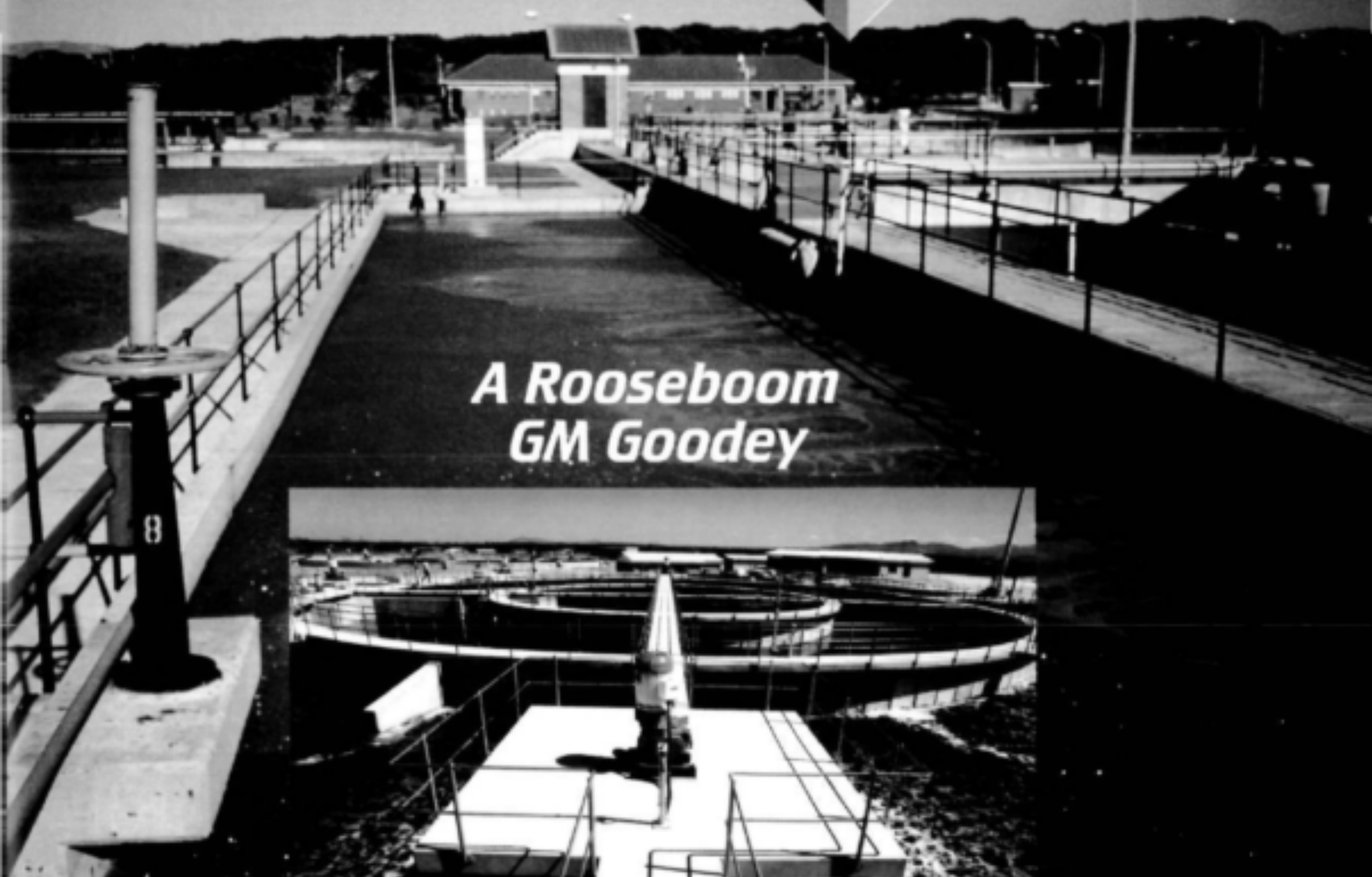
# Guidelines for the Calibration of Measuring Flumes in Sewers



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GM Goodey

# GUIDELINES FOR THE CALIBRATION OF MEASURING FLUMES IN SEWERS


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## SYNOPSIS

ERWAT operates countless flow-measuring flumes which have been designed and constructed by different organisations. Uncertainty existed regarding the accuracy of these flumes as many had not been constructed according to standard specifications. It was also necessary to investigate the use of velocity recorders in conjunction with stage (depth) recorders as ERWAT had already started to use velocity recorders together with stage recorders for integrated flow measurement, particularly at flumes where submergence had caused problems.

The impact of submergence on the calibration coefficients of typical measuring flumes was also investigated.

Tests were also performed on different flumes in order to establish the impact of differences in shape and surface roughness on calibration coefficients. It has been found that differences in shape led to a maximum error of 2.7% and that surface roughness caused a maximum error of 1%. It is thus evident from the laboratory test results that both shape and surface roughness play only minor roles with respect to the accuracy of flow measurement in flumes.

Guidelines were compiled on the calibration of measuring flumes.

Information has been included on the measurement of discharges in pipes which flow partially full under uniform flow conditions. This information may be used to measure discharges by means of velocity recorders in cases where it is not practicable to install (more accurate) flumes.

A standard measuring flume has been calibrated accurately. This flume may be used in up-or down-scaled versions for accurate flow measurement under a wide range of conditions.

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LIST OF SYMBOLS

$w$ = width of measuring flume (m)

$W$ = width of channel (m)

$C_d$ = coefficient of discharge

$C_v$ = coefficient of velocity

$C$ = calibration coefficient ($C_d \cdot C_v$)

$g$ = gravitational acceleration ($9.81 m/s^2$)

$h_1$ = depth of flow upstream from the flume (m)

$h_2$ = depth of flow in measuring flume (m)

$h_3$ = depth of flow downstream from the flume (m)

$h_{max}$ = maximum depth of flow measured (m)

$h_3/h_1$ = degree of submergence of measuring flume

$L$ = length of measuring flume (m)

$Q$ = discharge ($m^3/s$)

**LIST OF FIGURES**

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**ACKNOWLEDGEMENTS**

The authors would like to express their appreciation to Messrs

JW Bester
V Jonker
LF Pieterse

for their important contributions.

**Appendix A** is mainly the product of the work of Messrs Bester and Jonker. Mr Pieterse conducted additional tests to validate previous findings.

**Appendix A** contains a detailed account of the tests which were carried out on various Venturi flumes.

**Appendix D** is mainly the product of the work of Messrs Bester and Jonker. Mr Pieterse conducted additional tests to validate previous results.

**Appendix D** discusses all laboratory tests at length and the findings are repeated in this report and briefly explained. The **Appendix** therefore contains more detailed information on how the laboratory tests were conducted and plots of the results obtained.

The financial support received from ERWAT (East Rand Water Care Company) and the WRC is acknowledged with special thanks.

A special word of thanks also to:

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## 1. INTRODUCTION

Flow measurement in open channels may be done in a number of ways. The most common structures used in South African rivers are measuring weirs (multi-notch or V-notch) and measuring flumes. Due to the solids content in sewage, measuring weirs cannot be used to measure flow in sewage works, as the solids are deposited upstream from the weirs. For this reason measuring flumes, i.e. controls created by horizontal contractions in open channels, are most commonly used in sewage works to measure flow. Standard equations for calibration curves are available to calculate flow through these measuring flumes but these equations are subject to measuring flume compliance with certain specifications.

Due to the fact that many of the measuring flumes which have been taken over by the East Rand Water Care Company (ERWAT) do not comply with specifications or have other defects, the accuracy of flow metering at these measuring flumes is questionable. Of particular concern is the impact of deviating dimensions, inlet shape, roughness in the flume itself, as well as submergence of the flume, on the accuracy of flow metering.

Extensive tests were conducted in the Hydraulics Laboratory of the University of Stellenbosch which attempted to establish calibration coefficients, enabling ERWAT and other organisations to accurately calibrate all their measuring flumes. As flows were tested at high Reynolds numbers, the ratios as calibrated with relatively clean water are representative of those which would be obtained with sewage, on condition that the suspended matter concentrations in the laboratory are high enough to be registered by the measuring equipment.

A measuring flume with standard dimensions was calibrated accurately in the laboratory. Up- or down-scaled versions of this flume, with known calibration curves, could be constructed. Similar flumes could also be constructed to calibrate flow recorders.

As it is sometimes particularly difficult to install standard structures in existing pipelines, tests to allow conversion of velocity measurements to discharges within pipelines, were also conducted. By means of this conversion it is possible to measure flows in the sewer at a manhole on existing pipelines without having to make any structural changes.

## 2. THEORETICAL BACKGROUND

### 2.1 General

Of the wide variety of existing measuring flumes which have been developed in the past, only a few have been adequately studied and tested in laboratories. *British Standards 3680: Part 4C* recommends three types of measuring flumes, namely:

a) the rectangular inlet measuring flume
b) the trapezoidal inlet measuring flume
c) the U-shaped inlet (curved bed) measuring flume.

The conventional (rectangular inlet) type of measuring flume is generally known as the *Venturi* measuring flume and comprises curved inlet sides, parallel passage and a divergent outlet as shown in Fig. 2.1(a). Figure 2.1(b) shows a measuring flume with convergent non-curved inlet sides and divergent outlet. The rectangular inlet measuring flume is much more popular than the other types, because of its simplicity, easy construction, accuracy and low price.

Relatively little backing-up occurs in the sewer upstream from this type of measuring flume, as a result of the contraction in the channel, making this measuring flume extremely suitable for flow metering in channels where the depths of flow in the upstream section of the flume are limiting.

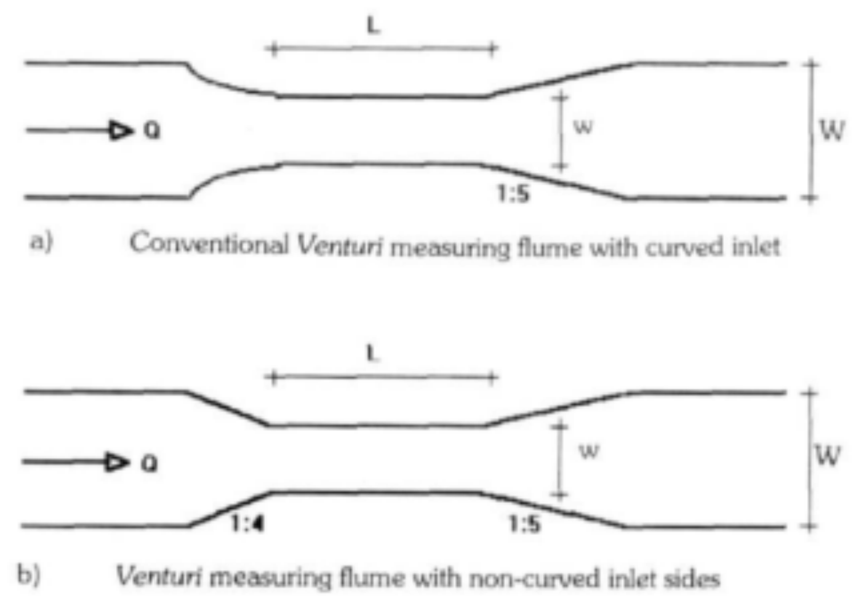


**Figure 2.1 Layout of measuring flumes**

The throat length (L) of the measuring flume must be long enough to ensure that the surface profile of the water can change gradually. There is, however, also a special group of "short" measuring flumes which are cheaper to construct than the ideal "long" measuring flumes. The disadvantage of the "short " measuring flumes is that the surface profile of the water varies more rapidly which hampers the theoretical analysis of flow through the flume. An empirical relationship for these types of flumes must therefore be found by means of experiments. For this reason "short" measuring flumes are usually constructed according to a standard design (e.g. the Parshall flume) which has already been calibrated thoroughly.

The throat width (w) of the rectangular measuring flume also plays an important role in the efficient performance of a measuring flume. The width of the flume must be narrow enough to allow critical conditions to prevail in the flume at all times, which ensures that the downstream depth of flow ($h_3$) will not influence the upstream depth of flow ($h_1$) (i.e. $h_3/h_1<0.75$). With critical flow assured, only the upstream depth of flow ($h_1$) need then be known to calculate the discharge by means of Eq. (2.1). The contraction in the measuring flume channel causes water to back up in the upstream section of the flume. Should the throat width (w) of the measuring flume be too narrow, the backed-up water levels could cause problems. The throat of the flume should therefore be wide enough to limit the backing-up of water, but should at the same time be narrow enough to ensure that critical flow in the flume is maintained[1].

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1 *British Standards 3680* (1981) *Part 4C, Flumes*

2.2 **Calculation of discharge (Q)**

Contracted discharge is calculated by applying Eq. (2.1)[2]. The equation is universally valid for contractions where the depth of flow ($h_2$) downstream from the flume will not influence the upstream depth of flow ($h_1$), i.e. $h_3/h_1<0.75$. Only the upstream depth of flow and the width of the flume (w) need then be known to calculate the discharge.

$$Q = 1.71 C_d C_v w h_1^{\left(\frac{3}{2}\right)}$$
$$= 1.71 C w h_1^{\left(\frac{3}{2}\right)} \qquad (2.1)$$

$C_d$ and $C_v$ are coefficients which respectively provide for contraction and energy losses.

Should the downstream depth of flow, however, influence the upstream depth of flow, Eq. (2.2) is employed to calculate the discharge.[3] The equation is universally valid for contractions where $0.75<h_3/h_1<0.9$. The upstream depth of flow ($h_1$) and the depth of flow in the flume ($h_2$) are required to calculate the discharge by means of the equation:

$$Q = \frac{C_d h_2 w \sqrt{2g(h_1 - h_2)}}{\sqrt{1 - \left(\frac{w h_2}{W h_1}\right)}} \qquad (2.2)$$

The value of the coefficient $C_d$ is generally between 0.96 and 0.99.

2.3 **The points of measurement in the measuring flume**

Figure 2.2 shows the points of measurement in the measuring flume. The depth of flow upstream from the measuring flume ($h_1$) must be measured at a distance of three to four times the depth of the highest depth of flow to be measured (i.e. between $3h_{max}$ and $4h_{max}$) upstream of the contraction. The depth of flow in the flume ($h_2$) must then be measured at a distance equal to the width of the flume downstream of the end of the contraction. The downstream depth of flow ($h_3$) is measured at a distance of 1 m downstream of the divergence in the channel.

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2 Webber NB (1965) *Fluid Mechanics for Civil Engineers*. p 228

3 Webber, NB (1965) *Fluid Mechanics for Civil Engineers*. p 227

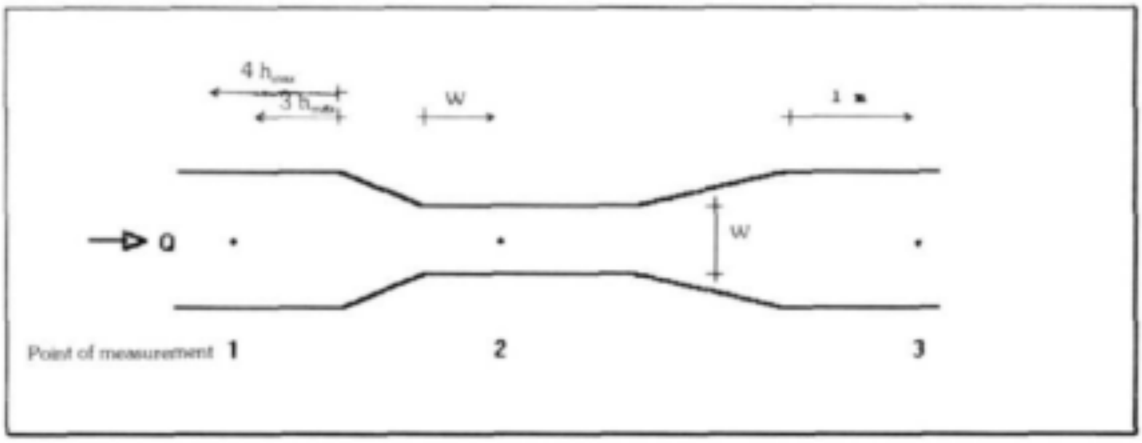



**Figure 2.2 Points of measurement in the measuring flume**

## 3. DETERMINATION OF CALIBRATION COEFFICIENTS

By plotting calibration coefficients (C and $C_d$) obtained from model studies, a calibration coefficient for any w/W, $h_3/h_1$ and $h_1/W$ ratio can be found. Two sets of plots were drawn up: for partially submerged and for submerged conditions.

### 3.1 The influence of submergence on the calibration coefficients

The degree of submergence is given by the $h_3/h_1$ ratio i.e. the ratio between the downstream and the upstream depth of flow. In general two types of conditions are found in the measuring flume, i.e. submerged and partially submerged conditions.

a) **Partially submerged condition** (Fig. 3.1)

Partially submerged conditions are found in the measuring flume when critical conditions prevail, i.e. the downstream depth of flow ($h_3$) does not influence the upstream depth of flow ($h_1$). A hydraulic jump then also occurs in or just behind the measuring flume. For partially submerged conditions to occur the $h_3/h_1$ ratio must be smaller than 0.75. With known w/W and $h_1/W$ ratios the calibration coefficient C can then be found from Fig. 3.1 and the discharge can be calculated by using Eq. (2.1).

b) **Submerged condition** (Figs. 3.2 to 3.4)

Submerged conditions conducive to measuring exist when the $h_3/h_1$ ratio falls within the range $0.9 > h_3/h_1 > 0.75$. The calibration coefficient $C_d$ (coefficient of discharge) is very sensitive to change in the degree of submergence. Three rating curves were prepared, each of which makes provision for a different $h_3/h_1$ ratio. With known w/W and $h_1/W$ ratios and by also measuring the depth of flow in the flume ($h_2$) the discharge can now be calculated by means of Eq. (2.2). It was found that the best position for measuring the depth of flow in the flume ($h_2$) is at a distance w from the start of the contraction (Fig. 2.2).

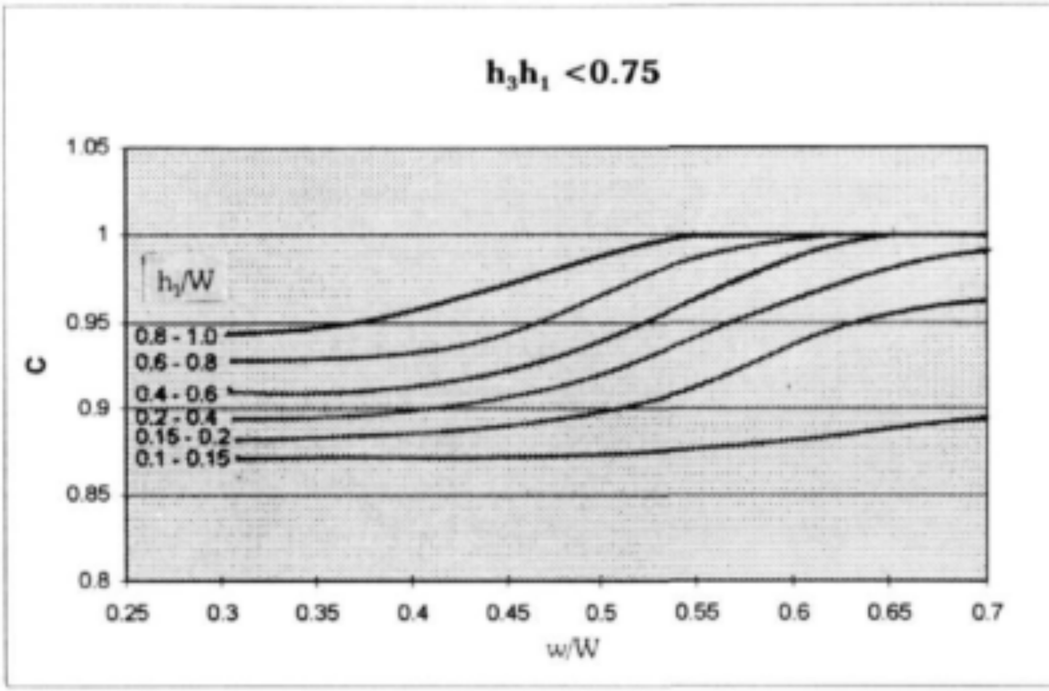



**Figure 3.1 Determination of the calibration coefficient C**

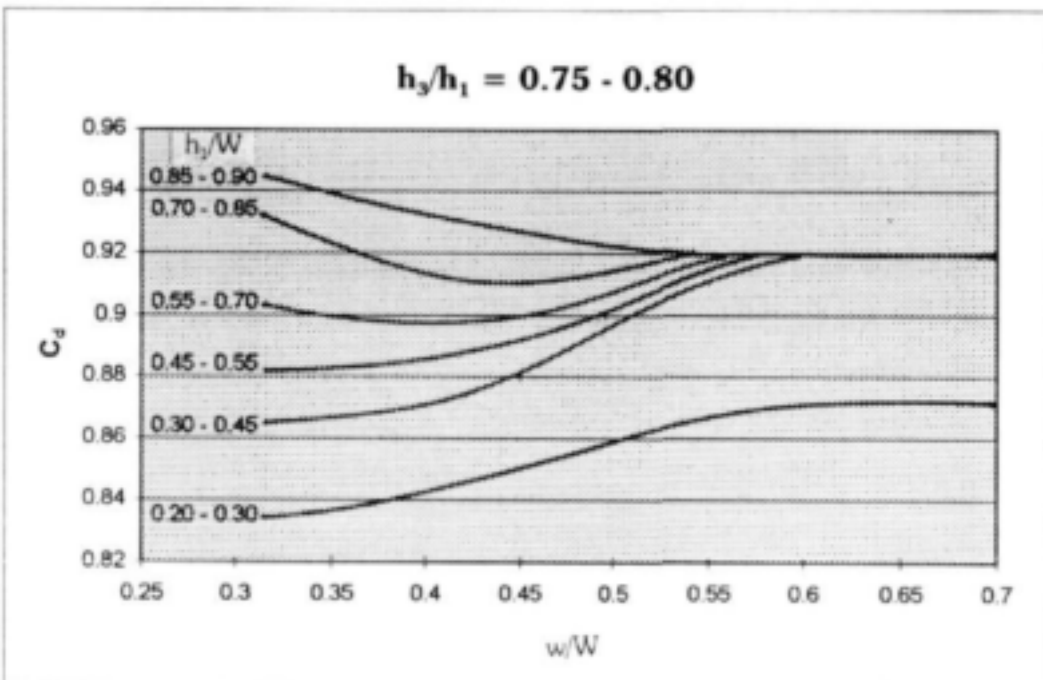



**Figure 3.2 Determination of the calibration coefficient $C_d$ ($0.75<h_3/h_1<0.80$)**

## 3.2 The effect of inlet shape on calibration coefficients

Two extreme inlet shapes (refer to Fig. 2.1) were tested: a quarter-round and a non-curved (1:4) inlet-side shape. Based on these tests a form factor was derived which makes provision for the various inlet shapes. The form factor given in Table 3.1 must be multiplied by calibration coefficients C and $C_d$ to provide new calibration coefficients which take account of the inlet shape.

**Table 3.1 Form factor**

| $h_3/h_1$ | Inlet shape | | Multiplied by |
|---|---|---|---|
| | Quarter-round | Non-curved (1:4) | |
| <0.75 | 1.010 | 1.000 | C |
| 0.75 - 0.90 | 1.027 | 1.000 | $C_d$ |

Although these two inlet shapes represent extremes, the coefficient values do not vary much. By interpolation a reliable form factor can be obtained for any inlet shape between flat and circular. The inlet shape recommended by *British Standards 3680* (R≥ 2 (W-w)) lies approximately between the curved and the non-curved (1:4) inlets and the form factor can be interpolated accordingly.

## 3.3 Influence of flume roughness on the calibration coefficient

In some measuring flumes roughness is increased due to erosion of the cement and sand in between the aggregate (stone). Increased roughness occurs mainly in the bottom part of the flume. Tests were done to determine the effect of increased roughness on the calibration coefficient and to establish a factor by means of which the normal factors can be multiplied to allow for the roughness.

**Table 3.2 Roughness factor**

| $h_3/h_1$ | Flume roughness | | Multiplied by |
|---|---|---|---|
| | Drastic | None to small | |
| <0.75 | 0.99 | 1.000 | C |
| 0.75 - 0.90 | 0.99 | 1.000 | $C_d$ |

It was found that roughness has a negligible influence on calibration coefficients. Table 3.2 shows that, for cases where the measuring flume sides are very rough, the C and $C_d$ values can be multiplied by a roughness factor of 0.99 to establish new calibration coefficients which allow for flume roughness. This means that the roughest surface will only lead to a 1% reduction in discharge, on condition that the basic dimensions in the throat orifice are not affected.

# 4. THE USE OF VELOCITY RECORDERS IN FLOW MEASUREMENT

The velocity recorder which was used comprised a *Flowtra* instrument and a small floating raft which floats on the water surface. The action of the floating raft and *Flowtra* instrument is based, in broad terms, on the *Doppler* effect, as the signal which is sent by the floating raft, is reflected by particles in the water and received by the floating raft again. The difference in wave length between the downward and the reflected signal is converted to velocity by the velocity recorder. The average water velocity between 0 and 100 mm beneath the water surface is measured by the floating raft. In addition an electronic stage recorder can be attached to the *Flowtra* instrument and the discharge can then be calculated by this instrument.

In practice the velocity recorder is used over a period of 15 min. At the end of the 15 min interval, the average discharge, as calculated over 15 min, is given.

### 4.1 The calibration of the velocity recorder

By means of the calibration coefficients, determined as described in **Paragraph 3** and by measuring the depth of flow at the measuring flume, it is now possible to determine the precise discharge for any measuring flume. With the discharge known the velocity recorder can then be calibrated *in situ* for any measuring flume.

### 4.2 The performance of the velocity recorder

Tests were performed under submerged and partially submerged conditions. It could thus be determined whether the velocity recorder is sensitive enough to record a change in velocity as a result of the influence of the downstream depth of flow on the upstream depth of flow. The velocity recorder is installed at a distance of between $4h_{max}$ and $5h_{max}$ upstream from the measuring flume and measures both the velocity and the depth of flow, from which the discharge is calculated. If preferred, the velocity only can be indicated by the instrument and the discharge can then be calculated afterwards.

It was found that the velocity recorder is in fact sensitive enough to register small changes in the velocity such as the change brought about by the effect of downstream depth of flow on the upstream depth of flow, should submerged conditions occur in the flume.

### 4.3 The accuracy of the velocity recorder

The accuracy of the velocity recorder as well as that of the electronic stage recorder was determined by calibrating the K-factor (calibration factor) at various discharges. The K-factor was calibrated for above-average, average and below-average discharges. The discharge is then decreased and increased systematically upon which the discharges, calculated by the *Flowtra* instrument, are compared with the true discharges.

It was found that the best results are obtained when both the flow velocity and the depth of flow are calculated by the *Flowtra* instrument and the K-factor of the floating raft is calibrated at an average discharge. The results obtained when calibrating the K-factor at a below-average or above-average flow are, however, still acceptable.

It is recommended that the velocity recorder not be used under conditions of more than 90% submergence, but rather to modify the flume lay-out to reduce the submergence to below 90%, as it was found that conditions became very unstable at $h_3/h_1 > 0.90$. Techniques for structural changes to a measuring flume are discussed in **Paragraph 7**.

## 5. FLOW MEASUREMENT IN PIPELINES

### 5.1 Introduction

Often it is not possible to install a flume in a sewer, particularly in existing pipelines. This could be due to a lack of space but more often the added depth of the backed-up water and energy losses cannot be accommodated. In cases where uniform-flow pipelines can be accessed, the measurement of surface velocity and depth of flow is an attractive option. These values can then be used to calculate the metered discharge.

Tests were performed on semicircular pipelines (with vertical side-walls above the half-rounds) with diameters of between 400 mm and 595 mm.

Major problems were encountered when attempting to calibrate the *Flowtra* instrument under these circumstances. It was postulated that the laboratory water solids concentration was too low to obtain proper readings. A different type of velocity recorder, i.e. a DETEC 3013 was therefore used to do calibrations.

The following graphs were plotted and can be used to derive the mean velocity from the velocity immediately below the surface. In the calibration tests the mean velocity of the top 100 mm was determined in accordance with the measuring range of the *Flowtra* instrument. As the calibration tests were carried out on a 595 mm diameter pipeline, the graph shown in Fig. 5.1 will be accurate for pipelines with the same diameters. The graph should also provide reasonably accurate results for pipelines with slightly smaller or bigger diameters. Where there is doubt, the ratio between the mean velocity in the pipeline and the measured velocity can be determined by means of the velocity contours shown in Fig. 5.2.

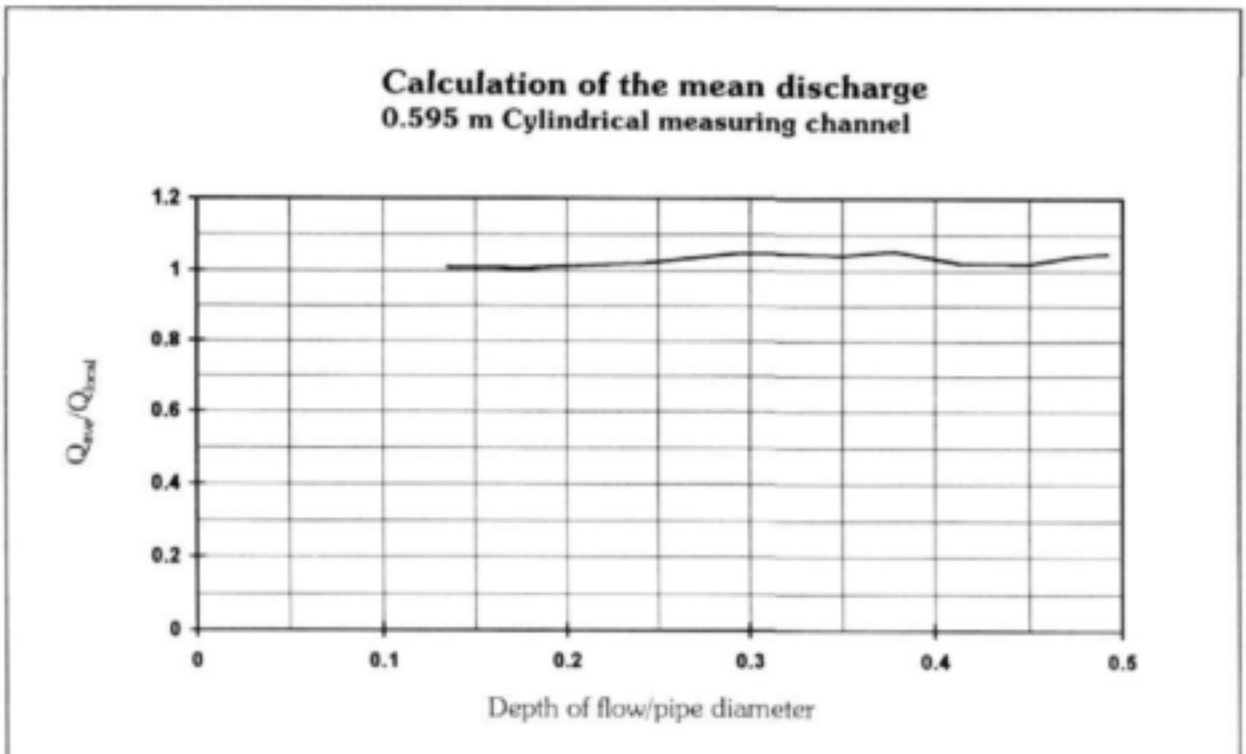



**Figure 5.1 Calculation of the mean velocity from the measured sub-surface velocity**

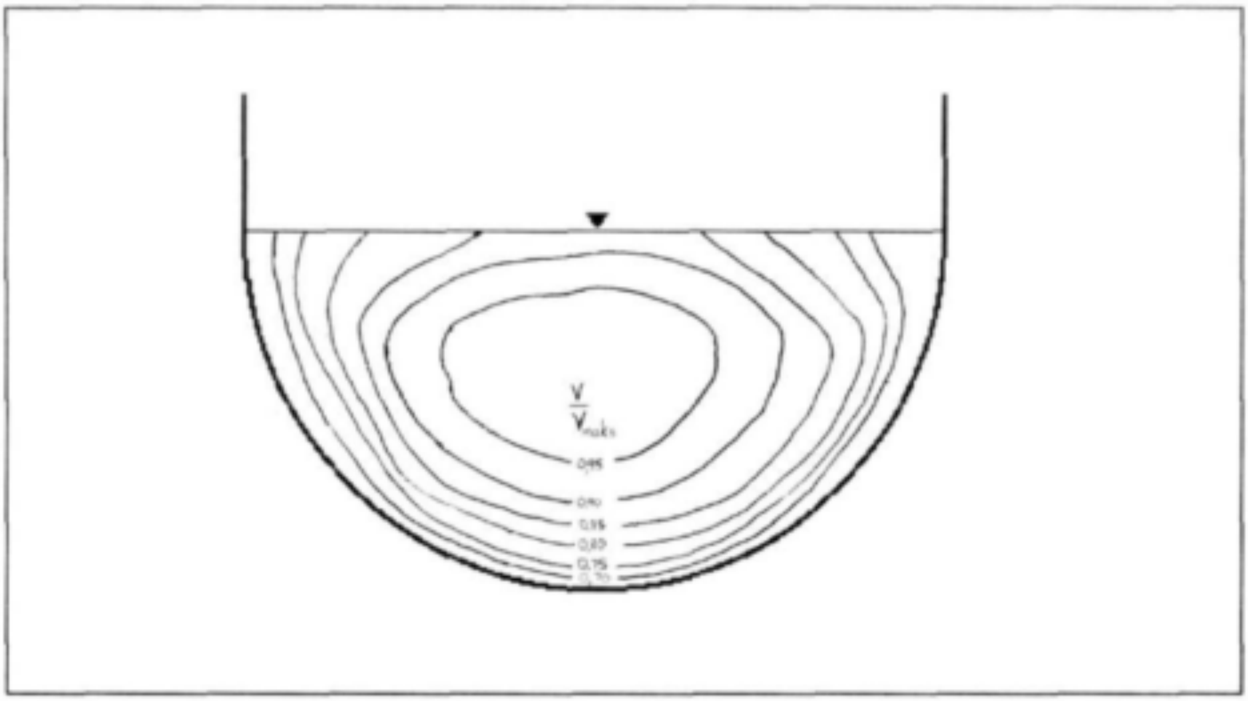


**Figure 5.2 Typical velocity contours in a cylindrical measuring channel**

## 6. CALIBRATION OF A MEASURING FLUME IN A RECTANGULAR CHANNEL

In this section a description is given of how any measuring flume can be calibrated *in situ* by means of the calibration coefficients (C and $C_d$) to find a unique relationship between the upstream depth of flow and the discharge.

### 6.1 Algorithm for the *in situ* calibration of a measuring flume

The best relationship between the upstream depth of flow and the discharge is found by conducting the calibration over a reasonable time period. If possible, the values selected for the calibration should cover the anticipated range of discharges to be measured.

**Step 1**: Set up three stage recorders at Points 1, 2 and 3.
Fig. 2.2 shows the points of measurement. At Points 1 and 3 electronic stage recorders could be used, but at Point 2 a needle gauge must be used as the electronic recorder cannot accurately measure the varying water level in the flume.

**Step 2**: Measure the depth at Point 1 ($h_1$)and Point 3 ($h_3$) for the peak discharge.
Calculate $h_3/h_1$
For $h_3/h_1$:
<0.75 go to Step 2a
0.75 to 0.90 go to Step 2b
>0.90 go to Step 2c

**Step 2a**: Partially submerged conditions ($h_3/h_1<0.75$)

Measure $h_1$ over the total flow range
Determine C for every $h_1$ from Fig. 3.1
Calculate the discharge (Q) by means of Eq. (2.1)
Find relationship between Q and $h_1$
Plot relationship between Q and $h_1$ on graph paper

**Step 2b**: Submerged conditions ($0.75<h_3/h_1<0.90$)

Measure $h_1$, $h_2$ and $h_3$ over the total flow range

If $0.75<h_3/h_1<0.90$:
Determine $C_d$ for each case from Figs. 3.2 to 3.4
Calculate the discharge (Q) by means of Eq. (2.2)

**Step 2c**: Submerged conditions ($h_3/h_1>0.90$)

Conditions become very unstable for $h_3/h_1>0.90$ which makes it impossible to determine calibration coefficients accurately. Should it therefore appear that a flume is more than 90% submerged the flume has to be improved structurally in order to bring submergence down to below 90%. Various techniques to improve flumes structurally are discussed in **Section 7**.

The end-product of the calibration process is therefore a unique relationship between the discharge and the upstream depth of flow. This relationship can then be used to calculate the discharge or it could be used to calibrate the velocity recorder *in situ*.

Worked examples of the determination of calibration coefficients are given in **Appendix A** and **Appendix B** contains worked examples of the procedure to find a unique relationship between Q and $h_1$.

## 7. IMPROVING EXISTING MEASURING FLUMES

Where flume submergence is greater than 90% i.e. $h_3/h_1>0.90$, the measuring flume has to be improved structurally to ensure more accurate discharge measurements. Various techniques are available to bring about an improvement:

i) Decrease the width (w) of the measuring flume.

The head then increases in the upstream section of the flume which decreases the $h_3/h_1$ ratio.

ii) Elevate the flume bed.

This method once again increases the head upstream from the flume and can be used if the flume is already very narrow. The technique is described fully in *BS 3680: Part 4C* (1981) and a sketch is shown on p. 18 in the same code.

iii) Lower the bed downstream from the measuring flume.

This technique may be used if the conduit floor can be lowered on the downstream side, especially in instances where new pipelines are being designed.

Techniques (i) and (ii) both increase the head upstream from the flume and therefore provision must be made to raise channel walls upstream of the measuring flume, if necessary.

## 8. GUIDELINES FOR CONSTRUCTING FUTURE MEASURING FLUMES

Based on the large number of tests performed in the laboratory, and the first-hand knowledge obtained, guidelines were drawn up for future measuring flumes.

### 8.1 General guidelines

i) In the first instance the measuring flume should comply with the requirements of the *BS 3680: Part 4C: Flumes* (1981). Paragraph 10.6 (*Limits of Application*) and Fig. 1 on p. 18 should be noted in particular.

ii) The code specifies that $w/W<0.70$ and no lower limit is specified. Theoretically it would be a good idea to ensure that w/W is small enough to be sure that $h_3/h_1<0.75$. It should, however, be borne in mind that the narrower the flume the higher the backed-up water level upstream from the flume.

Laboratory tests showed that a w/W ratio of between 0.40 and 0.55 proved to be the best. For $w/W<0.40$ the back-up in the upstream section of the flume becomes very high and requires a reasonably deep channel. For $w/W>0.55$ the upstream depth of flow becomes more sensitive to changes in the downstream depth of flow and critical conditions in the flume are no longer well defined.

The w/W ratio should therefore, as far as possible, be kept at between 0.40 and 0.55. If contraction is necessary to prevent submergence, the flume could be further contracted to a w/W ratio of 0.30.

iii) The *BS 3680: Part 4C* recommends that $h_1/L<0.50$. The length of the contraction should therefore be at least twice the size of the maximum upstream depth of flow. Critical conditions in the flume are thus more defined and the longer length provides more effective separation between the upstream and the downstream depths of flow under submerged conditions.

iv) As described in **Section 6**, the maximum $h_3/h_1$ ratio in a flume should preferably be less than 0.75, but submergence up to 0.90 is still manageable. This should be taken into account when the measuring flume is installed upstream of a sluice or other structures which could cause flume submergence.

v) The effect of the inlet shape on measuring flume calibration coefficients is minimal. Therefore non-curved inlets, with a contraction of 1:4, are just as acceptable as curved inlets. The non-curved shape is, however, recommended as it is cheaper and easier to construct.

vi) As the velocity and stage recorders are installed at approximately $4h_{max}$ upstream from the flume, provision must be made that the upstream distance from the flume is sufficient so that the measurements at $4h_{max}$ are not disturbed by conditions further upstream

vii) In accordance with *BS 3680: Part 4C* the measuring flume bed must be horizontal from $6h_{max}$ upstream from the flume up to the end of the contraction, i.e. up to the divergent section of the measuring flume.

simple. Up- or down-scaling of an already calibrated measuring flume could, however, also be used. This method is described in **Paragraph 8.2**.

## 8.2 Up-or down-scaling of a standard measuring flume

A standard measuring flume was calibrated in the Hydraulics Laboratory of the University of Stellenbosch for future up- or down-scaling of the flume in practice. The dimensions of the standard measuring flume are given in Fig. 8.1.

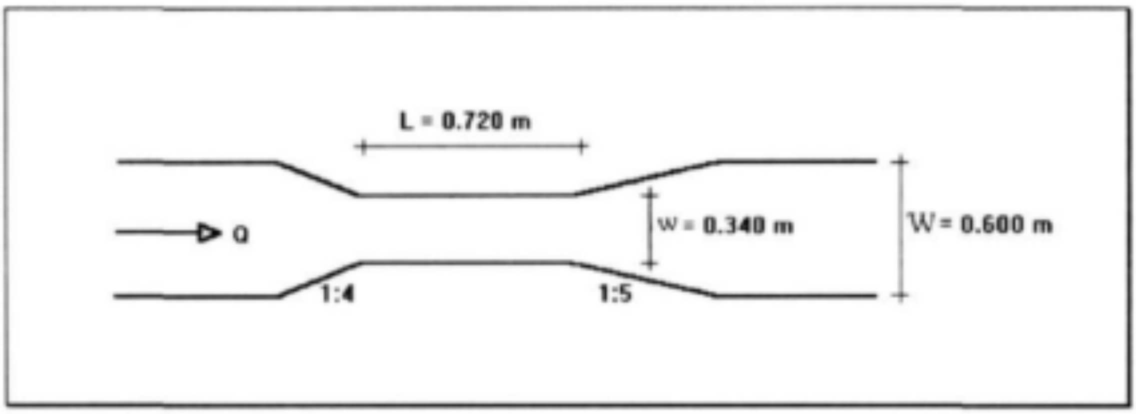



**Figure. 8.1 Standard measuring flume dimensions**

Standard measuring flume calibration curves are available and the discharge for various upstream depths of flow, can be found. The plot of discharge (Q) vs. upstream depth of flow ($h_1$) for the standard measuring flume is shown in Fig. 8.2.

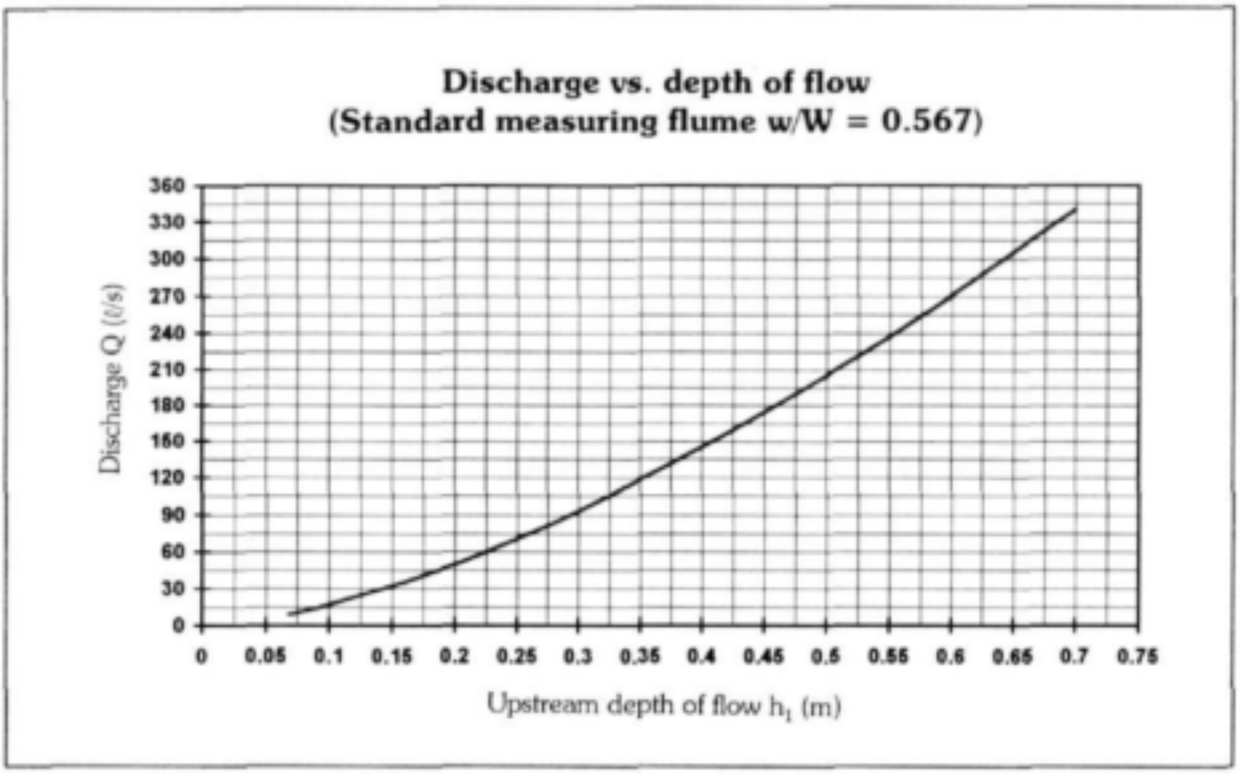



**Figure 8.2 Discharge vs. depth of flow (only for standard measuring flumes)**

In cases where the measuring flume is either up- or down-scaled, the discharge can be found from Fig. 8.3. For a chosen channel width all other dimensions have to be adapted by the same ratio. The discharges for channel widths of 0.4, 0.5, 0.6, 0.7 and 0.8 m have already been calculated and are shown in Fig. 8.4. For channel widths between the given values Fig. 8.4 can be interpolated on a straight line. For more accurate discharge calculations Eq. (2.1) can be used. The calibration coefficient C may be read from Fig. 8.3, which is valid for any up- or down-scaled version of the standard measuring flume.

In **Appendix C** larger versions of Figs. 8.2 to 8.4 are given to make it easier to read off values.

The calibration curves and method of flow measurement are valid only for cases where there are no obstructions downstream from the measuring flume, which could cause water to back up. Should downstream water back-up occur, however, care must be taken to ensure that measuring flume submergence is not more than 75%.

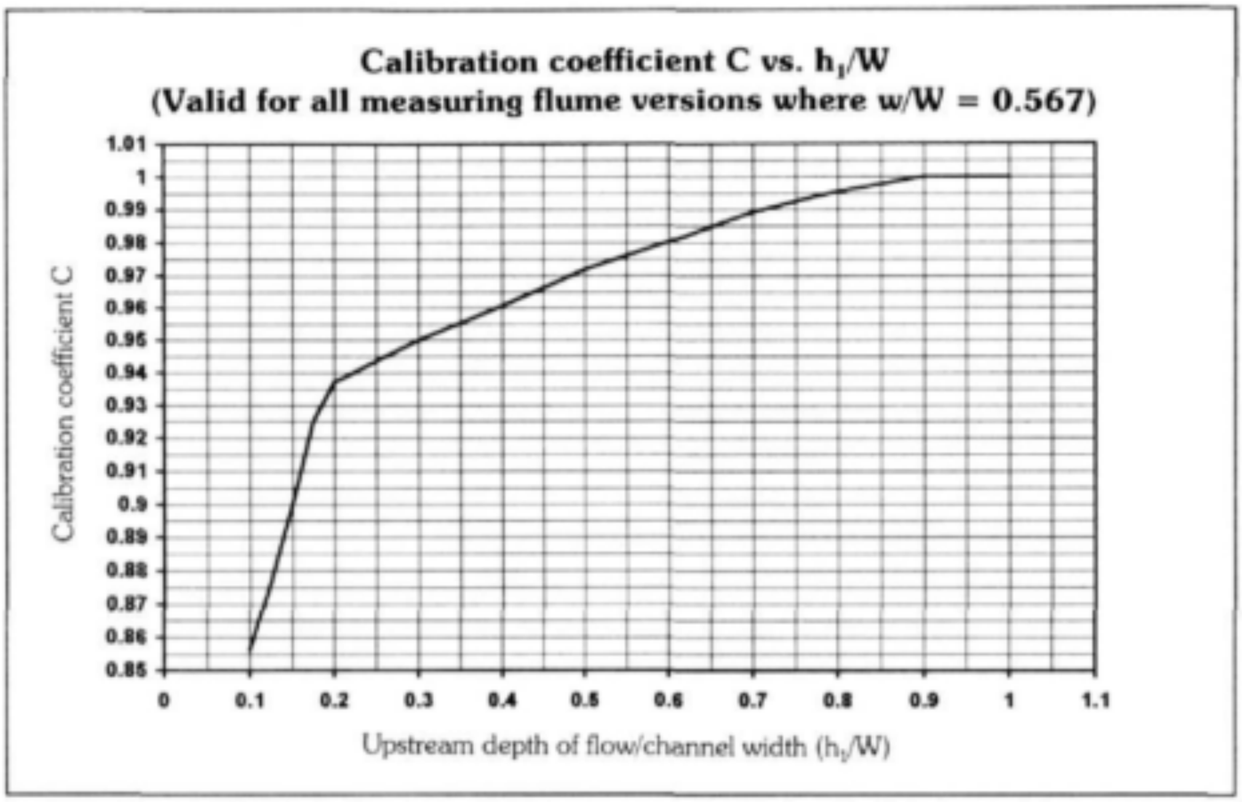



**Figure 8.3** C vs. $h_1/W$ (valid for standard flumes and any up- or down-scaled version)

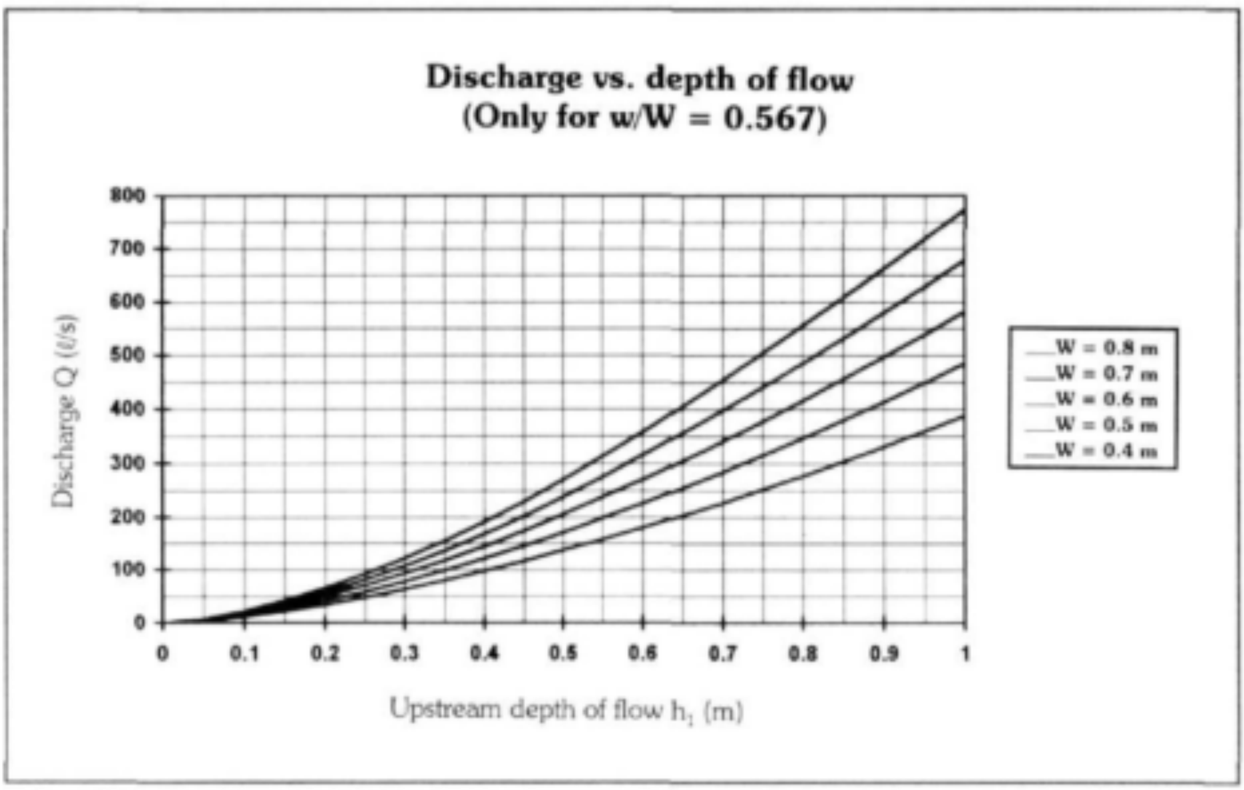



**Figure 8.4** Discharge vs. upstream depth of flow (valid for standard flumes and any up- or down-scaled versions)

## REFERENCES

*British Standards* 3680 (1981) *Part 4C, Flumes*
Featherstone, RE and Nalluri, C (1988) *Civil Engineering Hydraulics* (2nd edn.)
Massey, BS (1989) *Mechanics of Fluids* (6th edn.)
Webber, NB (1965) *Fluid Mechanics for Civil Engineers*

**APPENDIX A**

## WORKED EXAMPLES
## (DETERMINATION OF CALIBRATION COEFFICIENTS)

**Example 1**: **(Partially submerged conditions)**

Determination of calibration coefficients for a measuring flume with the following data:

**Rectangular measuring flume**:

Channel width (W) = 0.600 m

Flume width (w) = 0.340 m

Inlet shape: Curved

Flume roughness: Smooth walls

Upstream depth of flow ($h_1$) = 0.200 m

Downstream depth of flow ($h_3$) = 0.125 m

Calculate $h_3/h_1$ $= \frac{0.125}{0.200}$

$= 0.625$

The ratio $h_3/h_1$ is smaller than 0.75, which means that critical flow on the flume is assured and that partially submerged conditions prevail. To determine calibration coefficient C in terms of Fig. 3.1 the ratios w/W and $h_1/W$ are required:

$$w/W = \frac{0.340}{0.600} = 0.567$$

$$h_1/W = \frac{0.200}{0.600} = 0.333$$

According to Fig. 3.1 the value of coefficient C will be 0.954. The calibration coefficient C must be multiplied by a form factor and a roughness factor to yield a new calibration coefficient C which accounts for both of the above-mentioned factors.

From Tables 3.1 and 3.2 the form factor is 1.010 and roughness factor is 1.0.

New calibration coefficient C = (Form factor)·(roughness factor)·C

= (1.010)·(1.0)·(0.954)

= 0.964

**Example 2**: **(Submerged conditions)**

Determination of calibration coefficients in a measuring flume using the following data:

**Rectangular measuring flume**:

Channel width (W) = 0.600 m

Flume width (w) = 0.340 m

Inlet shape: Curved

Flume roughness: Erosion of cement between stone (measuring flume is very rough)

Upstream depth of flow ($h_1$) = 0.300 m

Downstream depth of flow ($h_3$) = 0.250 m

Calculate $h_3/h_1$ $= \frac{0.250}{0.300}$

$= 0.833$

The ratio $0.75<h_3/h_1<0.90$ means that critical flow is not developed in the measuring flume and that conditions of submergence prevail. To determine calibration coefficient $C_d$ in terms of Fig. 3.3 ($0.80<h_3/h_1<0.85$) the ratios w/W and $h_1$/W are required:

$$w/W = \frac{0.340}{0.600} = 0.567$$

$$h_1/W = \frac{0.300}{0.600} = 0.50$$

From Fig. 3.3 the value of the calibration coefficient $C_d$ equals 0.913. The calibration coefficient $C_d$ must be multiplied by a form factor and a roughness factor to establish a new calibration coefficient $C_d$ which accounts for both of the above-mentioned factors.

From Tables 3.1 and 3.2 the form factor is 1.01 and the roughness factor is 0.99.

New calibration coefficient $C_d$ = (Form factor)·(roughness factor)·$C_d$

= (1.01)·(0.99)·(0.913)

= 0.913

## WORKED EXAMPLES (METHOD TO ESTABLISH A UNIQUE RELATIONSHIP BETWEEN Q AND $h_1$)

**Example 1: (Partially submerged conditions)**

Determination of a unique relationship between Q and $h_1$ for a measuring flume with the following data:

**Rectangular measuring flume**:

Channel width (W) = 0.600 m

Flume width (w) = 0.340 m

Inlet shape: Curved

Flume roughness: Smooth walls

(The algorithm as described in **Paragraph 5.1** is followed to obtain the relationship between Q and $h_1$)

**Step 1**: *Position the stage recorders at measuring Points 1, 2 and 3.*

**Step 2**: Find the ratio $h_3/h_1$ for the peak discharge.

Peak discharge:

Upstream depth of flow ($h_1$) = 0.200 m

Downstream depth of flow ($h_3$) = 0.147 m

$$\frac{h_3}{h_1} = \frac{0.147}{0.200}$$

$$= 0.735$$

The ratio $h_3/h_1 < 0.75$ ensures critical flow on the flume and partially submerged conditions prevail.

**Step 2a**: Partially submerged conditions ($h_3/h_1 < 0.75$)

Measure upstream depth of flow ($h_1$) over the anticipated range of flows to be measured (e.g. over a 24 h period) and obtain C from Fig. 3.1. The discharge is determined by solving Eq. (2.1). The calculated values are given in Table B.1

**Table B.1 Calculation of discharge from measured depths of flow**

| **Depth of flow $h_1$ (m) (measured)** | **Calibration coefficient (C) from Fig. 3.1** | **Discharge Q (ℓ/s) from Eq. (2.1)** |
|---|---|---|
| 0.005 | (0.856)·(1.01) = 0.865 | 0.2 |
| 0.020 | (0.856)·(1.01) = 0.865 | 1.4 |
| 0.040 | (0.856)·(1.01) = 0.865 | 4.0 |
| 0.060 | (0.856)·(1.01) = 0.865 | 7.3 |
| 0.080 | (0.884)·(1.01) = 0.893 | 11.7 |
| 0.090 | (0.900)·(1.01) = 0.909 | 14.2 |
| 0.100 | (0.916)·(1.01) = 0.925 | 17.0 |
| 0.110 | (0.929)·(1.01) = 0.938 | 19.9 |
| 0.120 | (0.937)·(1.01) = 0.946 | 22.9 |
| 0.130 | (0.939)·(1.01) = 0.948 | 25.8 |
| 0.140 | (0.941)·(1.01) = 0.950 | 28.9 |
| 0.145 | (0.942)·(1.01) = 0.951 | 30.5 |

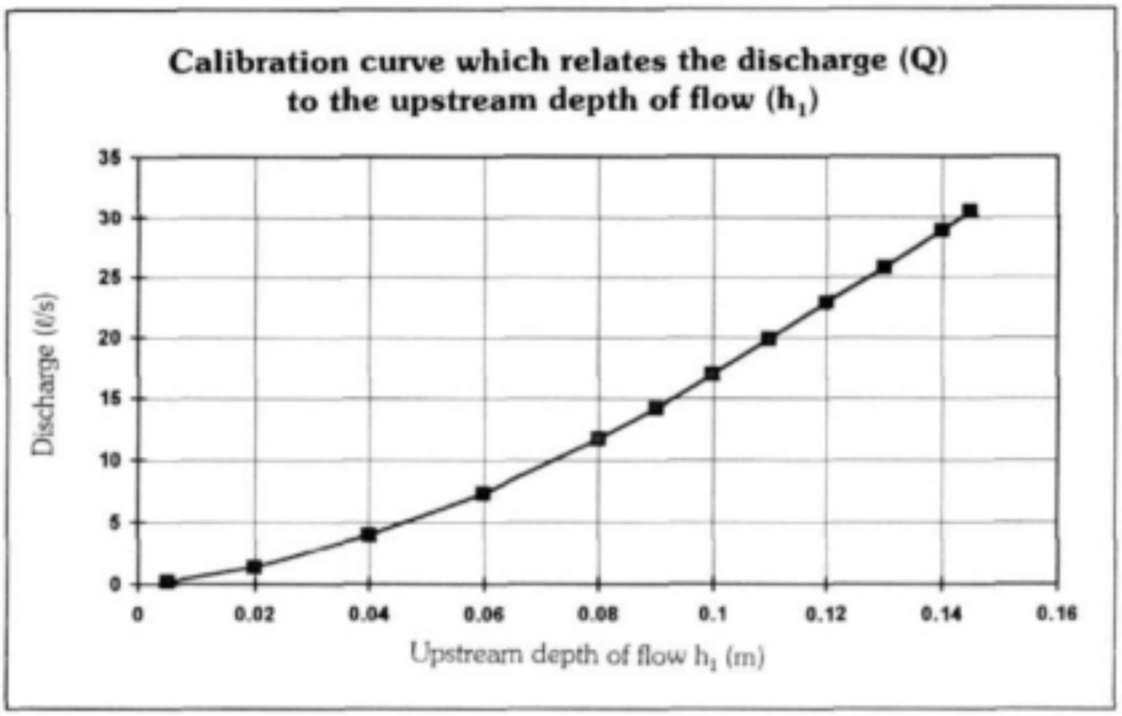



**Figure B.1 Unique relationship between discharge (Q) and upstream depth of flow ($h_1$)**

**Example 2**: **(Submerged conditions)**

Determination of a unique relationship between Q and $h_1$ in a measuring flume with the following data:

**Rectangular measuring flume**:

Channel width (W) = 0.600 m
Flume width (w) = 0.340 m
Inlet shape: Curved
Flume roughness: Erosion of cement between stone (flume walls very rough)

(The algorithm as described in **Paragraph 5.1** is followed to find the relationship between Q and $h_1$)

**Step 1**: Position stage recorders at measuring Points 1, 2 and 3

**Step 2**: Find $h_3/h_1$ for the peak discharge

Peak discharge:

Upstream depth of flow ($h_1$) = 0.300 m

Downstream depth of flow ($h_3$) = 0.265 m

$$\frac{h_3}{h_1} = \frac{0.265}{0.300}$$

$$= 0.883$$

The $h_3/h_1$ ratio is larger than 0.75 but still smaller than 0.90. Critical conditions in the measuring flume are therefore not assured at all times and submerged conditions may occur at higher discharges.

**Step 2b**: Submerged conditions ($0.75<h_3/h_1<0.90$)

Measure upstream depth of flow ($h_1$), downstream depth of flow ($h_3$) and the depth of flow in the flume ($h_2$) over the anticipated range of flows (e.g. over a 24 h period). The calibration coefficients C and $C_d$ may be read from Figs. 3.1 to 3.3. Discharges are determined by solving Eq. (2.1) for $h_3/h_1<0.75$ and Eq. (2.2) for $0.75<h_3/h_1<0.90$. The calculated values are given in Table B.2.

**Table B.2: Calculation of discharge from measured depths of flow**

| $h_1$ (m) | $h_2$ (m) | $h_3$ (m) | $h_3/h_1$ | C (Fig. 3.1) | $C_d$ (Fig. 3.2 - Fig. 3.3) | Q (ℓ/s) |
|---|---|---|---|---|---|---|
| 0.020 | - | 0.014 | 0.711 | 0.856 | - | 1.4 |
| 0.040 | - | 0.029 | 0.714 | 0.856 | - | 4.0 |
| 0.060 | - | 0.043 | 0.718 | 0.856 | - | 7.3 |
| 0.080 | - | 0.056 | 0.723 | 0.884 | - | 11.6 |
| 0.100 | - | 0.073 | 0.734 | 0.916 | - | 16.8 |
| 0.120 | - | 0.090 | 0.748 | 0.937 | - | 22.6 |
| 0.150 | 0.092 | 0.114 | 0.760 | - | 0.868 | 35.9 |
| 0.180 | 0.126 | 0.140 | 0.778 | - | 0.893 | 50.7 |
| 0.210 | 0.157 | 0.169 | 0.805 | - | 0.908 | 65.1 |
| 0.240 | 0.187 | 0.198 | 0.825 | - | 0.918 | 79.6 |
| 0.270 | 0.219 | 0.230 | 0.852 | - | 0.907 | 91.9 |
| 0.300 | 0.255 | 0.265 | 0.883 | - | 0.907 | 102.6 |

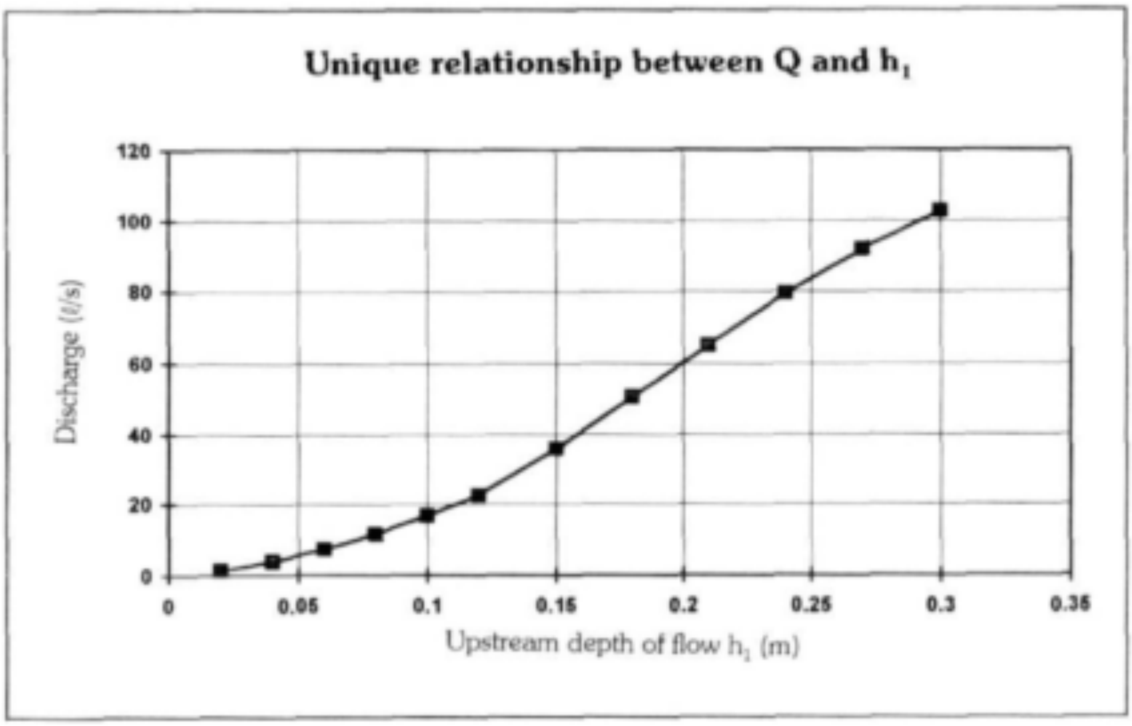



**Figure B.2 Unique relationship between discharge (Q) and the upstream depth of flow ($h_1$)**

# APPENDIX C

# UP- AND DOWN-SCALING OF

# A STANDARD MEASURING FLUME

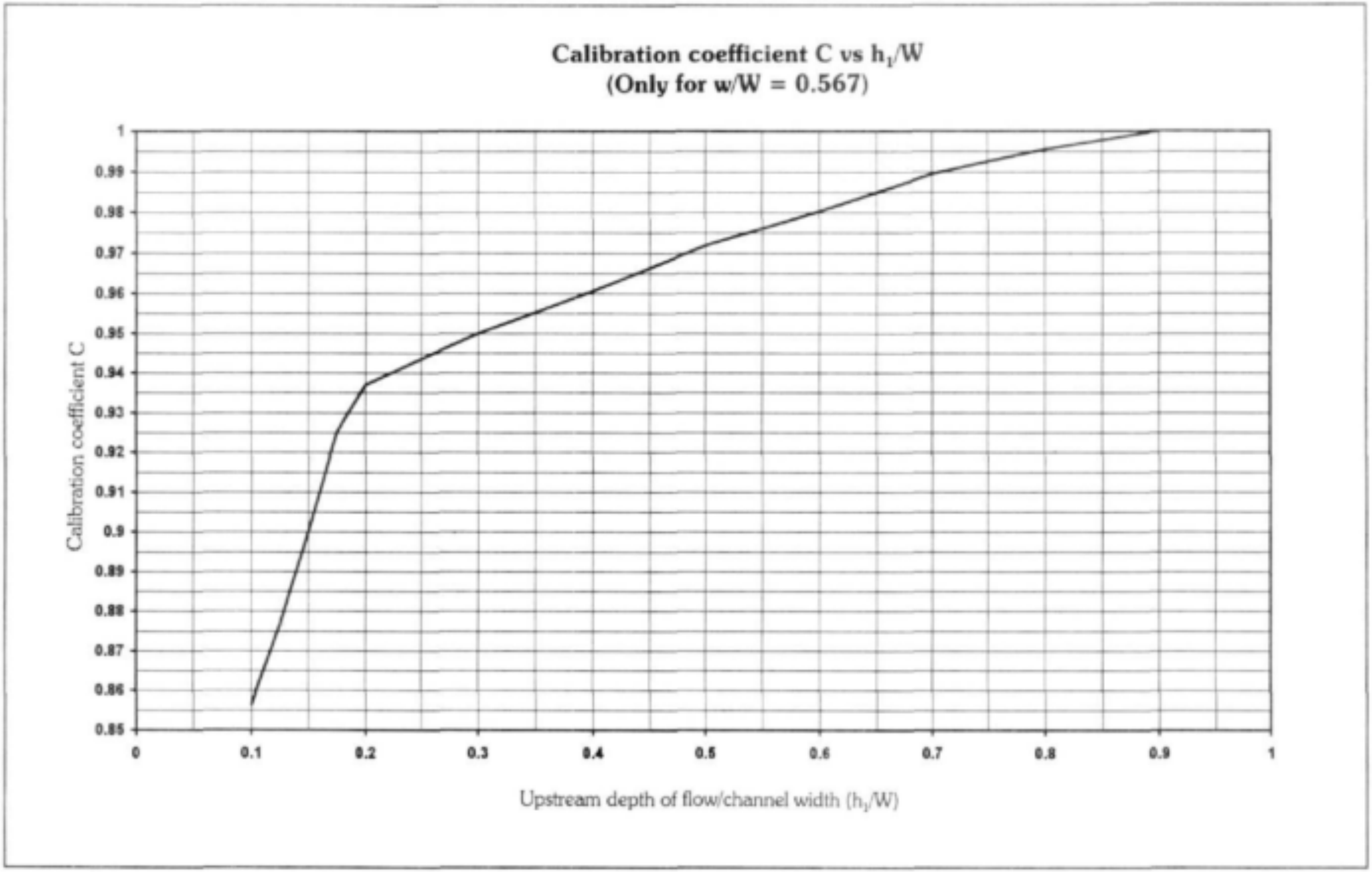



**Figure C.1: Calibration coefficient C vs. $h_1/W$ for w/W = 0.567**

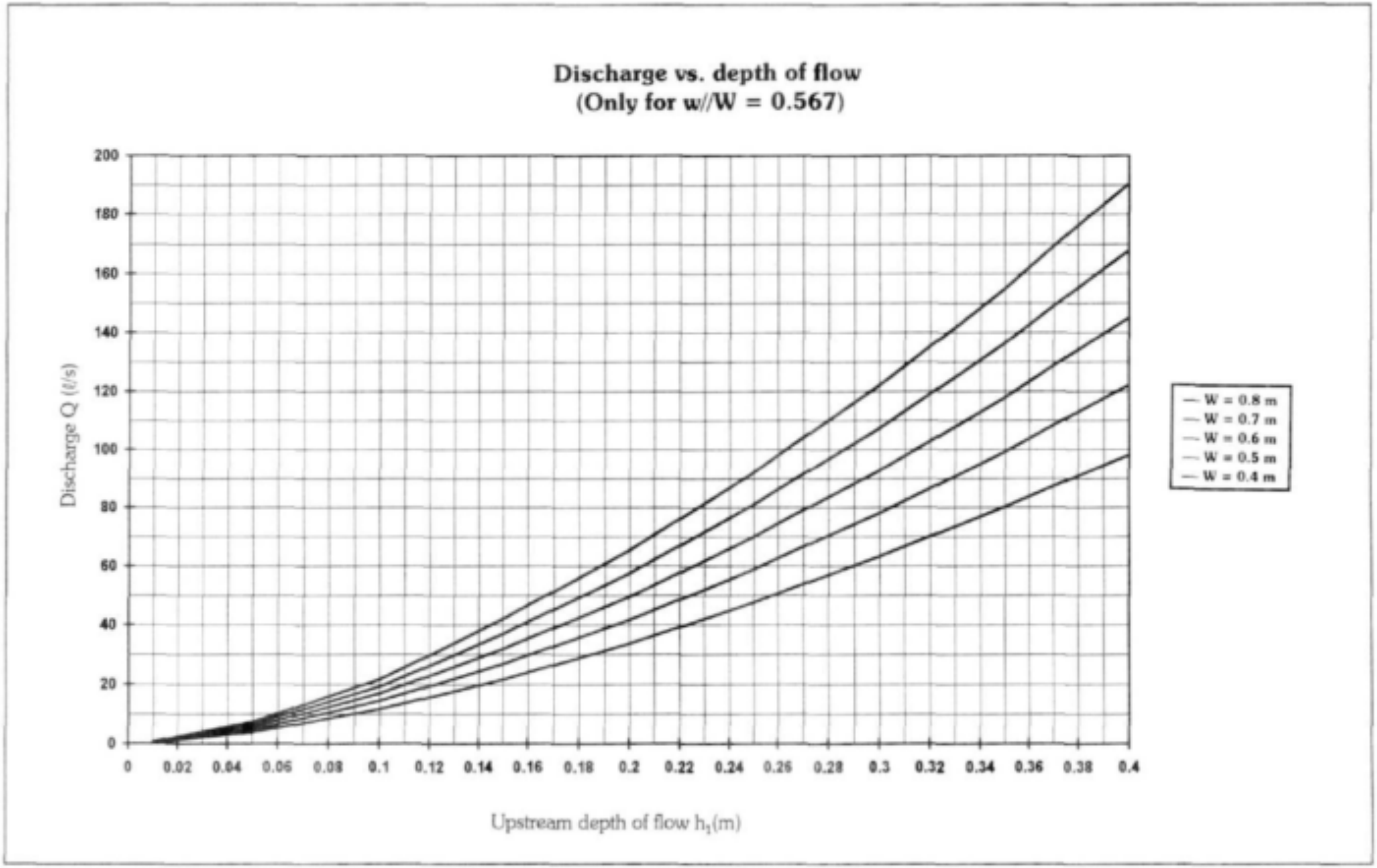



Figure C.2: Discharge vs. depth of flow for w/W = 0.567 and $0 \leq h_1 \leq 0.4$ m

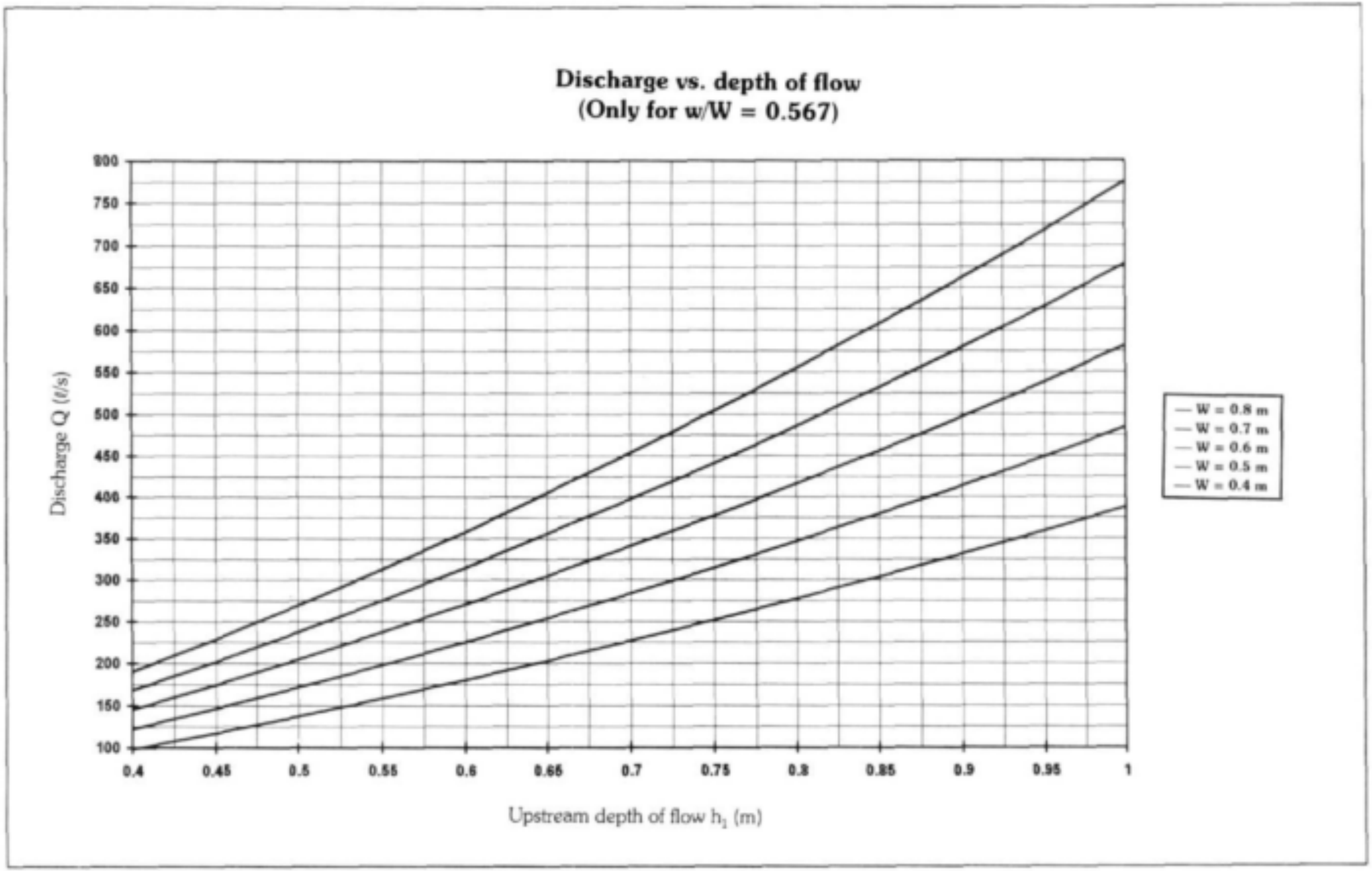



**Figure C.3: Discharge vs. depth of flow for w/W = 0.567 and $0.4 \leq h_1 \leq 1$ m**

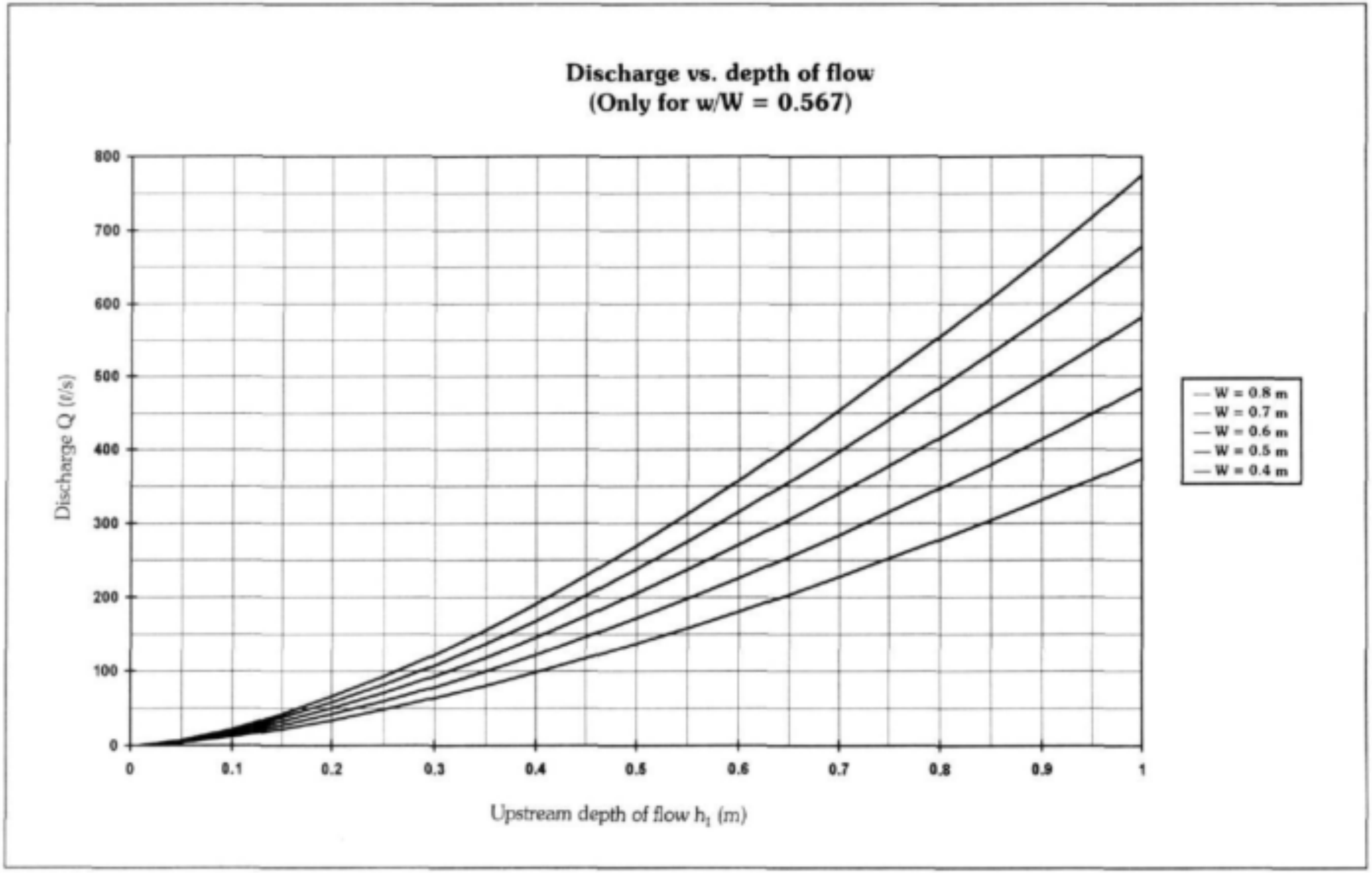



**Figure C.4: Discharge vs. depth of flow for w/W = 0.567 and $0 \le h_1 \le 1$ m**

# APPENDIX D

# THE CALIBRATION OF MEASURING FLUMES IN SEWERS

**Prepared by**

**JW Bester**
**V Jonker**

**Sigma Beta Consulting Engineers**

# CONTENTS

## LIST OF FIGURES

## 1 INTRODUCTION

Open-channel flow measurement can be done in various ways. The two most common methods that are used in South Africa to measure flows are measuring weirs (multi-notch or V-notch structures) and measuring flumes. Due to the solids content in sewage, measuring weirs cannot be employed to measure flows in sewage works as the weirs will rapidly silt up due to upstream solids deposition. Measuring flumes (i.e. horizontal contractions in channels) are therefore most commonly used to measure wastewater flows in sewage works channels. Standard equations are available to calculate the flow through these measuring flumes, but the use of these equations is subject to measuring flume compliance with certain specifications.

In view of the fact that a number of measuring flumes, operated by ERWAT, do not comply with the specifications, or are deficient in other respects, uncertainty existed regarding the accuracy of these flumes. As charges levied by ERWAT are based on flows measured by these flumes, it is vitally important that these measurements are accurate.

Tests were therefore conducted in the Hydraulics Laboratory of the University of Stellenbosch by means of which it was endeavoured to establish calibration coefficients which could then be used by ERWAT to accurately calibrate their existing measuring flumes *in situ*.

We trust that this report will make a contribution towards improving the standard of accuracy in measuring flume flow measurement.

## 2. OBJECTIVE OF PROJECT

As pointed out in your letter dated 23 March 1998 the overall objective of the project was to upgrade, rehabilitate and calibrate approximately 50 monitoring stations which are in operation on the East Rand at present. As many of the measuring stations do not comply with the requirements of *BS 3680: Part 4C* (1981): *Flumes*, or are deficient in other respects, it was impossible to accurately apply existing equations and coefficients to calibrate these measuring flumes. In addition, depth of flow and flume width ratios also vary significantly between the various measuring flumes. The specific instruction to *Sigma Beta Consulting Engineers* was to establish calibration guidelines and coefficients by means of which existing and future measuring flumes could be calibrated *in situ*. This means that a unique relationship between depth of flow and discharge can be derived and that the velocity recorder can be calibrated *in situ*, because the discharge can now be determined very accurately by means of these coefficients.

In addition it was also specified that the influence of the inlet shape and wall roughness on measuring flume calibration should be investigated. In the final instance *Sigma Beta Consulting Engineers* was also requested to test the velocity recorder in the laboratory with specific reference to the K-factor and the accuracy of the velocity recorder.

## 3 LABORATORY AND MODELLING SET-UP

### 3.1 Laboratory layout

Figure 3.1 shows the general set-up for laboratory modelling. The modelling studies were conducted in a 600 mm wide glass channel with a plastic floor. The channel is ± 20 m in length and has a depth of 1 200 mm. Water is supplied to the channel by means of a 300 mm feed pipe from a constant-head tank. Flow is measured by means of a plate orifice and a manometer in the channel feed pipe, as well as a 90° V-notch at the head of the channel. The range of flows which can be tested varies from 0 to 200 ℓ/s. The measuring flume model is located approximately halfway through the channel and a sluice gate in the channel outlet can be used to simulate any submergence situation in the channel.

## 3.2 Modelling set-up

The two types of measuring flume tested are shown in Fig. 3.2. The various parameters are also defined here. Compressed wood (20 mm gauge) was used to construct the models and 1 mm sheet-metal was used for the quarter-round inlets.

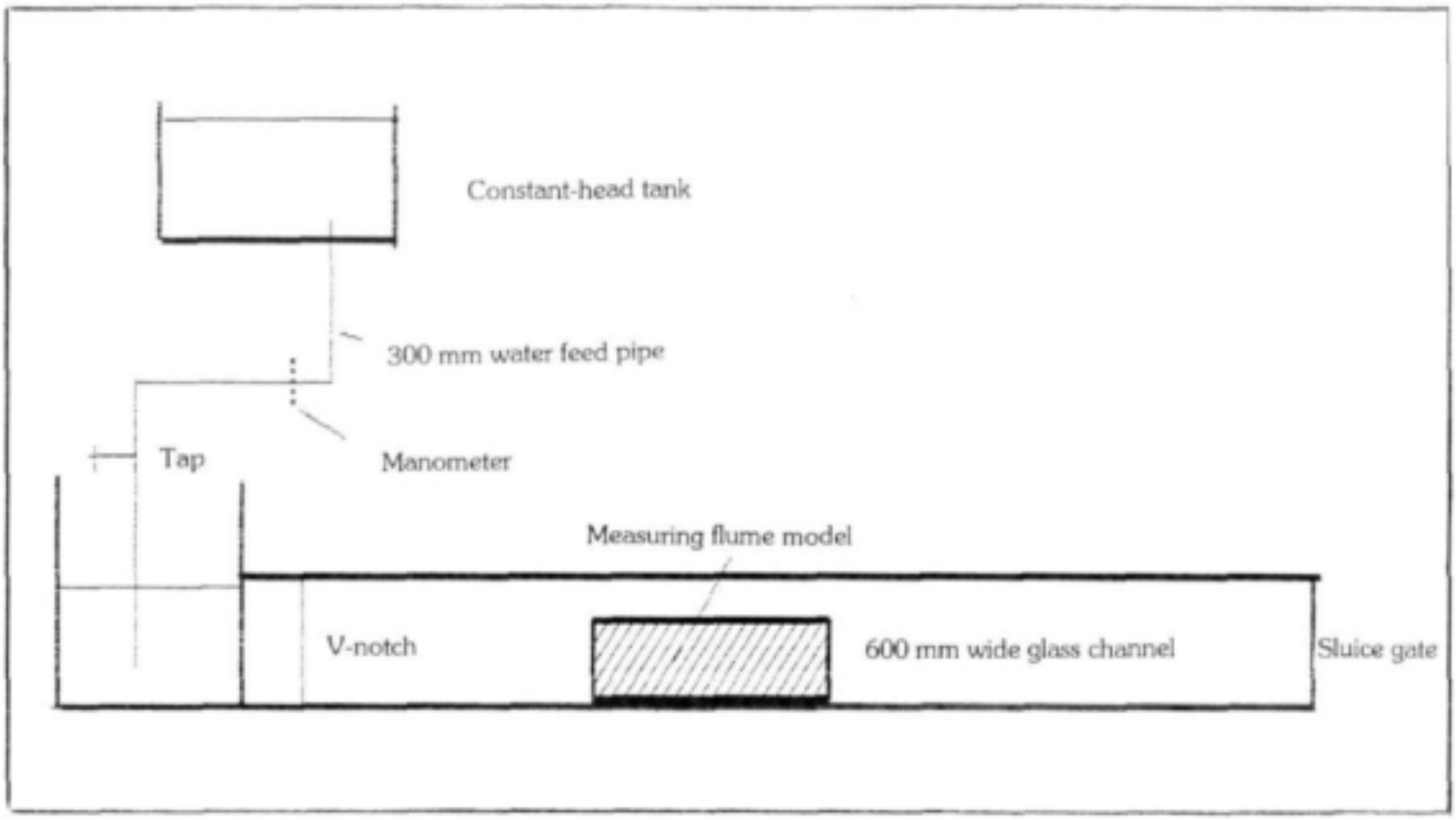



**Figure 3.1 Schematic model layout in the laboratory**

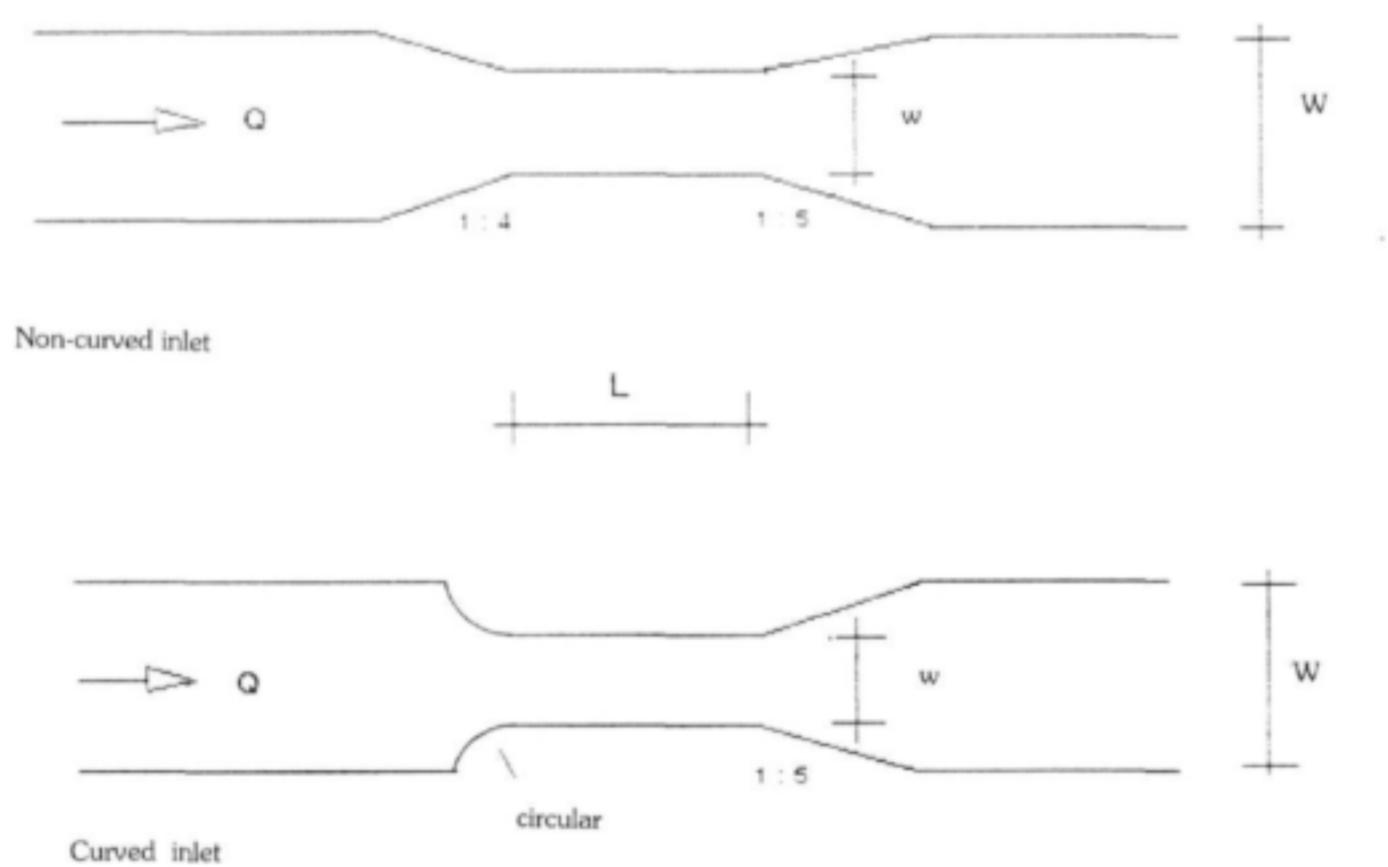



**Figure 3.2 Modelling set-up: Detailed sketches**

# 4 MODE OF OPERATION

## 4.1 Selecting representative measuring flumes

Before proceeding with the investigations, the most representative measuring flumes, covering the full range of parameters such as w/W, L/W, w, W and L, had to be selected. The parameter definitions are shown in Fig. 3.2. This was found to be necessary as it was impossible to test all the configurations of the measuring flumes in the laboratory even though it is necessary to determine the effect of the various parameter values on the calibration process.

In **Appendix 4A** a list of numbered measuring flumes is given, as well as plots of parameter W vs. w/W (Fig. 4A.2) and parameter W vs. L/W (Fig. 4 A.3). From these plots five measuring flumes, which best represented the full range of parameters, were then selected. These five measuring flumes are No 5, 9, 10, 17 and 30, in other words, No MS105, MS501, MS502, MS514 and MS626. Only measuring flume No 9 (MS501) was constructed at full scale in the laboratory; the other measuring flumes were either up- or down-scaled. As Parshall measuring flumes may be calibrated using standard calibration curves, these flumes were not tested in the laboratory.

## 4.2 Determining the calibration coefficients

A model was constructed for each of the selected measuring flumes mentioned above and a range of tests was conducted subsequently. The procedure followed to determine the calibration coefficients for each model set-up was typically:

- Seven rates of flow ranging between 0 and 200 ℓ/s were run through each model
- For each of these discharges three conditions in the measuring flume were then tested:

  - **Partially submerged condition** - critical flow is developed in the flume and the downstream depth of flow does not have an effect on the upstream depth of flow
  - **Modular condition** - downstream depth of flow just starts affecting the upstream depth of flow
  - **Submerged condition** - the downstream to upstream depth of flow ratio is more or less 80% to 95%.

- For each of the conditions the depths of flow were determined at five points by means of a needle gauge:

  - Upstream between $3h_{max}$ and $4h_{max}$
  - At points w, 1.5 w and 2 w in the contraction
  - Downstream from the measuring flume (1 m in the full-scale model).

  The measuring positions are shown in Fig. 4.1.

- The following equations, from Webber (1965), which are universally valid for contractions, were used to calculate the calibration coefficients:

$$Q = 1.71 C w h_1^{\left(\frac{3}{2}\right)}$$

(4.1)

This equation is valid only when critical conditions are assured in the flume and the downstream depth of flow does not affect the upstream depth of flow. Only the upstream depth of flow ($h_1$) is required to calculate the discharge by means of the following equation:

$$Q = \frac{2 g C_d h_2 w \sqrt{h_1 - h_2}}{\sqrt{1 - \left(\frac{W h_2}{w_1 h_1}\right)^2}}$$

(4.2)

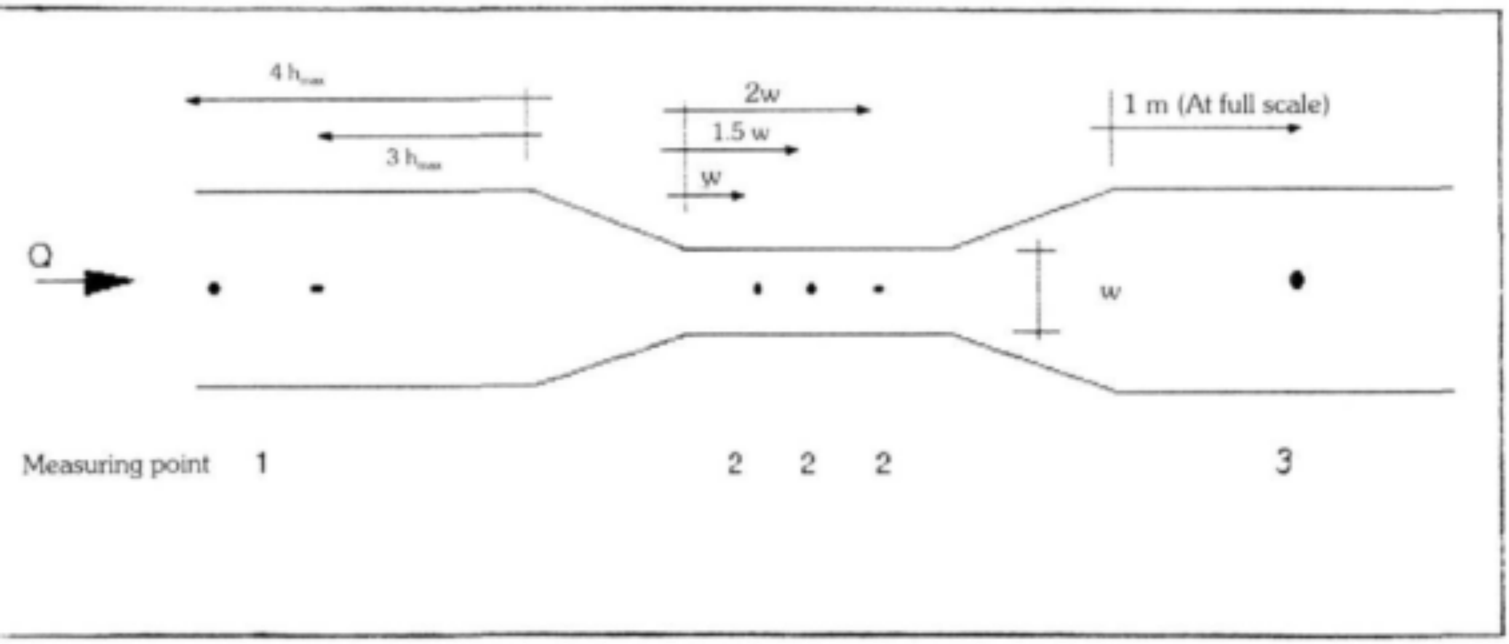



**Figure 4.1 Definition of measuring points**

This equation is valid for critical conditions in the flume, and also for submerged conditions when the downstream depth of flow starts affecting the upstream depth of flow. The upstream depth of flow ($h_1$) and the flume depth of flow ($h_2$) are required to calculate the discharge by means of the equation (Eq. (4.2)).

As the real discharge and the depths were measured during the tests, the calibration coefficients C and $C_d$ respectively can be calculated by means of the equation.

### 4.2.1 Effect of submergence on calibration coefficients

As the downstream depth of flow was measured throughout, the degree of submergence ($h_3/h_1$) can be determined and thus the influence of submergence on the calibration coefficients can be determined.

### 4.2.2 Effect of flume inlet shape on the calibration coefficients

Two extreme inlet shapes, i.e. a curved and a non-curved (1:4) inlet shape, were tested in the first modelling set-up. The calibration coefficients obtained using these two shapes could then be compared. Based on this range of tests where both shapes had been used, a form factor with respect to the various inlet shapes could be derived. As the difference between the calibration coefficients was very small, the remaining test runs were conducted using the non-curved (1:4) inlet shape. The influence of w, W and L on the calibration coefficients was also determined.

### 4.2.3 Effect of roughness on the calibration coefficients

From photographs taken of some of the ERWAT measuring flumes, it was clear that the sewage had caused scouring of the cement between the aggregate in some of the measuring flumes. The exposed aggregate causes increased surface roughness in the flume inlet and the contraction. This increase in roughness was found only in the bottom part of the measuring flume. Tests were therefore conducted to determine the effect of this increase in roughness on the calibration coefficients and to establish appropriate roughness factors.

### 4.3 Calibration of the velocity recorder

By means of the calibration coefficients which were determined as described in **Paragraph 4.2** and by measuring the depths of flow at the measuring flume, the discharge in any measuring flume may now be determined accurately. With known discharge the velocity recorder can therefore be calibrated *in situ* for any measuring flume.

The velocity recorder was, however, also tested in the laboratory, and the accuracy thereof at different flows, as well as the validity of the K-factor, were also established.

## 5. RESULTS

### 5.1 Calibration coefficient

By using the calibration coefficients C and $C_d$ as determined in the five modelling set-ups, calibration curves could be plotted and a calibration coefficient for any w/W, $h_3/h_1$ and $h_1/W$ ratio could be obtained. Two sets of calibration curves were plotted and they can be used to determine the calibration coefficients:

a) **Partially submerged condition** (Fig. 5.1)

This condition is valid only for $h_3/h_1 < 0.75$. Thus, by measuring the downstream depth of flow ($h_3$) and the upstream depth of flow ($h_1$), and with known w/W and $h_1/W$ for any discharge, the calibration coefficient may be read from Fig. 5.1 and the discharge can be determined accurately by solving Eq. (4.1).

b) **Submerged condition** (Figs. 5.2 to 5.4)

This condition is valid for $0.75 < h_3/h_1 < 0.90$. As the calibration coefficient $C_d$ is very sensitive to changes in the degree of submergence ($h_3/h_1$), three rating curves were plotted, each for a different $h_3/h_1$ ratio. By means of Eq. (4.2) and by measuring the depth of flow in the flume ($h_2$), the actual discharge can then be determined. From the tests conducted it was obvious that the best position for measuring the depth of flow in the flume proved to be at a distance w from the start of the contraction (Fig. 4.1).

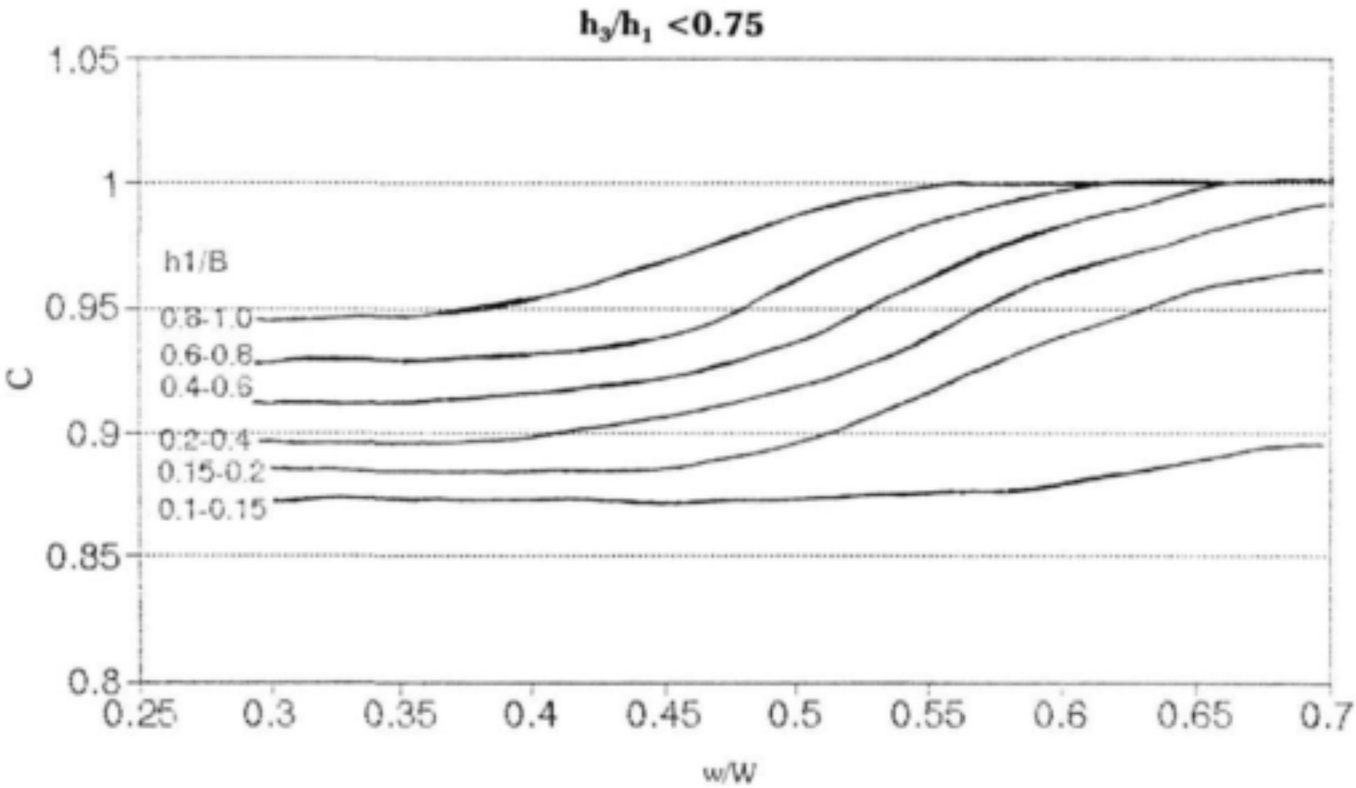



**Figure 5.1 Determining the calibration coefficient C ($h_3/h_1$<0.75)**

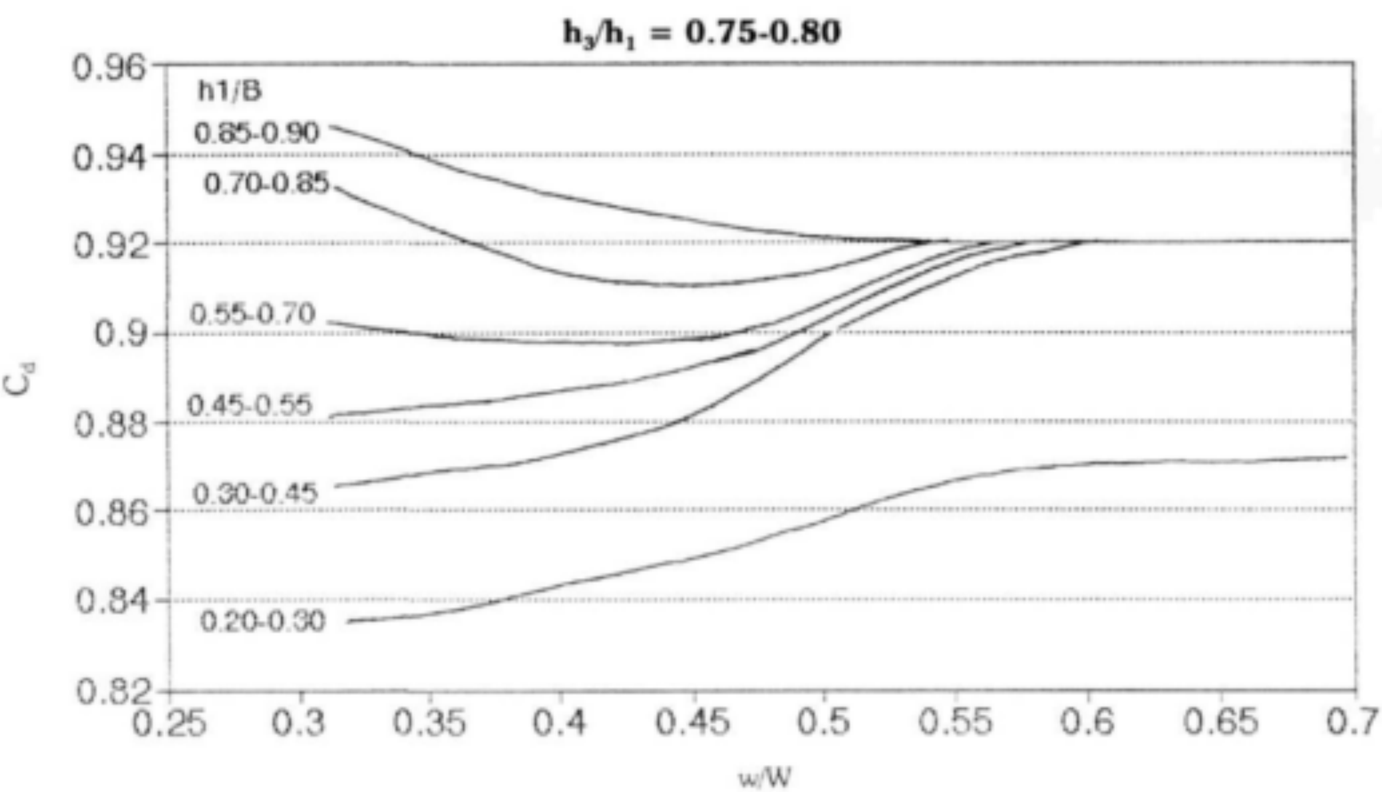



**Figure 5.2 Determining the calibration coefficient $C_d$ ($h_3/h_1$=0.75 to 0.80)**

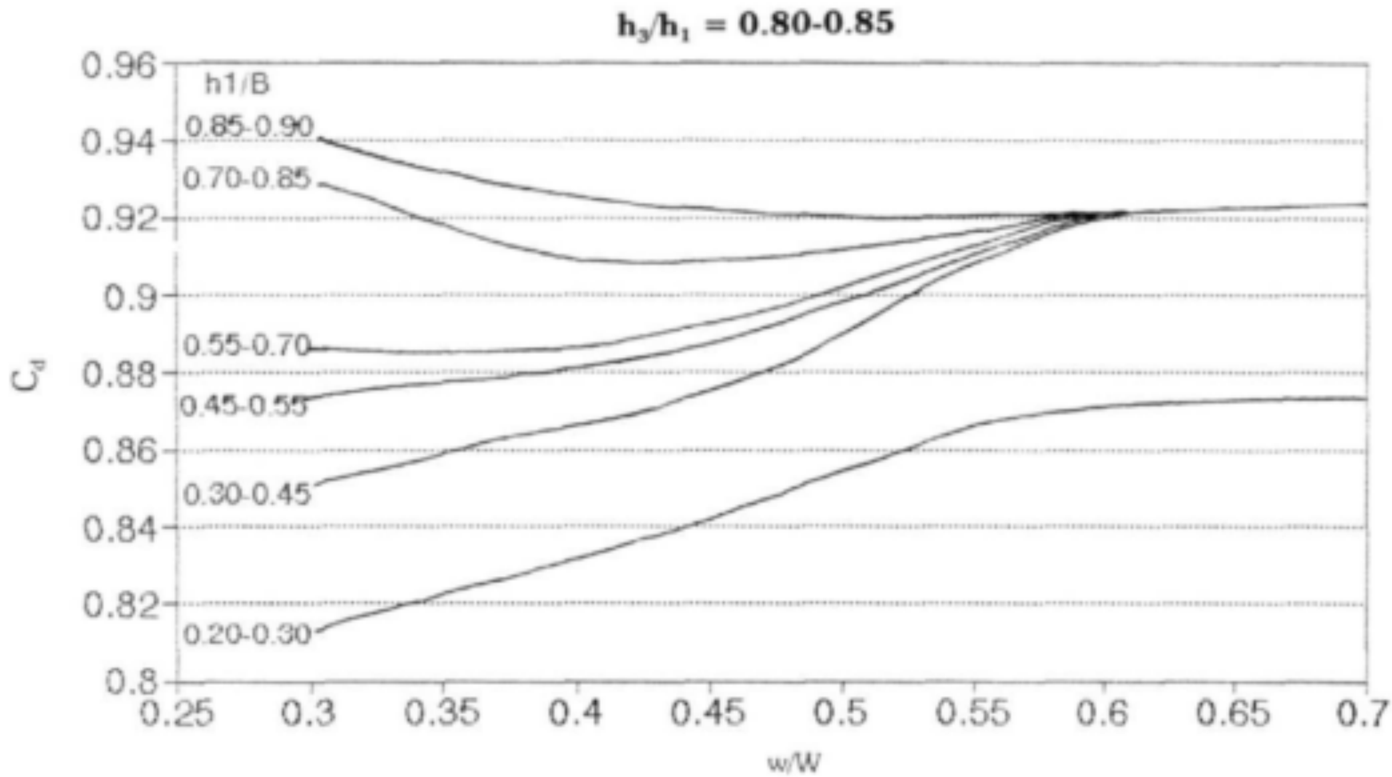



**Figure 5.3 Determining calibration coefficient $C_d$ ($h_3/h_1$=0.80 to 0.85)**

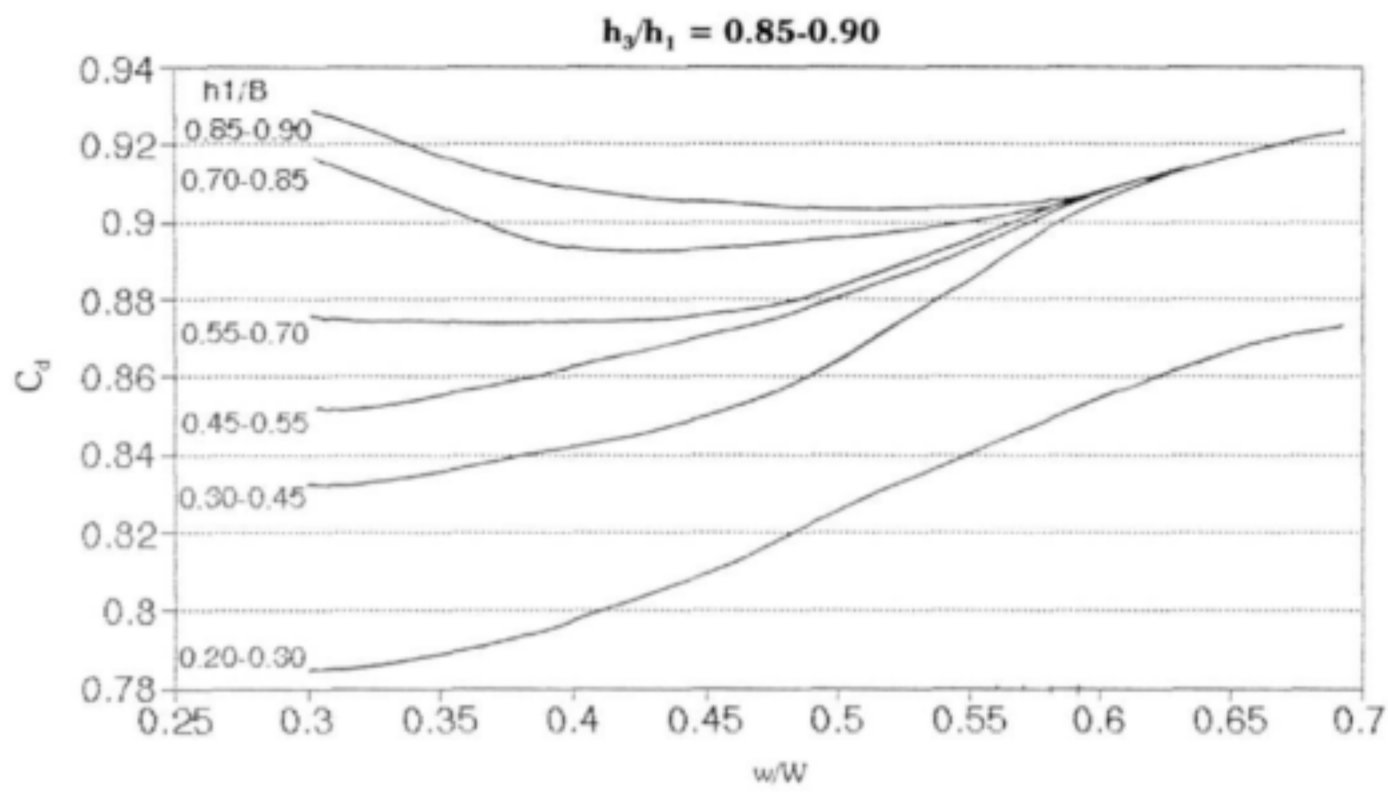



**Figure 5.4 Determining calibration coefficient $C_d$ ($h_3/h_1$=0.85 to 0.90)**

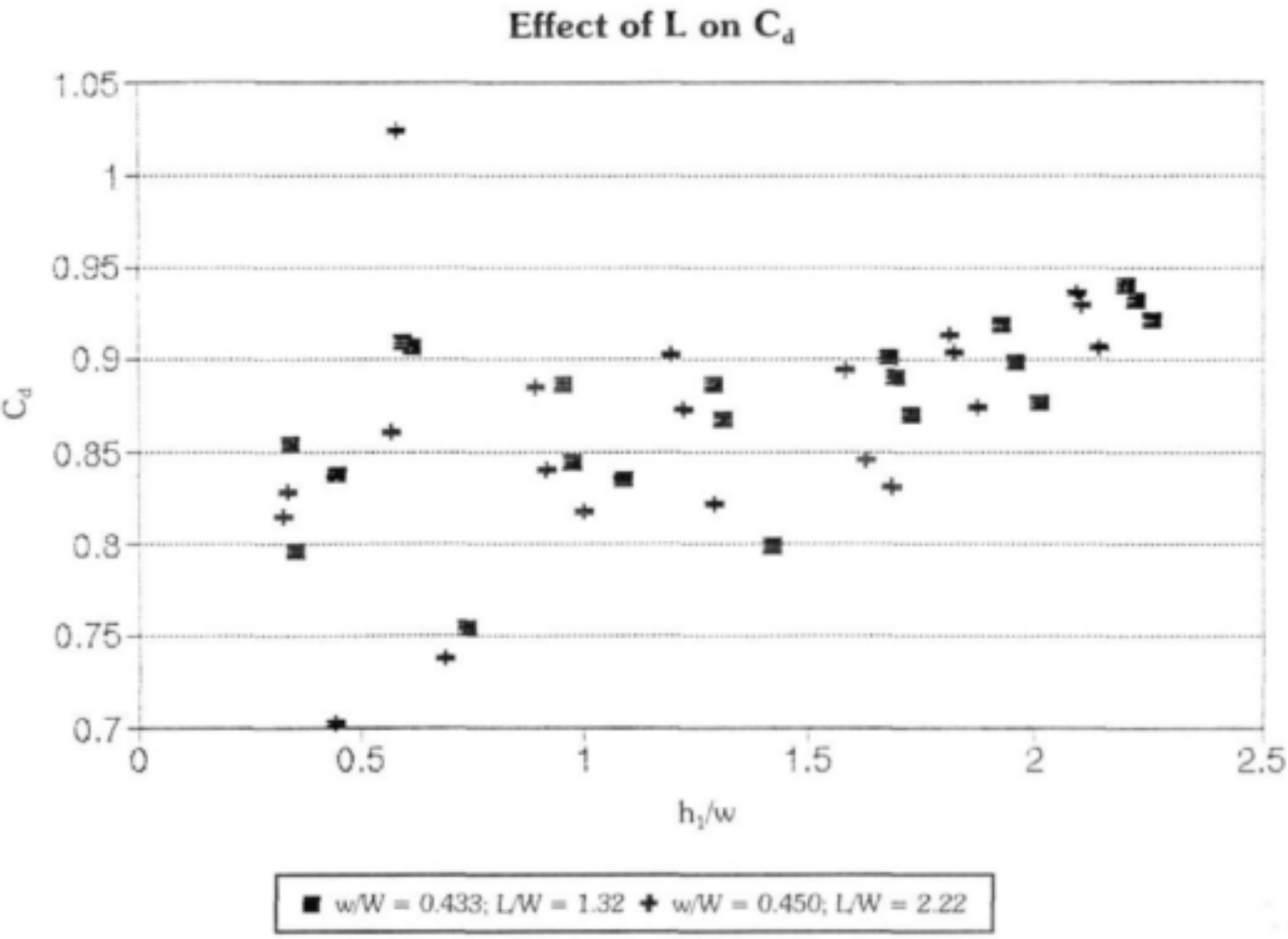



**Figure 5.5 The effect of parameter L on the calibration coefficient $C_d$**

Thus, in order to determine the calibration coefficient (C or $C_d$) the downstream depth of flow ($h_3$) and the upstream depth of flow ($h_1$) must be measured. In the case of a partially submerged condition ($h_3/h_1 < 0.75$) the rate of flow can then be calculated with known values for only $h_1$ and C, but for a condition of submergence ($h_3/h_1 > 0.75$) a depth of flow measurement in the flume ($h_2$) must also be taken in order to calculate the discharge. The point of measurement in the flume must be at distance w from the start of the contraction.

From Figs. 5.1 to 5.4 it is clear that the parameter L plays no part in determining the calibration coefficient. Figure 5.5 shows the calibration coefficients as determined for two different measuring flume models which have roughly the same w/W ratios, but extreme L/W ratios. In both instances the difference between the $C_d$ values is small and leads to the conclusion that L has no effect on the calibration coefficients.

### 5.1.1 The effect of flume inlet shape on the calibration coefficient

In **Paragraph 4.2.2** it was mentioned that the series of tests conducted on the full-scale model was initially done using a non-curved (1:4) inlet shape and subsequently repeated using the quarter-round inlet. Two plots showing the test results are given in **Appendix 5A**. In Figs. 5A.1 and 5A.2 the effects of the various inlet shapes on the calibration coefficients C and $C_d$, respectively, are shown.

From these plots a form factor was then determined, by means of which the calibration coefficients which are valid for non-curved inlet shapes (Figs. 5.1 to 5.4) could be adapted. In order to find the new calibration coefficients, with respect to inlet shape, the form factor has to be multiplied by the calibration coefficients given in Figs. 5.1 to 5.4.

**Table 5.1: The form factor**

| $h_3/h_1$ | Inlet shape | | Multiply by |
|---|---|---|---|
| | Quarter-round | Non-curved | |
| <0.75 | 1.010 | 1.000 | C |
| 0.75 - 0.90 | 1.027 | 1.000 | $C_d$ |

Although these two inlet shapes represent extreme cases, the values of the coefficients do not differ much. By interpolation a reliable form factor can be found for any inlet shape between non-curved and circular. The curved inlet recommended in the *British Standards* (R≥2 (W-w) lies more or less between the circular and the non-curved (1:4) inlet shapes and the form factor may be interpolated accordingly from Table 5.1

### 5.1.2 The effect of flume roughness on the calibration coefficient

In order to determine the effect of roughness on the calibration coefficient, the series of tests were repeated on one of the measuring flume models, after the surface roughness thereof had been altered. The latter was achieved by drilling holes in it, applying a layer of glue over the bottom half of it and then sprinkling 6 mm crusher stone over it (Fig. 5.6). As the scale of this model was three times smaller than the prototype, the stone used actually represents 18 mm stone in the prototype. In addition the surface roughness was applied not only to the bottom half of the flume inlet, but also over the contraction itself, in comparison with the prototype, where the surface roughness reaches only over the bottom third or quarter of the flume inlet area (Fig. 5.7).

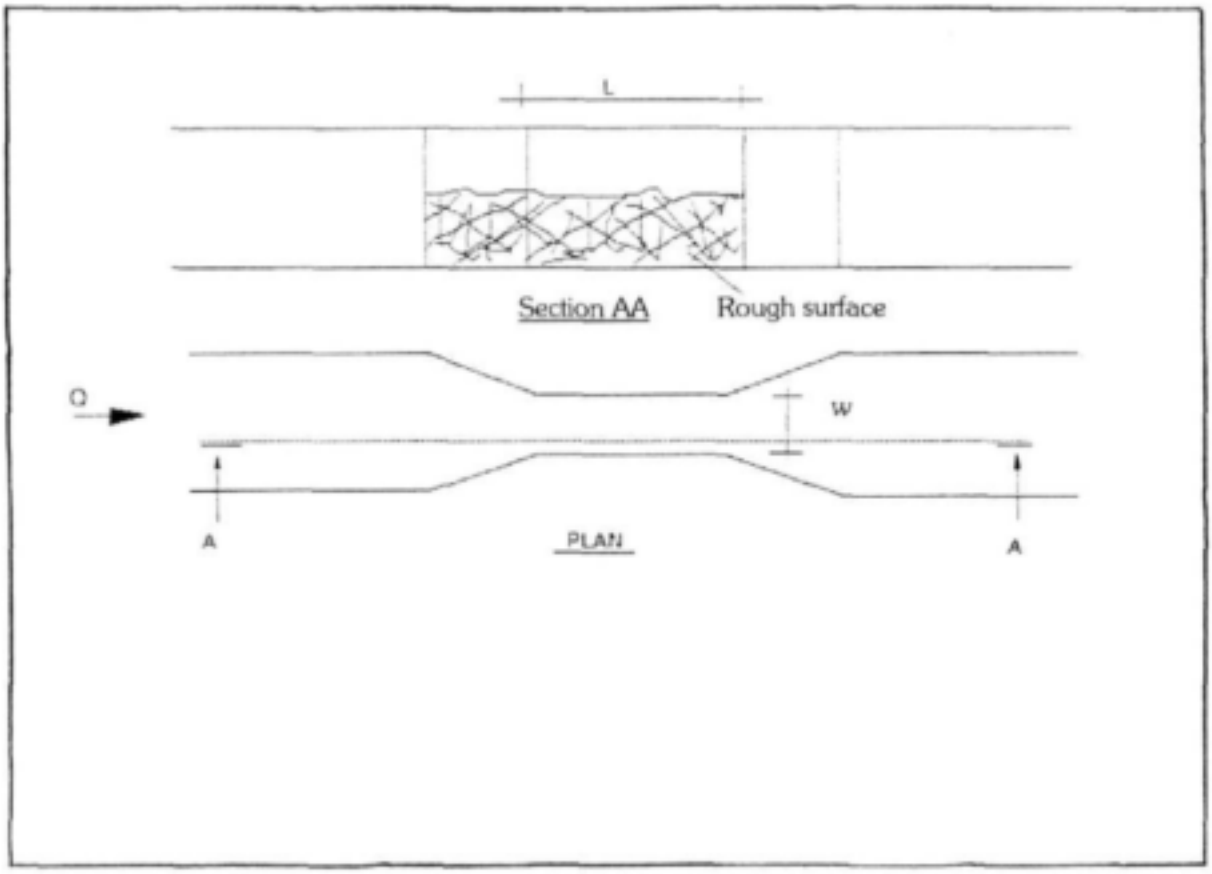



**Figure 5.6 Measuring flume surface area roughened for roughness tests**

**Figure 5.7 Surface roughness in prototype**

The tested roughness was therefore exaggerated. By comparing the values for C and $C_d$ obtained from tests on the smooth- and the rough-surface models, the effect of roughness, if any, can then be determined. In **Appendix 5B** Figs. 5B.1 and 5B.2 show the effect of roughness on the values for C and $C_d$.

In order to ensure that any change in the calibration coefficients was in fact caused by surface roughness, and not by a change in the value of parameter w as a result of the gravel having been applied to the walls, when calculating C and $C_d$ for the roughened surface model, the value of w was decreased by 5 mm less than that for the smooth-surface model. This 5 mm adjustment therefore compensates for the fact that the physical dimension of w will change somewhat as a result of the gravel added and any change in C or $C_d$ could thus solely be ascribed to the effect of roughness.

Figures 5B.1 and 5B.2 show that the C and $C_d$ values for the smooth- and the rough-surface models, respectively, do not differ much. It should also be noted that the roughness tested was extremely exaggerated and in fact represented 18 mm stone. It is therefore accepted that the role of surface roughness is negligible. Should it be taken into account, however, Figs. 5B.1 and 5B.2 show that both C and $C_d$ values, in the rough-surface case, would be approximately 0.99 times the values for the smooth-surface case.

In instances where measuring flume walls are fairly rough, this can be accounted for by multiplying the values for C and $C_d$ by a roughness factor of 0.99.

## 5.2 Velocity recorder

Up to this point calibration coefficients have been established by means of which any measuring flume could be calibrated in terms of the depth of flow at different measuring points. However, due to the fact that ERWAT uses velocity recorders to calculate the discharge at some of its measuring flumes, tests on these velocity recorders were also conducted in the laboratory. Basically two sets of tests were run:

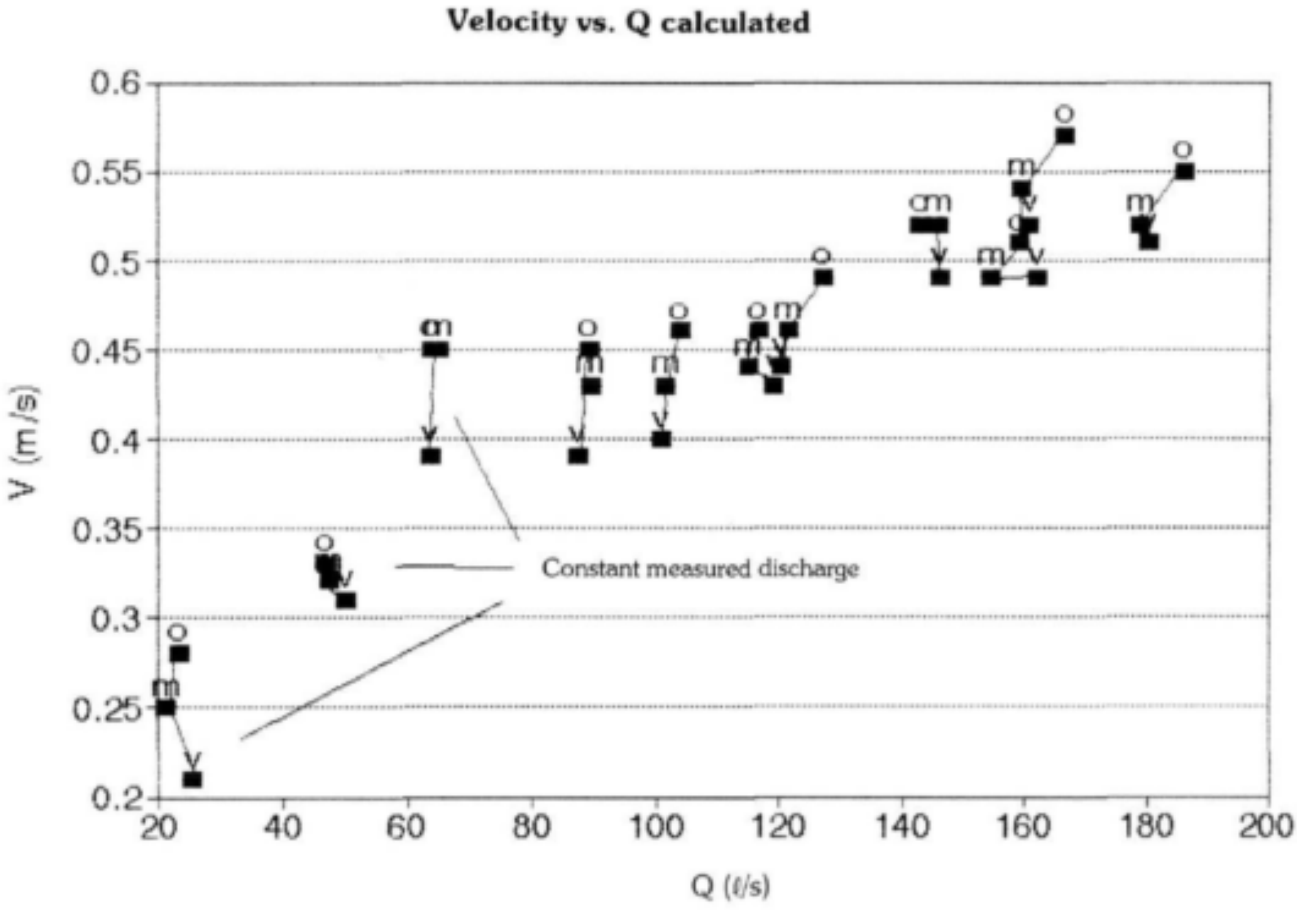
a) Tests to check the performance of these velocity recorders when subjected to conditions of submergence.

b) Tests to check the accuracy of the K-factor (calibration factor) and to check its calibration.

### 5.2.1 Velocity recorder performance under conditions of submergence

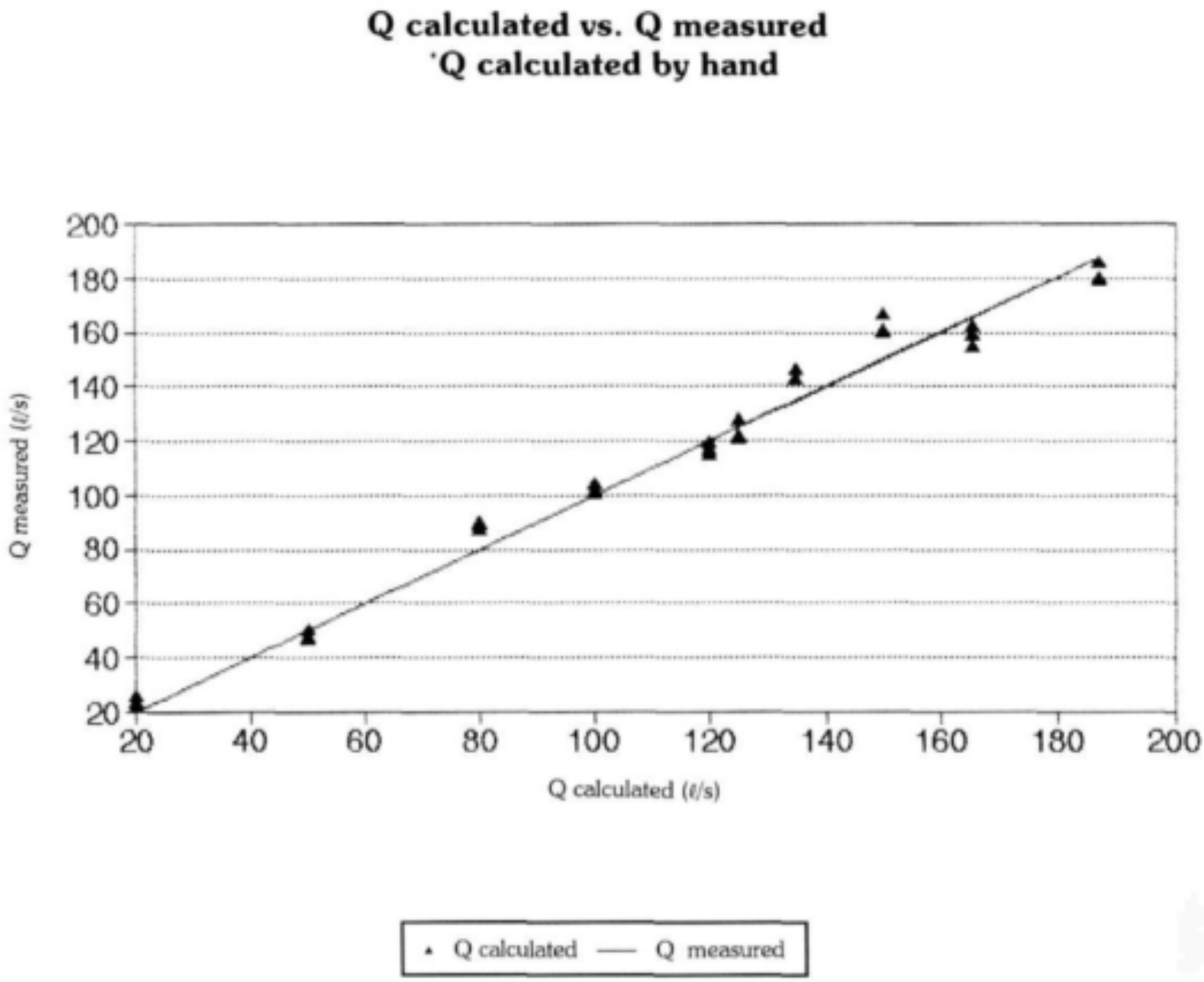
#### 5.2.1.1 Mode of operation

All tests on the velocity recorders were conducted on the full-scale model. This first set of tests was conducted by discharging water at flow rates of between 0 and 200 ℓ/s through the model. For each rate of flow the partially submerged ($h_3/h_1<0.75$), modular ($0.75<h_3/h_1<0.80$) and submerged ($0.80< h_3/h_1<0.90$) conditions were simulated again. By means of the velocity recorder the velocity in each case was then measured at a distance of between $4h_{max}$ and $5h_{max}$ upstream from the measuring flume. Thus it could be determined whether the velocity recorder was in fact sensitive enough to register changes in velocity as a result of the effect of the downstream depth of flow on the upstream depth of flow. In terms of the continuity principle, with Q=A·V, the velocity should therefore decrease, as the surface area increases due to rising upstream water levels under conditions of submergence. Depths were measured by means of a needle gauge at distances of between $3h_{max}$ and $4h_{max}$ upstream.



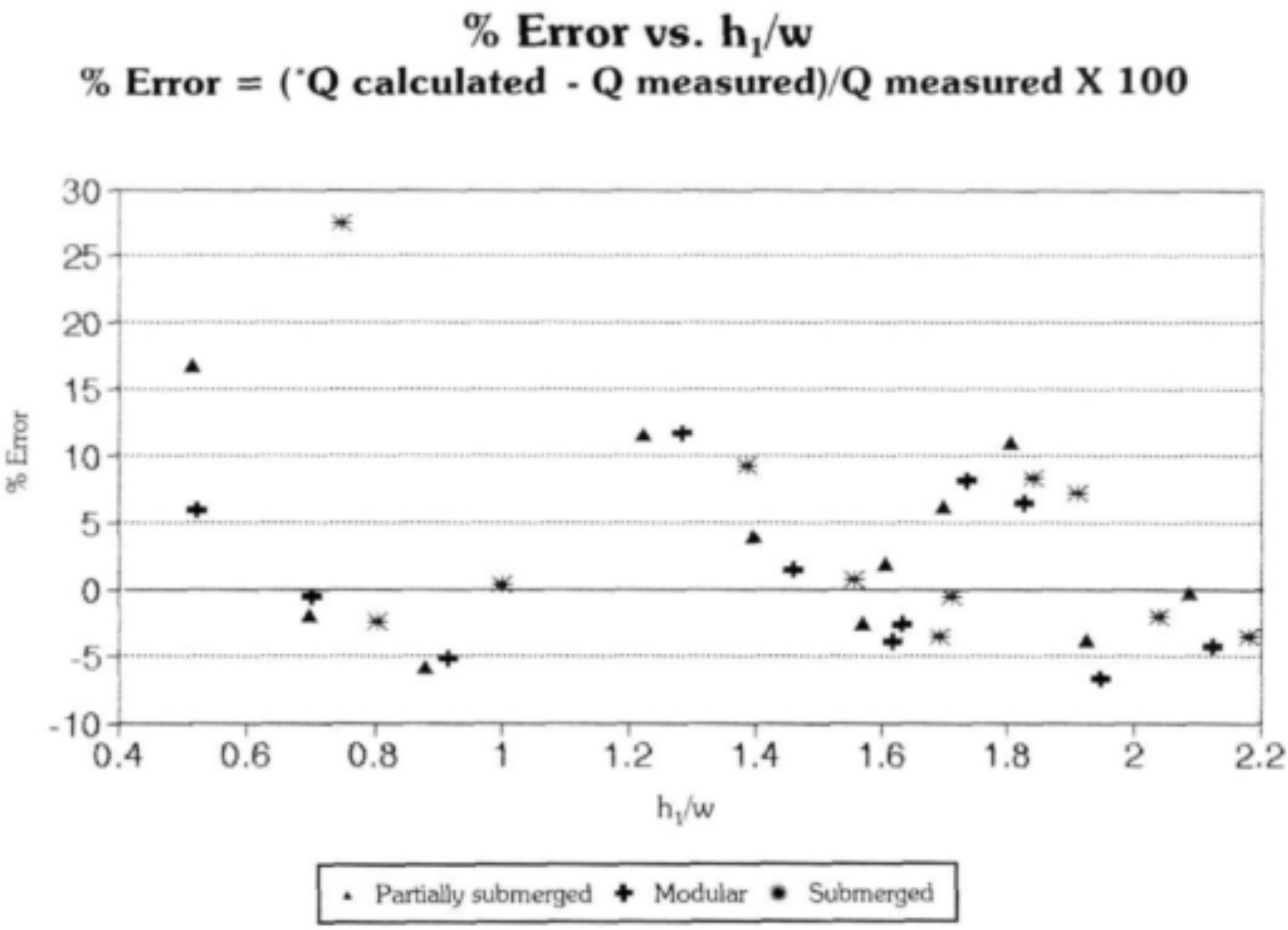

O - Partially submerged condition; M - Modular condition; V - Submerged condition

**Figure 5.8 The effect of submergence on the measured velocity upstream from the flume**




* "Q calculated by hand" means that the velocity recorder measures the velocity only and does not calculate the discharge. The discharge is then calculated by multiplying the measured velocity by the depth of flow and the channel width

**Figure 5.9 A comparison between the measured and the calculated discharge**




* Q Calculated by hand

**Figure 5.10 The % error in calculated discharge vs. parameter $h_1/w$**

#### 5.2.1.2 **Results**

In Fig. 5.8 it can be seen that the velocity does indeed decrease under modular or submerged conditions for the same discharge and when the calculated discharge for every condition is plotted vs. the measured discharge (Fig. 5.9) it is found that they compare very well and that there is no clear error pattern ($Q_{measured}$ is obtained by multiplying the measured velocity by the measured area ($W \cdot h_1$)).

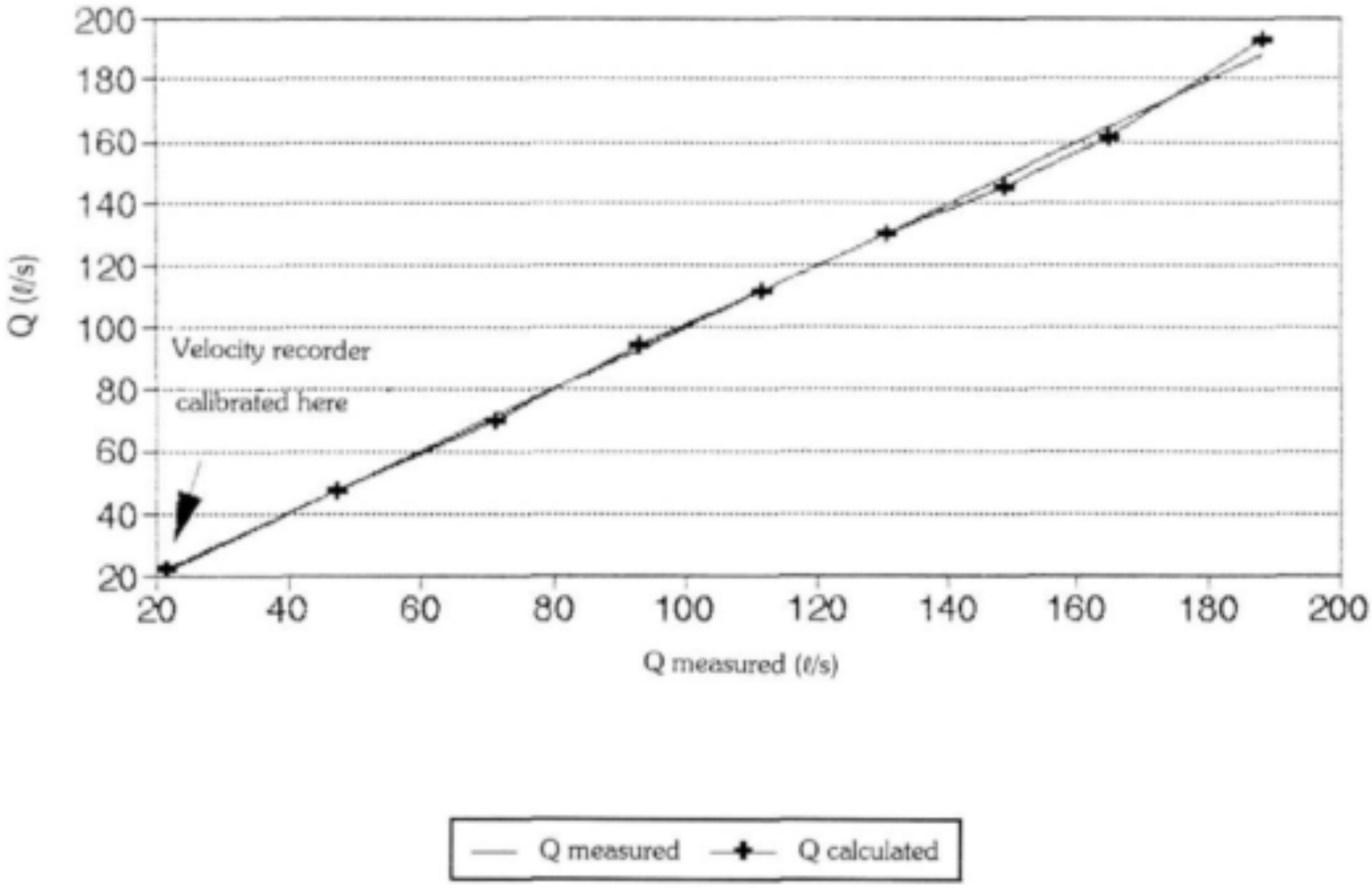
In the final instance the % error was plotted vs. the parameter $h_1/w$ which represents the discharge (Fig. 5.10). Figure 5.10 shows that, except for cases of very low flows, the % error lies scattered between 0 and ± 10%. It can also be seen that the partially submerged, modular and submerged points are scattered randomly about the zero line It can therefore be deduced that the velocity recorder operates equally well under conditions of submergence and partial submergence and that the recorder is therefore sensitive enough to register changes in velocity as a result of submergence.

The deviation at low flows as well as the errors between 0 and ± 10% appear to be relatively high. This could, however, also be ascribed to the variability in velocity readings which is described in the following section.

### 5.2.2. The accuracy of the K-factor and the calibration thereof

During the tests the variability in velocity readings was conspicuous. For the same discharge and condition the velocity meter reading typically varied by approximately 8 units on the second decimal, e.g. between 0.40 and 0.48 m/s.

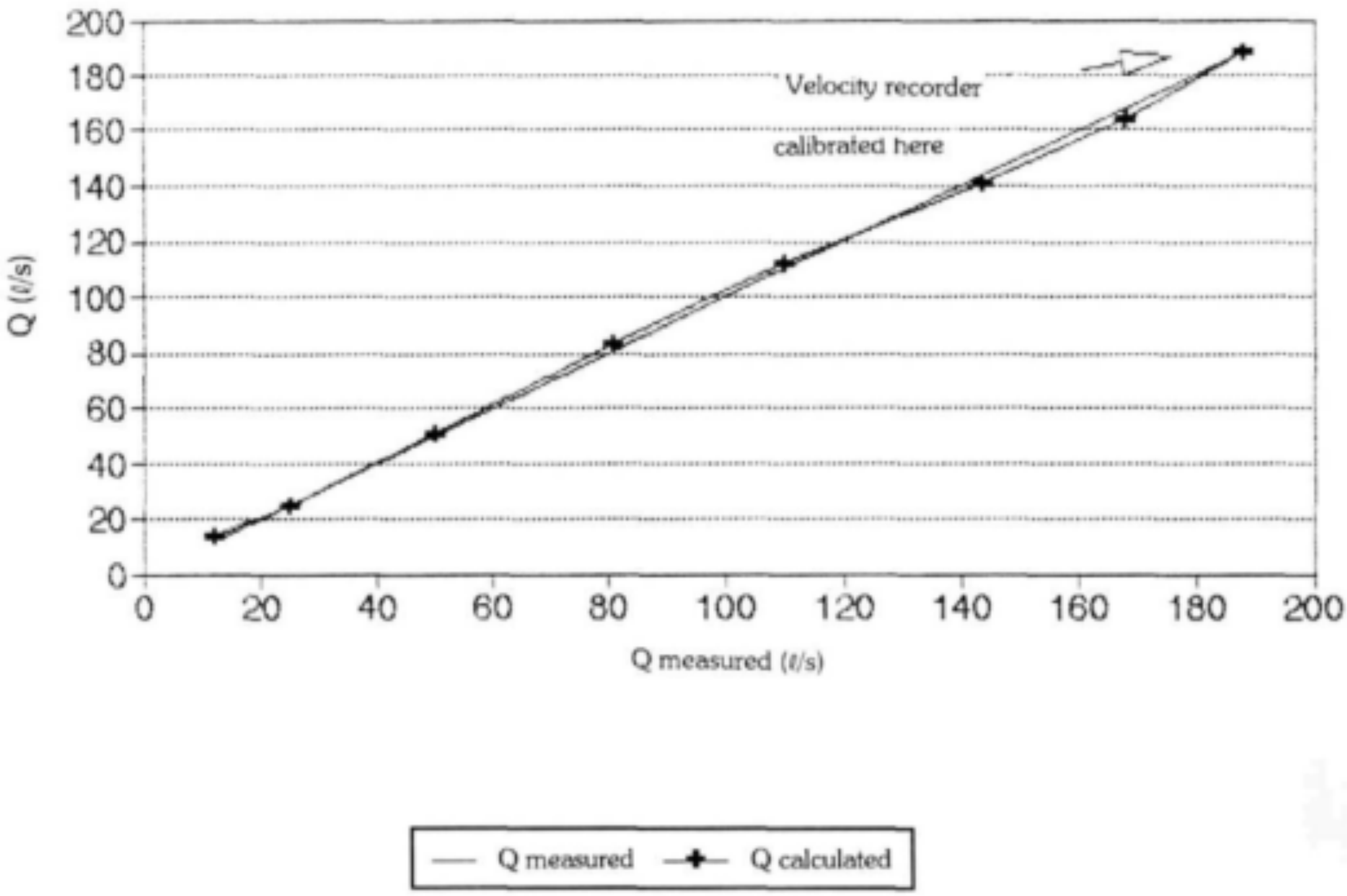
**Q measured vs. *Q calculated**
**Calibrated at low flow (partially submerged)**




* Q calculated as calculated by velocity recorder

**Figure 5.11 A plot showing measured vs. calculated discharges after the velocity recorder had been calibrated by means of the K-factor**

# Q measured vs. *Q calculated
# Calibrated at high flow (partially submerged)




* Q calculated as calculated by velocity recorder

**Figure 5.12 A plot of measured vs. calculated discharges after the velocity recorder had been calibrated by means of the K-factor**

#### 5.2.2.1 **Mode of operation**

For the second series of tests a velocity recorder and an electronic stage recorder were attached to the *Boatra* instrument. The instrument was then calibrated by means of a K-factor and the discharge as calculated by the instrument, was reflected. The instrument was first calibrated at a low flow and the discharge was then progressively increased. (Fig. 5.11). Subsequently the discharge was decreased again after the velocity recorder had been calibrated at a higher discharge (Fig. 5.12). For each discharge an average discharge was again read off on the instrument as it fluctuated all the time. In addition only conditions of partial submergence were tested as the previous set of tests had been conducted under conditions of submergence.

#### 5.2.2.2 **Results**

Figures 5.11 and 5.12 show that the difference between the calculated and the measured discharges is very small, irrespective of whether the instrument had been calibrated at low or high flows. This indicates that there is no variability in instrument readings due to increased or decreased discharges. It was also observed that the very small difference between measured and calculated discharges in Figs. 11 and 12 is in sharp contrast with the significant differences shown in Fig. 5.10. This observation can be ascribed to the fact that the discharges in Figs. 5.11 and 5.12 are calculated electronically, i.e. the instrument continuously corrects for varying velocity and depth. For Fig. 5.10 a velocity reading was used together with a measured depth to calculate the discharge manually. This procedure led to greater fluctuations.

### 5.2.3 **Conclusion**

According to Mr JM Vosloo, who designed the velocity recorder, the *Boatra* instrument gives velocities averaged over the previous 15 minutes This method of measuring is ideal as all the preliminary tests conducted had shown that the velocity recorder does not lose accuracy under conditions of submergence and that the K-factor can be calibrated at both low and high flows and still gives accurate results over the total range of flows. The only aspect worth mentioning was the persistent fluctuations in velocity and depth readings and therefore also in calculated discharges. The practice of measuring over a 15 min interval in order to obtain an average, is therefore an effective method to counter these fluctuations and to obtain the actual discharges.

Laboratory tests therefore proved that the *Boatra* instrument gives valid average readings under conditions of submergence and partial submergence and that the K-factor, after having been calibrated once, gives accurate readings for any discharge. Based on these findings a *Boatra* instrument could be installed on any measuring flume and the discharges as calculated by the instrument should be reasonably accurate. This practice is, however, not recommended, as laboratory conditions differ vastly from the actual conditions found in practice, especially those regarding water composition. In addition, sediment deposition upstream from the measuring flume could also have an effect, unknown at this stage, on the depth and velocity readings in practice. It is therefore recommended that the actual discharge is calculated by means of the calibration coefficients. (**Paragraph 5.1**) and that these calculated values are then compared with those calculated by the *Boatra* instrument, which is installed in the channel at the same time. In this manner the *Boatra* instrument could then be calibrated *in situ* should it be found that the discharges calculated by the instrument differ from the actual discharges calculated by means of the calibration coefficients.

As conditions were found to become very unstable at $h_3/h_1>0.90$, it is recommended that the velocity recorder not be used under conditions of submergence higher than 90%, but that the measuring flume should rather be modified to bring submergence down to below 90%.

## 6. CALIBRATION OF THE MEASURING FLUME BY MEANS OF CALIBRATION COEFFICIENTS

In this section a description is given of the procedure followed for the *in situ* calibration of a measuring flume in order to find a unique relationship between the upstream depth of flow and the discharge. In addition a method is described on how measuring flumes, under conditions of submergence higher than 90%, could be structurally improved to bring submergence down to below 90%.

### 6.1 Algorithm for the *in situ* calibration of a measuring flume

In order to obtain the best relationship between the upstream depth of flow and the discharge, the calibration has to be performed over a reasonable period of time, probably 24 h, during which time the discharges should cover the anticipated range of flows to be measured and calibrated.

1) Position three stage recorders at Points 1, 2 and 3 as shown in Fig. 4.1. Point 2 is at a distance w from the start of the contraction. Electronic stage recorders could be installed at Points 1 and 2, but at Point 2 a needle gauge must be used because the electronic recorder cannot measure the sloped water level.

2) Measure the depth at Point 1 ($h_1$) and Point 3 ($h_3$) during the peak discharge and calculate $h_3/h_1$

For $h_3/h_1$:

$< 0.75$ go to (2a)
0.75 to 0.90 go to (2b)
$> 0.90$ go to (2c)

2a) Partially submerged condition ($h_3/h_1<0.75$)
Measure $h_1$ at various discharges
Obtain C from Fig. 5.1
Calculate Q by solving Eq. (4.1)
Find the relationship between Q and $h_1$

2b) Submerged condition ($0.75<h_3/h_1<0.90$)
Measure $h_1$, $h_2$ and $h_3$ at various discharges
If $h_3/h_1<0.75$ go to (2a)
If $h_3/h_1>0.75$ and $<0.90$ obtain $C_d$ from Figs. 5.2 to 5.4

Calculate Q by solving Eq. (4.2)
Find the relationship between Q and $h_1$

2c) Submerged condition ($h_3/h_1 > 0.90$)
As conditions become very unstable for $h_3/h_1 > 0.90$ and it becomes impossible to determine the calibration coefficient accurately, there are no calibration coefficients for this case. Should it therefore be found that a flume is more than 90% submerged, it must be improved structurally in order to bring the degree of submergence down to below 90%. Various techniques are available to bring about this improvement:

i) Contract the flume, in other words, make w smaller. In this way the upstream water level rises and $h_3/h_1$ drops.

ii) Should the flume already be very narrow, the flume bed could be elevated. This will once again increase the upstream water level. The procedure is described fully in *BS 3680: Part 4C* (1981) and an explanatory sketch is included on p.18 of the same code.

Both techniques increase the depth of flow upstream of the flume and therefore provision must be made to increase the height of the channel walls upstream of the flume, if necessary.

iii) Alternatively the bed downstream of the flume could be lowered if sufficient gradient is available.

The discharge may therefore be related to the upstream depth of flow and the final product in the calibration process is a unique relationship between the discharge and the upstream depth of flow, which can then be used to calculate the discharge or it could be used to calibrate the velocity recorder *in situ*.

## 7. GUIDELINES FOR CONSTRUCTING FUTURE MEASURING FLUMES

Based on the large number of tests done in the laboratory and first-hand knowledge gained in this way, guidelines for constructing future measuring flumes were drawn up.

i) In the first instance measuring flumes must comply with the requirements as described in *BS 3680: Part 4C: Flumes* (1981). Information given in Paragraph 10.6 (*Limits of Application*) and in Fig. 1 on p. 18 is of particular importance.

ii) The code specifies that $w/W < 0.75$ and no lower limit is given. Theoretically it would be a good idea to keep w/W very small in order to ensure that $h_3/h_1 < 0.75$. It should, however, be borne in mind that the narrower the flume, the higher the backed-up water level in the upstream section of the flume.

In laboratory tests it was shown that the best w/W ratio proved to be between 0.4 and 0.55. For w/W smaller than 0.4 the level of the backed-up water in the upstream section becomes high and a very deep channel is required. For $w/W > 0.55$ the upstream depth of flow becomes much more sensitive to changes in the downstream depth of flow and critical conditions in the flume are also not as well defined.

The w/W ratio should therefore be at between 0.4 and 0.55 and if the flume needs to be contracted to counter submergence, it could be contracted to a minimum w/W ratio of 0.30.

iii) As proven in **Paragraph 3.1** the length of the contraction does not play a significant part. The BS recommends that $h_1/L < 0.5$ in other words the length must be twice as much as the maximum upstream depth of flow. Thus critical conditions in the flume are better defined and the longer length of the contraction also provides improved separation between the upstream and the downstream depths of flow during conditions of submergence.

iv) As already described in **Paragraph 6**, the maximum $h_2/h_1$ flume ratio should preferably be smaller than 0.75, but submergence up to 0.90 is still manageable. This is of particular importance when a measuring flume is to be installed upstream from a sluice gate or other structure which could cause varying levels of submergence at the flume.

v) It was also shown that the inlet shape has a minimal effect on the calibration coefficients of measuring flumes. Therefore the non-curved inlet with 1:4 contraction, is as acceptable as a curved inlet. The non-curved inlet is recommended due to ease of construction.

vi) As both the velocity recorder and the stage recorder have to be installed at approximately $4h_{max}$ upstream from the flume, provision must be made for sufficient distance upstream of the flume in order that the measurements at $4h_{max}$ are not hampered by conditions further upstream.

vii) In order to improve the accuracy of the stage and velocity measurements upstream of the flume, a floating raft could be placed in the channel further upstream from the measuring point. A graphical illustration of such a floating raft is given in Fig. 7.1. The raft has a damping effect on surface wave action, resulting in a smoother water surface and more accurate measurements.

viii) As we had been informed by ERWAT that sediment deposition upstream from the flume was proving to be a huge problem, it was decided to include a schematic representation of the newly developed measuring flume (sluicing flume), which had been designed by the Hydraulics Laboratory at the University of Stellenbosch for the Department of Water Affairs and Forestry. Figure 7.2 shows the measuring flume which was specifically designed to sluice the sediment, thus preventing its build-up behind the measuring weir. Depth measurements are done in the flume itself and very satisfactory results have been obtained. Future research could be aimed at investigating whether the principle of operation of this measuring flume could perhaps be employed in solving the problem of sediment deposition upstream of flumes in sewers.

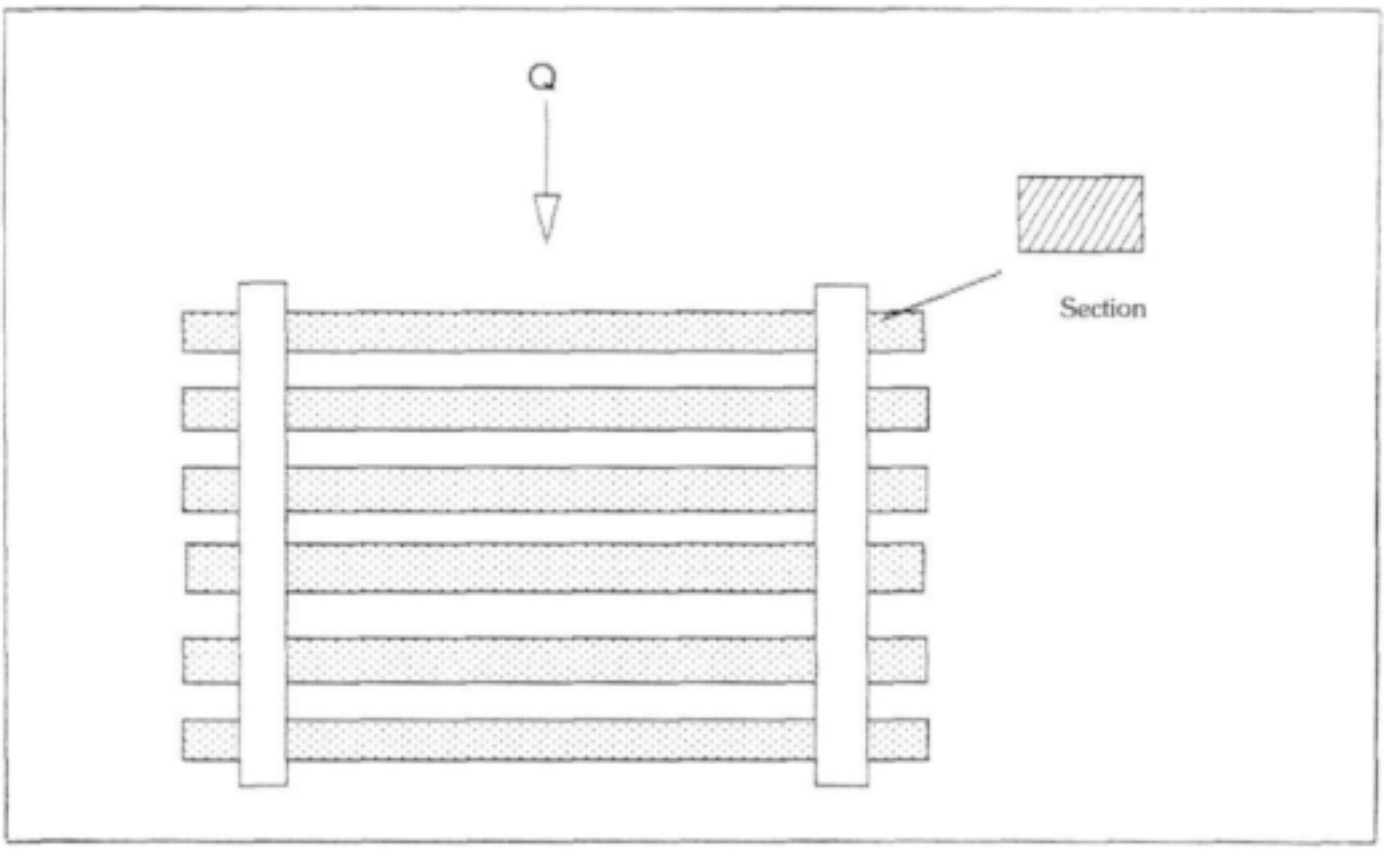



**Figure 7.1 Wooden slats to dampen surface wave action**

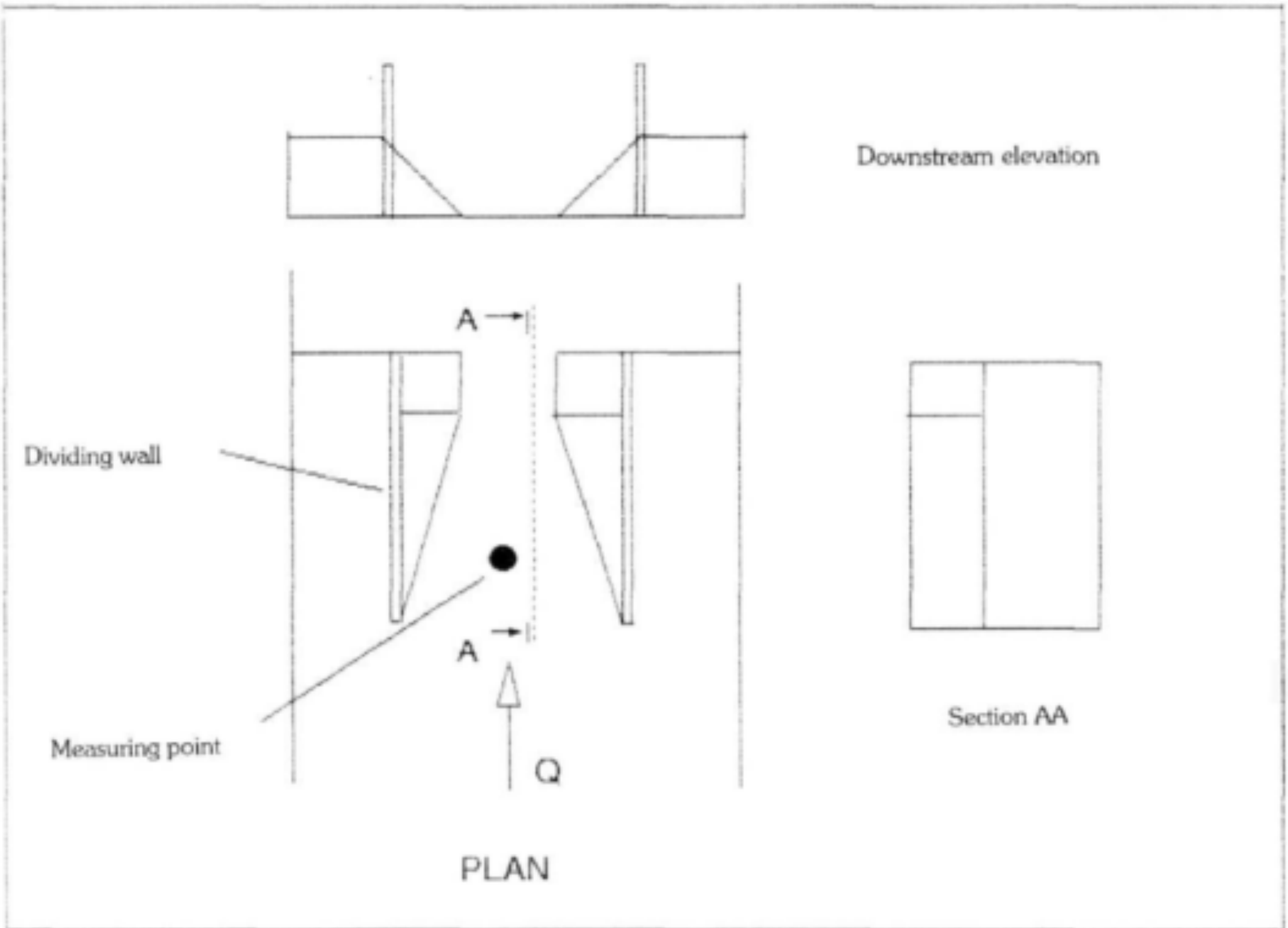



**Figure 7.2 Typical new measuring flume (sluicing flume) designed to sluice sediment**

# APPENDIX 4A

# SELECTING MEASURING FLUMES WHICH ARE REPRESENTATIVE OF THE TOTAL RANGE OF PARAMETERS

*List of measuring flumes*

| No | w(mm) | L(mm) | W(mm) | w/W | L/W |
|---|---|---|---|---|---|
| 1 | 305 | 550 | 455 | 0.670 | 1.209 |
| 2 | 150 | 1020 | 297 | 0.505 | 3.434 |
| 3 | 303 | 540 | 455 | 0.666 | 1.187 |
| 4 | 120 | 370 | 230 | 0.522 | 1.609 |
| 5 | 200 | 602 | 300 | 0.667 | 2.007 |
| 6 | 455 | 2050 | 900 | 0.508 | 2.278 |
| 7 | 100 | 280 | 280 | 0.357 | 1.000 |
| 8 | 790 | 1360 | 1489 | 0.531 | 0.913 |
| 9 | 270 | 1330 | 600 | 0.450 | 2.217 |
| 10 | 385 | 530 | 680 | 0.566 | 0.779 |
| 11 | 275 | 840 | 925 | 0.297 | 0.908 |
| 12 | 775 | 1745 | 1225 | 0.633 | 1.424 |
| 13 | 350 | 2315 | 1000 | 0.350 | 2.315 |
| 14 | 300 | 1500 | 750 | 0.400 | 2.000 |
| 15 | 190 | 900 | 500 | 0.380 | 1.800 |
| 16 | 300 | 1300 | 1000 | 0.300 | 1.300 |
| 17 | 300 | 1200 | 1000 | 0.300 | 1.200 |
| 18 | 300 | 1230 | 1000 | 0.300 | 1.230 |
| 19 | 800 | 1520 | 1200 | 0.667 | 1.267 |
| 20 | 203 | 500 | 308 | 0.663 | 1.634 |
| 21 | 490 | 1120 | 1050 | 0.467 | 1.067 |
| 22 | 800 | 900 | 990 | 0.606 | 0.808 |
| 23 | 485 | 1000 | 800 | 0.606 | 1.250 |
| 24 | 510 | 1600 | 1210 | 0.421 | 1.322 |
| 25 | 500 | 1930 | 1220 | 0.410 | 1.592 |
| 26 | 480 | 2055 | 1230 | 0.390 | 1.671 |
| 27 | 450 | 1410 | 1000 | 0.450 | 1.410 |
| 28 | 600 | 1660 | 1500 | 0.400 | 1.107 |
| 29 | 305 | 1015 | 620 | 0.492 | 1.637 |
| 30 | 762 | 2315 | 1759 | 0.433 | 1.316 |
| 31 | 510 | 1955 | 1210 | 0.421 | 1.616 |

* This list contains information on all measuring flumes as provided by ERWAT. Parshall measuring flumes are not included.

**Figure 4A.1 Numbered measuring flumes out of which 5 representative measuring flumes were selected**

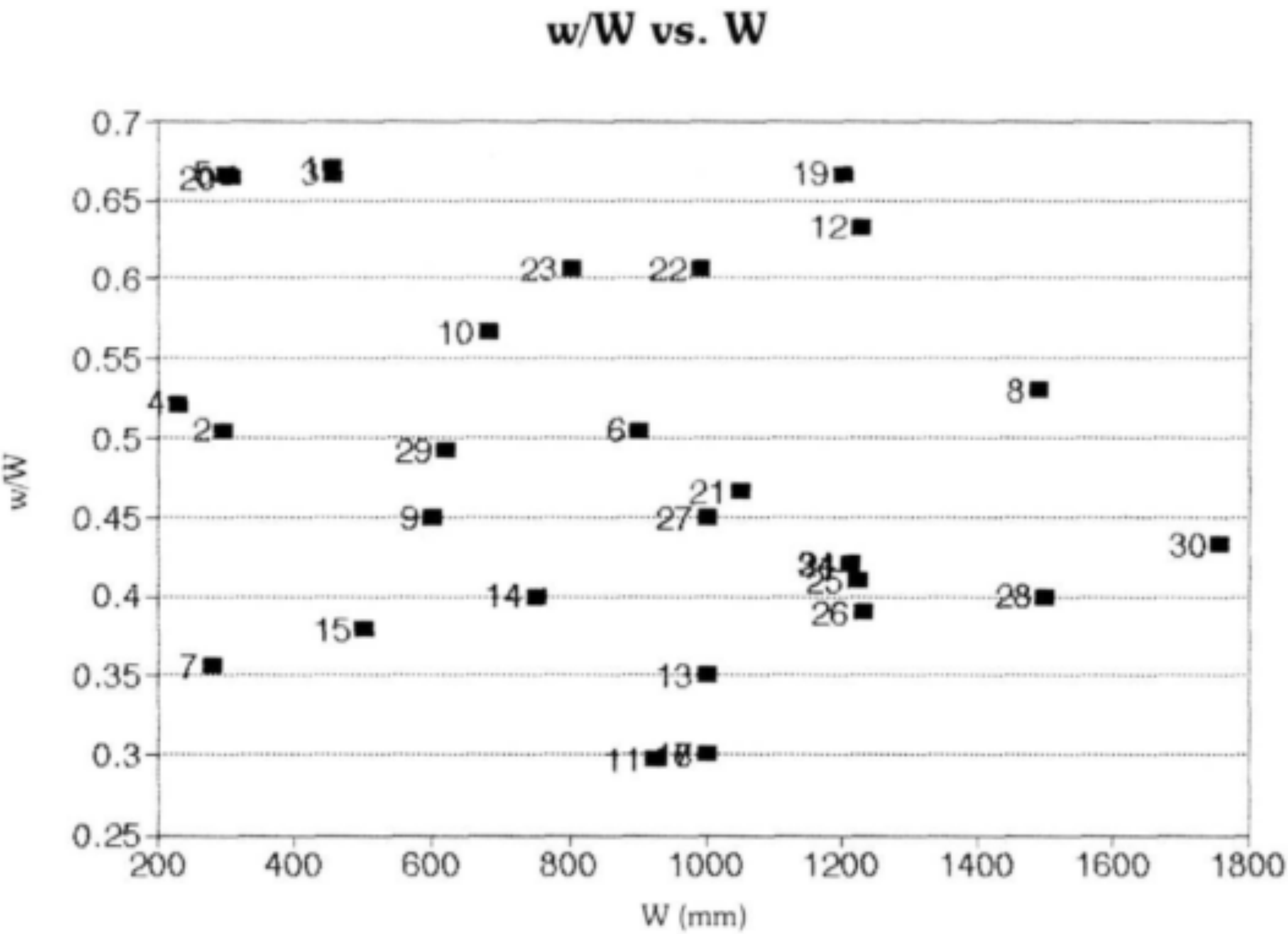



**Fig. 4A.2 Plot of parameter W vs. w/W**

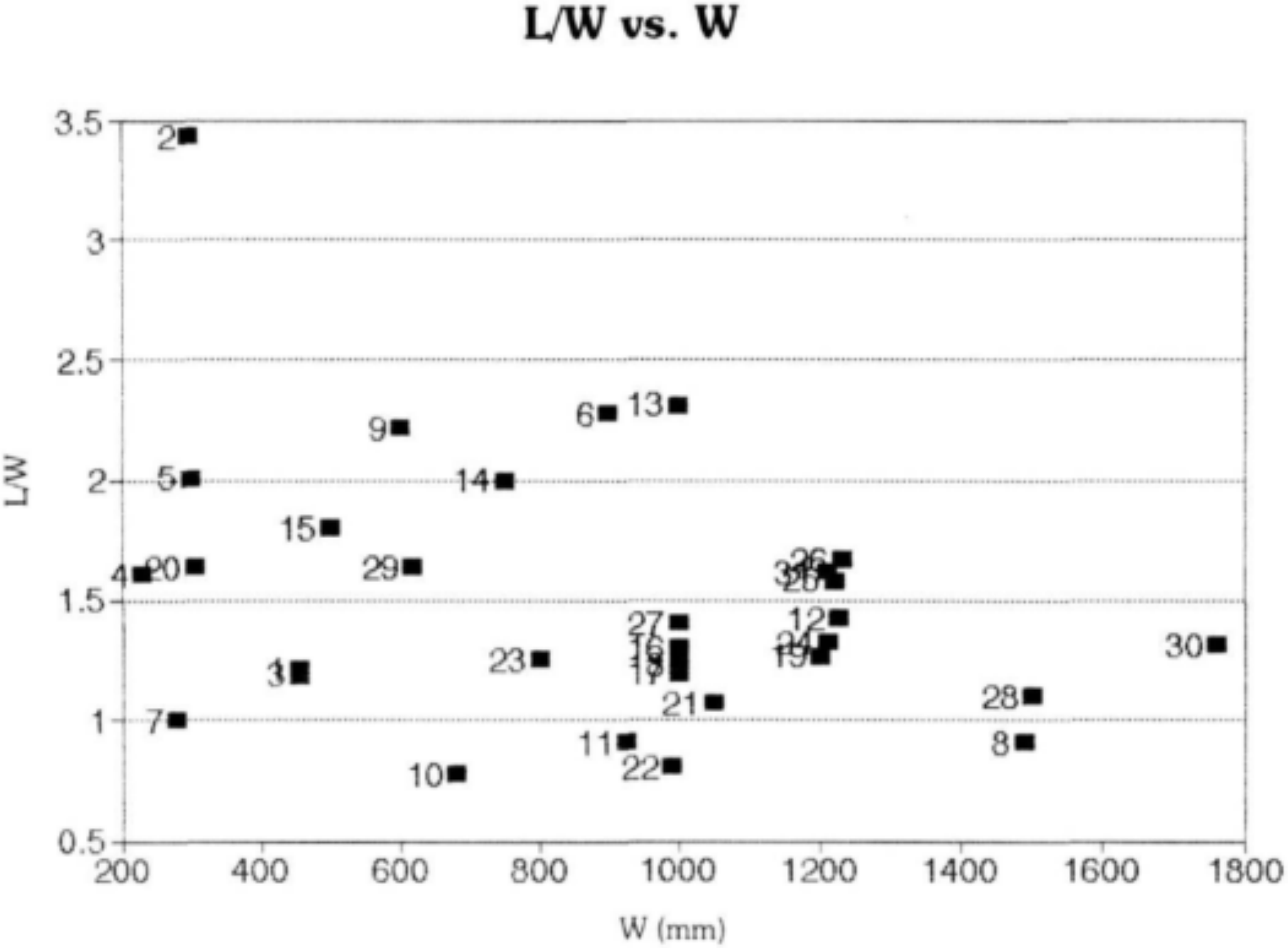



**Fig. 4A.3 Plot of parameter W vs. L/W**

# APPENDIX 5A

# THE EFFECT OF FLUME INLET SHAPE ON THE CALIBRATION COEFFICIENTS C AND $C_d$

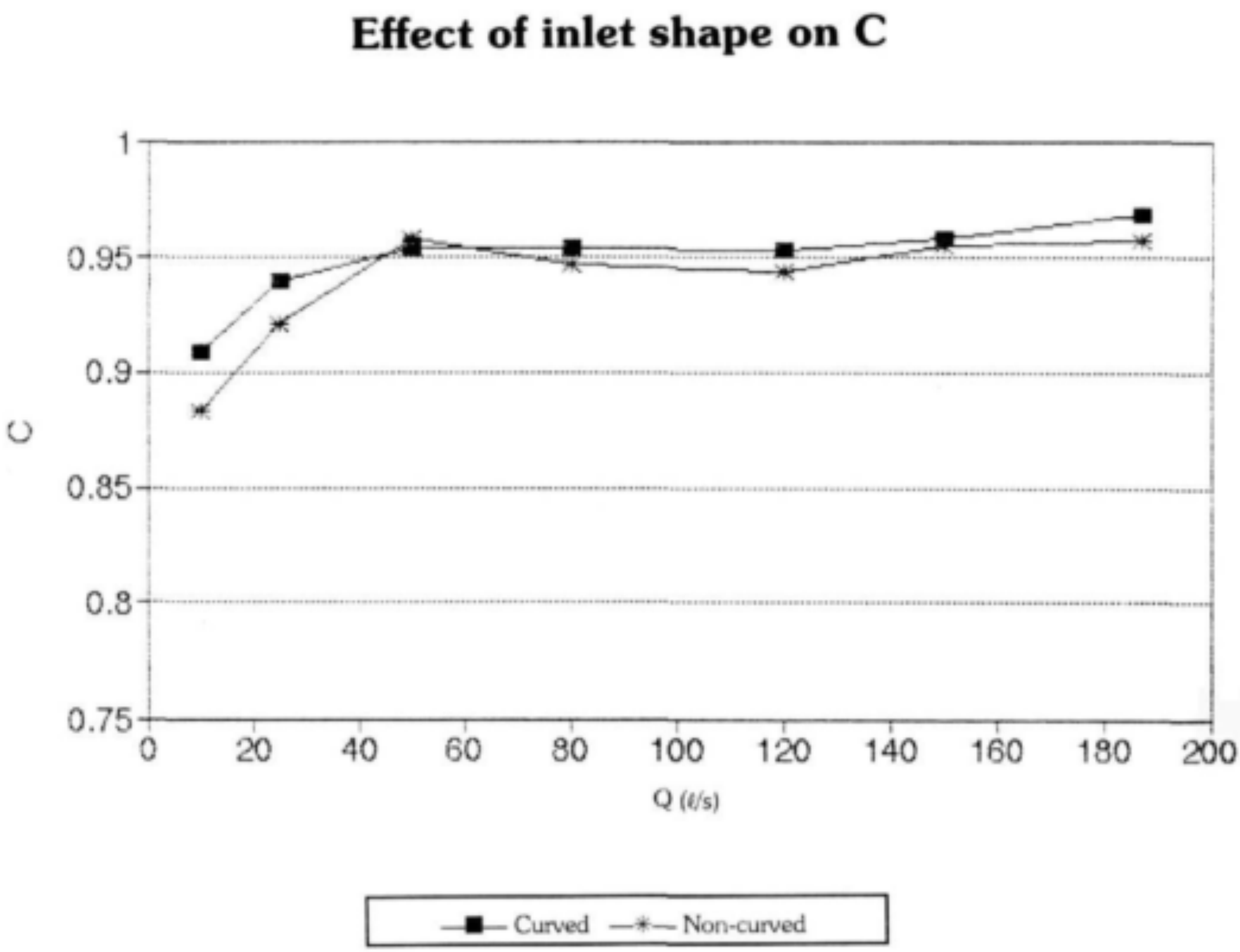



**Figure 5A.1 The effect of inlet shapes on the calibration coefficient C**

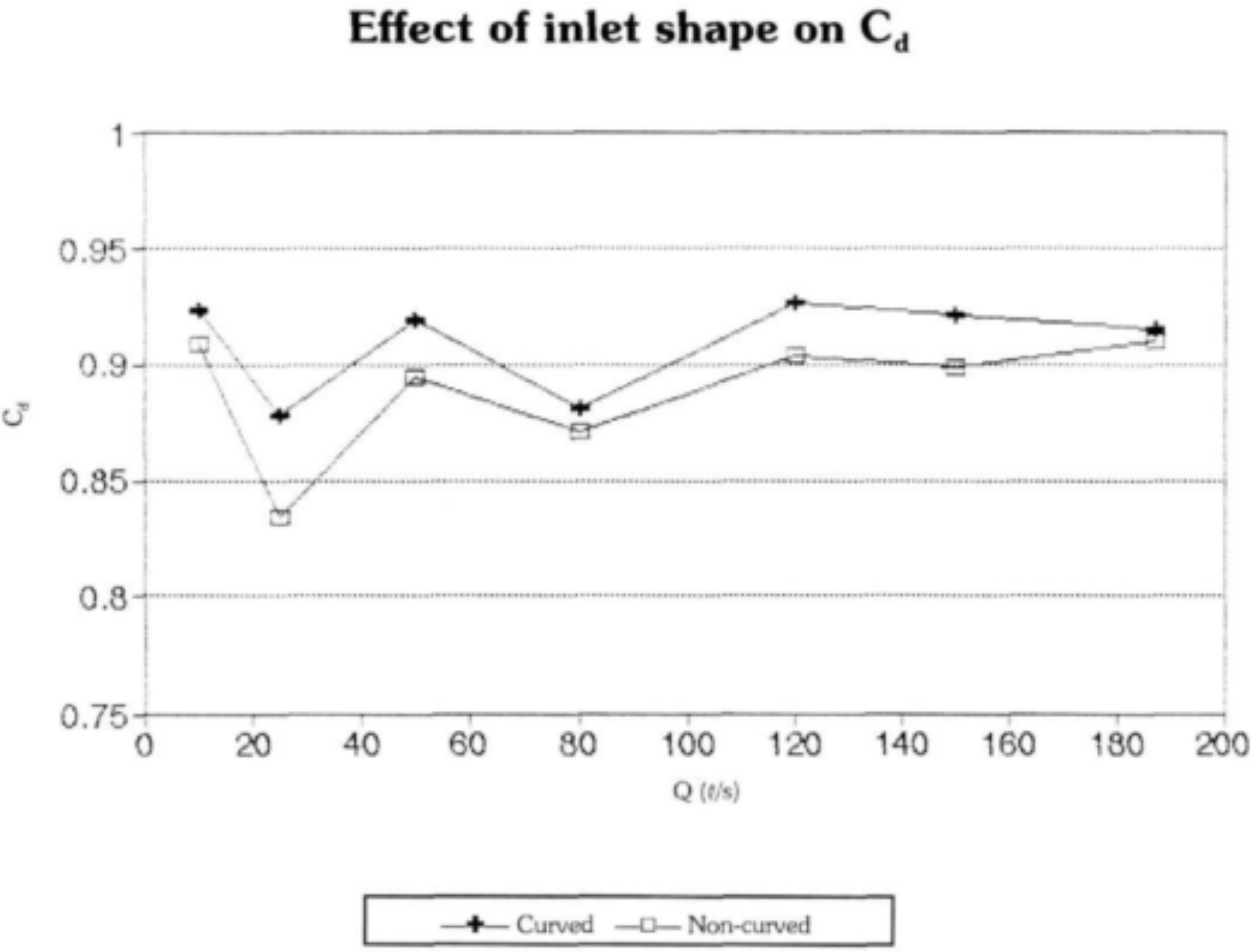



**Figure 5A.2 The effect of inlet shapes on the calibration coefficient $C_d$**

# APPENDIX 5B

# THE EFFECT OF FLUME ROUGHNESS ON THE CALIBRATION COEFFICIENTS C AND $C_d$

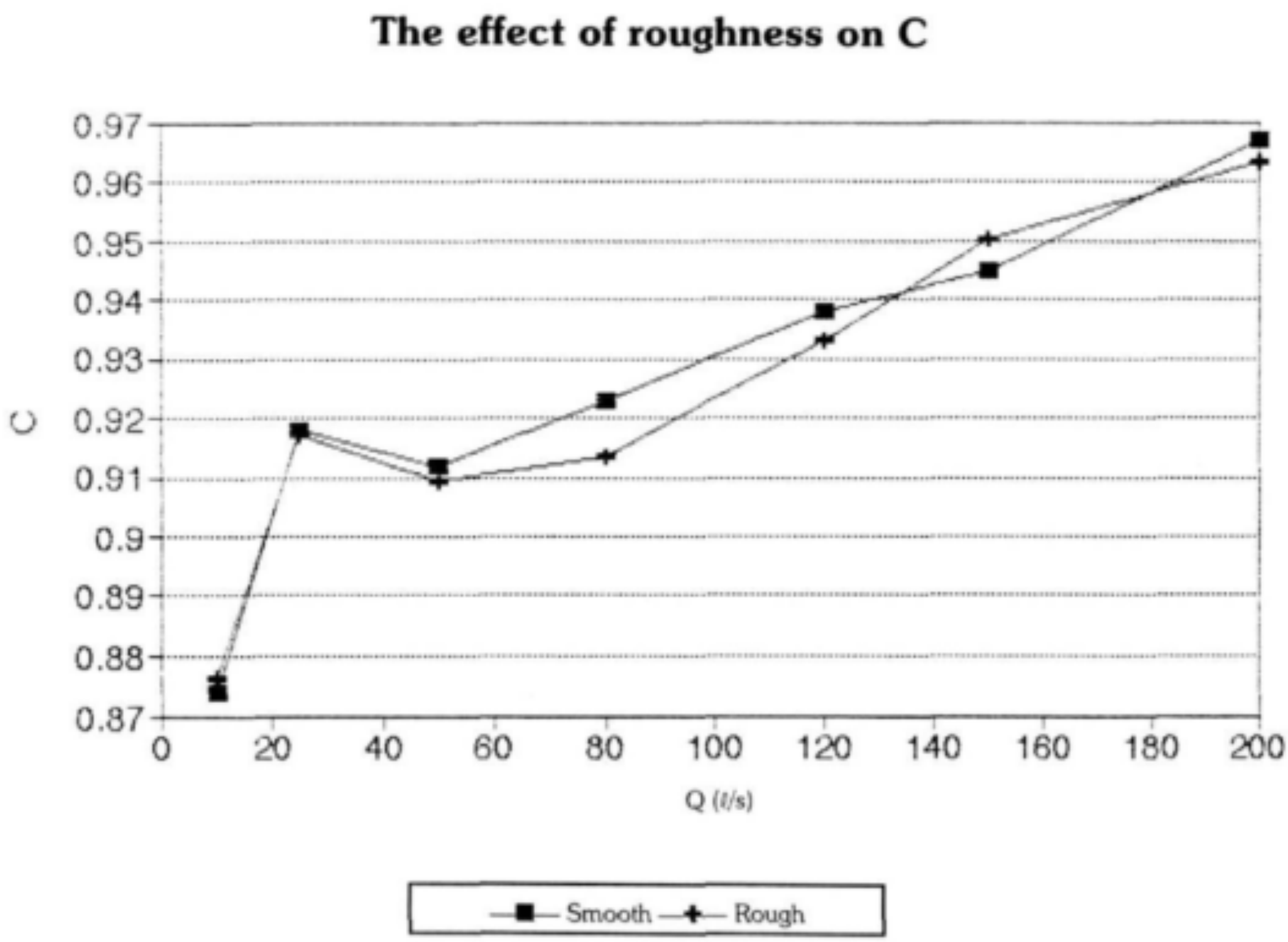



**Figure 5B.1 Effect of flume roughness on calibration coefficient C**

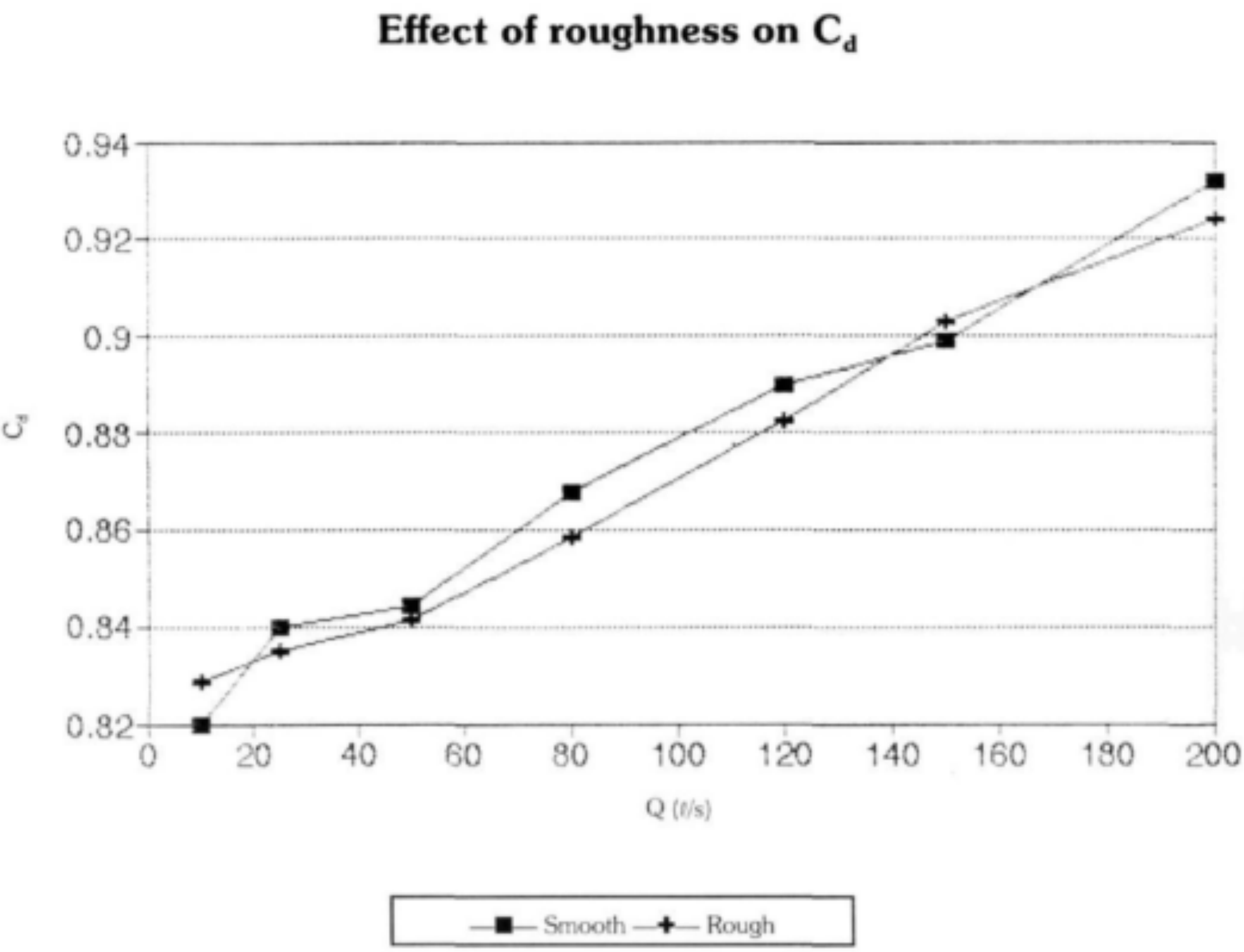



**Figure 5B.2 Effect of flume roughness on the calibration coefficient $C_d$**