

**ASSESSMENT OF THE RICHMOND
HILL III PARSHALL FLUME**

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1. Introduction

In response to concerns about the performance of the Richmond Hill III (RH) Parshall Flume, the Ministry of the Environment commissioned the Hydraulics Division of the National Water Research Institute to undertake an initial assessment of the flume and, if required, to recommend remedial measures. The scope of this assessment was defined in the original proposal (NWRI, 1986) and the Memorandum of Understanding signed by both parties. In summary, the assessment should evaluate the suitability of the existing flume for accurate flow measurement and, if required, propose remedial measures to correct any shortcomings of the existing structure.

The initial assessment of the RH Parshall flume has been completed and is presented in the report that follows.

2. Operation of the Parshall Flume

This section describes applications of the Parshall flume, its dimensions, head measurements, rating curves, and accuracy. In most cases, the discussion is limited to the RH Parshall flume.

2.1 Applications of the Parshall Flume

The Parshall flume was introduced into flow measurement practice more than 60 years ago and, since that time, it has gained

wide acceptance for discharge measurements in flows carrying sediments. Although the Parshall flume (as well as other Venturi flumes) is more expensive than weirs, its main advantages include a low head loss and uninterrupted passage of sediment through the flume. For these two reasons, the Parshall flume is particularly popular for sewage flow measurements and the use of this flume at the Bayview/Highway No. 7 location was a good choice.

Because the Parshall flume has been developed over an extended time period using a purely empirical approach, the users had to design new installations according to the specifications given in the original reference (Chow, 1959). Only for flumes meeting such specifications, it is possible to adopt the standard flume rating curves (Parshall, 1950) and achieve an overall field accuracy of $\pm 5\%$ (Replogle, 1971).

2.2 Parshall Flume Dimensions

As the first step in the assessment of the RH Parshall flume, its dimensions are compared to those of the standard Parshall flume. The standard flume dimensions were adopted from the original reference, converted into metric units and presented in Table 1 (Parshall, 1950). In the same table, the dimensions of the RH flume, supplied by the client, are also shown. For further explanations of the individual dimensions, reference is made to a notation sketch in Fig. 1.

Table 1. Dimensions of the Parshall Flume: Recommended and Measured in the RH Installation

	Dimension (mm)						
	W	A	2/3 A	B	C	D	E
Recommended	1829	2134	1422	2092	2134	2667	914
Measured	1780- 1845	2106	1400	2065	2140	2670	1105*
	F	G	K	N	R	M	P
Recommended	610	914	76	229	610	457	3442
Measured	618	914*	76*	305*	N/A	457	3580

*Determined from a drawing.

A comparison of the recommended and measured flume dimensions indicates a fairly good agreement. Although the recommended tolerances for Parshall flume dimensions are fairly strict and for the flume under consideration could be as small as ± 10 mm (Parshall, 1950), they apply only to the critical dimensions, such as the flume throat width. For other dimensions, higher tolerances, in the order of several percents, are acceptable (Replogle, 1971). Considering the above tolerances, only two dimensions, W and N, show significant deviations. In the latter case, the depression in the flume bottom N was designed unnecessarily too deep, but there are no obvious reasons why this should affect the flume operation or the rating curve.

The deviation in the throat width W is more serious. It appears that the throat side walls are not planar and the west wall protrudes inward in the lower half. It was suggested in the literature that errors in W cause errors in discharge of the same relative

magnitude (Bos, 1976). Consequently, the estimated error in W of $\pm 1\%$ will cause an error of $\pm 1\%$ in the measured discharge. This point is further discussed in Section 2.5.

Besides the comparison of recommended and actual dimensions of the 1.83 m (6 ft) Parshall flume, there is a more fundamental consideration to be made - whether this flume size is appropriate for the 1800 mm pipe feeding into this installation. In order to obtain the flume entrance width P of 3580 mm (see Fig. 1), the installation includes a diffuser with an expansion angle of 20° . This arrangement is clearly causing problems because the expansion angle is too large and flow separation takes place. Such problems are further aggravated by the relatively fast feeding pipe flow which is characterized by Froude numbers as high as 0.9. Problems with flume operation caused by the malformed diffuser and high velocities led to recent flume modifications described below.

In an attempt to improve the RH flume performance, the flume geometry was modified by installing two vertical walls in the entrance section and placing a weir plate at the end of the 1800 mm pipe. The first measure attempts to correct the malformed diffuser and the second measure attempts to reduce the excessive inflow velocity. Velocity measurements in the flume entrance section (see Section 3) indicate that the above measures do not remedy the approach flow problems completely. It can be also concluded that the existing RH Parshall flume installation departs from the standard

flume design and this limits the applicability of the standard rating curve to this installation.

The problems encountered in the entrance section of the RH Parshall flume could have been avoided by reducing the slope (and thereby the velocity) of the 1800 mm pipe and using a modified Parshall flume designed for installation at the end of a circular pipe. Such a design is shown schematically in Fig. 2 (Chen et al., 1972).

Compared to the existing flume, the design in Fig. 2 has a narrower throat (1080 mm, compared to 1829), a smaller maximum inlet width (2422 mm, compared to 3580 mm in the original design), and a slightly greater overall length (10.772 m, compared to 10.194 m). It should be noted that this special flume could be fitted into the existing metering vault by reducing the downstream transition whose length is not critical for flume operation. Note also that the expansion angle of the diffuser in this special design is only 8°. The maximum flow rate for the flume shown in Fig. 2 was estimated as $1.710 \text{ m}^3/\text{s}$. It should be emphasized that this flume layout is also non-standard and a special rating curve would have to be used.

2.3 Flume Head Measurement

An important feature of the standard Parshall flume is the location and method of measurement of the flume head. The head should be measured at a point located $2/3 A$ upstream of the flume

throat and this condition is met in the RH flume installation. At this location, the head should be measured in a stilling well connected by a 20 mm inlet tube (perpendicular to the flume side wall) to the flume. The use of the stilling well is extremely important, in order to achieve good measuring accuracy. The stilling well dampens out fast fluctuations of the water surface, particularly those caused by surface waves in a fast flowing water. Replogle (1971) noted that such waves become particularly large in approach flows with Froude numbers greater than 0.50. Considering the Froude numbers in the RH 1800 mm pipe being as high as 0.9, the effects of surface waves on the flume head measurement cannot be neglected. The presence of such waves and air bubbles will further reduce the measuring accuracy of the ultrasonic sensor and the air bubbler used in the RH installation.

2.4 Parshall Flume Rating Curves

In general, the rating curve of a Venturi flume can be expressed as (Bos, 1976)

$$Q = a C_d C_v C_s W h^u \sqrt{g} \quad (1)$$

where a and u are numerical constants, C_d is the coefficient of discharge, C_v is the approach velocity coefficient, C_s is the

submerged flow reduction coefficient, W is the throat width, h is the flume head, and g is the gravitational acceleration.

For a Parshall flume without submergence ($C_s = 1$, which is the case for the RH flume), all the coefficients and constants in Eq. (1) were determined experimentally (Parshall, 1950) and, after substituting for W , Eq. (1) can be reduced to the following form

$$Q[\text{m}^3/\text{s}] = 4.52 h^{1.595} [\text{m}] \quad (2)$$

Equation (2) was compared to the rating curve tabled for the RH flume and a good agreement was found. It should be recognized, however, that because of deviations of the RH flume from the standard design specifications (see Section 2.2), Eq. (2) may not approximate well the actual rating curve of the RH installation.

2.5 Error Analysis

The error analysis of the Parshall flume is based on Eq. (1) and assumptions that $C_s = 1$ (no submergence effects), and constants a , u and g are not subject to error (Bos, 1976). This reduces the sources of error, referred to below as factors F , to four terms - C_d , C_v , W and h .

The composite error in Q is defined as the composite relative standard deviation expressed as (Bos, 1976)

$$\sigma'_Q = \left[\sum_{i=1}^n G_i^2 \sigma_i'^2 \right]^{1/2} \quad (3)$$

where $G_i = \frac{\partial Q}{\partial F_i} \frac{F_i}{Q}$, F_i is a factor influencing Q (its error is independent of errors in other factors), and σ'_i is the estimate of the relative standard deviation of the factor F_i . By applying Eq. (3) to Eq. (1), it can be found that, for C_d , C_v and W , $G_i = 1$, and, for h , $G_i = u$.

Errors in Q measured by a Parshall flume comprise two components - random errors and systematic errors. The former type is caused by only one factor - h and the latter type is caused by all four factors.

The random error component can be written as

$$\sigma'_{QR} = (u^2 \sigma_{hR}'^2)^{1/2} \quad (4)$$

and the systematic component can be written as

$$\sigma'_{QS} = (\sigma_{C_v}'^2 + \sigma_{C_d}'^2 + \sigma_W'^2 + u^2 \sigma_{hS}'^2)^{1/2} \quad (5)$$

Equations (4) and (5) can now be used to estimate flow measurement errors of the RH flume. Such estimates are presented

below for $h = 0.3$ m and the main purpose of these error calculations is to indicate the relative importance of various error factors.

Random errors - these are caused by random errors in measured h . Assuming $\sigma_{hR} = 6$ mm, $\sigma'_{hR} = 6/300 = 0.02$ and after substitution into Eq. (4) ($u = 1.6$), σ'_{QR} is obtained as 0.032. Thus, the random error in measured Q 's is about 3%. This error is not particularly important because the discharge is integrated to obtain the volume and the random errors would cancel out.

Systematic errors - these are considered for two cases. The first one refers to a standard flume installation meeting all flume specifications. In that case, Bos (1976) estimated the combined error for C_v and C_d as $\sigma'_c = 0.03$; for a properly constructed flume $\sigma_w = 0$; and, the error in head measurements in a stilling well can be estimated $\sigma'_h = 5$ mm/300 mm = 0.017. After substitution into Eq. (5), one obtains $\sigma'_{QS} = 0.04$. Such an estimate is consistent with other estimates given in the literature (Replogle, 1971).

The second case to be considered is the RH flume installation. In that case, the combined error for C_v and C_d was somewhat arbitrarily taken as twice the value for standard installations, $\sigma_c = 0.06$; σ_w was earlier estimated as 0.01; and, errors in h were estimated as $\sigma'_h = 15$ mm/300 mm = 0.05. After substitution into Eq. (5), one obtains $\sigma'_{QS} = 0.10$. The above calculations demonstrate that the accuracy of flow measurements by the RH flume is somewhat reduced and it depends largely on errors in C_v , C_d and h .

3. Field Measurements of Discharge

In order to obtain a better understanding of the operation of the RH flume, the discharge through the flume was measured during three time periods. A brief description of these measurements and their results follows.

The discharge through the flume was measured at a cross-section located 2.2 m upstream of the flume throat. Flow velocities were measured at six verticals distributed across the channel as shown in Fig. 3. At each vertical, velocities were simultaneously measured at two points, located 75 mm and 225 mm above the flume bottom, by means of Ott propeller current meters. Because of concerns that floating debris may get caught on the propeller and impede its rotation, the measurements were repeated three times at each point. Current meter operation was monitored closely and when the meter suddenly slowed down, the measurement was abandoned, the meters pulled out of water, cleaned and the whole procedure was repeated.

After processing the meter data, averages of the three repeated readings were established and individual readings compared to these averages. Any reading smaller than 0.9 of the average was excluded from the data set. After such a treatment, the original set of 108 readings was reduced to 99 readings with a mean value of deviation from the average of repeated readings of 3.5%.

During velocity measurements, the depth of flow was also measured using custom made point gauges inside of small cylindrical stilling wells inserted directly into the flow. At the same time, flow rates indicated by the two flowmeters installed at the RH flume were also recorded.

The results of flow velocity measurements are shown in Fig. 3. The velocity plots in Fig. 3 show high non-uniformity with marked vertical and horizontal gradients. Along the verticals, the highest velocities are found in the lower half of velocity profiles, particularly in the central part of the cross-section. This is caused by the flow of water over the weir at the end of the 1800 mm sewer pipe. Although this weir is helpful in reducing the approach velocity, which would be close to the critical velocity, it also distorts the normal velocity distribution.

In the lateral direction, the velocity profiles are fairly symmetrical with the highest velocities found in the central part. This is caused by the concentrated inflow of water from the 1800 mm pipe and inadequate diffusion of flow velocities across the full channel width.

The main value of the velocity data consists in their indication of highly nonuniform velocity distributions in the approach section of the RH flume. Such distributions then adversely affect the measuring accuracy of the RH flume as discussed in the preceding section.

The velocity data were further used to estimate discharges through the RH flume. Towards this end, velocity profiles along verticals were drawn, graphically integrated and the mean velocities at each vertical determined. Using such mean velocities, the velocity profile across the channel was drawn, graphically integrated, and the mean cross-section velocity was determined. The discharge was then calculated as the product of the flow area and the mean cross-sectional velocity. All the measured discharges are listed in Table 2 together with the flow rates read from the charts recorded by the ultrasonic probe and the air bubbler.

Table 2. Flow Rates Measured by Current Meters and the Permanent Instruments

Measurement Number	Discharge (m^3/s)		
	Current Meters	Left Recorder (ultr. probe)	Right Recorder (air bubbler)
1	0.472	0.585	0.545
2	0.499	0.600	0.590
3	0.416	0.580	0.540

Comparison of flows in Table 2 indicates deviations between both flow recorders whose readings exceed the flows measured by current meters. The recorded discharges listed in Table 2 were obtained as averages for the periods during which velocity measurements were taken. For the right recorder, the difference between

the discharges measured by current meters and those recorded by the flume are, on the average, about 21%. This average is somewhat elevated by the high third reading. Assuming somewhat arbitrarily the accuracy of discharge measurements by current meters as $\pm 10\%$, the flume-recorded discharges exceed the measured ones by at least 10%. Such exceedances are significant and should be further investigated.

4. Improvements of the RH Parshall Flume

The RH flume represents a sizeable investment intended to provide accurate flow measurements at this site. This initial objective can be met through modifications or redesign of the existing structure. From the operational and economical point of view, the former alternative is much more attractive.

To improve the measuring accuracy of the existing flume, it is required to address the points in which it departs from a standard installation. Three areas of potential improvements are obvious - the distribution of approach velocity, inlet section geometry and head measurements. The first two items are interrelated and, consequently, they are discussed together below.

To improve the inflow conditions, it should be attempted to achieve an uniform velocity distribution by means of removable walls and baffles. The layout of such walls and baffles would be best determined in a scale model which could be also used to establish the rating curve of the modified flume. It should be recognized that the

addition of walls and baffles may require more frequent maintenance of the facility.

As observed in the RH flume and reported in the literature (Replogle, 1971), direct measurements of the head in the flume are inaccurate. Such errors are then magnified (1.6 times) and produce even larger relative errors in the discharge. It is therefore imperative to improve the accuracy of head measurements in the RH flume by installing a stilling well in the area behind the partitions inserted into the flume. Such an arrangement would change the location of the head measurements (further upstream), but this can be accounted for in the rating curve as demonstrated by Davis (1961). The feasibility of such a measure could be also checked in a scale model. Should the modified flume layout prevent the installation of a stilling well, the existing head recording system and its accuracy should be further examined. The smoothing of head readings by means of signal processing should be considered.

The second option for improving the existing facility would be a complete redesign and reconstruction using the layout shown in Fig. 2. Such a measure would disrupt the operation of the existing installation and it would be quite costly. The redesigned flume would be non-standard and its rating curve would have to be determined from the literature data, or by calibration. For the above reasons, the redesign option is rather unattractive and should be

considered only if the earlier proposed flume modifications would fail to produce acceptable results.

5. Conclusions

- (i) The Richmond Hill Parshall flume deviates from the standard flume design by the layout of the approach section and the direct methods of head measurements.
- (ii) Relatively fast flows overfalling a weir at the end of the 1800 mm feed pipe and a fairly sudden channel expansion result in a highly nonuniform distribution of the approach velocity. This distribution then reduces the measuring accuracy of the RH flume.
- (iii) Although the specifications of the standard Parshall flume call for head measurements in a stilling well, in the RH flume, such measurements are done directly in the flume. Direct head measurements lead to large errors, caused by water surface disturbances, and these errors then contribute to even larger, 1.6 times, errors in the discharge. Such an error magnification corresponds to the exponent of head h in Eq. (2) and is common to all Venturi flumes.
- (iv) In retrospect, the flow measurement at the discussed site could have been accomplished better by reducing the slope of the feed pipe, designing the flume with a

throat 1080 mm wide (see Fig. 2), and equipping the flume with a stilling well for head measurements.

- (v) Field observations indicate that the existing RH flume overestimates the actual discharges. The magnitude of overestimation is difficult to determine, but for the data in Table 2 and assumed accuracy of current meter measurements of $\pm 10\%$, it may be conservatively estimated at 10%. At this time, no assessment of flow measurement accuracies outside of the range of the observed flows can be made.
- (vi) The measuring accuracy of the RH flume could be significantly improved by modifying or redesigning the flume, particularly its approach section, and by retrofitting it with a stilling well for head measurements.

6. Recommendations

- (i) The flow measurement accuracy of the Richmond Hill Parshall flume should be improved by modifying the existing structure, calibrating the modified flume, and retrofitting it with a stilling well.
- (ii) A scale model of the existing flume should be built and used to finalize the layout of the approach section which should provide an uniform velocity

distribution. The final layout should be calibrated in the same model, which can be also used to reproduce the earlier configurations of the RH flume and estimate errors in their rating curves. It may not be possible, however, to estimate the corresponding head measurement errors caused by surface waves in the flume.

- (iii) It is recommended to proceed with Phase 2 of the original proposal (NWRI, 1986 - Section 6.2) expanded for the testing of the final layout (NWRI, 1986 - Item 6.3). The cost of such activities is estimated as $\$4,963.00 + \$1,413.50 = \$6,376.50$ plus the cost of the final report of $\$1,283.00$. Thus, the total cost is $\$7,659.50$.

7.

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FIGURES

PLAN

Diagram showing the plan view of the structure with dimensions and labels:

- Overall width: 1800
- Overall length: 10194
- Labels: Retrofitted partition, A, P = 3580, D = 2670, A = 2106, 1400, W = 1780 - 1845, C = 2140, M = 457, B = 2065, F = 618, G = 914, 2889.

The diagram illustrates the cross-section of a weir structure. Key dimensions and components are labeled as follows:

- Overall Height:** 1800 (indicated on both the left and right sides).
- Retrofitted Weir:** Indicated by an arrow pointing to the left side of the structure.
- Horizontal Dimensions:**
 - 3251: Distance from the left face to the first vertical partition.
 - 94: Thickness of the first vertical partition.
 - 1105: Thickness of the central vertical partition.
 - 6943: Distance from the central vertical partition to the right face.
 - 10194: Total width of the structure.
- Structural Labels:**
 - $E =$: Label for the central vertical partition.
 - $N = 305$: Label for the central vertical partition.
 - $K = 76$: Label for the rightmost vertical partition.

Fig.1 Richmond Hill III Parshall Flume Layout (Dimensions in mm)

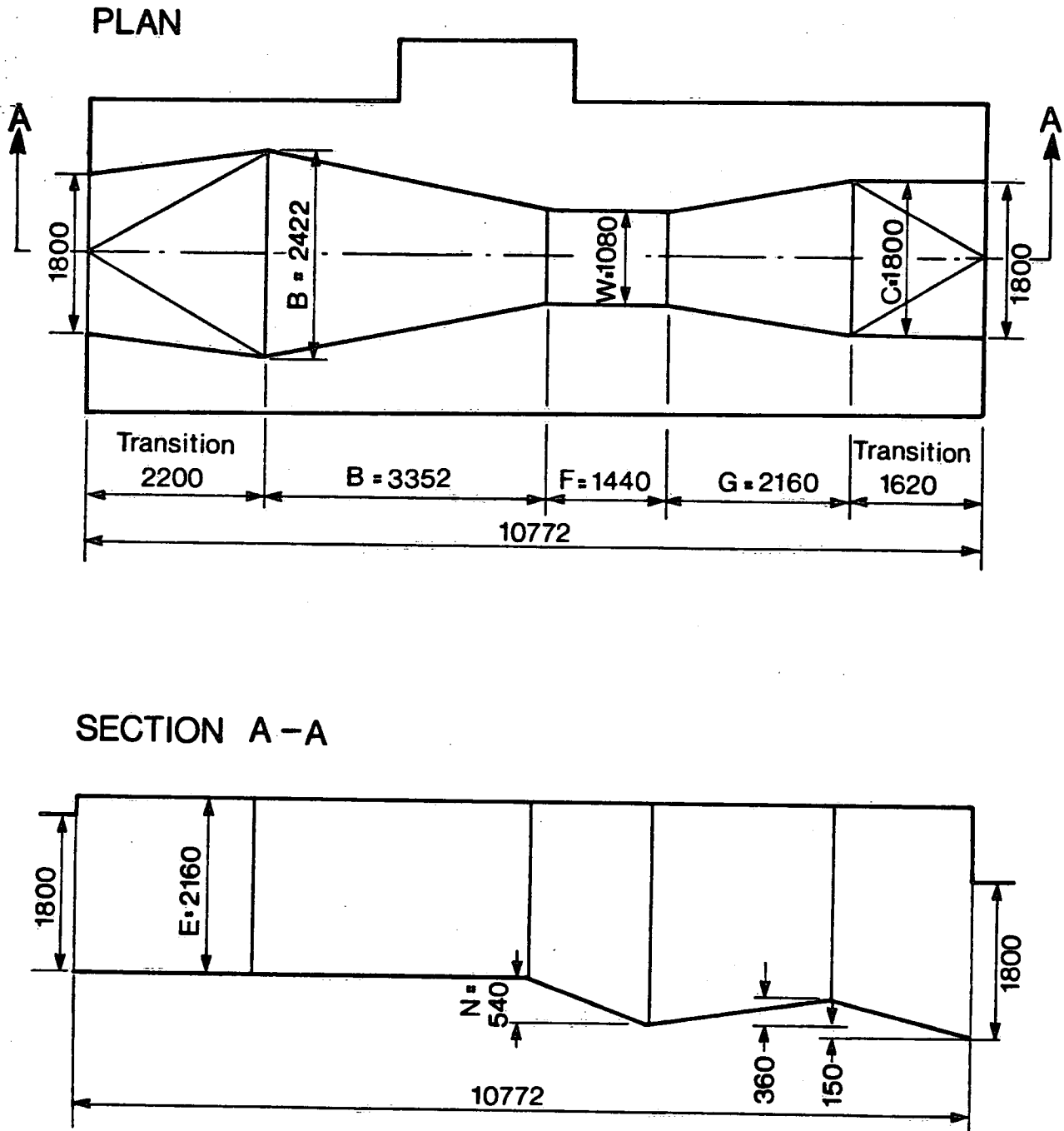


Fig.2 Parshall Flume attached to a pipe (After Chen et al., 1972)

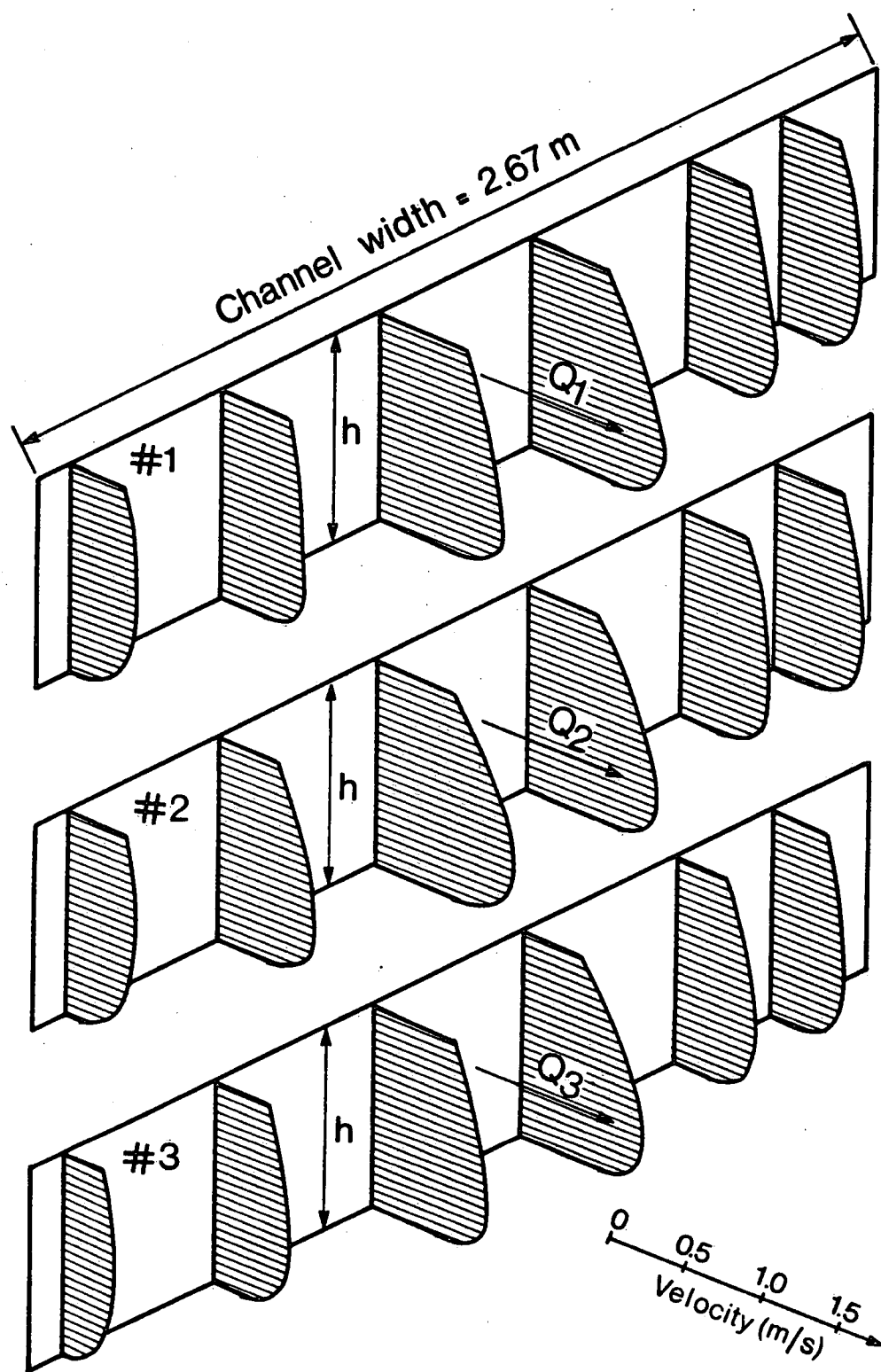


Fig.3 Observed velocities in the Richmond Hill III Parshall Flume.