; Parshall flumes, Montana flumes, Cutthroat flumes, H-flumes, Trapezoidal flumes, Replogle-Bos-Clemmens (RBC) flumes, Palmer-Bowlus flumes and Central Baffle flumes (CBF). Based on the stage and discharge relationship, the reviewed flumes have a reasonable accuracy of ± 10 % over a wide range of flows. RBC flumes are the most accurate flumes (± 2 %). For flows that deal with a lot of sediments, most flumes have self-cleaning capability except for Palmer-Bowlus flumes and Central Baffle flumes. H-flumes have low resistance to submergence. The submergence transition for H-flumes is only 25-30 %. RBC flumes and Palmer-Bowlus flumes have the highest submergence (90 %). CBF and Palmer-Bowlus flumes need to be improved in order to have self-cleaning capability. Submerged flow corrections need to be developed and published for Palmer-Bowlus flumes and RBC flumes. The reviewed flumes effectively operate with a minimal head loss. The review has provided an insight on selection of an appropriate type of flume for flow measurement in open channels.

Keywords: accuracy, discharge, flumes, open channel, self-cleaning, submergence.

Izvleček

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Članek obravnava različna korita, ki se uporabljajo za merjenje pretoka pri toku s prosto gladino, podaja vpogled v zasnovo meritev in izračuna pretoka, obravnava natančnost in dopustno stopnjo potopljenosti, ter prednosti in omejitve pri uporabi posameznih korit. Obravnavana so Parshallova korita, korita Montana, korita Cutthroat, H-korita, trapezna korita, Replogle-Bos-Clemmensova (RBC) korita, Palmer-Bowlusova korita in korita s sredinsko oviro (CBF). Če delujejo korita v ustreznih pogojih, lahko merijo pretok z natančnostjo do ±10 %. Korita RBC so najbolj natančna (±2 %). Večina korit ima sposobnost samočiščenja pri tokovih z veliko sedimenti, razen Palmer-Bowlusovih korit in korit CBF. Najmanjšo dovoljeno potopljenost imajo H-korita (25 do 30 %), največjo dovoljeno potopljenost (do 90 %) pa korita RBC in Palmer-Bowlusova korita. Ugotovljeno je, da je treba korita CBF in Palmer-Bowlusova korita spremeniti, če naj bi ta imela samočistilno sposobnost. Za Palmer-Bowlusova korita in korita RBC pa je treba raziskati in objaviti način določanja pretoka v pogojih potopljenosti. Pregledana korita so učinkovita z minimalno izgubo energije. Prikazan je tudi pregled zahtev za pravilno izbiro korita glede na terenske razmere in posebne zahteve ob vgradnji korit.

Ključne besede: natančnost, pretok, merilna korita, tok s prosto gladino, samočiščenje, potopljenost.

1. Introduction

Globally, millions of people are hugely affected by water scarcity and approximately 1.2 billion people live in areas where water scarcity has severely affected agricultural production (FAO, 2020). Climate change continues to cause adverse and irreversible losses in the ecosystem. The largest impacts have been recognized in Africa, Asia, Central and South America where there is acute reduced water security (IPCC, 2022). With increasing water demands from various users such as agriculture, municipal needs, industry, and recreational use, there is a need for water users to efficiently use the vital natural resource. One of the best approaches is to promote effective flow measurement in open channel systems. Flow measurement is one of the basic elements of water management since it facilitates effective and equitable distribution of water among water users (Samani, 2017).

In open channels, the use of hydraulic structures for flow measurement is the common approach. Flumes are the best examples of static flow-measuring hydraulic structures (Aali and Vatankhah, 2023). They are critical flow-measuring devices that are accurate and economically reasonable for use in open channels (Dabrowski and Polak, 2012). Flow-measuring flumes are developed to produce a critical depth in the throat section and thereby creating a direct relationship between upstream water depth and flow rate in an open channel. An illustration on development of critical depth in the throat section of the flume is shown in Figure 1.

On Figure 1, H is the upstream measured depth (m), P is the crump height (m), h_L is the head loss(m), v_1 is the flow velocity before the hydraulic jump, v_2 is the flow velocity after the hydraulic jump, g is the acceleration due to gravity ($m.s^{-2}$), y_1 is the depth of flow before the hydraulic jump (m), and y_2 is the depth of flow after the hydraulic jump (m).

For submerged flow, it is necessary to measure the downstream head (Gill and Niblack, 2009; Shaw et al., 2011; Basu, 2019; Adeogun and Mohammed, 2020)

There are numerous types of flumes and each type of flume has its own distinct characteristics and suitability to a given field condition. This implies that not all flow-measuring flumes are suitable for all conditions, there are a number of factors that are considered when selecting a specific flume, such factors include: adaptability to field conditions, flow characteristics, economy, simplicity in construction, installation and maintenance. The review process involved eight flumes, namely: Parshall flumes, Montana flumes, Cutthroat flumes, H-flumes, Trapezoidal flumes, Replogle-Bos-Clemmens (RBC) flumes, Palmer-Bowlus flumes and Central Baffle flumes (CBF). The purpose of the review was to explore various flumes used for measuring flow rate in open channels and provide insight into operational concepts, discharge measurement, range of flow, head loss requirements, degree of accuracy, degree of submergence, advantages and limitations for use.

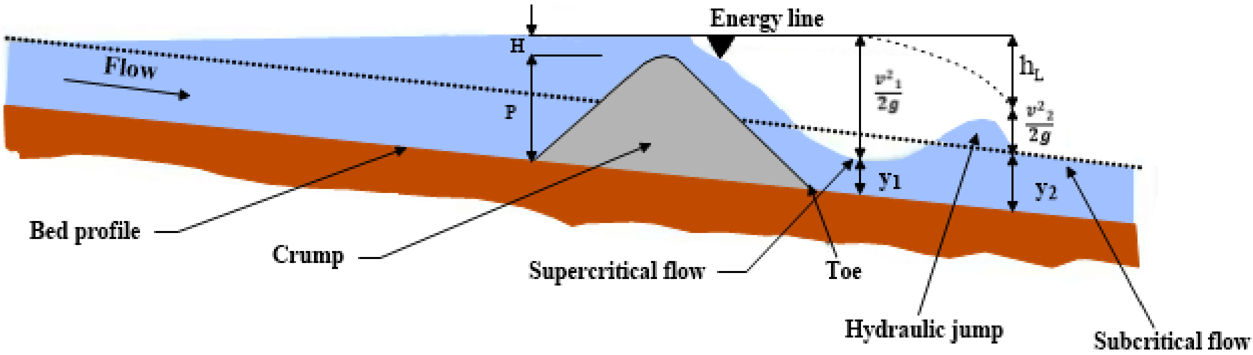

Figure 1: *An illustration of the induced critical depth in the throat section of the flume (AL-Naely et al., 2018).*
Slika 1: *Prikaz inducirane kritične globine v zoženem odseku korita (AL-Naely et al., 2018).*

2. Methodology

The approach involved reviewing and examining various flow-measuring flumes. Numerous research articles were studied. The review was confined to hydraulic performance of open channel flow measuring flumes.

3. Detailed review of flow-measuring flumes

3.1. Classification of flumes

According to USBR (2001), flumes are classified into two (2) major categories namely; short-throated flumes and long-throated flumes.

Based on Adeogun and Mohammed (2020), short-throated flumes control the flow rate in a region that produces curvilinear flow. Basically, the flow pattern in the control section of a short-throated flume is characterized by a strong free surface curvature and a departure from the hydrostatic distribution of pressure (Dufresne and Vazquez, 2013).

According to Hager (2010), flumes are classified as short or long throated based on relative constriction length (L_e/h_1) in which L_e is the throat length, and h_1 is the upstream flow depth. He further specified that a flume is considered as short throated when $L_e/h_1 < 1$. Such scenarios can be observed in Parshall flumes, Montana flumes, Cutthroat flumes, and H-flumes where curvilinear flow can easily be experienced.

Herb and Hernick (2020) reported that long throated flumes control the flow rate in the throat section causing nearly parallel flow lines in the region of flow control. In a long-throated flume, the prismatic throat section has a sufficient length in the streamwise direction in order to achieve a nearly parallel flow situation and a hydrostatic pressure distribution (Clemmens *et al.*, 2001). Furthermore, as guided by Hager (2010), in long throated flumes, the relative constriction length is expected to be greater than 1 ($L_e/h_1 > 1$). Trapezoidal flumes, RBC flumes, and Palmer-Bowlus flumes are notable examples of flumes in which the nearly parallel flow lines in the region of flow control can easily be experienced.

Though examples of flumes have been provided for short and long throated flumes, it should also be noted that the same flume can act as long or short throated flume depending on the scenario of the relative constriction length.

Long throated flumes can almost have any desired cross-sectional shape and custom fitted into most canal site geometry. Bos et al., (1991) reported that long-throated flumes have greater tolerance to submergence than short-throated flumes. They highlighted that short-throated flumes (e.g Parshall flume) require 3 to 4 times the absolute water surface fall through the structure for free-flow measurements than long-throated flumes.

3.2. Field application of flumes

Flumes are commonly used to measure flow for various monitoring settings, such as field runoff, stormwater, municipal storm sewers, dam seepage discharge, industrial effluent discharge, watershed monitoring, irrigation canal discharge, ditch and furrow discharge, spring discharge, mine discharge, and stream gauging (Tekade et al., 2016, Heyrani et al., 2022; Luxmi et al., 2022; Heiner and Barfuss, 2011; Marr et al., 2010; USBR, 2001; Todeschini et al., 2020; Ribeiro et al., 2021).

3.3. Notable advantages of flumes

In situations where weirs are unsuitable for effective flow measurement (e.g natural channel flow with excessive sediments), flumes are the best choice. Flumes are self-cleaning, they allow sediments and trash to pass through easily. They are very suitable in measuring stream flows containing sediment because the increased velocity through the flume tends to make it self-cleaning (Chadwick et al, 2004). Examples of such flumes are Parshall flumes, Montana flumes, Cutthroat flumes, H-flumes, Trapezoidal flumes, and Replogle-Bos-Clemmens (RBC) flumes. Furthermore, flumes are relatively less sensitive to varying approach velocity.

Using flumes, it is also possible to operate with a very small head loss which cannot be achieved with a similar weir structure, and this makes flume to be adopted in many areas where the available head is limited. According to USBR (2001), the head loss in flumes is less than one quarter of that required to operate a sharp-crested weir having the same control width. Under the same conditions, in long-throated flumes, the head loss is as low as one-tenth.

Flumes have a reasonable accuracy over a wide range of flows and have the capacity to measure higher flow rates than a comparably sized weir. It is possible to obtain an accuracy within ±2 to 5% (for the flume itself) with overall system accuracy for a typical installation being ±10% when all factors are considered (Adeogun and Mohammed, 2020). As compared to Weirs, there is less effect of submergence on accuracy of most flumes.

Some flumes are inexpensive, easy to install, fabricate, and operate. Furthermore, they have low maintenance cost since locally available materials can be used (Clemmens et al., 2001, Walkowiak, 2006; Komiskey et al., 2013). Examples of such flumes include: Montana flumes, Cutthroat flumes, H-flumes, and central baffle flumes.

Flumes are available in a wide range of sizes hence applicable for use in various open channel sizes. They also have the ability to measure higher flow rates than a comparably sized weir.

3.4. Key limitations of flumes

The stage and discharge relationship developed for modular flow conditions does not apply effectively for the submerged conditions, therefore further consideration on the downstream depth needs to be incorporated in order to get accurate discharge (Robinson, 1965).

Flumes are prone to discharge errors when the upstream section close to the device has turbulent flow. It is important to make sure the approaching flow is tranquil with mild slopes, free of curves, projections, and waves (USBR, 2001).

According to Herb and Hernick (2020), for the flumes to attain modular flow, the Froude number in the upstream section should always be ≤ 0.5 in order to avoid water surface instability in the approach channel.

Flumes should be operated within their flow limits and head range, otherwise their degree of accuracy is affected. Although a minor slope will not significantly affect flume's accuracy, proper flume levelling should be considered in both longitudinal and transverse directions (Adkins, 2006).

3.5. Specific features of individual flumes

3.5.1. Parshall Flume

The Parshall flume was originally developed in 1926. After further improvements, in 1930, the flume was named after Ralph L. Parshall, the engineer who designed it (Heyrani et al., 2022). The flume consists of a converging section, a throat section, and diverging section. Its design includes a contraction of both sidewalls and a drop in the floor at the flume's throat (Khosronejad et al., 2021). Parshall flumes are sized by throat width, according to USBR (2001), the throat width sizes range from 2.54 to 1524 cm.

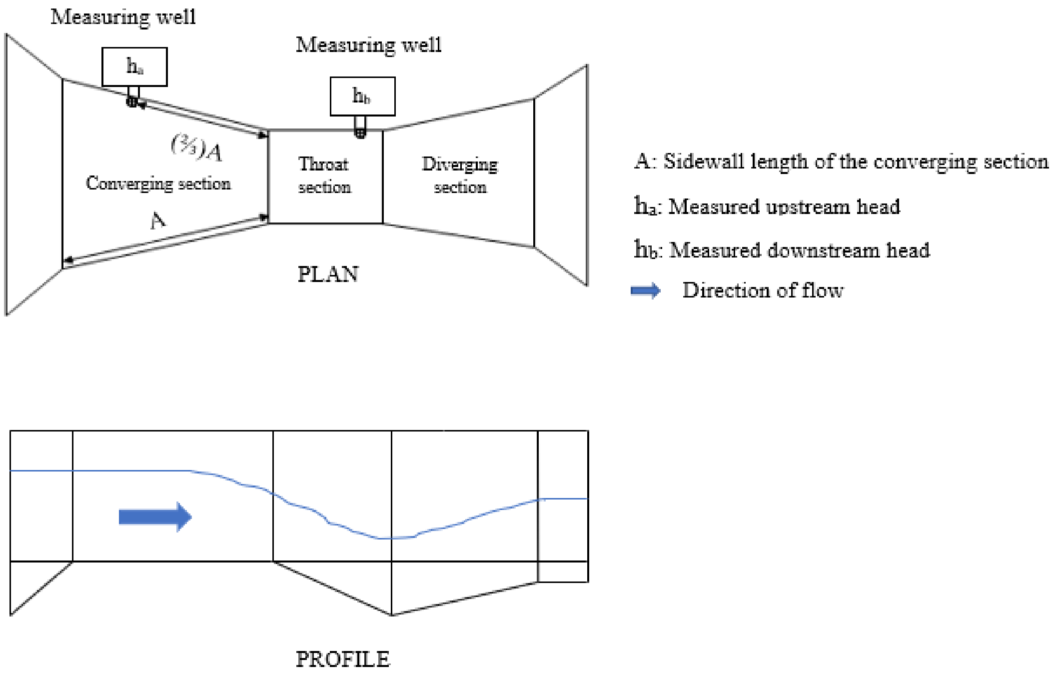

Figure 2: *Plan and profile view of Parshall flume (Ribeiro et al., 2021).*
Slika 2: *Tloris in vzdolžni prerez Parshallovega korita (Ribeiro et al., 2021).*

Table 1*: Discharge characteristics of Parshall flumes.*

Preglednica 1: *Pretočne značilnosti Parshallovih korit.*

Throat width	Equation	Head range (m)		Modular limit
	$(Q = Kh_a{}^u)$	Minimum	Maximum	
1" (0.0254 m)	$Q = 0.0604\ h_a{}^{1.55}$	0.015	0.21	0.5
2" (0.0508 m)	$Q = 0.1207\ h_a{}^{1.55}$	0.015	0.24	0.5
3" (0.0762 m)	$Q = 0.1771\ h_a{}^{1.55}$	0.03	0.33	0.5
6" (0.1524 m)	$Q = 0.3812\ h_a{}^{1.58}$	0.03	0.45	0.6
9" (0.2286 m)	$Q = 0.5354\ h_a{}^{1.53}$	0.03	0.61	0.6
1' (0.3048 m)	$Q = 0.6909\ h_a{}^{1.522}$	0.03	0.76	0.7
1'6" (0.4572 m)	$Q = 1.056\ h_a{}^{1.538}$	0.03	0.76	0.7
2' (0.6096 m)	$Q = 1.428\ h_a{}^{1.550}$	0.046	0.76	0.7
3' (0.9144 m)	$Q = 2.184\ h_a{}^{1.566}$	0.046	0.76	0.7
4' (1.2192 m)	$Q = 2.953\ h_a{}^{1.578}$	0.06	0.76	0.7
5' (1.5240 m)	$Q = 3.732\ h_a{}^{1.587}$	0.06	0.76	0.7
6' (1.8288 m)	$Q = 4.519\ h_a{}^{1.595}$	0.076	0.76	0.7
7' (2.1336 m)	$Q = 5.312\ h_a{}^{1.601}$	0.076	0.76	0.7
8' (2.4384 m)	$Q = 6.112\ h_a{}^{1.607}$	0.076	0.76	0.7
10' (3.0480 m)	$Q = 7.463\ h_a{}^{1.60}$	0.09	1.07	0.8
12' (3.6576 m)	$Q = 8.859\ h_a{}^{1.60}$	0.09	1.37	0.8
15' (4.5720 m)	$Q = 10.96\ h_a{}^{1.60}$	0.09	1.67	0.8
20' (6.0960 m)	$Q = 14.45\ h_a{}^{1.60}$	0.09	1.83	0.8

25' (7.6200 m)	$Q = 17.94\, h_a^{1.60}$	0.09	1.83	0.8
30' (9.1440 m)	$Q = 21.44\, h_a^{1.60}$	0.09	1.83	0.8
40' (12.1920 m)	$Q = 28.43\, h_a^{1.60}$	0.09	1.83	0.8
50' (15.2400 m)	$Q = 35.41\, h_a^{1.60}$	0.09	1.83	0.8

Q *is the Parshall flume discharge in m³/s,* $\boldsymbol{h_a}$ *is the upstream measured head in m, and* ***modular limit*** *is the submergence ratio at which there is transition from free flow to submerged flow. Reference: Bos (1989).*

3.5.1.1. Discharge measurement, range of flows, and head losses through Parshall flumes

According to Figuérez et al. (2021), Adeogun and Mohammed (2020), Seth and Samani (2016), under modular flow conditions, discharge through the Parshall flume depends on the measured upstream head which is expressed in Equation (1):

$$Q = K{h_a}^u \tag{1}$$

where Q is the flume discharge (m³/s), K is the discharge coefficient which is the function of throat width, h_a is the upstream head of water (m) measured at ⅔ of the sidewall converging section from the throat and u is the flow exponent. Various equations based on throat width of the Parshall flume are presented in Table 1.

As for submerged flow, the discharge is expressed in Equation (2)**:**

$$Q = \frac{C_s(h_a - h_b)^{n_f}}{[-(Log_{10}S + 0.0044)]^{n_s}} \tag{2}$$

where Q is the flume discharge (m³/s), h_a is the measured upstream head of water (m), h_b is the measured downstream head of water (m), n_f is the free-flow exponent, n_s is the submerged flow exponent, C_s is the submergence constant and S is the submergence ratio $\left(\frac{h_b}{h_a}\right)$.

Based on the throat size (0.0254 to 15.24 m), Parshall flume discharge ranges from 0.09 x 10^{-3} to 93.04 m³/s (Boss, 1989).

The Parshall flume operates under low head loss. For very small flumes with throat width of 0.0254 to 0.2286 m (1 to 9 inches), head losses are usually less critical such that the difference between upstream depth (h_a) and downstream depth (h_b) is adequate for estimation of head loss. For larger flumes with throat width of 0.3048 to 15.24 m (1 to 50 feet), USBR (2001) and Boss (1978) provided charts for estimation of head loss depending on percentage of submergence, throat width and maximum flume discharge.

3.5.1.2. Degree of accuracy and submergence for Parshall flumes

Heiner and Barfuss (2011) and Heyrani et al. (2022) reported that the Parshall flume measures flow rate with an accuracy of ± 3 to 5 % under normal field conditions. It should further be noted that under submerged flow conditions, the discharge error increases. According to USBR (2001), the degree of submergence for Parshall flumes ranges from 50 to 80 %. Other authors like Abt et al. (1994) have reported a maximum degree of submergence of 90 %. They reported that the accuracy of a Parshall flume also depends on the slope of settlement and submergence. For lateral settlement of 2 %, the flume's discharge error under 70 %, 80 %, and 90 % submergence was 3 %, 5 % and 11 %, respectively.

3.5.1.3. Specific advantages and limitations of Parshall flumes

The Parshall flume can operate under relatively high degrees of submergence without affecting the flow rate. The flume is also adaptable to a variety of channel types (Saran et al., 2020); Vanani and Ostad-Ali-Askari, 2022).

As regards to limitations, the Parshall flume is prone to clogging especially for throat sizes below 30.48 cm. It is not accurate at low flow rates. Another biggest drawback of Parshall flumes is that these flumes are not made to be scale models, if there are multiple Parshall flumes of different sizes, there is a need to rate each flume individually in order for the readings to be accurate (Kittila and Zurich, 2019). It is also noted that the configuration of the throat section of a Parshall flume, including a sloping floor, makes its construction and field installation difficult. The submergence ratio should not exceed 0.90, otherwise the flume ceases to operate as the flow measuring device.

3.5.2. Montana Flume

The Montana flume is a modification of the widely used Parshall flume. It is a truncated version of the Parshall flume. It takes its shape from the Parshall flume but only has the flat-floored converging section. Montana flumes are sized by the throat width. There are twenty-two (22) different sizes of Montana flumes.

3.5.2.1. Discharge measurement, range of flows, and head losses through Montana flumes

In Montana flume, the flow is released directly out of the end of the flume since there are no throat and discharge sections. The contraction and released discharge accelerate the flow from a slow subcritical state to a super-critical one. As a result, the flow rate is accurately determined in the upstream converging section of the flume by measuring a single head reading at a specific point of measurement (USBR, 2001). Under modular flow, Equation (1) is also used in Montana flumes and rating curves used for Parshall flumes are also applicable. However, under submerged conditions, the flow rate deviates by 15 % from modular flow equations. Under minimal head losses, the developed Montana flumes measure flow rate in the range of 0.1416 to 92,890 ℓ/s (Willeitner et al., 2012).

3.5.2.2. Degree of accuracy and submergence for Montana flumes

Montana flume have laboratory accuracy of ± 2%. However, practical considerations such as approach flow, installation, and dimensional tolerances makes its modular flow discharge to be closer to ± 5% as per ASTM D1941. Heyrani et al. (2022) reported that Montana flume measures modular flow discharge with an accuracy of ± 3 to 5 % under normal field conditions. The modular flow conditions occur with a submergence limit of 50 to 60 %.

3.5.2.3. Specific advantages and limitations of Montana flumes

The special property of Montana flume as regards to cost of production relies on its less requirement of materials due to the shorter lay length. The flume is also accurate in measuring discharge in a variety of applications. It has a flat bottom which makes installation easier than Parshall flumes (Willeitner et al., 2012; Heyrani et al., 2022).

Montana flume always requires free-spilling discharge under all flow conditions. Though the flume has challenges to withstand submergence conditions due to the absence of the throat and diverging sections, some researchers e.g Willeitner et al. (2012) developed correction coefficients for flow measurement under submergence condition. They carried out a study on a 15.2-cm Montana flume with 45° entrance wing walls. The correction factor of 0.896 was used on a smooth 15.2-cm Montana flume with submergence of 45 – 90 %. Montana flumes smaller than 0.0762 m (3 inches) in size should be avoided for use on unscreened sanitary flows, due to the possibility of clogging.

3.5.3. Cutthroat Flume

The Cutthroat flume was developed during 1966 - 1967 at the Utah Water Research Laboratory, Utah State University. Since the flume has no throat length, it was named "Cutthroat" by the developers; Skogerboe, Hyatt, Anderson, and Eggleston (Das *et al.*, 2017). It is sometimes called a flat-bottom flume. The Cutthroat flume has three (3) main components namely; the converging section, throat width, and diverging section. The converging (inlet) section is ⅓ the length of the flume, with the opposite flat sidewalls contracting at a uniform 3: 1 ratio. The diverging (outlet) section is ⅔ the length of the flume, with the opposite flat sidewalls expanding at a uniform 6: 1 ratio. The throat width sizes range from 2.54 to 182.88 cm (Temeepattanapongsa *et al.*, 2013).

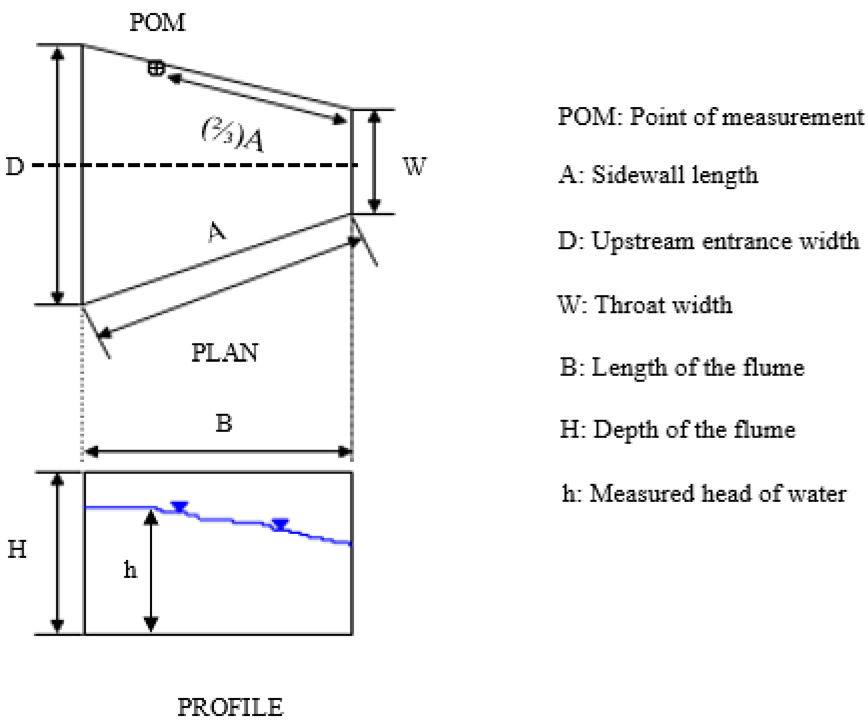

***Figure 3:** Plan and profile view of Montana flume (Luxmi et al., 2022).*

***Slika 3:** Tloris in vzdolžni prerez korita Montana (Luxmi et al., 2022).*

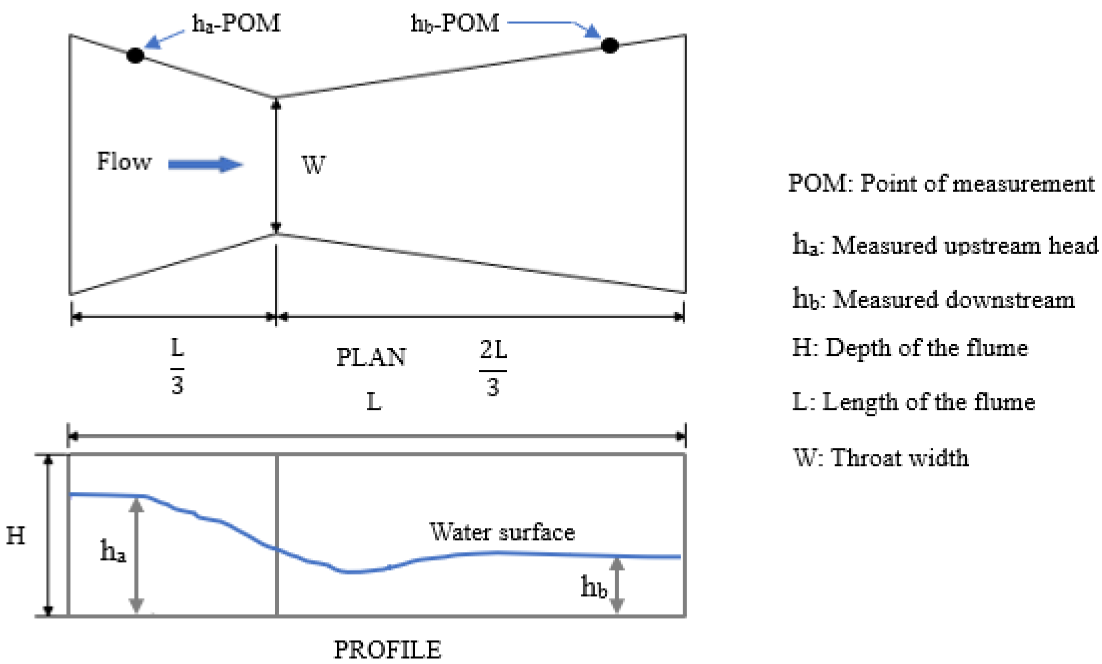

***Figure 4:** Plan and profile view of a Cutthroat flume (Temeepattanapongsa, 2013).*

***Slika 4:** Tloris in vzdolžni prerez korita Cutthroat (Temeepattanapongsa, 2013).*

3.5.3.1. Discharge measurement, range of flows, and head losses through Cutthroat flumes

In Cutthroat flumes, the upstream head is measured at a distance of $\frac{2L}{9}$ upstream of the throat (L is the flume length). The downstream head (h_b) is used to determine the submergence of a Cutthroat flume, it is measured near the outlet of the flume, $\frac{5L}{9}$ downstream of the throat. Several researchers proposed empirical discharge rating equations as a function of upstream head (Skogerboe et al., 1972; Keller, 1984; Manekar *et al.*, 2007; Torres and Merkley, 2008) but in this review, Equation (3) was adopted for modular flow conditions as guided by Das *et al.*, (2017) and Manekar *et al.* (2007):

$$Q = KW^{1.025}{h_a}^n = C{h_a}^n \quad (3)$$

where Q is the flume discharge (m^3/s), K is the flume discharge coefficient (it varies depending on flume length), W is the throat width (m), C is the flume discharge coefficient (it varies depending on flume length and throat width), and h_a is the measured upstream head (m).

As for the submerged flow, the discharge is determined using Equation (4);

$$Q_s = \frac{C_s(h_a - h_b)^{n_f}}{(-log(S))^{n_s}} \quad (4)$$

where f and s are free and submerged flow subscripts respectively, Q_s is the estimated flume discharge for submerged flow (m^3/s), C_s is the submerged flow coefficient, n_f and n_s are free-flow and submerged-flow exponents respectively, *ha* and h_b are upstream and downstream heads (m) and S is submergence ratio

$$S = \frac{h_b}{h_a} \quad (5)$$

Furthermore, Temeepattanapongsa and Merkley (2014) proposed generic unified rating equations that should be applied to estimate the discharge using Cutthroat flume. The computation of discharge is done using Equation (6):

$$\text{Q} = C_f\left(y_{uf}\right)^{nf} \quad (6)$$

$$C_f = 0.036 + 2.058(W)^{0.979} \quad (7)$$

$$n_f = 1.514(L)^{0.021}(W)^{-0.027} \quad (8)$$

where Q is the discharge (m^3/s), y_{uf} is the equivalent modular flow upstream water depth (m), W is the throat width of the flume (m), and L is the length of the flume (m).

Unlike the Parshall flume, the point of measurement for downstream head (h_b) in the Cutthroat flume is located away from the throat section in order to simplify determination of the water level. The flow rate in Cutthroat flumes ranges from 0.0223 to 3458 ℓ/s.

According to Ran et al. (2018), the head losses through a trapezoidal cutthroat flume is less than the head losses through a rectangular cutthroat flume under the same discharge conditions.

3.5.3.2. Degree of accuracy and submergence for Cutthroat flumes

According to Temeepattanapongsa (2012), it is reported that the standard Cutthroat flume can measure discharge up to an accuracy of ±5 % under any flow condition. Sun *et al.* (2021), explored the hydraulic characteristics of the Cutthroat flume and the results revealed that the average discharge error of the flume was 3.17 %. However, in curved-streamline open-channel flows, the error can be high up to ±10 % (Zerihun, 2019). As for the degree of submergence, it mostly ranges from 60 to 80 % but in certain Cutthroat flumes e.g 0.914-m (3-ft) Cutthroat flume, it can be high up to 95 % (Torres and Merkley, 2008).

3.5.3.3. Specific advantages and limitations of a Cutthroat flumes

As opposed to the Parshall flume, Cutthroat flumes are easier to construct/install inside a channel. The flat-bottomed design allows the flume to be retrofitted into an existing channel without a requirement to raise the flume or adjust downstream flow characteristics. The use of consistent geometric shape allows accurate predictions of discharge ratings for intermediate flume sizes. Another important aspect is that every flume length has the same entrance and exit section lengths, this allows the same form or pattern to be used for any desired throat width. For a Cutthroat flume greater than 7.62 cm in size, clogging does not occur easily as observed in a Parshall flume (Emamgholizadeh *et al.*, 2009; Yarahmadi and Vatankhah, 2021).

When using Cutthroat flumes in earthen channels, the converging section side walls should properly be sealed, otherwise, there is a great potential for occurrence of upstream bypass and downstream scouring. Cutthroat flumes with a throat width below 7.62 cm in size should not be utilized on unscreened sanitary flows because clogging occurs under such conditions (Temeepattanapongsa, 2012).

3.5.4. H-Flume

The H-flume was designed in 1930s by the US Soil Conservation Service. It consists of a flat floor, a uniformly converging inlet, and a rectangular cross-section. The throat is formed by sloping the top of the flume downwards in the flow direction. The result is the truncated V-shape when viewed in elevation from the end of the flume (Tulip et al., 2018).

H-flumes are elevated above the effluent so that water can freely spill out of the flume.

3.5.4.1. Discharge measurement, range of flows, and head losses through H-flumes

In Operation of an H-flume relies on the venturi principle. The flume restricts the flow area due to lateral restrictions, causing the water level to rise on the upstream section from the throat. This type of flume can be used under both modular and submerged flow conditions although operation of the flume under modular flow conditions is strongly recommended. According to Tulip *et al.* (2018), Equation (9) is used to express the H-flume discharge as a function of the head.

$$log\,Q = A + B\,log\,h_a + C(log\,h_a)^2 \qquad (9)$$

where Q is the discharge through the H-flume (m^3/s), h_a is the measured upstream water depth (m), *A*, *B* and *C* are constants obtained from tables based on flume depth as indicated in Table 2.

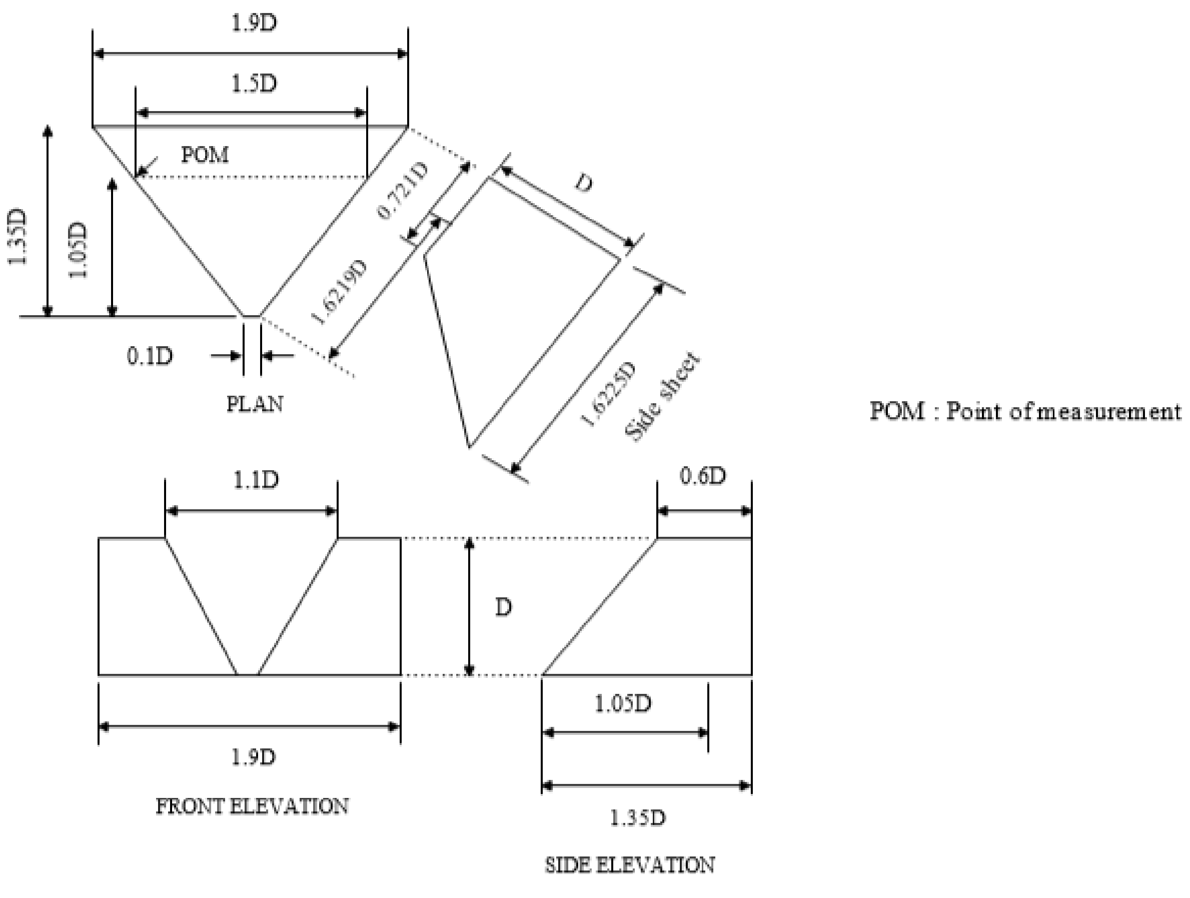

Figure 5: *Plan view and front elevation of H-flume (Payero et al., 2021).*
Slika 5: *Tloris in sprednji naris H-korita (Payero et al., 2021).*

Table 2: *Discharge characteristics of the three types of H-flumes. Source: Gwinn and Parsons (1976).*

Preglednica 2: *Pretočne značilnosti treh vrst H-korit. Vir: Gwinn and Parsons (1976).*

Flume type	Flume depth (D)		Maximum discharge ($m^3/s \times 10^{-3}$)	Constants applied in the empirical formula ($log\ Q = A + B\ log\ h_a + C(log\ h_a)^2$		
	ft	m		A	B	C
HS	0.4	0.122	2.27	-0.4361	2.5151	0.1379
HS	0.6	0.183	6.14	-0.4430	2.4908	0.1657
HS	0.8	0.244	12.7	-0.4410	2.4571	0.1762
HS	1	0.305	22.3	-0.4382	2.4193	0.179
H	0.5	0.152	9.17	0.0372	2.6629	0.1954
H	0.75	0.229	26.9	0.0351	2.6434	0.2243
H	1	0.305	53.5	0.0206	2.5902	0.2281
H	1.5	0.457	150	0.0238	2.5473	0.2540
H	2	0.61	309	0.0237	2.4918	0.2605
H	2.5	0.762	542	0.0268	2.4402	0.2600
H	3	0.914	857	0.0329	2.3977	0.2588
H	4.5	1.37	2366	0.0588	2.3032	0.2547
HL	3.5	1.07	2370	0.3081	2.3935	0.2911
HL	4	1.22	3298	0.3160	2.3466	0.2794

For example, Bos (1976) developed an empirical discharge equation for the 0.122 m HS flume as indicated in Equation (10).

$$log\ Q = -0.4361 + 2.5151\ log\ h_a + 0.1379(log\ h_a)^2 \qquad (10)$$

where Q is the discharge through the HS-flume (m^3/s), h_a is the measured upstream water depth (m).

3.5.4.2. Degree of accuracy and submergence for H-flumes

The H-flume measures flow rate with an accuracy of ±3 %. Tulip et al. (2018) designed and constructed the H-flume at the Department of Irrigation and Water Management, Bangladesh Agricultural University (BAU). They found out that the average discharge error was 3.46 %. According to Marr et al. (2010), the accuracy of H-flumes also depends on the length of the approach section. They reported that longer approach sections provide more accurate results than shorter approach sections. The location of the point of measurement also affects the accuracy of H-flumes. Grant and Dawson, 2001 reported that the point of measurement should be at a distance of 1.05 times the flume depth, upstream from the tip of the flume exit for accurate measurement of discharge. The modular limit for H-flumes ranges between 0.25 and 0.30.

3.5.4.3. Specific advantages and limitations of H-flumes

An H-flume is a better flume for water management operations that measure a broad range of flows and experience free spillage.

H-flumes are prone to clogging especially when used with sanitary waste. The other limitation of H-flumes is that it is only feasible for operations when free spillage occurs, otherwise, measurements at the high end can be inaccurate (Komiskey et al., 2013; Kittila and Zurich, 2019). These flumes should not be operated under submergence of more than 30 % and the approach channel slope should be < 2 %.

3.5.5. Trapezoidal Flume

In a Trapezoidal flume, the sides diverge from the floor of the flume to its surface relative to each other (Figure 6).

3.5.5.1. Discharge measurement, range of flows, and head losses through Trapezoidal flumes

Discharge through a trapezoidal flume under modular flow conditions is determined by applying Equation (11):

$$Q = C{h_a}^n \qquad (11)$$

where Q is the discharge through flume (m^3/s), C is the discharge coefficient which is the function of throat width, h_a is the measured upstream head (m) and n is the flow exponent. Tables are available for coefficients corresponding to throat size. The flow rate in trapezoidal flumes ranges from 0.0880 to 1508 ℓ/s.

Overall, the trapezoidal flume has the lowest head loss due to its flat bottom but there is need to develop standard head loss charts and tables for the flume as observed in Parshall flumes and RBC flumes, respectively.

3.5.5.2. Degree of accuracy and submergence for Trapezoidal flumes

Discharge measurement in trapezoidal flumes is within the accuracy of ± 2 to 5 %. To maintain the desired accuracy in trapezoidal flumes, the submergence ratio should not exceed 80 %. For flows with submergence exceeding 80 %, flow correction factors are applied (USBR, 2001; Clemmens *et al.,* 2001).

3.5.5.3. Specific advantages and limitations of Trapezoidal flumes

The trapezoidal flume is able to maintain its accuracy when measuring a wide variety of flows. It has the capacity to measure low flow rates (< 0.6309 ℓ/s). As compared to the Parshall flume of the same throat width, the trapezoidal flume carries a wider range of flows. The trapezoidal flume is easy to install on flat surfaces. It also operates under a high submergence level (80 %), therefore, without using a correction factor, the discharge can be determined with a small error. In trapezoidal flumes, maintenance costs are lower than in other flumes (Shayannejad *et al.,* 2017; Vanani and Ostad-Ali-Askari, 2022).

Trapezoidal flumes are more difficult to fabricate than other flumes e.g Cutthroat. When compared to other flumes, trapezoidal flumes are very good for low flow measurements, but they are somehow limited in their total flow range capability (Shayannejad *et al.,* 2017).

3.5.6. Replogle-Bos-Clemmens (RBC) Flumes

The RBC flume is an example of portable long-throated flumes. It has a trapezoidal section with a sufficient contraction in the cross-section, forcing the flow to accelerate and pass through the critical state over its throat section. The contraction is introduced in the form of a raised invert as illustrated in Figure 7.

The RBC flume was named after the developers namely; Replogle, Bos, and Clemmens (Styles *et al.,* 2013). These RBC flumes are categorized based on throat width such as 50 mm, 75 mm, 100 mm, 150 mm, and 200 mm (Wahl *et al.,* 2005).

3.5.6.1. Discharge measurement, range of flows and head losses through RBC flumes

Water in the canal is allowed to flow through the flume with a raised trapezoidal ramp. On the converging ramp section, the flow is raised on a slope. The flow is then extended for a throat distance before dropping off at the end of the ramp. After attaining stable modular flow, the sill-referenced head (Sh_1) is measured on the gauging point located at the upstream section of the flume. The discharge is computed as a function of the sill-referenced head. According to Wahl *et al.,* (2005), computation of discharge is based on Equation (12):

$$Q = K_1(Sh_1 + K_2)^u \qquad (12)$$

where Q is the flume discharge ($\ell\ s^{-1}$), Sh_1 is the measured sill-referenced head (mm), K_1 is 0.002189, K_2 is 5.457 and u is 1.879.

The RBC measures discharge accurately over a wide range of flows and minimal head loss over the flume is required to sustain critical flow in the throat section. This ensures a distinctive relationship between the upstream sill-referenced head and the discharge. The range of discharge and maximum head losses with respect to throat width and length are outlined in Table 3.

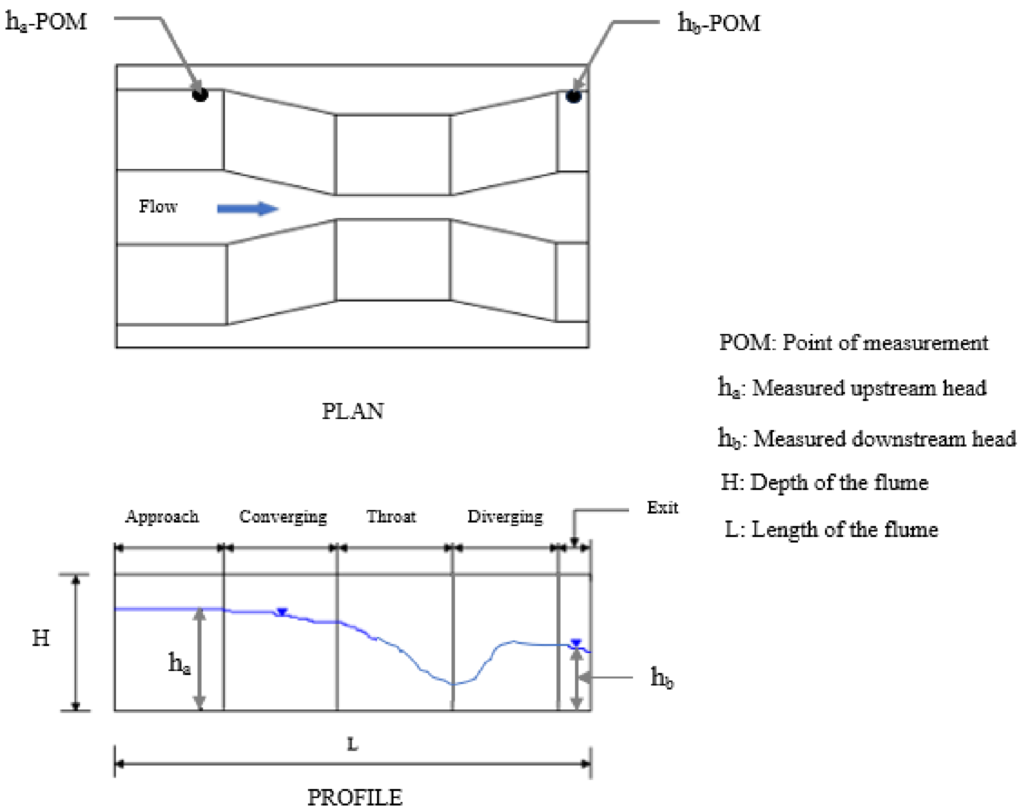

Figure 6: *Plan and profile view of the trapezoidal flume (Vanani and Ostand-Ali-Askari, 2022).*

Slika 6: *Tloris in vzdolžni prerez trapeznega korita (Vanani in Ostand-Ali-Askari, 2022).*

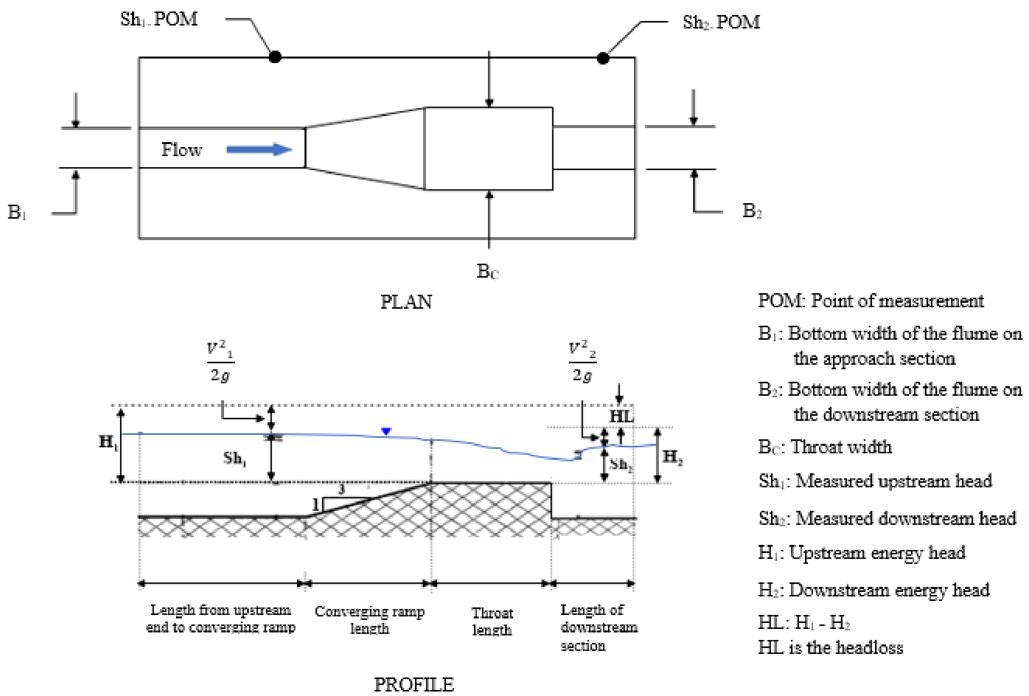

Figure 7. *Plan and profile view of the RBC flume (Clemmens et al., 2001).*

Slika 7: *Tloris in vzdolžni prerez korita RBC (Clemmens et al., 2001).*

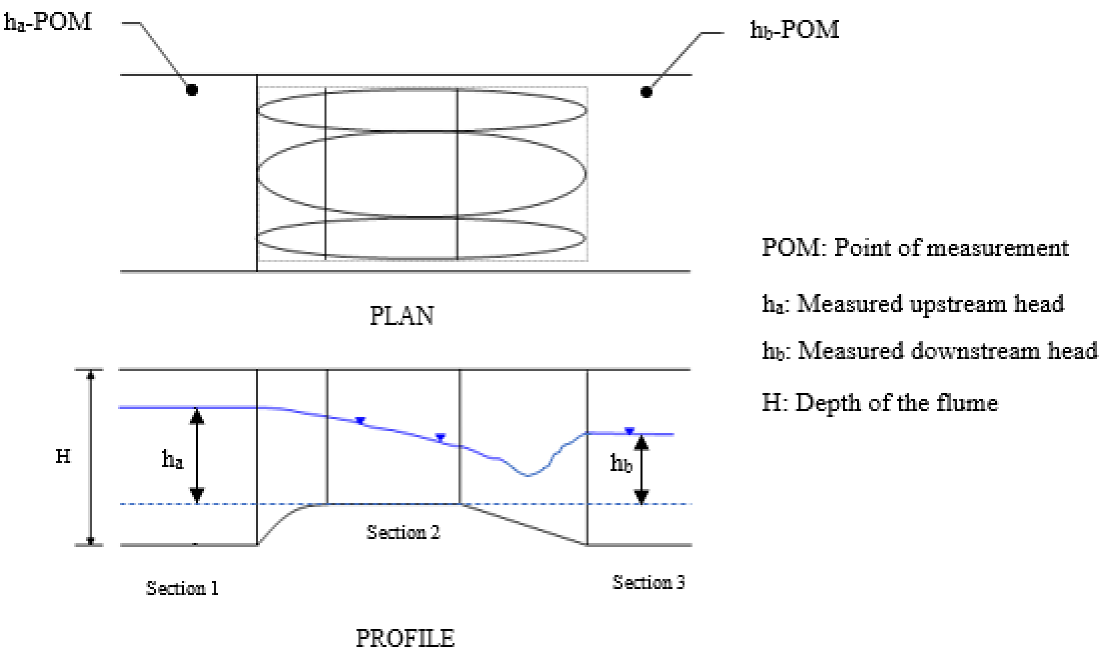

Figure 8: *Plan and profile view of a Palmer-Bowlus flume (Dabrowski and Polak, 2010).*
Slika 8: *Tloris in vzdolžni prerez Palmer-Bowlusovega korita (Dabrowski in Polak, 2010).*

Table 3: *The range of discharge and maximum head losses with respect to throat width and length of RBC flume. Source: Clemmens et al. (2001),*

Preglednica 3: *Razpon pretoka in maksimalne izgube energije glede na širino in dolžino zožitve korita RBC. Vir: Clemmens et al. (2001).*

Throat width (mm)	Throat Length (mm)	Discharge range (ℓ/s)	Maximum allowable head loss (mm)
50	75	0.03-1.5	10
75	112.5	0.07-4.3	15
100	150	0.16-8.7	20
150	225	0.40-24.0	30
200	300	0.94-49.0	40

3.5.6.2. Degree of accuracy and submergence for RBC flumes

The RBC flume measures discharge with an accuracy of ± 2 % (Wahl *et al.*, 2005). However, under practical considerations, it is extended to ± 5 %. Under such conditions, the degree of submergence is within the range of 70 – 90 % (USBR, 2001; Clemmens *et al.*, 2001).

3.5.6.3. Specific advantages and limitations of RBC flumes

The flume is adaptable to a variety of channel shapes, hence regarded as a flexible tool for measuring flow rate in open channels.

Although the flume's converging section design allows sediments to be transported through the flume under sub-critical and critical flow, there is always standing water upstream of the RBC flume due to the throat ramp. This provides room for deposition of heavier sediments on the upstream section of the flume. It is also challenging to determine discharge under submerged flow using RBC flumes because submerged flow equations have not been developed and published for use (Samani, 2017).

3.5.7. Palmer-Bowlus Flumes

This type of flume was named after its inventors, Harold Palmer and Fred Bowlus of the Los Angeles County Sanitation Department in the 1930s. The flume has a U-shaped cross-section which is helpful in minimizing the flow transition through the flume. Over the years, Palmer-Bowlus flume sizes have been developed ranging from 10.16 to 182.88 cm. In practice, Palmer-Bowlus flumes with sizes above 60.96 cm are not commonly used.

3.5.7.1. Discharge measurement, range of flows, and head losses through Palmer-Bowlus flume

The flume develops critical flow in the throat section which makes discharge a distinctive function of the measured upstream head for a given throat shape and upstream channel geometry. Both the inlet and outlet of the Palmer-Bowlus flume are at the same elevation. Computation of discharge is based on Equation (13):

$$Q = C\, {h_a}^{n} \qquad (13)$$

where Q is the flume discharge (m^3/s), C is the free-flow coefficient of the flume which depends on flume width, h_a is the measured upstream head (m) and n is the flow exponent which varies depending on flume width. Tables are available for coefficients corresponding to throat size. For example, in case of a 0.102 m Palmer-Bowlus flume, Walkowiak (2006) developed equation (14) for computation of discharge.

$$Q = 468.34(\, h_a)^{1.9} \qquad (14)$$

where Q is the flume discharge (ℓ/s), and h_a is the measured upstream head (m)

Considering flume sizes from 2.54 to 60.96 cm, the discharge ranges from 0.2436 to 268 ℓ/s.

3.5.7.2. Degree of accuracy and submergence for Palmer-Bowlus flumes

Palmer-Bowlus flumes measure discharge with an accuracy of ±3 to 5 %. The degree of submergence for Palmer-Bowlus flumes is high (85 - 90 %). Notably, submerged flow corrections in Palmer-Bowlus flumes have not been published hence it is recommended that Palmer-Bowlus flumes only be used in applications where they will not become submerged. (Nordvåg, 2017)

As observed in Trapezoidal flumes, Palmer-Bowlus flumes also experience minimal head losses, but there is need to develop standard head loss charts and tables for the flume as observed in Parshall flumes and RBC flumes, respectively.

3.5.7.3. Specific advantages and limitations of Palmer-Bowlus flumes

For measuring sanitary flows, the most popular choice is the Palmer-Bowlus flume. The flume discharge is accurate regardless of measuring the head at any point upstream of the throat section. The Palmer-Bowlus is also easily installed (Sitaram, 2015).

Palmer-Bowlus flumes are more vulnerable to upstream sedimentation as compared to other flumes. Furthermore, for the flume to function correctly, the upstream area should be safe from curves or drops in elevation.

While Palmer-Bowlus flumes are easy to install in circular pipes, their high flow characteristics limit the measurable flow range. They are not very accurate at lower flow rates. So, if the flow in the system is low or inconsistent, then it is better to choose another type of flume. Submerged flow corrections in Palmer-Bowlus flumes have not been developed and published hence effective application of Palmer-Bowlus flumes is only reliable to modular flow conditions (Grant and Dawson, 2001).

3.5.8. Central Baffle Flumes (CBF)

According to Niyazi et al. (2022), the Central Baffle Flume (CBF) was first introduced by Peruginelli and Bonacci as a simple and low-cost flow measurement device used in open channel. The CBF is created by contracting a channel with a baffle which gradually diminishes the width of the channel in the direction of flow (Ferro, 2016). The CBF can be utilized to measure discharge in open channels under modular and submerged flow conditions.

3.5.8.1. Specific limitations of Central Baffle Flumes (CBF)

The notable challenges of CBF are that the flow capacity decreases as the central baffle length increases. Furthermore, the smaller flow depths should be avoided due to possible scale effects (Kolavani *et al.*, 2019). CBF do not have self -

cleaning capabilities, a good example is the circular mobile flume which traps floating material, this affects reliability and functioning of the measuring device (Krupavati *et al.,* 2012).

3.5.8.2. Types of Central Baffle Flumes (CBF)

There are different types of Central Baffle Flumes (CBF) namely; Triangular Central Baffle Flumes (TCBF), Conical Central Baffle Flumes, Cylindrical Central Baffle Flumes (CCBF), Circular Mobile Flumes, Samani and Magallanez (S-M) flumes.

Triangular Central Baffle Flumes (TCBF)

The triangular central baffle flume consists of a triangular shaped obstacle inserted in the channel axis. Figure 9 shows the plan, upstream and profile view of the triangular central baffle flume.

Bijankhan and Ferro (2019) investigated the flow through a triangular central baffle flume and they proposed the stage-discharge formula presented in Equation (15). They further discovered that the contraction ratio is a key parameter to differentiate modular flow from submerged flow through a TCBF. Equation (15) is applicable for a triangular baffle with an apex angle of 75° and $0.17 \leq B_c/B \leq 0.76$.

$$Q = 0.6925\, {B_C}^{5/2} \times g^{1/2} \times \left(\frac{h_a}{B_C}\right)^{1.5734} \quad (15)$$

$$B_C = B - b \quad (16)$$

where Q is the discharge through the flume (m^3/s), g is the acceleration due to gravity (m/s^2), B_C is throat width (m), and h_a is the upstream flow depth (m).

Kolavani *et al.* (2019) investigated the flow through the central baffle flume to quantify the impact of the throat length (L) and apex angle (α), on the stage-discharge relationship. From their study, they proposed a central baffle flume with an entrance apex angle of 75° and no guide wall installation (L = 0), to minimize the construction costs.

Bijankhan and Ferro (2019) formulated Equation (17) to show the submergence threshold condition for triangular central baffle flumes:

$$\frac{h_{th}}{B_c} = 0.9478 \left(\frac{h}{B_c}\right) r^{0.3705} \quad (17)$$

where h_{th} is the maximum tailwater depth increase (m) for transition of flow from free to submerged flow, B_c is the throat width (m), h is the upstream flow depth (m), and r is the contraction ratio (B_c/B).

Based on equation (17), they reported that for a given flow rate (Q) and contraction ratio (r), any downstream water depth greater than h_{th} would indicate that the flume is under submerged flow condition. Under these conditions, the discharge error is ± 5%.

Although the triangular central baffle flume minimises the flume size and weight, Kolavani *et al.* (2019) reported that it is more sensitive to submergence especially when the tailwater depth cannot be adjusted. Therefore, to ensure modular flow condition, during installation in earthen channels, it is suggested to make the soil bed slightly deeper at the tailwater section.

Conical Central Baffle Flume (CCBF)

According to Kapoor *et al.* (2023), the conical central baffle flume consists of a cone-shaped obstruction positioned vertically at the centre of an open channel. The concept of use of a portable circular cone as a baffle obstruction in trapezoidal channel was also introduced by Hager (1986) and later on, a comprehensive investigation was done by Kapoor *et al*. (2019) who developed the design criterion for a portable conical central baffle flume. The flume is feasible for use in small rectangular channels used as wastewater channels or irrigation channels in agricultural fields. Figure 10 shows the plan and profile of the conical central baffle flume.

Nair *et al.* (2023) proposed a discharge prediction model for determination of discharge in open channels using a conical central baffle flume. They reported that the proposed model is applicable for trapezoidal and rectangular channels. The discharge is computed using Equation (18) :

$$Q_p = \sqrt{\frac{(B_c y_c + C {y_c}^2)^3\, g}{(B_c + 2c y_c)}} \quad (18)$$

$$c = m_1 + m_2 \quad (19)$$

where Q_p is the discharge through the flume (m^3/s), B_c is the contracted width at critical section (m), C is the effective side slope, m_1 is the channel side slope,

m_2 is the slope of the cone, y_c is the critical flow depth, and g is the acceleration due to gravity (m/s^2).

For submergence less than 80 %, the error in discharge is always less than 10 % with an average value of 3 % (Kapoor *et al.,* 2021). The conical obstruction in the flume provides good stability against the water current. The conical central baffle flume can measure a wider range of flows due to its similarity to the V-notch weir (Kapoor *et al.*, 2019).

Cylindrical Central Baffle Flumes (CCBF)

A cylindrical central baffle flume is a modified venturi flume formed by placing portable cylinders vertically upright in an open channel, resulting into a flow constriction which further creates a critical flow condition. Figure 11 shows the plan and profile of cylindrical central baffle flumes.

Equation (20) is the stage -discharge equation used to compute discharge.

$$Q = 0.407m^{0.589} \times B^{5/2} \times g^{1/2} \times \left(\frac{D}{B}\right)^{-1.240} \times \left(\frac{y}{B}\right)^{2.416} \quad (20)$$

where Q is the flow discharge (m^3/s), m is the side slope of the channel, B is the channel bed width (m), g is the acceleration due to gravity (m/s^2), D is the diameter of the cylinder (m), and y is the upstream flow depth(m).

Using the CCBF, it was discovered that the submergence limit was attained when the ratio of tailwater depth to upstream depth was greater than 0.62. The ratio of tailwater depth to upstream depth under submergence limit conditions varies from 0.618 to 0.853 (Ghare *et al.,* 2020). For submergence less than 62 %, the discharge error is always less than 10 % (Shayan *et al.*, 2021).

Circular mobile flumes

A circular mobile flume is constructed using two pieces of pipes, one installed vertically inside the other with the vertical inner pipe reducing the cross-sectional flow. This creates critical flow condition. The diameter of the inner column is approximately one-third of the flume's diameter. This device does not require an elevation drop and can be installed at level slope. They are commonly used for measuring drainage discharge, and canal discharge (Kolavani *et al.*, 2018). Figure 12 shows the cross-sectional view and longitudinal profile of the circular mobile flume.

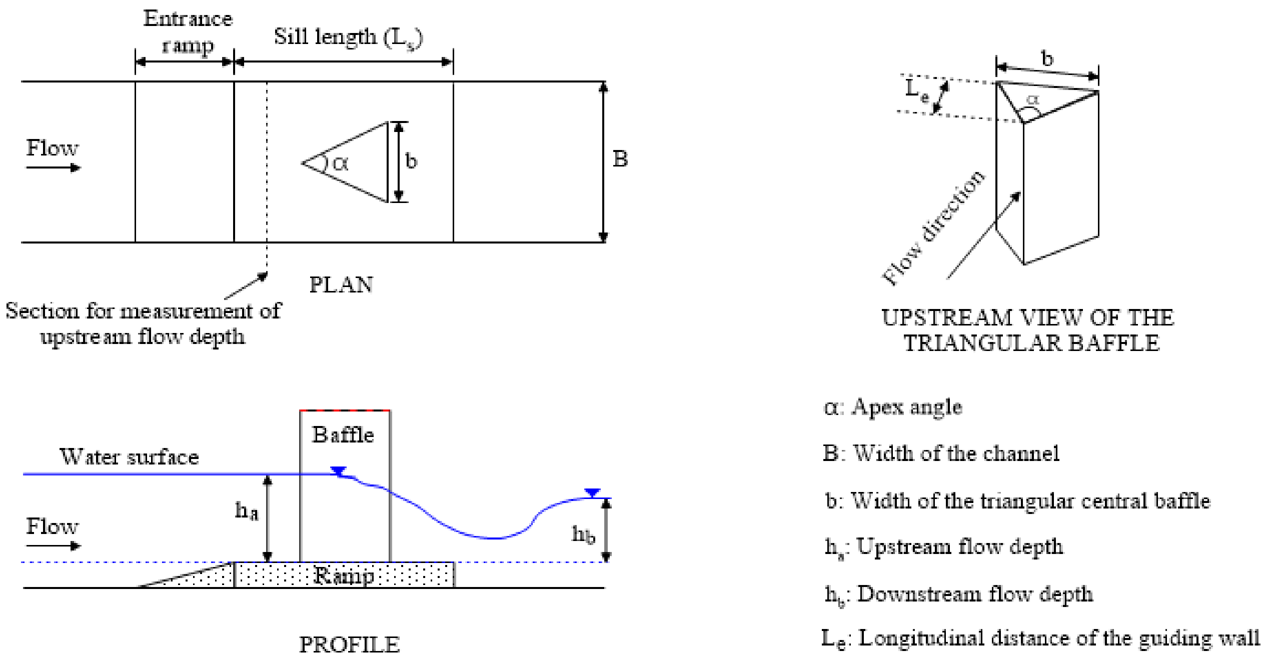

Figure 9: *Plan and profile view of the triangular central baffle flume (Bijankhan and Ferro, 2019; Bijankhan et al., 2022).*

Slika 9: *Tloris in vzdolžni prerez trikotnega korita s sredinsko oviro (Bijankhan and Ferro, 2019; Bijankhan et al., 2022).*

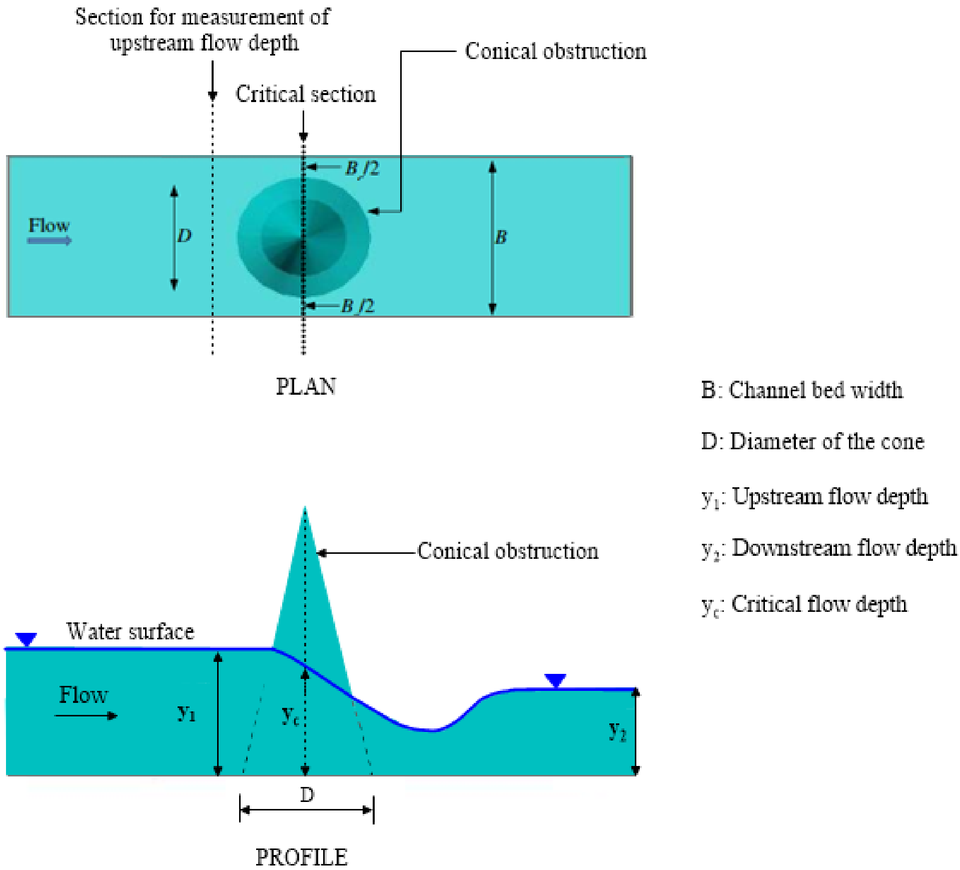

***Figure 10:** Plan and profile view of the conical central baffle flume (Kapoor et al., 2019).*

***Slika 10:** Tloris in vzdolžni prerez korita s stožčasto sredinsko oviro (Kapoor et al., 2019).*

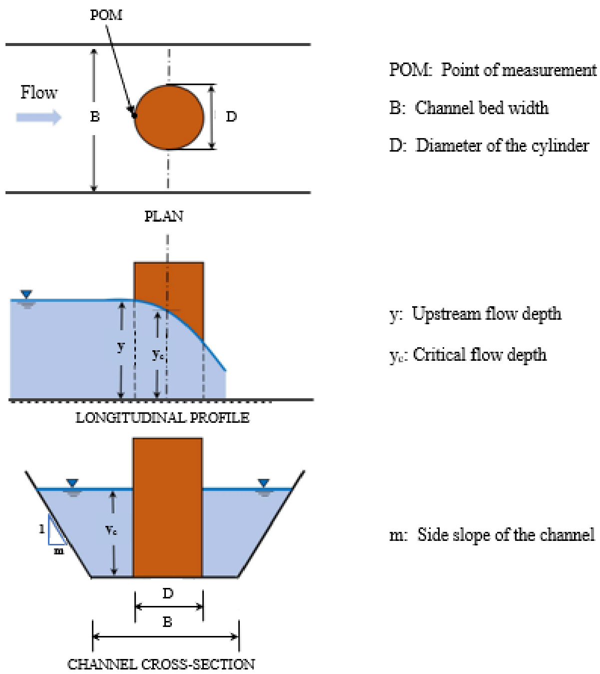

***Figure 11:** Plan, profile, and channel cross-sectional view of the cylindrical central baffle flume (Shayan et al., 2021).*

***Slika 11:** Tloris, vzdolžni prerez in prečni prerez kanala korita s cilindrično sredinsko oviro (Shayan et al., 2021).*

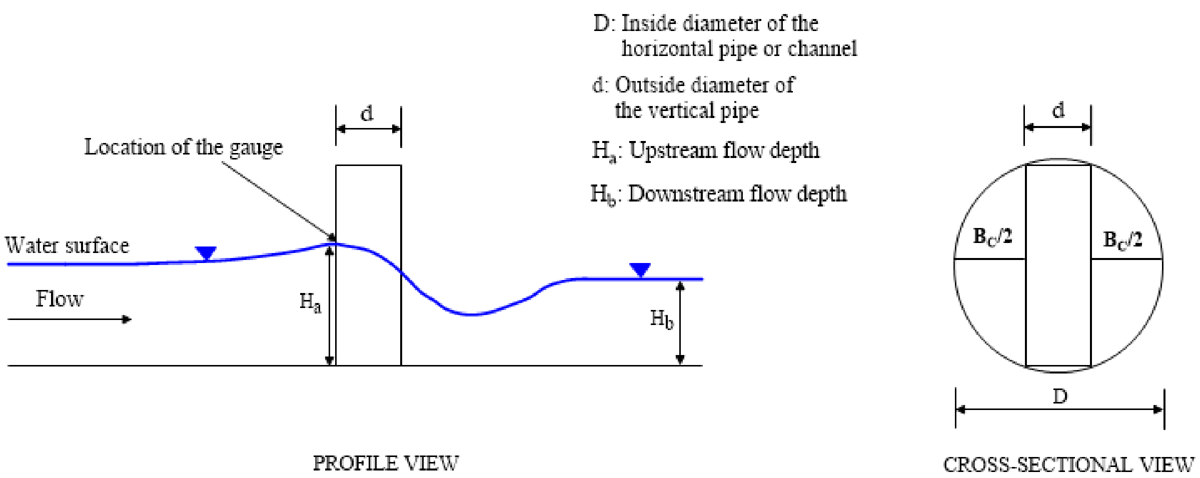

Figure 12: *Profile and cross-sectional view of circular mobile flumes (Seth and Samani, 2016).*

Slika 12: *Vzdolžni in prečni prerez krožnih premičnih korit (Seth in Samani, 2016).*

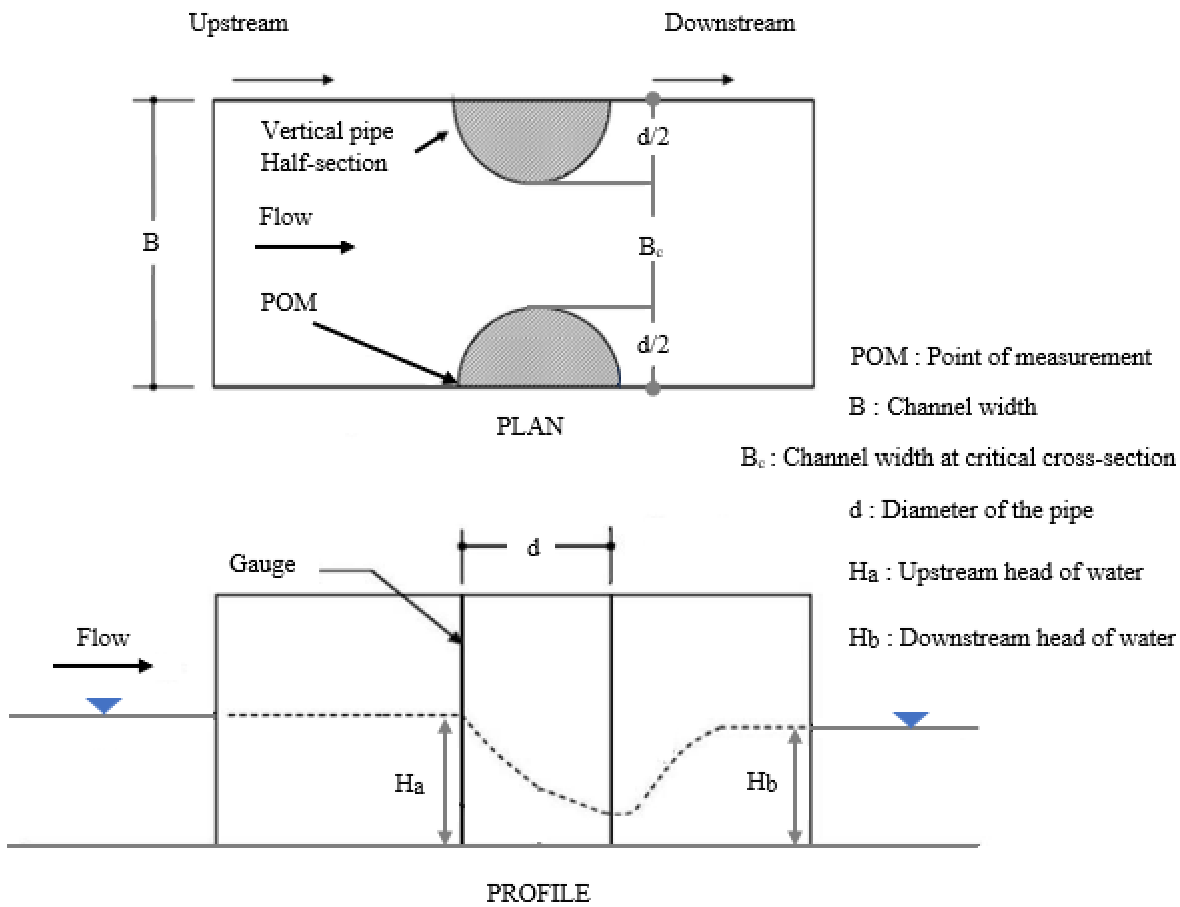

Figure 13: *Plan and profile view of S-M flume (Samani et al., 2006).*

Slika 13: *Tloris in vzdolžni prerez korita S-M (Samani et al., 2006).*

According to Seth and Samani (2016), the discharge in circular mobile flumes is computed using Equation (21).

$$Q = 0.421 \times B_C^{2.5} \times g^{1/2} \times \left(\frac{H_a}{B_C}\right)^{2.31} \quad (21)$$

$$B_C = D - d \quad (22)$$

where Q is the discharge (m^3/s), H_a is the measured upstream head of water (m), g is the acceleration due to gravity (m/s^2), D is the inside diameter of the horizontal pipe or channel (m), d is the outside diameter of the vertical pipe (m), B_c is the width of the channel at critical cross-section (m).

Krupavati et al. (2012) and Sucharitha et al. (2020) reported that accurate measurement of flow in open channels using circular mobile flumes can be maintained if the maximum submergence ratio does not exceed 0.8, once this condition is attained, there is an assurance that the deviation of discharge under modular flow conditions is kept within the accuracy range of ± 5 %.

The circular mobile flume has the capacity to measure a wide range of flow. It is also feasible for variable flow conditions. The flume is the accurate flow measuring device. It is portable and easy to install. The circular mobile flume is feasible for measuring flow through furrows because its circular shape fits well to the natural shape of a furrow, reducing the possibility of lateral flow around the flume (Kolavani et al., 2018; Seth and Samani, 2016).

As the circular mobile flume can be used to collect data over long period, it is very important to ensure it is kept as level as possible to keep the critical flow zone occurring in the proper location. Even small increase in slope can have significant effects on discharge.

Samani-Magallanez (S-M) flume

This flume was named after the developers; Samani and Magallanez. In S-M flume, the contraction is made by cutting a pipe into 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. This creates critical flow between the two half pipes and flushes sediments and debris through the flume (Samani and Magallanez, 2000). Figure 13 shows the plan and profile view of S-M flume.

According to Seth and Samani (2016), the discharge in S-M flume is computed using Equation (23):

$$Q = 0.701 \times B_C^{2.5} \times g^{1/2} \times \left(\frac{H_a}{B_C}\right)^{1.51} \quad (23)$$

where Q is the discharge (m^3/s), H_a is the measured upstream head of water (m), g is the acceleration due to gravity (m/s^2), B_c is the width of the channel at critical cross-section (m).

For the discharge to be accurately measured and ensure critical flow exists, the ratio of the diameter of the pipe (d) to the width of the rectangular channel (B) should be greater than 0.40 or conversely $Bc/B \leq 0.6$. To maintain accurate measurement of flow in S-M flumes, the maximum submergence ratio should not exceed 0.8. This provides an assurance that the deviation of discharge under modular flow conditions is kept within the range of ± 5 % (Samani and Magallanez, 2000; Seth and Samani, 2016).

The S-M flume can easily be used in irregular or trapezoidal shaped channels. The flume provides very accurate measurement of channel flow. However, the S-M flumes flume traps floating material as observed in circular mobile flumes, this affects reliability and function of the measuring device (Seth and Samani, 2016).

4. Conclusions

Flumes are accurate and effective flow-measuring devices in open channels. For larger flows, Parshall flumes and Montana flumes are the best options as compared to other flumes. Under suitable conditions, RBC flumes are the most accurate type of flumes, they can operate with an accuracy of ± 2 % while other flumes exhibit accuracies within the range of ± 3 to 10 %. For flows that deal with a lot of solid materials and debris, most flumes have self-cleaning capability except for Palmer-Bowlus flumes and Central Baffle flumes. H-flumes have low resistance to submergence. The submergence transition for H-flumes is only 25-30 %. RBC flumes and Palmer-Bowlus flumes have the highest degree of submergence (90 %). Corrections for submerged flow have not been developed and published for Palmer-Bowlus flumes and RBC flumes. Almost all flumes are easy to install and have minimal head loss requirement, except for the Parshall flume which has some difficulties to install in flat ditches. The review has provided insight into operational concepts, discharge measurement, range of flow, head loss requirements, degree of accuracy, degree of submergence, key advantages, and flume's limitations for use. The outcome of this review is useful when considering a criterion for selection of an appropriate type of flume for flow measurement in open channels.

5. Future Research and Perspectives

Based on the outcome of the review, the following aspects can be considered for future research and perspectives:

a) Submerged flow corrections need to be developed and published for Palmer-Bowlus flumes and RBC flumes.
b) Palmer-Bowlus flume sizes have been developed ranging from 10.16 to 182.88 cm, however, sizes above 60.96 cm are not commonly used. There is a need to test the performance of these flumes with sizes greater than 60.96 cm and find out specific factors that limit their use.
c) Palmer-Bowlus flumes and Central Baffle flumes need to be improved in order to have self-cleaning capability.
d) There is need to develop standard head loss charts and tables for Trapezoidal flumes, Palmer-Bowlus flumes, and Central Baffle Flumes (CBF).

Declaration of Competing Interest

The authors have declared that there is no any conflict of interest regarding the publication of the paper.

Authors Contributions

Davis Sibale, Etienne Umkiza, Romain Ntole, and Zechariah Jeremaiho were responsible for preparation of the draft review paper. Thomas Apusiga Adongo, Sylvester Chikavumbwa, and Erion Bwambale were responsible for reviewing and editing the paper.

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