Extending the Scope of Standard Specifications for Open Channel Flow Gauging Structures

W R White
E Whitehead
E J Forty

Report SR 564
March 2000

HR Wallingford

Address and Registered Office: HR Wallingford Ltd. Howbery Park, Wallingford, OXON OX10 8BA
Tel: +44 (0) 1491 835381 Fax: +44 (0) 1491 832233

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Contract

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Prepared by W R White ....

(name)

Senior Consultant. ....

(Title)

Approved by ....

(name)

....

(Title)

Date 02.02.00 ....

Summary

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The performance data given in existing flow measurement Standards for open channel flow gauging structures are qualified by strict limitations which are imposed because the original supporting research did not anticipate the more extensive range of conditions used today by the water industry and the civil engineering profession. Commonly used gauging structures often operate outside the limits specified in the Standards and this could lead to gross inaccuracies in measured flows.

The Department of the Environment, Transport and the Regions (DETR) partly funded this research project to extend the range of conditions in which a stage-discharge relationship for a particular structure can be predicted, thereby permitting the extension of the scope of certain flow measurement Standards. Additional financial contributions came from HR Wallingford (HRW), the Environment Agency (EA), the Scottish Environment Protection Agency (SEPA) and Yorkshire Water plc.

Information available in flow measurement Standards was summarised and the key experimental limitations were highlighted in the Interim Report, SR 532, December 1998 (see Table 1). Additionally the Interim Report contained a review of the current usage of flow gauging structures. This was based on documents such as registers of gauging structures, reports of studies undertaken for Water Service plc's and asset surveys undertaken for the Environment Agency. Individual experts and operators of structures were also consulted to identify the areas where the Standards needed extending.

The information from the review of flow measurement Standards and the review of current usage was drawn together in order to decide what laboratory tests might be undertaken to provide information which would enable the Standards to be extended to cover more of the structures in common use. This definition of the proposed experimental work was also covered in the Interim Report, SR 532, December 1998.

Following the market survey and review, the experimental work commenced in January 1999 and was designed to cover three of the more important issues identified in SR 532, namely:

Summary continued

- to extend the range of permissible flow conditions in terms of head to weir height ratios, h / P.
- to evaluate the performance characteristics of compound weirs without divide piers.
- to extend the availability of drowned flow performance data.

This final report covers all three of these issues.

Notation

Symbol	Description	Unit of measurement
A	area of cross-section of flow	m^2
b	crest width	m
b_e	effective crest width	m
B	width of approach channel	m
C	modular coefficient of discharge for the Thin Plate weir	non-dimensional
C_b	basic modular coefficient of discharge for the Thin Plate weir	non-dimensional
C_{de}	effective modular coefficient of discharge for the Crump weir	non-dimensional
C_{dr}	drowned flow reduction factor	non-dimensional
C_e	effective modular coefficient of discharge for the Thin Plate weir	non-dimensional
f	drown flow reduction factor	non-dimensional
Fr	Froude Number	non-dimensional
g_n	acceleration due to gravity	m/s^2
h	gauged head above crest level	m
h_e	effective gauged head above crest level	m
h_{max}	maximum modular upstream head	m
H	total head above crest level	m
L	distance from the crest to the head measurement position	m
P	height of weir crest above mean upstream bed level	m
q	discharge per unit width	m^2/s
Q	total discharge	m^3/s
V	mean velocity in cross-section	m/s
V_a	mean velocity in approach channel	m/s
α	Coriolis coefficient	non-dimensional
Δ	difference in weir crest levels	m
δ	boundary layer displacement thickness	m
ε	coefficient in the J. I. S. formula for Thin Plate weirs	non-dimensional

Suffixes

1	denotes upstream value
2	denotes downstream value
e	denotes "effective" value taking into account fluid property effects

Superscripts

G	refers to gauging section
T	refers to crest tapping section
S	refers to any other section

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1. INTRODUCTION

The UK reference work for flow measurement using gauging structures (Ackers et al, 1978, see Ref. 1) gives the specifications for many types of gauging structure together with performance data which enables the user to compute flows based on head measurements (water levels relative to crest level) at the structure. The book was written by employees of HR Wallingford and the content is mainly based on experimental and theoretical work carried out at HR Wallingford, the work being financially supported by various UK Government Departments. Many of the British and International Standards for flow gauging structures are derived from this work.

Information available in flow measurement Standards was summarised and the key experimental limitations were highlighted in the Interim Report, SR 532, December 1998 (see Table 1). Additionally the Interim Report contained a review of the current usage of flow gauging structures. The information was drawn together in order to decide what might be done which would enable the Standards to be extended to cover more of the structures in common use.

The most pressing requirements for additional experimental data, taking into account both the extent of usage and the extent of non-compliance with Standards were:

- to extend of the range of flow conditions in terms of head to weir height ratios, h / P.
- to evaluate the performance characteristics of compound weirs without divide piers.
- to extend the availability of drowned flow performance data.

This report covers these three issues.

Extension of permissible flow conditions
Two weirs were tested, both of which are extensively used and both of which are regularly used outside their recommended range for the head to weir height ratios, h / P. The two-dimensional Triangular Profile Crump weir is extensively used in natural rivers and in many cases sediment accumulations upstream of the structure have increased maximum h / P ratios above the recommended limit of 3.5. Likewise, full-width Thin Plate weirs often exceed their recommended limit of 2.5.

Compound weirs without divide piers
Compound weirs are extensively used for flow measurement in rivers. The Standard specification requires that adjacent crests are separated by divide piers and discharge formula are given which are applicable to these weirs. Many compound weirs have been built without divide piers with no knowledge of the effect of this modification on the hydraulic performance of the structure. In this study a Compound Crump weir was tested with and without divide piers. The weir had two adjacent crest sections, the width of which could be adjusted. The effects of the absence of divide piers have been evaluated.

Drowned flow performance data
Two types of weir were tested, both of which are known to be used in the drowned flow range despite the absence of guidance from Standards. Rectangular Broad Crested weirs and Full Width Thin Plate weirs are found both in natural and artificial channels and, in many cases, the elevation of the crest has been set as low as possible in order to avoid major increases in upstream levels when installed. This both helps to minimise flood levels upstream and eases the passage of fish over the structure. However, in many cases, the performance of these weirs becomes affected by tailwater levels at relatively low flows. Thus, over much of the flow range, they operate under drowned flow conditions, intentionally or unintentionally.

2. EXPERIMENTAL FACILITY

All the experimental work was carried out in the General Purpose flume shown in Figure 1. The length, breadth and depth of the flume are 20m, 2.4m and 0.6m respectively. Water is supplied to the flume from a large capacity sump by a 0.17 m^3/s centrifugal pump, fluctuations in discharge being minimised by a constant head device on the delivery side of the pump.

Discharge is measured by deflecting the outflow from the flume into a volumetric tank for a measured length of time. Normally a minimum volume of 10 m^3 is measured and timing is by electronic timer, accurate to 0.01 s, operated automatically by the deflector gear. Steady state levels in the volumetric tank at the start and end of the test are measured with micrometer screw gauges to 0.01 mm. The accuracy of flow measurement is estimated at 0.2 per cent at low flows and 0.4 per cent at high flows.

Water levels were measured by piezometric tappings set in the side of the flume at weir crest level upstream of the weirs and in the case of the drowned flow experiments 0.05m above the bed on the downstream side. These were connected to 0.15 m diameter stilling pots and micrometer screw gauges reading to 0.01 mm were used to measure the head.

The main flume was narrowed down to between 400 mm and 750 mm in width for the current series of experiments in order that sufficient head could be generated over each of the weirs with the installed flow capacity. Flow smoothing was provided at the upstream end in order to provide good approach flow conditions to the weirs.

Plate 1 shows the general arrangement of the flume. Plate 2 shows the deflector gear for the volumetric tank.

Extension of permissible flow conditions
Both weirs had nominal breadths of 0.4m and nominal heights above upstream bed level of 0.06m. These values were chosen so that high values of h / P could be achieved with the discharge available within the test facility. Upstream heads were measured at three locations upstream of each weir in order to assess the effects of drawdown and the frictional resistance of the upstream channel. The locations were chosen so as to span the recommended location given in the Standard.

Figure 1 shows that both weirs were mounted in the flume simultaneously, the thin plate weir being downstream of the Crump weir. The purpose of doing this was to maximise the productivity of the testing in that a single measurement of flow provided calibration points for both weirs. The levels of the weirs and approach channels were chosen to avoid either of the weirs affecting the performance of the other. For high flows it was found necessary to complete the testing on the upstream Crump weir and then remove this weir before completing the testing of the Thin Plate weir.

Plates 3 and 4 show the Crump and Thin Plate weirs respectively.

Compound Crump weir without divide piers
The main flume was narrowed down to a 750 mm channel in order that sufficient head could be generated over the low section of the compound Crump weir with the installed flow capacity. Flow smoothing was provided at the upstream end in order to provide good approach flow conditions to the weir.

Two two-section compound Crump weirs were tested. Both weirs had nominal heights above upstream bed level of 0.06 m at the low crest and 0.12 m at the high crest. The low crest height was selected so that the British Standard maximum head to upstream weir height ratio, h / P, could be achieved at the low section of the weir with the available discharge. The nominal widths of the low and high parts were 0.5 m and 0.25 m respectively for the first weir and 0.25 m and 0.5 m respectively for the second weir. A removable pier of Standard length was fitted between the crests to allow comparison of the weirs with and without piers.

Heads were measured at three locations upstream of the weir on both banks to assess the effects of drawdown and the frictional resistance of the upstream channel. The locations were chosen so as to span the recommended location given in the Standard.

The weirs, with and without divide piers, are shown in Plates 5 and 6.

Drowned flow performance data

The main flume was narrowed down to a 400 mm channel in order that sufficient head could be generated with the installed flow capacity. Flow smoothing was provided at the upstream end in order to provide good approach flow conditions to the weirs.

Drowned flow tests were made on two types of weir:

The first weir was a Rectangular Broad Crested weir with a horizontal crest and vertical upstream and downstream faces. Upstream and downstream corners were square. The height of the weir was chosen so as to allow the Standard upper recommendation of head-to-weir height ratio of 1.6 to be reached for modular flow with sufficient extra freeboard for increased upstream head when the weir was drowned. The Standard ratio of weir length to weir height can vary between 0.1 and 4.0 and a ratio of 3.0 was chosen as representative of prototype practice.

The second weir was a Full Width Thin Plate weir designed to Standard specification. The height of the weir was set at 0.1 m to allow a head-to-weir height ratio of 2.2 to be reached for modular flow bearing in mind that upstream head would increase by up to 70% when the weir became drowned.

Upstream heads were measured at three locations upstream of each weir to assess the effects of drawdown and the frictional resistance of the upstream channel. The Standard location for the upstream head measurement position for both weirs is 4 h_{max} upstream of the crest and all modular readings would be taken at this point. Upstream readings were also taken at distances of 2 h_{max} and 8 h_{max} to assess whether measuring at either of these points would have significant benefits for drowned flow measurement. However, the fitting of an extra stilling well and measuring equipment at either of these positions would be complicated, expensive and not viable unless it was proved that the benefit was substantial.

Downstream heads were also measured at three locations to assess the influence of turbulence downstream of each weir on the consistency of the drowned flow performance. Head measurements were made at 0.25, 1.0 and 1.5 m downstream of the weirs which represent h_{max}, 4 h_{max} and 6 h_{max} respectively. The measurement at h_{max} was included because other research has suggested that flow conditions close to the weir are stable during drowned flow for some types of weir. The other two positions spanned an area downstream of the weir that was expected to be clear of local turbulence.

3. CRUMP WEIR: EXTENSION OF h / P RATIOS

The Standard Specifications for the Triangular Profile Crump weir is given in the following Standard:-

- BS 3680/4B:1986 (ISO 4360:1984) : *Triangular Profile weirs*

A brief summary of the performance characteristics of this type of weir and the limitations imposed on the design and operation of the weir are given in Appendix 1. The weir is shown in Figure 2.

3.1 Historic data

Flow conditions in the approach to typical weir installations are complex. Dimensional reasoning shows that the coefficient of discharge for a Triangular Profile Crump weir depends on the following geometrical factors:

- the total head above crest level, H_{1e}
- the distance from the crest to the upstream tapping position, L_1
- the weir crest height above upstream bed level, P_1

Hence:

$$C_{De} = \text{fn}\,[\,H_{1e} / P_1 \,,\, H_{1e} / L\,]$$

This indicates that the most appropriate position for the upstream tapping can be considered in relation to the crest height and the head on the weir. Previous HR results for the Triangular Profile Crump weir are shown in Figure 3. These cover the range $0 < H_{1e} / P_1 < 3.5$ and these were the results which were used to formulate the Standards.

3.2 New data

In the current study some repeat tests were carried out in the range $0 < H_{1e} / P_1 < 3.5$ in order to check that the same experimental facility, which had been used some 30 years previously for the original tests, was capable of reproducing the earlier results. Further tests were then carried out in the range $3.5 < H_{1e} / P_1 < 5.0$ in order to provide the extended range of data required by the users of this type of weir.

The repeat tests confirmed that the historic results could be reproduced, albeit with a slight increase in random and systematic uncertainties. This results from the wear and tear which has taken place over the number of years that this particular equipment has been in use. Figure 4 shows the new results including those which extend beyond the current limiting value of H_{1e} / P_1 of 3.5. Figure 5 shows of the historic results together with those obtained in the current study. It covers the full range $0 < H_{1e} / P_1 < 5.0$.

The results show that the coefficient of discharge of the Triangular Profile Crump weir is independent of the ratio H_{1e} / P_1 up to the newly defined limit of 5.0. Figure 6 plots coefficient values against H_{1e} / P_1 for all data in the range $H_1 / L_1 < 0.5$. The trend line shows a very minor increase from 0.633 to 0.634 over the range $0 < H_{1e} / P_{1e} < 5.0$ but this difference of less than 0.2% is not of practical significance. On the other hand coefficients of discharge increase progressively for values of H_{1e} / L_1 as shown in Figure 7. This is the result of a draw-down effects which are detected by the upstream tapping if it is placed too close to the weir crest. The trend line shows an increase from 0.625 to 0.639 over the range $0 < H_1 / L_1 < 1.25$. In the range $0 < H_1 / L_1 < 0.5$ the deviations from the Standard coefficient of 0.633 are not of practical significance. However, at the upper limit of the current testing the coefficient is increased by 1 per cent.

New installations
In the range $H_{1e} / L_1 < 0.5$ and $H_{1e} / P_1 < 5.0$, the coefficient of discharge of the Triangular Profile Crump weir is insensitive to the values of H_{1e} / P_1 and H_{1e} / L_1. This means that the upstream tapping, if it is located a distance of twice the maximum anticipated total head upstream of the crest line, will automatically provide accurate flow measurement throughout the range of discharges occurring at the installation.

Existing installations
Many existing weirs have been built with the upstream tapping closer to the weir than recommended by Standard specifications. This means that at high flood flows the value of H_{1e} / L_1 is greater than 0.5 and that the effective coefficient of discharge is higher than the Standard value of 0.633. A correction should be applied which varies with flow. The Standard coefficient is appropriate at low to medium flows when the upstream total head, H_{1e} is less than 0.5 of the distance to the upstream tapping, L_1. At higher flows a progressively higher coefficient should be applied until the maximum value of 0.639 is reached when the upstream total head is 1.25 times the distance to the upstream tapping, L_1. Practical recommendations are given in Chapter 5.

Upper limit for H_{1e} / P_1
There is a functional relationship between the Froude Number of the approach flow and the H_{1e} / P_1 ratio for any particular type of weir dependent upon its coefficient of discharge. This relationship is shown in Figure 8. At a value of H_{1e} / P_1 of 5.0 for the Triangular Profile Crump weir the Froude Number in the approach flow has reached approx. 0.65. Waves are beginning to develop on the surface of the flow and velocities are high for weirs of any significant size. As this condition is reached the weir is ceasing to be a control structure and hence it is not appropriate to attempt to use higher values. The value of H_{1e} / P_1 of 5.0 is thus a physical limitation as opposed to the currently stated limit of 3.5 which was determined by the coverage of the historical data. It is also worth noting that in practice the high velocities would keep sediment moving in natural channels and this would, in almost all cases, keep H_{1e} / P_1 values at or below 5.0.

4. FULL WIDTH THIN PLATE WEIR: EXTENSION OF h / P RATIOS

The Standard Specifications for the full width Thin Plate weir are given in the following Standards:-

- BS 3680/4A (1981): Thin-plate weirs and ISO 1438/1 (1980): *Thin-plate weirs.*

A brief summary of the performance characteristics of this type of weir and the limitations imposed on the design and operation of the weir are given in Appendix 2. The weir is shown in Figure 9.

4.1 Introduction

Standards for Thin Plate weirs cover the basic weir form in which the breadth of the crest may be any proportion of the breadth of the approach channel and also the special case where the crest breadth equals the breadth of the approach channel ie full width weirs. The current research is concerned with this latter special case where b / B = 1.0.

The following discharge formulae are recommended in the Standards:

Partial width weirs, 0.2 < b / B < 1.0
Kindsvater-Carter, 1957 (USA), see Ref. 2
S. I. A, 1926 (Switzerland), see Ref. 3

Full width weirs, b / B = 1.0
Kindvater-Carter, 1957 (USA)
S. I. A, 1926 (Switzerland)
Rehbock, 1929 (Germany), see Ref. 4
I. M. F. T, 1969 (France), see Ref. 5
J. I. S, 1990 (Japan)
HR Wallingford, 1975 (UK), see Ref. 6

Three of the formulations for discharge are based on gauged head, h, with a coefficient of discharge which increases with the ratio h / P. This applies to the following equations:

Kindvater-Carter, 1957 (USA)
Rehbock, 1929 (Germany)
HR Wallingford, 1975 (UK)

Two of the formulations for discharge are also based on gauged head, h, but the coefficient of discharge varies according to complex functions which involve both h and h / P. This applies to the following equations:

S. I. A, 1926 (Switzerland)
J. I. S, 1990 (Japan)

Finally the I.M.F.T uses a formulation for discharge which is based on total head. The coefficient of discharge in this formulation increases with the ratio H / P.

For simplicity two types of coefficient are referred to in the following sections. Assuming the equations for the coefficient of discharge take the form $C = C_b + \text{fn}\ \{h / P, h, \text{etc}\}$, C is referred to as the full coefficient. C_b is referred to as the basic coefficient.

4.2 Weir installation

The Standards give rigorous specifications for the geometry of the weir installation. Of relevance to the present work is the recommendation for the location of the upstream head measurement. The stipulated figure is 4 to 5 times the maximum head upstream from the weir.

4.3 Comparison of formulae

Limitations on h / P

The aim of the present study was to extend the range of data in terms of the h / P ratio subject to the available flow capacity of the test installations. Values of h / P of up to 4.0 were targeted, this being well in excess of the current stated limitations which are as follows:

Table 2 Limitations on permissible h / P ratios

Formula	Max. h / P
Kindvater-Carter	2.5
S.I.A	1.0
Rehbock	1.0
I.M.F.T	2.5
J.I.S	0.67
HR Wallingford	2.5

Comparison of computed flows

Comparisons of computed discharges using these six formulae show that differences of up to 10% can be obtained under certain circumstances. This has long been regarded as an unsatisfactory position and is confusing to users of the Standards. Users would like one formula which produces the correct answer! Previous attempts to resolve the matter from a scientific point of view have failed. The formulae were developed using test facilities in different countries at different times and it is not possible to go back to the original data and original test procedures. However, these earlier comparisons showed that the discrepancies between the formulae were increasing with h / P and hence the present tests, which are aimed at exploring much higher values of h / P than have hitherto been tested, do show up obvious shortcomings of some of the formulae. The new evidence thus gives better grounds for rationalising the formulae which should be included in future editions of the Standards. Details are given in Reference 1.

4.4 New data

In the current study some repeat tests were carried out in the range 0 < h / P < 2.5 in order to check repeatability with earlier results. Further tests were then carried out in the range 2.5 < h / P < 4.0 in order to provide the extended range of data required by the users of this type of weir.

Repeatability

As with the Crump weir, the repeat tests confirmed that the historic results could be reproduced. Figure 10 shows the new and original results compared with the HR Wallingford, 1975 (UK) equation. The recommended full coefficient C_e, is 0.596 when h / P = 0.0 and rises to 0.824 at the upper limit of h / P of 2.5 as defined by the Standard. The new and the historic results show good agreement with this recommendation in the range 0.0 < h / P < 2.5 with the exception of some of the new results. The latter results emanate from head measurements made at a significant distance upstream of the weir and suffer from frictional effects - the higher the measured head, the lower the derived coefficient of discharge, see below.

Location of the upstream head measurement

Three upstream head measurement positions were used in the new tests. These were located 0.54m, 1.08m and 2.16m upstream of the weir. The weir height was 0.06m and the maximum head measured, as limited by the capacity of the flume, was 0.24m.

The three upstream head measurement positions can, therefore be defined by the following ratios:

Table 3 Upstream head measurement position

Upstream head measurement	**Distance upstream of crest**	**Distance to weir height ratio, L / P**	**Distance to maximum head ratio, L / h_{max}**
1	0.54	9	2.25
2	1.08	18	4.5
3	2.16	36	9.0

The current recommended distance to the upstream head measurement position, L, given in the Standard is 4 to 5 h_{max}. Thus the central upstream head measurement used in the new tests corresponded with the mean of the recommended range of locations and the other two were on either side of the mean. Figure 10 shows the results for all three head measurement positions. At the higher h / P ratios there are three distinct values for the derived coefficients, the measurement furthest from the weir giving the lowest coefficients and the measurement closest to the weir giving the highest derived coefficients. The former suffer from head losses between the head measurement position and the weir, the latter do not.

At lower values of h / P the location of the upstream head measurement position is less critical because velocities are much lower and hence head losses are much lower.

The conclusion from this is that in the earlier tests, where h / P ratios and velocities were low, the location of the head measurement position was not critical. Water levels upstream of the weirs are nearly horizontal under these conditions and similar results are obtained wherever the upstream head is measured. The recommendation in the Standard of 4 to 5 h_{max} is adequate within the restricted range $0 < h / P < 2.5$. It is not appropriate at higher values of h / P and the location of the upstream head measurement position becomes increasingly crucial as the value of h / P rises.

Figure 11 again shows the new and historic results compared with the HR Wallingford, 1975 (UK) equation but in this figure the only data plotted is that which lies within the range $0.25 < h / L < 0.5$. This figure is thus based on upstream head measurements made between 2.0 and 4.0 times the maximum head upstream of the weir. Although there is some deviation from the recommended line, the scatter of the results associated with the location of the upstream head measurement is removed in this presentation. Comparison with Figure 10 indicates that a revised recommendation for the location of the upstream head measurement position is clearly required in future Standards if the permissible range of h / P values is to be extended from 2.5 to 4.0, see Section 5.

Some existing weirs have been built with the upstream tapping further from the weir than recommended by Standard specifications. This means that at high flood flows the value of H / L is less than 0.25 and that the effective coefficient of discharge is lower than the Standard value. A correction should be applied but this will vary with flow. The Standard coefficient is appropriate at low to medium flows when the upstream total head, H is less than 0.25 of the distance to the upstream tapping, L. At higher flows a progressively lower coefficient should be applied.

In the case of the Triangular Profile Crump weir the practical problem was existing installations with upstream head measurement positions too close to the weir and therefore affected by drawdown. The opposite problem exists at some full width Thin Plate weirs because the current Standard permits upstream head measurements at distances up to five times the maximum head upstream of the crest. In the light of this current research these measurements are shown to be too far upstream of the weir and are affected by frictional head losses between the head measurement position and the weir. Drawdown is largely unaffected by the velocity of approach to the weir but frictional resistance is very much dependent upon the velocity of approach to the weir. This means that, in the case of the Triangular Profile Crump weir a simple correction to the Standard coefficient of discharge can be made in terms of H / L, see Section 5, Table 6. In the case of the full width Thin Plate weir, however, the correction must be in terms of both h / L and h / P.

Practical recommendations for the correction to the Standard coefficient of discharge are given in Chapter 5.

4.5 Comparison of formulae with new (extended data)

As stated in Section 4.3 the various formulae do not agree even within the restricted range of usage defined in the current Standard. The extended data set provides a stiffer test for all the formulae. The following paragraphs compare the earlier and new HR Wallingford test results against all the formulae.

In comparing the various formulae only results based on upstream head measurements made between 2.0 and 4.0 times the maximum head upstream of the weir for the reasons given in Section 4.4 are presented. The full and the basic coefficients are presented for each formula.

It is useful to speculate on possible reasons for errors in the basic and full coefficients in each of the formulae but, because of the passage of time, it is unlikely that any concrete evidence will ever emerge as to why these formulae differ. In general, the basic coefficient is the coefficient which applies when h / P equals zero ie when there is no velocity of approach and when friction losses and drawdown effects are not relevant. The most likely cause for errors in the basic coefficient is thus faulty head measurement. The full coefficient takes into account the h / P effect which relates to the velocity of approach. It is thus subject to errors in flow measurement and errors which arise from the influence of the position of the upstream head measurement. The above argument does not strictly relate to the S. I. A., I. M. F. T. and the J. I. S. formulae which include a dimensional term in the derivation of the full coefficient which may or may not compensate for fluid property effects.

With these points in mind, full and basic coefficients are presented for all the formulae. The formulae are dealt with in the order that they occur in the Standard. Corresponding figure numbers are as follows:-

Table 4 Presentation of results

Formula	Basic coefficient	Full coefficient
Kindsvater-Carter, 1957 (USA)	Figure 12	Figure 13
S. I. A., 1926 (Switzerland)	Figure 14	Figure 15
Rehbock, 1929 (Germany)	Figure 16	Figure 17
I. M. F. T., 1969 (France)	Figure 18	Figure 19
J. I. S., 1990 (Japan)	Figure 20	Figure 21
HR Wallingford, 1975 (UK)	Figure 22	Figure 23

Kindsvater-Carter

The basic coefficient for this formula for full width weirs is 0.602, see Figure 12. Extrapolating the measured coefficients backwards to h / P = 0.0 suggests that this value is reasonable. The measured full coefficients shown in Figure 13 exceed those given by the formula by an amount which increases with h / P from 3% at h / P = 1 to 5% at h / P = 4. Assuming no systematic errors in the HR measurements, the Kindsvater-Carter formula underestimates flows by these amounts.

No conclusions about the performance of this formula, when used for weirs which do not occupy the full width of the channel, should be drawn from this study.

S. I. A.

The basic coefficient for this formula for full width weirs is 0.615, see Figure 14. Extrapolating the measured coefficients backwards to h / P = 0.0 suggests that this value is reasonable but the two lower points on the plot suggest that a slightly higher value may be better. The measured full coefficients are shown in Figure 15. The differences between the measured coefficients and those given by the formula increase dramatically at higher values of h / P with differences as high as 15% at an h / P value of 4.0.

Note: *The line on this plot is specific to the geometry of the current test rig. The full coefficients in the S. I. A. formula depend on h in addition to h / P. For a specific value of P (0.06m in this case), h and h / P are directly related. Weirs of different height would require a different curve on Figure 15.*

Rehbock

The basic coefficient in this formula is 0.602. (The same value was chosen for the Kindsvater-Carter formula some 45 years after the Rehbock formula had been published). The measurements are in good agreement with this value as shown in Figure 16. The measured full coefficients are shown in Figure 17 and these agree well with the results from the Rehbock formula.

I. M. F. T.

This formula is expressed in terms of total heads and hence coefficient values are not directly comparable with other formulae. The basic coefficient is quoted as 0.627 and the results support this value, see Figure 18. The full coefficient according to the formula is compared with the measured coefficients in Figure 19. The measured full coefficients are lower than those given by the formula by an amount which increases with h / P from 4% at h / P = 1 to 7% at h / P = 4. Assuming no systematic errors in the HR measurements, the I. M. F. T. formula overestimates flows by these amounts.

Note: *The line on this plot is specific to the geometry of the current test rig. The full coefficients in the I. M. F. T. formula depend on H in addition to h / P. For a specific value of P (0.06m in this case), H and h / P are directly related. Weirs of different height would require a different curve on Figure 19.*

J. I. S.

The basic coefficient in this formula is 1.785. The major difference between this value and the values quoted by other formulae arises because the coefficient includes numerical constants and the acceleration due to gravity. (This formula must only be used with metric units). The measurements are in good agreement with this value as shown in Figure 20. The measured full coefficients are shown in Figure 21 and these agree well with the results from the J. I. S. formula.

Note: *The line on this plot is specific to the geometry of the current test rig. The full coefficients in the J. I. S. formula depend on h in addition to h / P. For a specific value of P (0.06m in this case), h and h / P are directly related. Weirs of different height would require a different curve on Figure 21.*

HR Wallingford

The basic coefficient in this formula is 0.596. The measurements suggest that this should be increased slightly to 0.6. as shown by the second line in Figure 22. The measured full coefficients are shown in Figure 23. The measurements suggests that the HR Wallingford formula overestimates full coefficients (and hence flows) by around 2% when h / P = 4.0. This discrepancy is eliminated by substituting 0.085 for 0.091 in the formulation for the full coefficient, see Figure 23.

In the light of the new data obtained at HR Wallingford in this current study, covering the extended range 0 < h / P < 4, a new version of the formula is proposed as follows:-

Formula
HR Wallingford, 1999 (UK)

$Q = C_e \; 2/3 \; (2 \; g_n)^{0.5} \; b \; h^{1.5}$ (as before)

Basic coefficient:

$C_b = 0.600$ (cf 0.596 in 1975 version)

Full coefficient:

$C_e = C_b + 0.085 \, (h / P)$ (cf 0.091 in 1975 version)

4.6 Summary

The following formulae are the least satisfactory:

Kindsvater-Carter, 1957: (systematic underestimation of flows at high values of h / P)
S. I. A., 1926: (serious systematic underestimation of flows at high values of h / P)
I. M. F. T, 1969: (systematic overestimation of flows at high values of h / P)

The most satisfactory formulae are:

Rehbock, 1929:
J. I. S, 1990:
HR Wallingford, 1999:

The latter three formulae can be compared reasonably well if the J. I. S. equations are transformed to take a similar format to that of the other two equations. The result is as follows:

Table 5 Coefficient values for preferred formulae

Formula	**Basic coefficient, C_b**	**Full coefficient, C or C_e**
Rehbock, 1929	0.602	$C_b + 0.083 \, (h / P)$
J. I. S., 1990	0.604 [equivalent to 1.785 in Standard formulation]	$C_b + 0.0007 / h + 0.080 \, (h / P)$ [equivalent to $C_b + 0.00295 / h + 0.2367 \, (h / P)$ in the Standard formulation]
HR Wallingford, 1999	0.600	$C_b + 0.085 \, (h / P)$
Mean	**0.602**	C_b + **0.083 (h / P)** [neglecting the second order term in the J. I. S. formula]

It will be noted that these mean coefficients based on the three equations which best represent flow over full width Thin Plate weirs corresponds exactly to those in the Rehbock formula.

4.7 Analysis using upstream total head

Traditionally the analysis of flows over thin plate weirs has been in terms of gauged head. The reason for this is that early usage of the weir was to measure flows through deep tanks where the velocity head effect was minimal. Under these circumstances the gauged head was approximately equal to the total head and there was no point in differentiating between the two. In 1969 the I. M. F. T. formula was developed in terms of total head, presumably because, by this time, other weirs were being analysed in terms of total head and this approach was being seen as more fundamental and powerful. As seen in Section 4.5 the I. M.

F. T. is not appropriate at the high values of h / P which have been tested in the current work. This is no reflection on those that produced the I. M. F. T. formula because, at the time, no data above an h / P value of 2.5 were available.

The current measurements, together with earlier HR data, have been analysed in the current study using a total formulation of the basic discharge equation. Total head, H, was substituted for gauged head in the published HR formulation as follows:-

$$Q = C_e \ 2/3 \ (2 \ g_n)^{0.5} \ b \ H_e^{\ 1.5}$$

where

$$H_e \ (m) = H + 0.001$$

The results for the derived total head coefficient are shown in Figure 24. It can be seen that the derived total head coefficients rise with h / P and the variation in the coefficient is about 10%. This contrasts with the Triangular Profile Crump weir were the variation is less than 1%.

It can be seen, therefore, that analysis in terms of total head does not make the interpretation of the performance characteristics of Thin Plate weirs any simpler. Total head coefficients vary because the shape of the nappe in the immediate vicinity of the weir varies with weir height and flow intensity. Flow over the weir lacks the convenient geometrical similarity which is present in the case of the Triangular Profile Crump weir.

5. EXTENSION OF h / P RATIOS: CONCLUSIONS AND RECOMMENDATIONS

5.1 Triangular Profile Crump Weir

The current experimental work has confirmed historic data for the Triangular Profile Crump Weir and has extended the range of data now available for use in Standards.

The current work has shown that the coefficient of discharge is independent of H_{1e} / P_1 up to a newly defined limiting value of 5.0. The work has also shown that the coefficient of discharge increases at values of H_1 / L_1 in excess of 0.5 and has quantified this effect.

For the purpose of revising Standard specifications recommendations can be made for the design of new installations and for the better use of existing installations. These are as follows:

New installations

The upstream tapping, if it is located a distance of twice the maximum anticipated total head upstream of the crest line, will automatically provide accurate flow measurement throughout the range of discharges occurring at the installation and the current Standard coefficient of 0.633 applies. The revised limit for the maximum total head is five times the upstream weir height. ie

- $C_{De} = 0.633$
- $L_1 = 2.0\ H_{max}$
- $H_{max} = 5.0\ P_1$

Existing installations

At existing installations the upstream tapping is at a particular location and this may not satisfy the Standard specification, $L_1 = 2.0\ H_{max}$. Often the tapping is too close to the weir and the measurement is in the draw-down zone. Under these circumstances the coefficient of discharge is higher than the Standard specification. The actual coefficient of discharge depends on the ration H_{1e} / L_1 and hence varies with the flow conditions at the site. Table 6 should be used to evaluate the actual coefficient of discharge at different flows.

Table 6 The coefficient of discharge of the Triangular Profile Crump Weir as affected by drawdown

Range of values of H_{1e} / L_1	Coefficient of discharge, C_{De}
$0 < H_{1e} / L_1 < 0.5$	0.633
$0.5 < H_{1e} / L_1 < 0.75$	0.635
$0.75 < H_{1e} / L_1 < 1.0$	0.637
$1.0 < H_{1e} / L_1 < 1.25$	0.639

For computer applications the following expressions may be used:

If $H_{1e} / L_1 < 0.5$, $C_{De} = 0.633$

If $H_{1e} / L_1 > 0.5$, $C_{De} = 0.633 + 0.01\ (H_{1e} / L_1 - 0.500)$

5.2 Full width Thin Plate weirs

The current experimental work has confirmed historic HR Wallingford data for the full width Thin Plate weirs and has extended the range of data now available for use in Standards.

For the purpose of revising Standard specifications recommendations can be made for the design of new installations. These are as follows:

New Installations
Upstream head measurement position:

The upstream tapping should be located at a distance of between twice and four times the maximum anticipated gauged head upstream of the crest line. The Standard needs amending accordingly as the current recommendation could produce significant errors.

Formulae for the basic weir form (all values of b / B):

The Rehbock, 1929, formula gives the best overall agreement with the extensive data set which has now been built up at HR Wallingford. The number of formulae quoted in the Standard needs to be rationalised and reduced as follows:

The two formulae quoted in the Standard for the basic weir form are:

- Kindvater-Carter, 1957 (USA)
- S. I .A, 1926 (Switzerland)

These formulae have only been evaluated for the full width condition ie b / B =1.0. The former performed reasonably well, the latter showed significant error at high h / P values. Therefore, it is suggested that only the Kindvater-Carter formula should be retained for the general case where weirs are installed in channels and tanks where the upstream width may be up to five times the width of the weir.

Including the two formula above there are six formulae which are quoted in the Standard for full width weirs. These are as follows:

- Kindvater-Carter, 1957 (USA)
- S. I. A., 1926 (Switzerland)
- Rehbock, 1929 (Germany)
- I. M. F. T., 1969 (France)
- J. I. S., 1990 (Japan)
- HR Wallingford, 1975 (UK)

Improved coefficients have been suggested in Section 4.5 for the HR Wallingford formula yielding:

- HR Wallingford, 1999 (UK)

The best equations for the newly extended data set covering the range $0 < h / P < 4.0$ are Rehbock, J. I. S. and HR Wallingford, 1999. These equations differ by less than 2% in terms of computed discharges and the Rehbock equation sits mid-way between the other two. It is recommended, therefore, that only the Rehbock equation is quoted for full width weirs in the Standard.

Rationalising the formulae quoted in the Standard may not be straightforward. The policy of the British Standards Institution may be paraphrased as follows:-

- do it once
- do it properly
- do it internationally

Thus international agreement will be required on the rationalisation (and reduction of the number) of the formulae quoted in the Standard. This has proved a stumbling block in the past but may be eased this time around because of the more extensive and coherent data set now available. Once the International Standard is revised, it is a relatively straightforward matter to accept the new Standard as a dual numbered British Standard.

Revised limitations:

Revised limitations, in the light of the extended data set available and the testing of all formulae against this data set, are recommended as follows:-

a) $h / P < 4.0$
b) $0.03 < h$ (m) < 1.0
c) $b > 0.3$m
d) $P > 0.06$m

Existing installations
Upstream head measurement position:

In the case of the Triangular Profile Crump weir a simple correction to the Standard coefficient of discharge can be made in terms of H / L, see Section 5, Table 6. In the case of the full width Thin Plate weir, however, the correction must be in terms of both h / L and h / P. The recommendations for appropriate reductions to the Standard coefficients are based on the data presented in Figure 10. These are given in Table 7.

Table 7 The coefficient of discharge of the Thin Plate weir as affected by frictional effects in the upstream channel (expressed as a percentage of the Standard value)

h / P	**L / h**			
	2	**4**	**6**	**8**
3.5 to 4.0	100	100	96	92
3.0 to 3.5	100	100	97	94
2.5 to 3.0	100	100	98	96
2.0 to 2.5	100	100	99	98
Less than 2.0	100	100	100	100
h / P	**0.50**	**0.25**	**0.17**	**0.13**
	h / L			

6. COMPOUND CRUMP WEIR: ABSENCE OF DIVIDE PIERS

The specification for the Compound Crump Weir is given in the following Standard:-

- BS 3680/4D (1989): *Compound gauging structures*

An International Standard, FDIS 14139, is under preparation. An example of a compound weir design is shown in Figure 25

6.1 Introduction

The Standard method of calculating the discharge for a compound weir was developed from extensive field tests (White, 1975, see Ref. 7). It is based on the concept of a constant total head level across the weir. With each level of the weir operating at a different unit discharge and therefore a different velocity head, water level varies across the weir. Flow would be three-dimensional without piers dividing the sections which would increase the difficulty of determining total head level from a single tapping point. The Standard therefore specifies piers with the tapping point within the pier length so that the discharge relating to that reading is two dimensional and therefore distinct. The Standard location for the tapping point is at two times maximum head upstream of the crest.

6.2 Analysis

All the calculations used the Standard method of computing discharge whether piers were in place or not.

Figures 26 and 27 show the ratio of actual measured discharge to calculated discharge for Weir 1 where the low section was twice the width of the high section. These two figures relate to measurements made at the low and high crests respectively. Figures 28 and 29 show this same ratio for Weir 2 where the low section was half the width of the high section. Again, these two figures relate to measurements made at the low and high crests respectively.

Results for weirs with divide piers

Considering first the results with the divide pier in place as recommended by the Standard. In Figures 26 to 29 the results for the Standard head measurement position, 2h, give consistently good results. Thus the variations in the relative widths of the low and high crests and the two options of measuring head at the low or the high crest do not affect the accuracy of computed discharge. These results thus support the Standard method of calculation and the recommended location for the measurement of head for weirs with divide piers. As explained above, the calculation procedure recommended in the Standard was derived from the results of field tests. These field tests covered a limited range of head to weir height ratios, h / P, due to practical reasons. The current testing supports these findings and shows that the method can be extended to higher h / P ratios.

Head measurements at the high and low crests

There is a level of uncertainty in transferring the total head level calculated at the gauging crest to the other crests which is influenced by such factors as the ratio of velocity head to total head at the gauging crest, the proportion of the total discharge passing over the other crests and the step height between crests. It is noticeable that for Weir 2 the effect of location of the head measurement position is very pronounced when gauging at the low crest, see Figure 28. With this weir arrangement, the much longer high crest carries a high proportion of the flow at low heads which magnifies errors in the transferred head level. At head to step height ratios above two, the flow over the high crest is greater than the flow over the low crest whereas for Weir 1, see Figure 26, the flow over the high crest never exceeds one third of the flow over the low crest and variations due to the head measurement position at the low crest, while still significant, are less pronounced.

On the other hand, the calculated discharge is less affected by the head measurement position if the weir is gauged at the high crest and accurate results are obtained for both weirs despite the predominance of low crest flow on Weir 1, see Figures 27 and 29. This suggests that the lower velocity head at the high crest leads to smaller errors in the transfer of total head level to the ungauged crest.

Results for weirs without divide piers

When the pier is removed, the calculation substantially overestimates the true discharge at all head measurement positions when gauging is at the low crest, see Figures 26 and 28. However, when the weir is gauged at the high crest, the discharge is underestimated but only by 5% at the short flank weir of Weir 1, see Figure 27 and by only 2-3% at the long flank weir of Weir 2, see Figure 29.

Head measurements far enough upstream of the structure to be clear of three dimensional flow conditions

A feature of the results where the head measurement position is at the low crest is that there is little change in the water level at the most upstream tapping whether a pier is in place or not. To test the possibility that the velocity head may still be uniform across the channel at this distance from the weir, discharge calculations were made on this assumption. The discharge calculated in this way was much closer to the actual discharge than that calculated by the Standard method up to a head to step height ratio of approximately two but was significantly less accurate at higher ratios. This is thus not a practical option for improving the accuracy of the discharge calculations for compound weirs without divide piers.

7. ABSENCE OF DIVIDE PIERS: CONCLUSIONS AND RECOMMENDATIONS

The conclusions to be drawn from the results given in Chapter 6 are:

7.1 Standard weirs with divide piers

A compound weir design that follows the Standard, BS 3680/4D (1989): *Compound gauging structures*, with respect to (i) divide piers between adjacent crest sections and (ii) the location of the head measurement position, will give accurate discharge measurement whatever the proportions of the weir.

7.2 Non-Standard weirs without divide piers

The main difficulty in assessing the performance of compound weirs without divide piers is to determine the velocity head which relates to the measured gauged head in order to apply the Standard method of calculation. The wider the gauging crest relative to the other crests and the slower the velocity of approach, the more accurate the calculation by the Standard method will be.

Taking the gauging point further upstream and calculating the velocity head assuming a uniform velocity distribution across the channel does not provide an alternative approach because the computed flow is very susceptible to channel friction caused, for example, by weed growth.

A compound weir without piers will give reasonably accurate results provided that the head is gauged adjacent to the highest crest where the velocity of approach is lowest and that this crest is of sufficient breadth relative to the lower crests (i) to insulate the head measurement position from the influence of lateral flow at crest discontinuities and (ii) to ensure that the high (measured) crest takes a high proportion of the total flow.

7.3 Standard specifications

The current research has supported the validity of the recommendations given in the current Standard for compound weirs, BS 3680/4D (1989): *Compound gauging structures*. The need for divide piers to provide accuracy of flow measurement has been confirmed and the associated specifications, including the location of the head measurement position, have been shown to be sound.

The results for the compound weir without divide piers have shown the inherent difficulties in computing flows at such structures. Only tentative, qualitative recommendations, see Section 7.2, can be made for this type of weir and the matter will need to be discussed by the British Standards Committee CPI/113/SC2 to see whether any action should be taken regarding Standard recommendations for compound weirs without divide piers.

8. DROWNED FLOW PERFORMANCE DATA

8.1 Rectangular Broad Crested weir

Weirs are normally designed to operate in the modular range to as high a head as possible and the tests were therefore concentrated at the upper end of the range with modular head-to-weir height ratios, h / P, of 1.3 and 1.7. A third series was run at a modular head-to-weir height ratio, h / P, of 0.55 to provide general coverage of drowned flow conditions.

The results showed that there was no significant benefit in changing the upstream head measurement position during drowned flow and the results of these tests are not shown. The analysis was therefore concentrated on the results taken at the Standard upstream head measurement position.

Results are presented in terms of the ratio of the actual flow to the modular flow at the measured head, a ratio which is known as the drowned flow reduction factor, f. This factor can be related to the ratio of downstream total head to upstream total head, H_2 / H_1. The relationship is shown in Figures 30, 31 and 32 for upstream readings taken at the Standard location in all cases and with downstream heads measured at the three downstream locations.

When downstream head was measured close to the weir, see Figure 30, the modular limit and comparative values of the drowned flow reduction factor occurred at lower drowning ratios than when the head was measured further downstream of the weir. This indicated that there was a depression in the water surface close to the weir. There was also a rather larger variation of the reduction factor with changes in the h_1 / P ratio in the early stages of drowning than at the more downstream locations, suggesting that the depression did not hold a constant position. There was little difference in the results from the two locations further downstream indicating that the flow had stabilised before reaching the upstream tapping of the two.

It is known that the modular limit of a Rectangular Broad Crested weir varies as the head to weir length varies (see ISO 3846 (1989) Annex 4). In the tests where the downstream head measurement positions were 4 h_{max} and 6 h_{max} downstream of the weir, the modular limits observed were broadly in line with the information in the Standard but not in the tests where the location was h_{max} downstream of the weir.

Figures 30 and 31 include the results of experiments by Ramamurthy, Tim & Rao (Ref. 8). Although the reference did not specify the location of the downstream head measurement position, it is clear from Figure 30 that the location must have been close to the weir and the results agree with the present experiments for this position.

In view of the comparatively low spread of the results over the range of h_1 / P ratios and the compatibility with existing information, positioning of the downstream tapping clear of local disturbances is the preferred option. A single curve has therefore been fitted to the results and is shown in Figure 31.

The equations for the curve are:

$f = 1.045\ (0.76 - (H_2 / H_1)^{4.2})^{0.0645}$ in the range $0.750 < H_2 / H_1 < 0.925$

and

$f = 5.70 - 5.245\ (H_2 / H_1)$ in the range $0.925 < H_2 / H_1 < 0.985$

The preferred downstream head measurement position was 4 h_{max} downstream of the upstream face of the weir. No tests were done to refine this location since the laboratory installation could not be a scale representation of a particular weir which might have a deep or shallow stilling basin and a low or high cill depending on the tailwater characteristics. Since a calculation of velocity head is required, the downstream head measurement position should be located within the parallel sidewalls of the weir structure. If a stilling basin is included in the design it is recommended that a downstream head measurement should be located no closer to the weir than 0.5 h_{max} upstream of the terminal cill of the basin.

8.2 Full Width Thin Plate weir

The results showed that there was no significant benefit in changing the upstream head measurement position during drowned flow and the results of these tests are not shown. The analysis was therefore concentrated on the results taken at the Standard upstream location. Results are presented in terms of the ratio of the actual flow to the modular flow at the measured head, a ratio which is known as the drowned flow reduction factor, f. This factor can be related to the ratio of downstream gauged head to upstream gauged head, h_2 / h_1.

The downstream head measurement position closest to the weir was included to emulate the work of Cox (Ref. 9) whose recommendation was that the head measurement should be taken at a distance of 2.54 times the weir height ($L_2 / P = 2.54$) downstream of the weir. In the present tests this gave a distance of 0.25 m (~ h_{max}) and Figure 33 shows the test results when the head ratio was measured at this location. It can be seen that while the results for h_1 / P ratios of 0.5 and 1.0 where in general alignment, there was a distinct separation when the ratio was raised to 1.5 and 2.0. A comparison has been made in Figure 33 with the results of investigations by Cox (Ref. 9), Francis (Ref. 10) and Wu & Rajaratnam (Ref. 11). Cox and Francis cover only a small range of h_1 / P values and the current test results show agreement at low h_1 / P values. Wu & Rajaratnam give a single curve covering a wide range of values of h_1 / P up to 1.5 which is in general agreement with the current tests at this maximum value. The conclusions to be drawn are that all three investigations were made with a downstream tapping close to the weir and that h_1 / P is a significant variable that cannot be encompassed by a single curve.

The results obtained from the downstream head measurement position close to the weir showed considerable scatter when compared with the results measured at a location 4 h_{max} downstream of the weir, see Figure 34. Using this downstream location, there is a progressive variation with the value of h_1 / P and each set shows a smooth relationship between head ratio and the drowned flow reduction factor. The Cox relationship has been added to the figure to illustrate the influence of the selection of the downstream head measurement position on the results. Also shown are the results of Bazin's experiments at h_1 / P ratios of 0.5, 1.0 and 2.0. Agreement between Bazin's results and the present tests is excellent at h_1 / P values of 0.5 and 1.0 although there is no agreement at the highest value.

It will be noticed that all three of Bazin's curves give values of the drowned flow reduction factor, f, greater than unity at low drowning ratios, h_2 / h_1. An explanation for this is connected with the flow pattern over the crest during modular flow. The underside of the nappe springs well clear of the crest and is therefore contracted provided the pressure under the nappe is at atmospheric pressure. If the underside of the nappe is not fully aerated, the flow extracts the air and lowers the pressure which pulls down the underside of the nappe and reduces the contraction thereby increasing the discharge. A similar effect may occur during drowning of the weir when the downstream water level rises high enough to fill the pocket under the nappe. However, it appears unlikely that this effect would be quite as strong with high approach velocities as Bazin suggests and although the present tests broadly agree with Bazin as to the drowning ratio at which the drowned flow reduction factor, f, is unity, higher values of the drowned flow reduction factor, f, where not observed.

Figure 35 shows the results with the head measurement position at a distance of 6 h_{max} downstream of the weir and these are essentially identical to the results at the 4 h_{max} location indicating that the shorter distance is sufficiently far downstream to be clear of the turbulence associated with energy dissipation near to the weir.

The conclusions are that the ratio h_1 / P is a significant variable and that the modular limit increases with h_1 / P. Figure 36 shows the test results with curves fitted. The equations of the curves and the ranges of applicability given below.

For $h_1 / P = 0.5$ then $f = 1.007 (0.975 - (h_2 / h_1)^{1.45})^{0.265}$ in the range $0.00 < h_2 / h_1 < 0.97$

For $h_1 / P = 1.0$ then $f = 1.026 (0.960 - (h_2 / h_1)^{1.55})^{0.242}$ in the range $0.20 < h_2 / h_1 < 0.97$

For $h_1 / P = 1.5$ then $f = 1.098 (0.952 - (h_2 / h_1)^{1.75})^{0.220}$ in the range $0.50 < h_2 / h_1 < 0.97$

For $h_1 / P = 2.0$ then $f = 1.155 (0.950 - (h_2 / h_1)^{1.85})^{0.219}$ in the range $0.63 < h_2 / h_1 < 0.97$

The preferred downstream head measurement position was 4 h_{max} downstream of the upstream face of the weir. No tests were done to refine this location since the laboratory installation could not be a scale representation of a particular weir which might have a deep or shallow stilling basin and a low or high cill depending on the tailwater characteristics. Since a calculation of velocity head is required, the downstream head measurement position should be located within the parallel sidewalls of the weir structure. If a stilling basin is included in the design it is recommended that a downstream head measurement should be located no closer to the weir than 0.5 h_{max} upstream of the terminal cill of the basin.

9. DROWNED FLOW: CONCLUSIONS AND RECOMMENDATIONS

The conclusions to be drawn from the results given in Chapter 8 are:

9.1 Rectangular Broad Crested weir

Upstream head measurement
The Standard location for the upstream head measurement position of 4 h_{max} upstream of the upstream face of the weir is satisfactory for measurements in both the modular and drowned flow ranges. No change to the Standard specification is required.

Downstream head measurement
The preferred downstream head measurement position was 4 h_{max} downstream of the upstream face of the weir. At this location the turbulence associated with energy dissipation near to the weir has subsided to an acceptable level. The downstream head measurement position should be located within the parallel sidewalls of the weir structure. If a stilling basin is included in the design it is recommended that a downstream head measurement should be located no closer to the weir than 0.5 h_{max} upstream of the terminal cill of the basin. Modifications to the Standard specification are required along these lines.

Drowned flow performance
The drowned flow performance of the typical Rectangular Broad Crested weir tested in this study is shown in Figure 31. These results apply to weirs where the length (in the direction of flow) to height ratio is approximately 3.

The equations which define the drowned flow performance are:

$f = 1.045\,(0.76 - (H_2 / H_1)^{4.2})^{0.0645}$ in the range $0.750 < H_2 / H_1 < 0.925$

and

$f = 5.70 - 5.245\,(H_2 / H_1)$ in the range $0.925 < H_2 / H_1 < 0.985$

Modifications to the Standard are required to introduce these drowned flow performance data.

9.2 Full Width Thin Plate weir

Upstream head measurement
The Standard location for the upstream head measurement position of 4 h_{max} upstream of the upstream face of the weir is satisfactory for measurements in both the modular and drowned flow ranges. No change to the Standard specification is required.

Downstream head measurement
The measurement of downstream head at a location 4 h_{max} downstream of the weir is preferred. At this location the turbulence associated with energy dissipation near to the weir has subsided to an acceptable level. The downstream head measurement position should be located within the parallel sidewalls of the weir structure. If a stilling basin is included in the design it is recommended that a downstream head measurement should be located no closer to the weir than 0.5 h_{max} upstream of the terminal cill of the basin. Modifications to the Standard specification are required along these lines.

Drowned flow performance
The drowned flow performance of the typical Full Width Thin Plate weir is shown in Figure 36. The ratio h_1 / P is a significant variable and the modular limit increases with h_1 / P. The equations which define the drowned flow performance are:

For $h_1 / P = 0.5$ then $f = 1.007 (0.975 - (h_2 / h_1)^{1.45})^{0.265}$ in the range $0.00 < h_2 / h_1 < 0.97$

For $h_1 / P = 1.0$ then $f = 1.026 (0.960 - (h_2 / h_1)^{1.55})^{0.242}$ in the range $0.20 < h_2 / h_1 < 0.97$

For $h_1 / P = 1.5$ then $f = 1.098 (0.952 - (h_2 / h_1)^{1.75})^{0.220}$ in the range $0.50 < h_2 / h_1 < 0.97$

For $h_1 / P = 2.0$ then $f = 1.155 (0.950 - (h_2 / h_1)^{1.85})^{0.219}$ in the range $0.63 < h_2 / h_1 < 0.97$

Modifications to the Standard are required to introduce these drowned flow performance data.

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John Burns	SEPA
Issy Caffoor	Yorkshire Water
Steve Capel-Davies	BSI CPI/113/SC2
Rodney Day	University of Hertfordshire
Dennis Dring	Yorkshire Water plc
John East	EA - Anglia Region
Ian Fox	SEPA
Reg Herschy	BSI CPI/113/-
Richard Jones	BSI CPI/113/SC2
Michael Law	EA - NE Region
Terry Marsh	Institute of Hydrology
David Stewart	EA - NE Region
David Tyler	Anglia Water plc

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ISO 1438/1 (1980): *Thin-plate weirs*

BS 3680/4B (1986): *Triangular profile weirs*
ISO 4360 (1984): *Triangular profile weirs*

BS 3680/4C (1981): *Flumes*
ISO 4359 (1983): *Flumes*

BS 3680/4D (1989): *Compound gauging structures*
ISO 14139 (draft): *Compound gauging structures*

BS 3680/4E (1990): *Rectangular broad crested weirs*
ISO 3846 (1989): *Rectangular broad crested weirs*

BS 3680/4F (1990): *Round nose horizontal crest weirs*
ISO 4374 (1989): *Round nose horizontal crest weirs*

BS 3680/4G (1999): *Flat-V weirs*
ISO 4377 (1989): *Flat-V weirs*

BS 3680/4I (1986): *V-shape broad crested weirs*
ISO 8333 (1985): *V-shape broad crested weirs*

BS ISO 8368 (1999): *Guidelines for the selection of structure*

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Table

HR Wallingford

Table 1 Summary of Standard requirements for the different types of structure

Type of structure		Limitations on the configuration of the gauging structure: Upstream channel – Straight length	Upstream channel – Baffles	Upstream channel – Jump or wave	Upstream channel – Restrict Flow *	Downstream channel	Head measuring section	Structure or formula	Limitations due to fluid properties: P>	b>	h >	Experimental limits: h/p <	h <	Fr <	L/P	h/L	Others
Thin Plate ISO 1438	Rectangular notch	>10 h_{mx}	--	--		Free flowing nappe	4 – 5 h_{mx} u/s	K-C	0.1	0.15	0.03	**2.5**					(B-b)/2 > 0.1
	Rectangular full width							SIA	0.3	> 0.3 B	0.025 B/b	1	0.8				
								Reh.		0.3			0.75				
								IMFT	0.1	0.2	0.03	**2.5**	--				
								HRS									
	Triangular notch							K-S	0.09	--	0.06 and h > 0.1 p for 90°	**0.4-2 for 90° or 0.35**					20 <α <100
								BSI 3 angles	0.45		0.05	0.4	0.38 m or 0.2 B				B < 1
End depth method ISO 3847 - ISO 4371		> 20 he	S < 1/2000			Free flow & drop > he	At the brink	5 geometries	--	0.3	he>0.04/5	Trap. 0.5 < (m he/Bo) < 0.7 Parab. 0.019 < 2a < 0.33 Triang. 25 < α/2 < 45 Circ. 0.19 < he/r < 1.0					
Triangular profile	Crump ISO 4380	> 5 ch. width	> 5 h_{mx}	> 30 h_{mx}		DR	2 h_{mx} u/s and crest tap 20 mm d/s	Trunc. h_{mx} u/s and 2h_{mx} d/s	0.06	0.3	0.03-0.06	**3.5**	B/2				
	Streamlined ISO 9827		>10 h_{mx}			DR > 8 h_{mx}	4-5 h_{mx} u/s and 5-6 h_{mx} d/s	5 geom	0.15	0.3	0.03	1.4-1.6					C_{dr} > 0.9
Flat-vee ISO 4377		> 5 ch. width	>10 h_{mx}	> 20 h_{mx}	y	DR	3 h_{mx} or 10H' u/s and 3 h_{mx} or 25H' d/s	Trunc. h_{mx} u/s and 2h_{mx} d/s	--	--	0.03-0.06		**for h_{mx} /H'<1 h_{mx} < 2.5 P_2 for h_{mx} /H'>1 h_{mx}<8.2-4.2 P_2**	0.5			**H'/P_1 < 2.5**
Broad crested weirs	V-shaped ISO 8333	>10 ch. width	>10 h_{mx}	> 30 h_{mx}		No DR	3-4 h_{mx} u/s	0.1L<r<0.2L 0.2h_{mx}<r<0.4h_{mx} L > 2 h_{mx}			0.06 or > 0.05L	**1.5-3**	h<1.25H_b			**h/L < 0.57**	90 <α< 150
	Rectangular ISO 3846				y	No DR > 2 h_{mx} d/s			0.15	0.3	0.06	**1.6**			**0.1<L/P<0.4**	**0.1<h/L<1.6**	
	Trapezoidal ISO 4362					DR depending on slopes	3-4 h_{mx} u/s and 5-6 h_{mx} d/s		0.15	0.3	0.05	**1.3**		**0.3**	**0.2<L/p<2**	**0.1<h/L<1.5-3 rect 0.1<h/L<1.2 trap**	
	Round nose horizontal ISO 4374	> 5 ch. width				No DR	3-4 h_{mx} u/s	r > 0.2 h_{mx} L > 1.75 h_{mx} L+r > 2.25 h_{mx}	0.15	0.3 or > hmx or > L/5	0.06 or > 0.01 L	**1.5**				**h/L < 0.57**	
FLUMES – Long throat ISO 4359	Rectangular	> 5 ch. width	>10 h_{mx}	> 30 h_{mx}	y	No DR	3-4 h_{mx} u/s	Flat bed 2h_{mx} u/s u/s h>1.3 d/s h		0.1	0.05 or > 0.05 L		**h < 3b h < 2**	0.5-0.6	bh/(Bh+Bp)<0.7	**h/L<0.5-0.67**	
	Trapezoidal					Modular limit depend on H/H_d		Width throat < width of approach walls					**h < 2**				
	U-shaped									D > 0.1						**h/L<0.5-0.67**	
FLUMES – Short ISO 9826	Parshall	>10 ch. width	--	--	y	Max submerg. 0.95					0.03-0.09		h<0.8-1.83	0.5			
	SANIIRI					Max submerg. 0.9					0.09-0.1		h<1.1-1.83				
Vertical underflow gates and radial gates ISO 13550		> 5 ch. width	>10 h_{mx}	> 30 h_{mx}		DR > 8 h_{mx}	2-3 h_{mx} u/s 10 h_{mx} d/s	0 < d < 2e R_{pier} > b'/4-b'/8			h_1 > 2a (vertical undeflow)		h_1 < a/0.6 (radial gate)				Limited experimental range
Compound ISO 14139		> 5 ch. width	>10 h_{mx}	> 30 h_{mx}	y		Min 2 h_{mx} u/s of each substruct.	0.3m width pier 0.5m max drop between crests						0.5			

* approach channel can be restricted by vertical walls but curvature of transition must have a radius R>2 h_{mx} and the distance between end of transition and head measuring section must be > h_{mx}

Figures

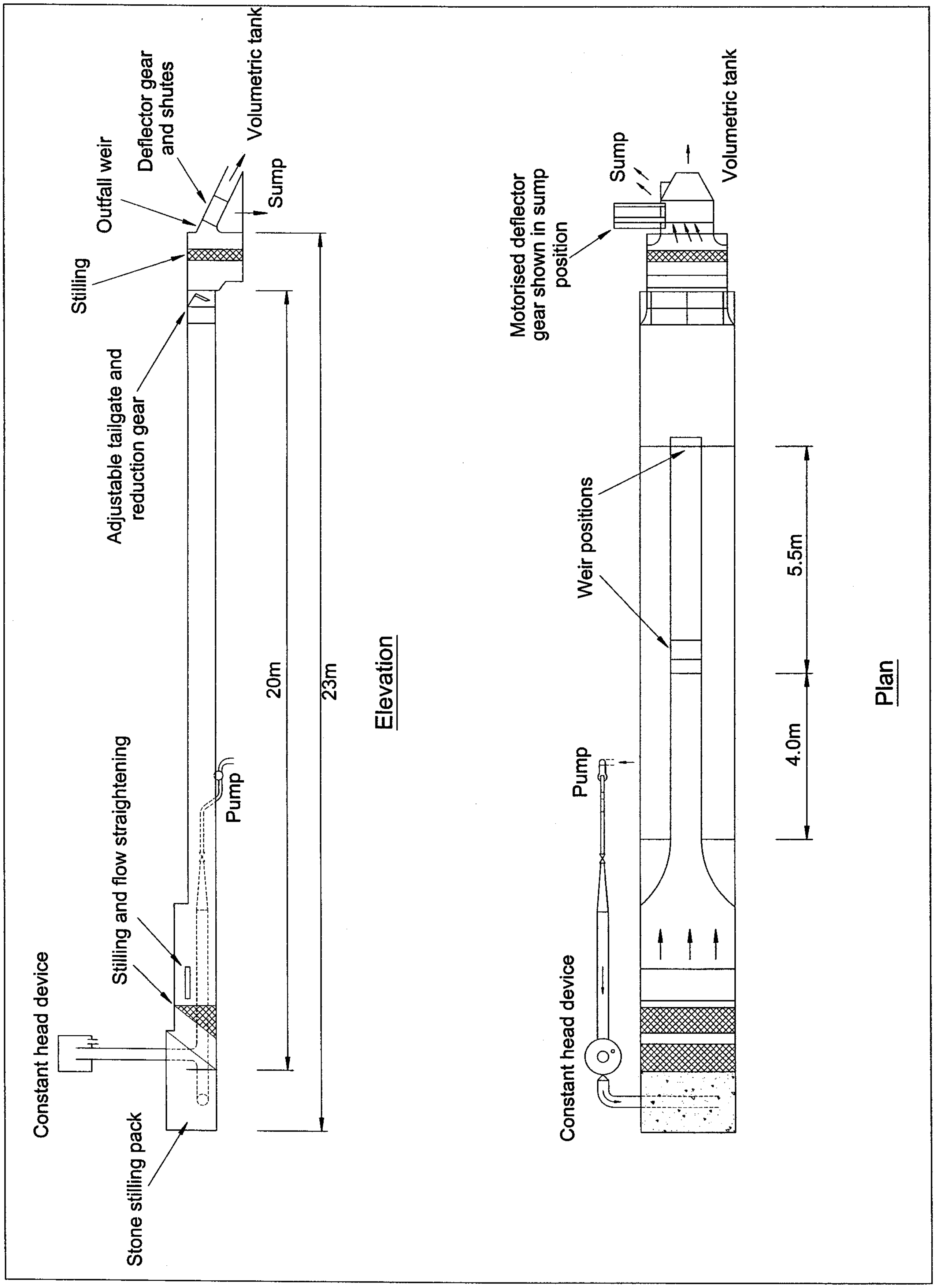
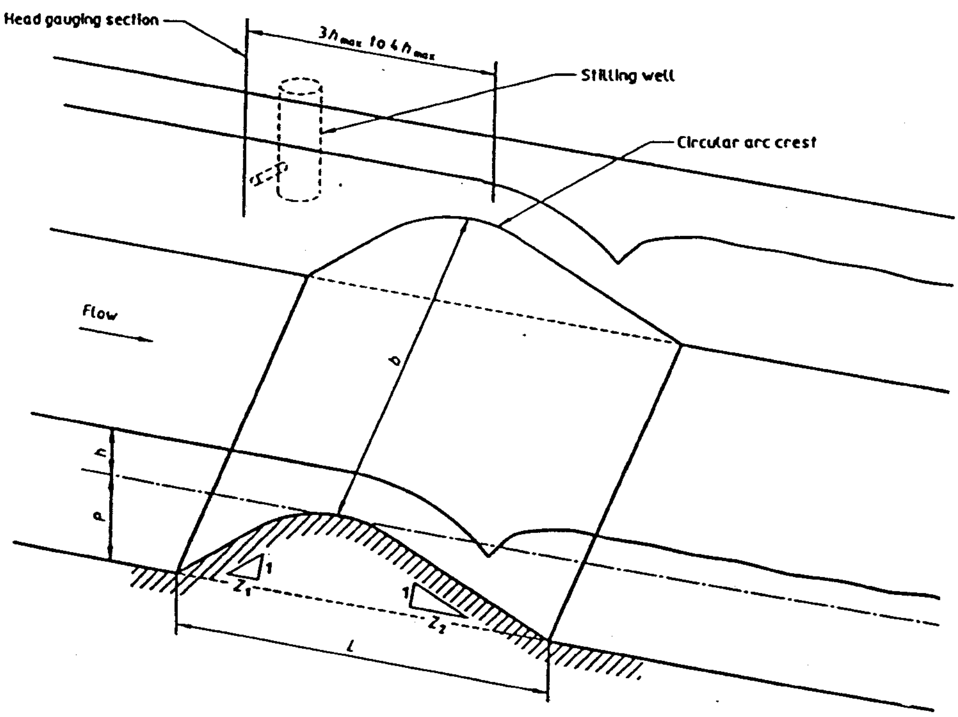
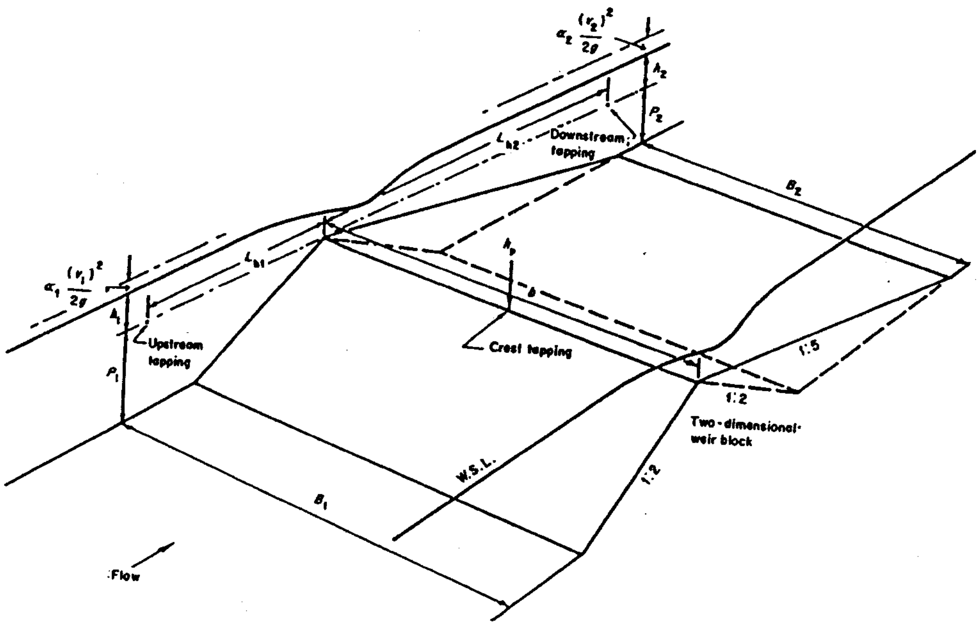


Figure 1 General Purpose flume



Streamlined triangular profile weir



Triangular-profile two-dimensional weir

Figure 2 Triangular Profile weirs: Crump and streamlined (after ISO 4360 and ISO 9827)

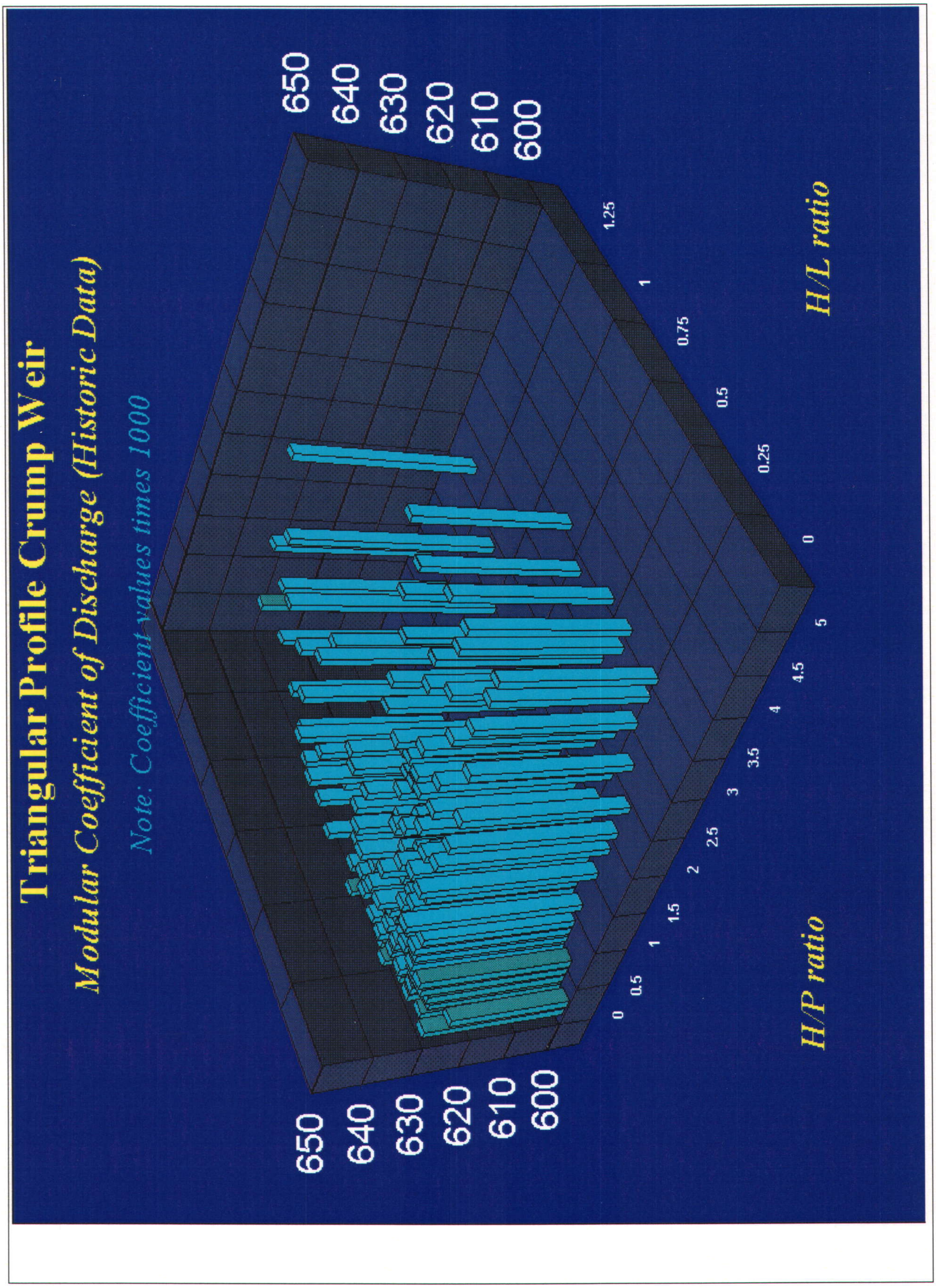


Figure 3 Previously published coefficients of discharge for the Triangular Profile Crump weir

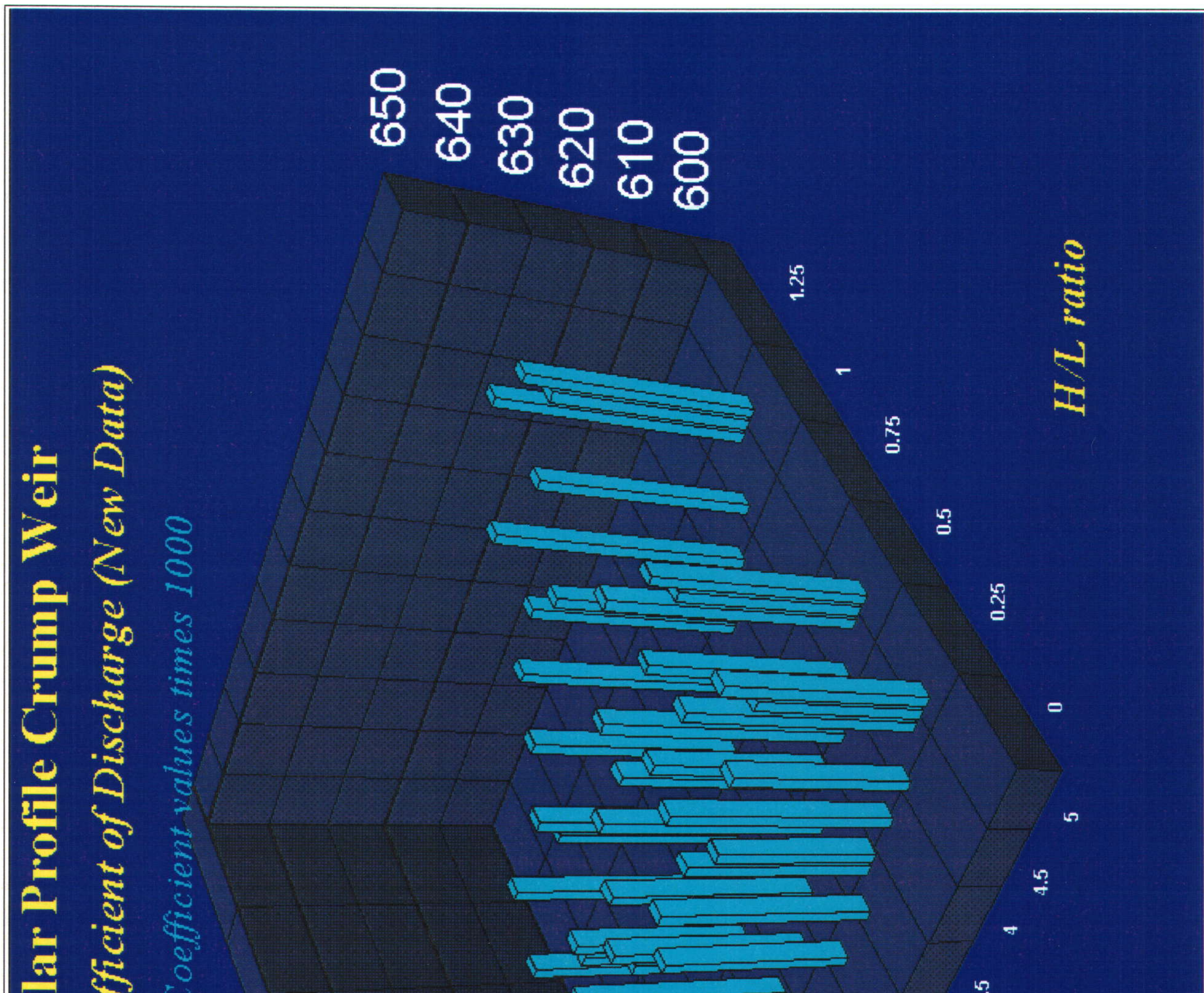


Figure 4 **Coefficients of discharge for the Triangular Profile Crump weir determined in the current study**

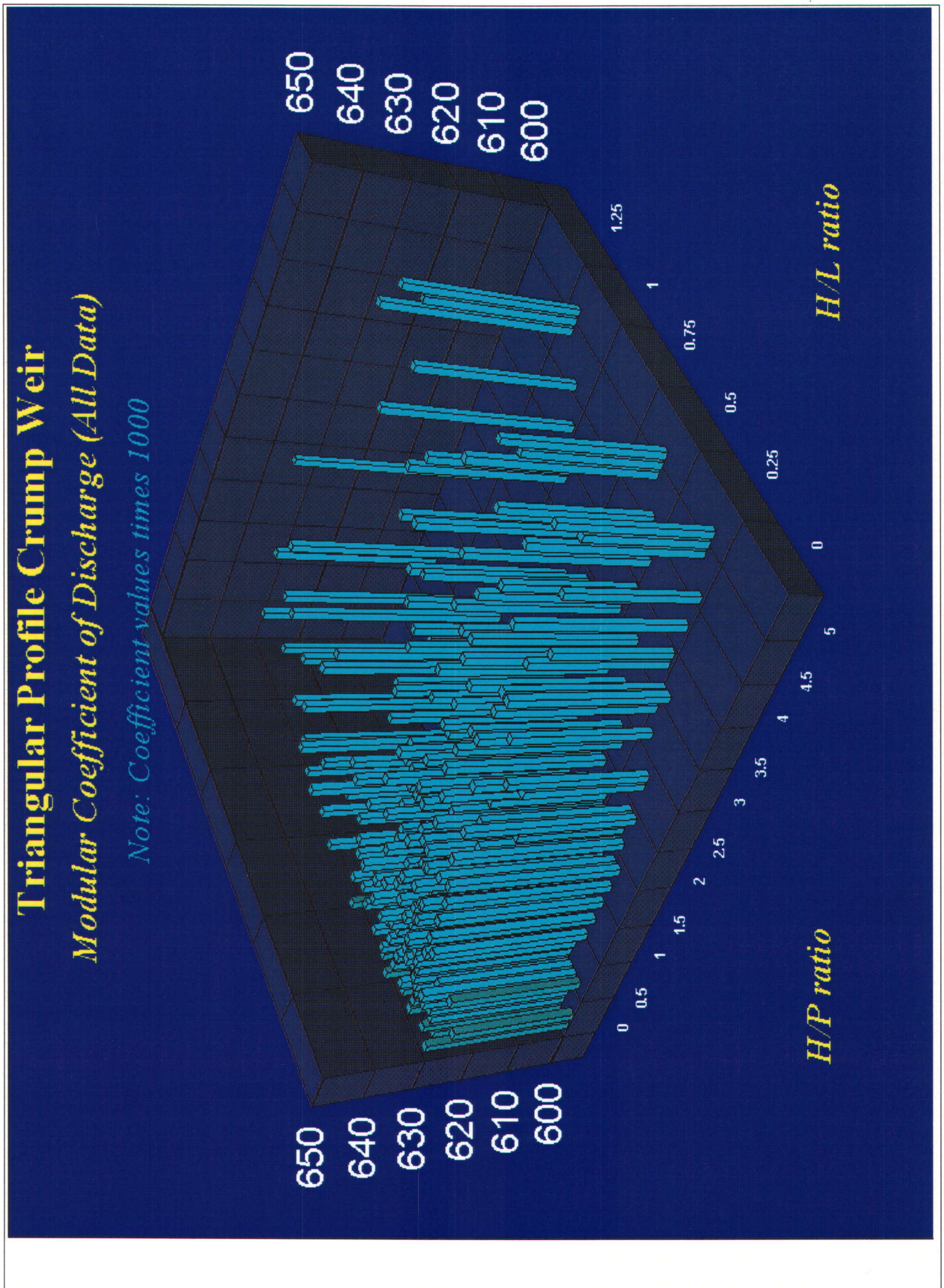


Figure 5 **Coefficients of discharge for the Triangular Profile Crump weir**

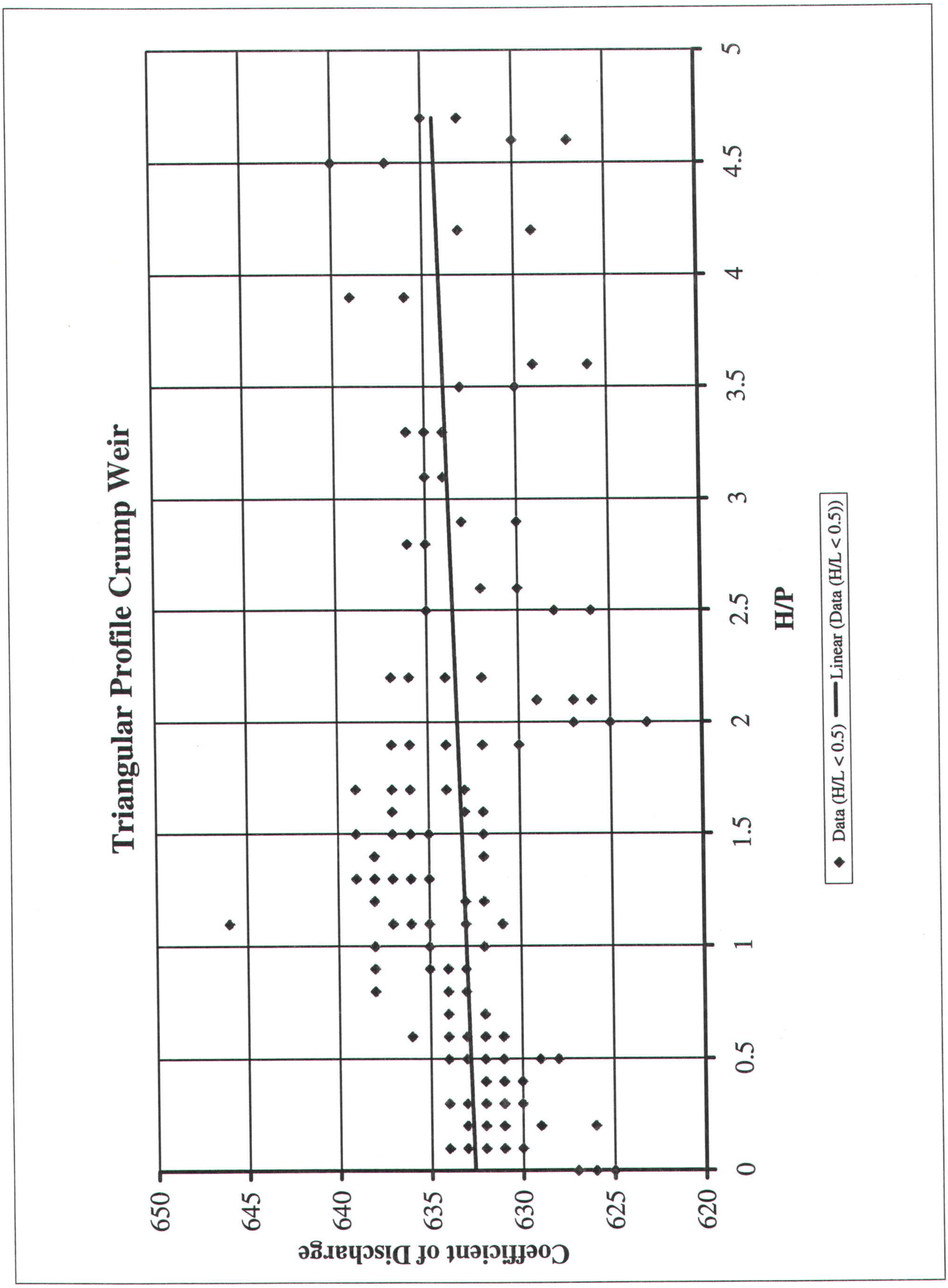


Figure 6 C_{De} versus H_{1e} / P_1 for data in the range $0 < H_1 / L_1 < 0.5$

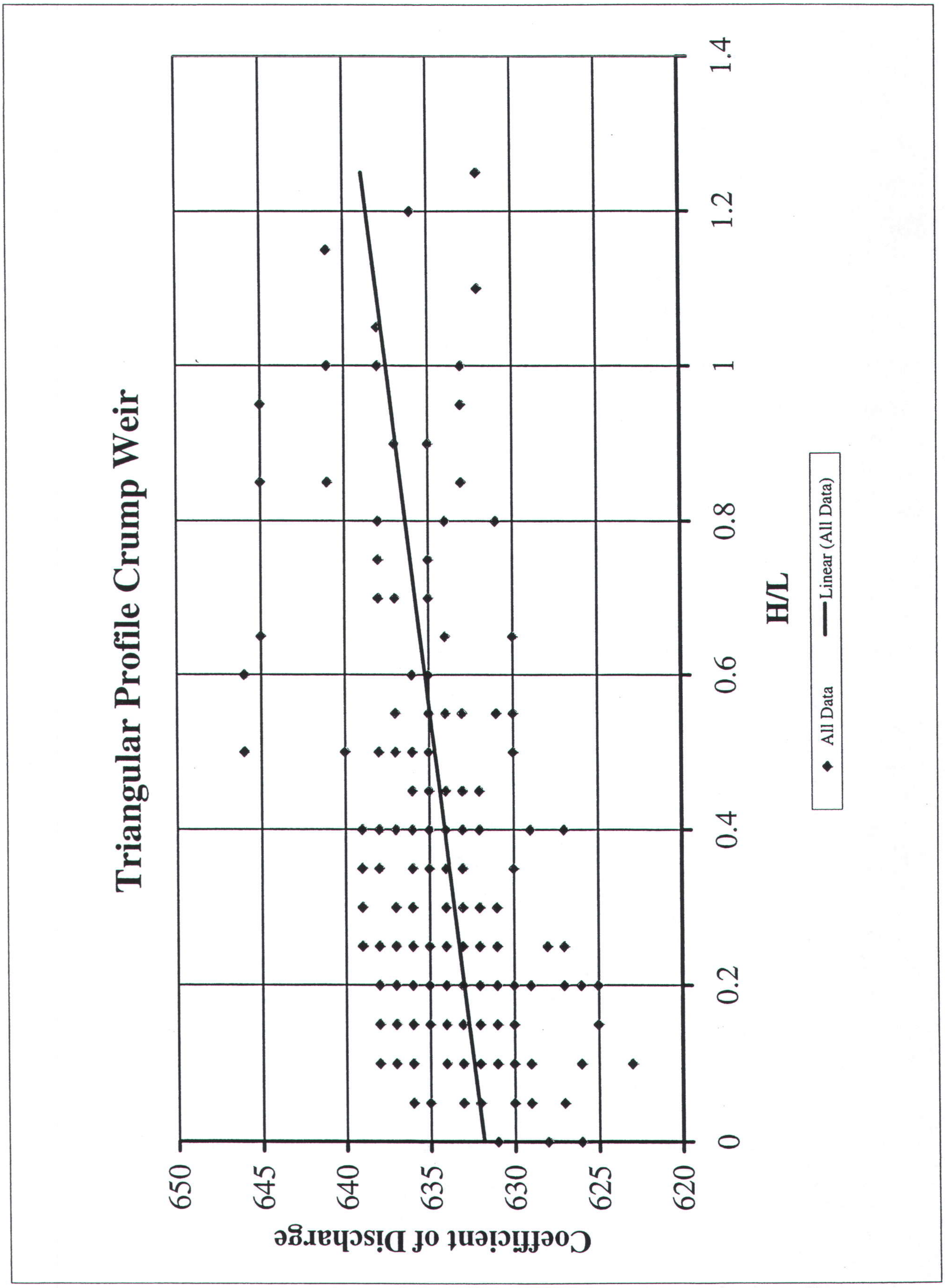


Figure 7 C_{De} versus H_1 / L_1 for all data

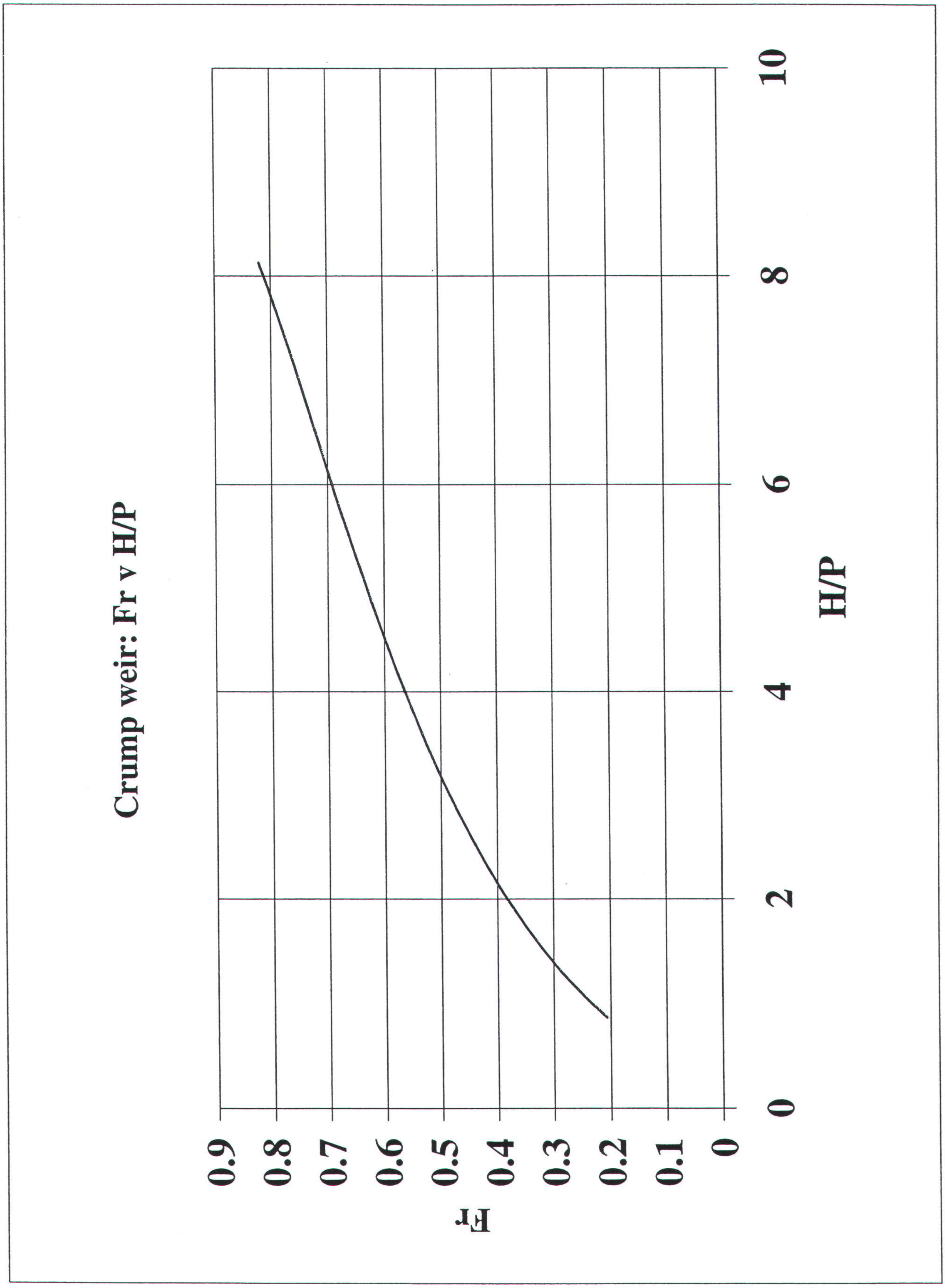


Figure 8 **Fr versus H_{1e} / P_1**

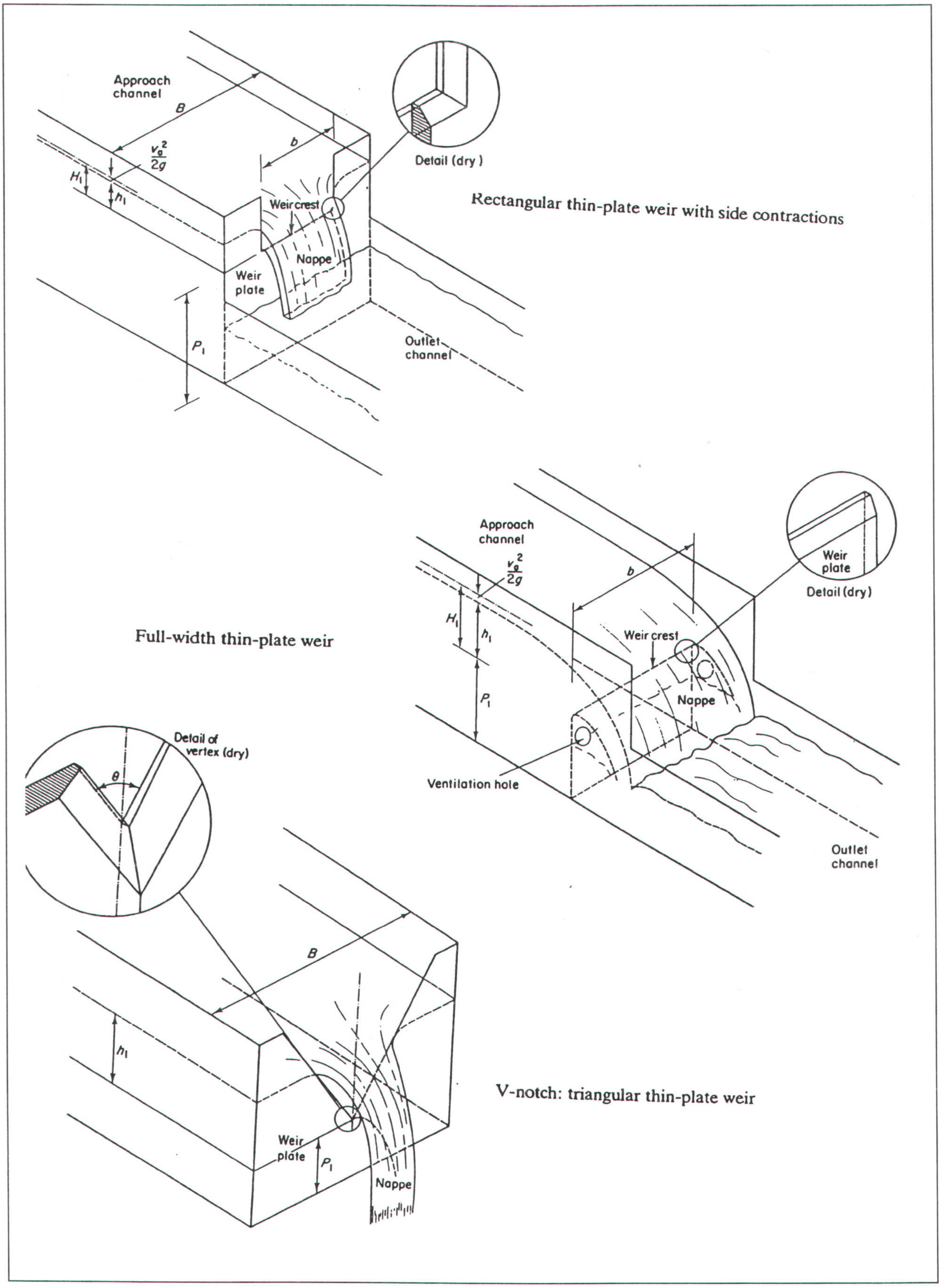


Figure 9 Thin Plate weirs (after Ackers et al.)

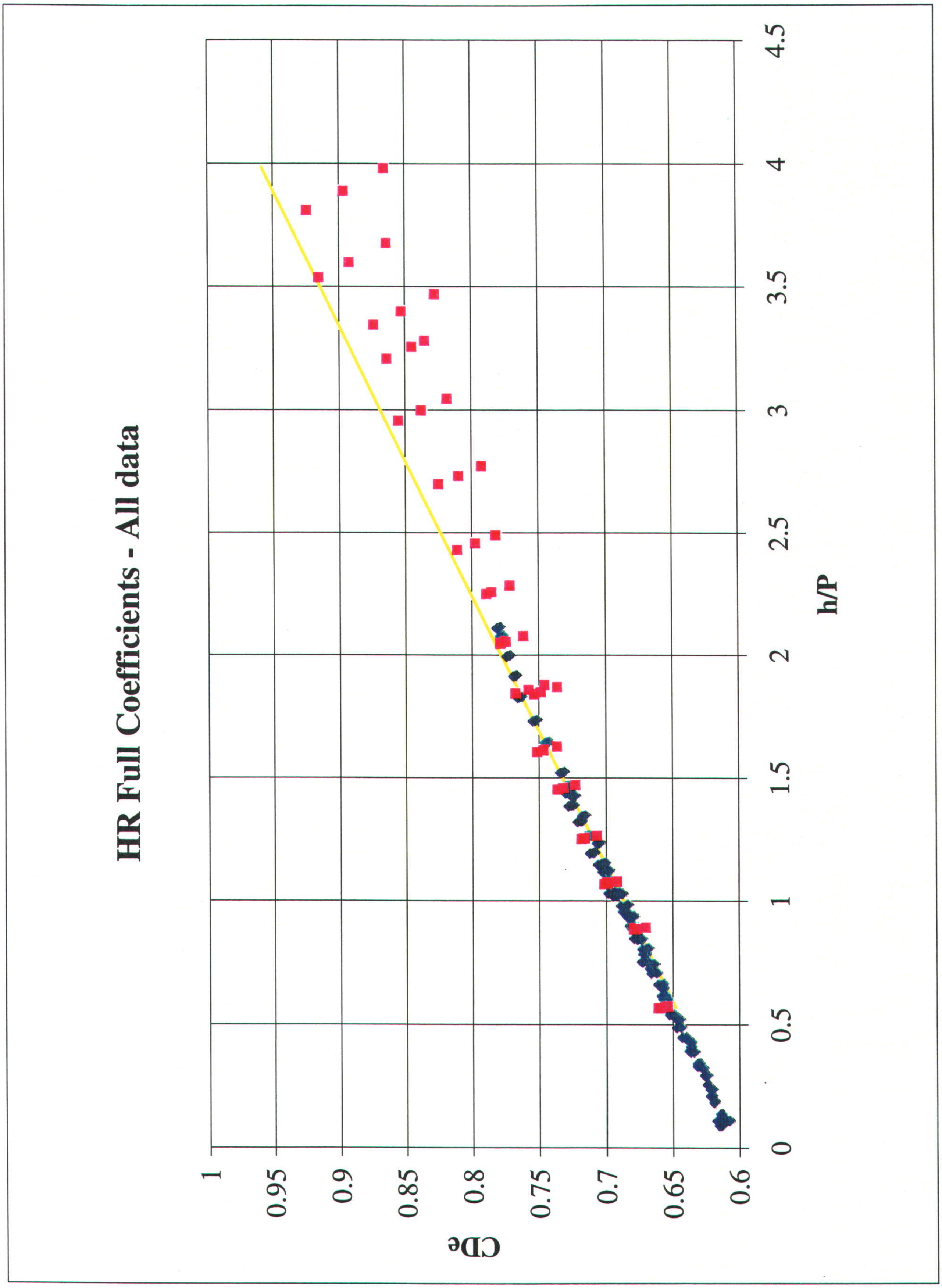


Figure 10 Coefficients of discharge for the full width Thin Plate weir, all results

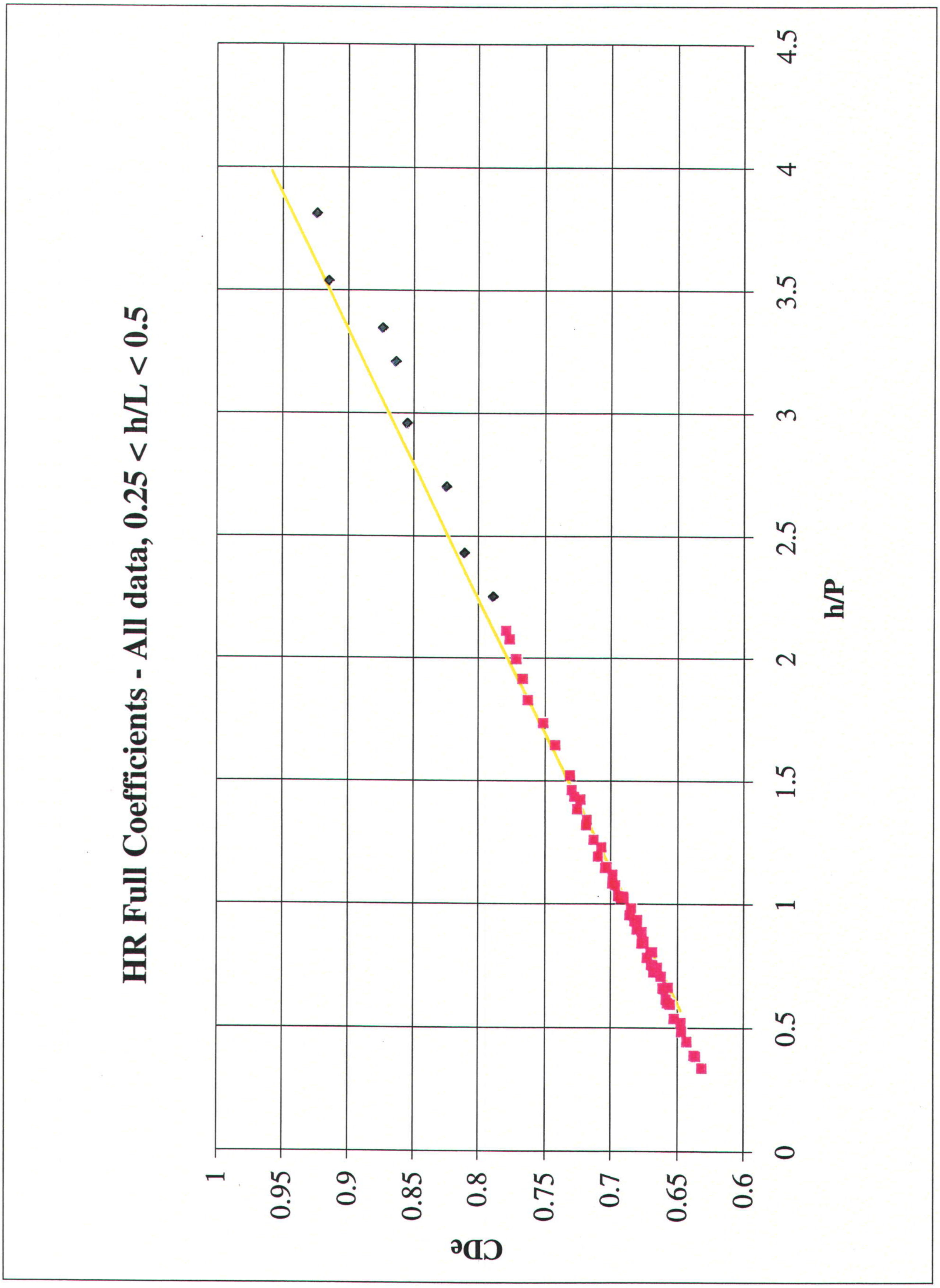


Figure 11 Coefficients of discharge for the full width Thin Plate weir, 0.25 < h / L < 0.50

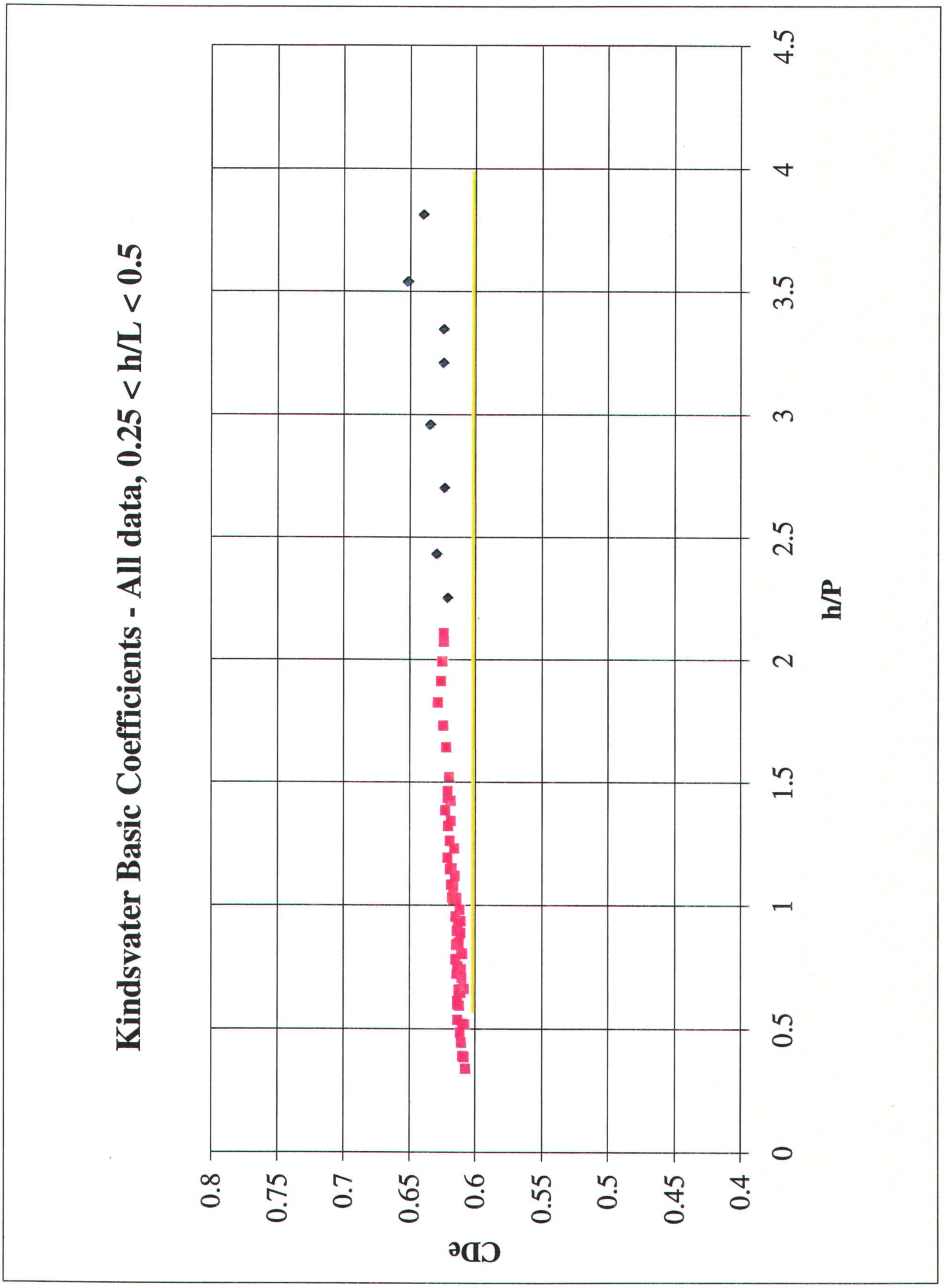


Figure 12 Basic coefficient of discharge, Kindvater-Carter, 1957 (USA)

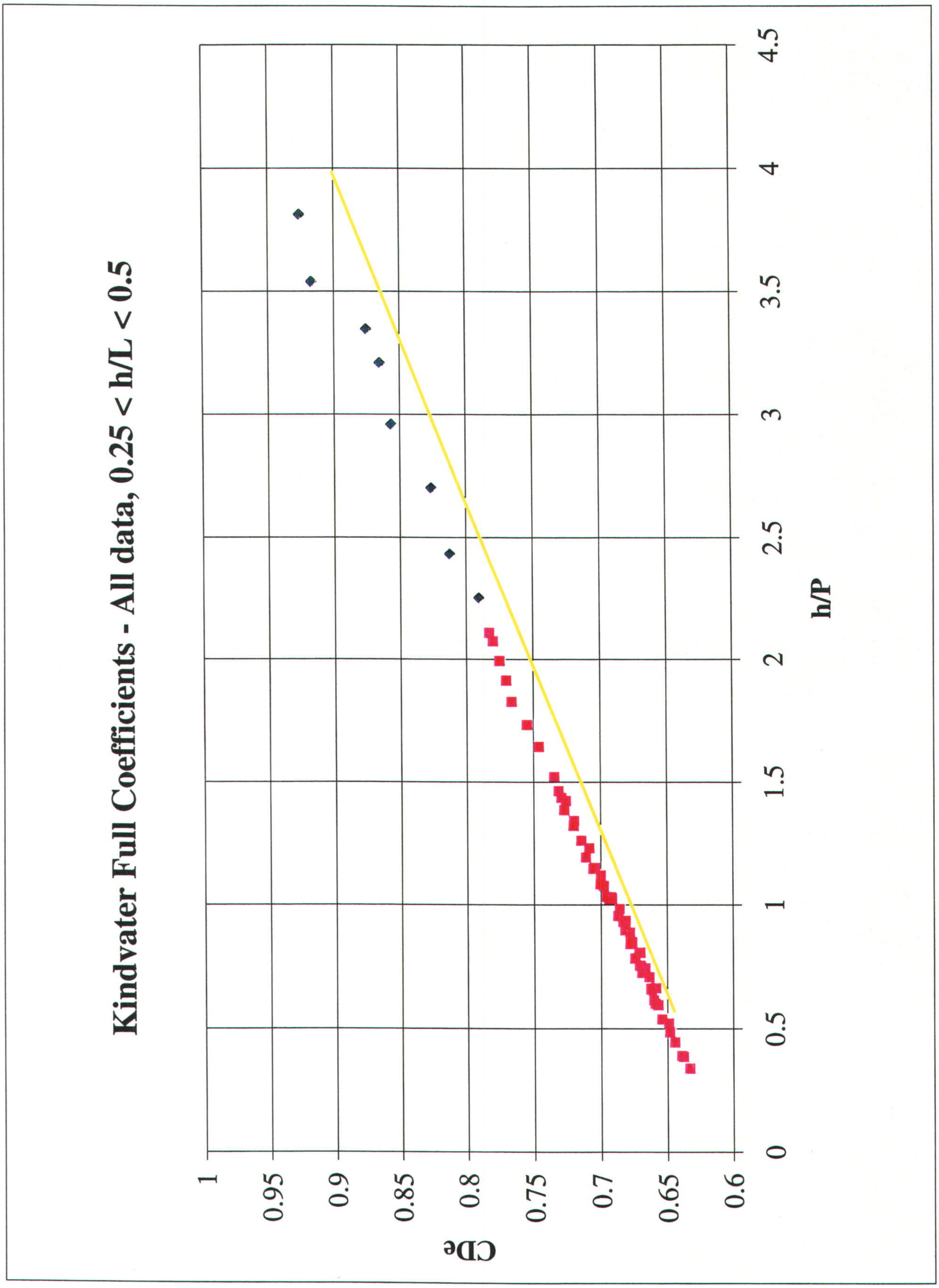


Figure 13 Full coefficient of discharge, Kindvater-Carter, 1957 (USA)

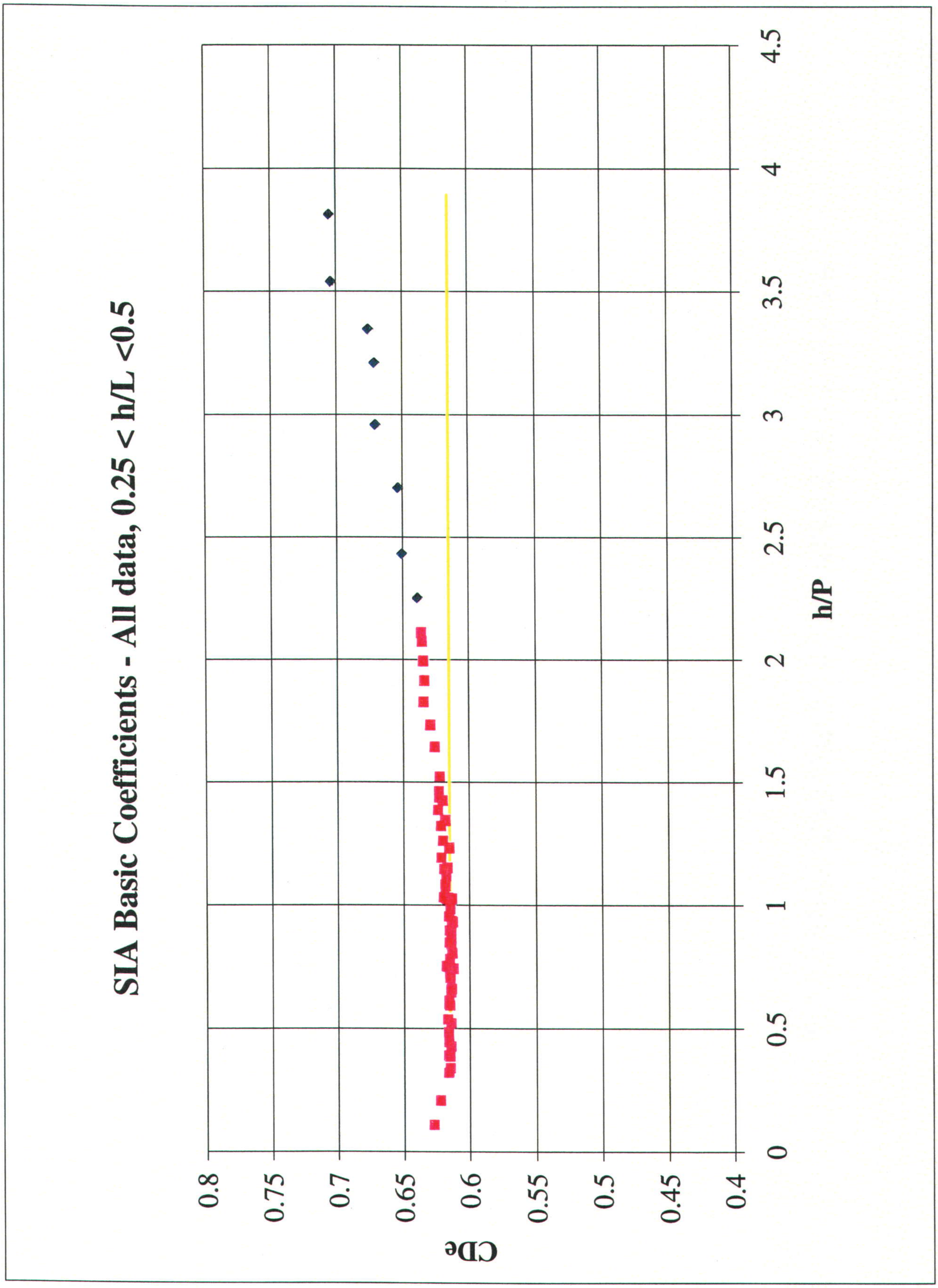


Figure 14 Basic coefficient of discharge, S. I. A., 1926 (Switzerland)

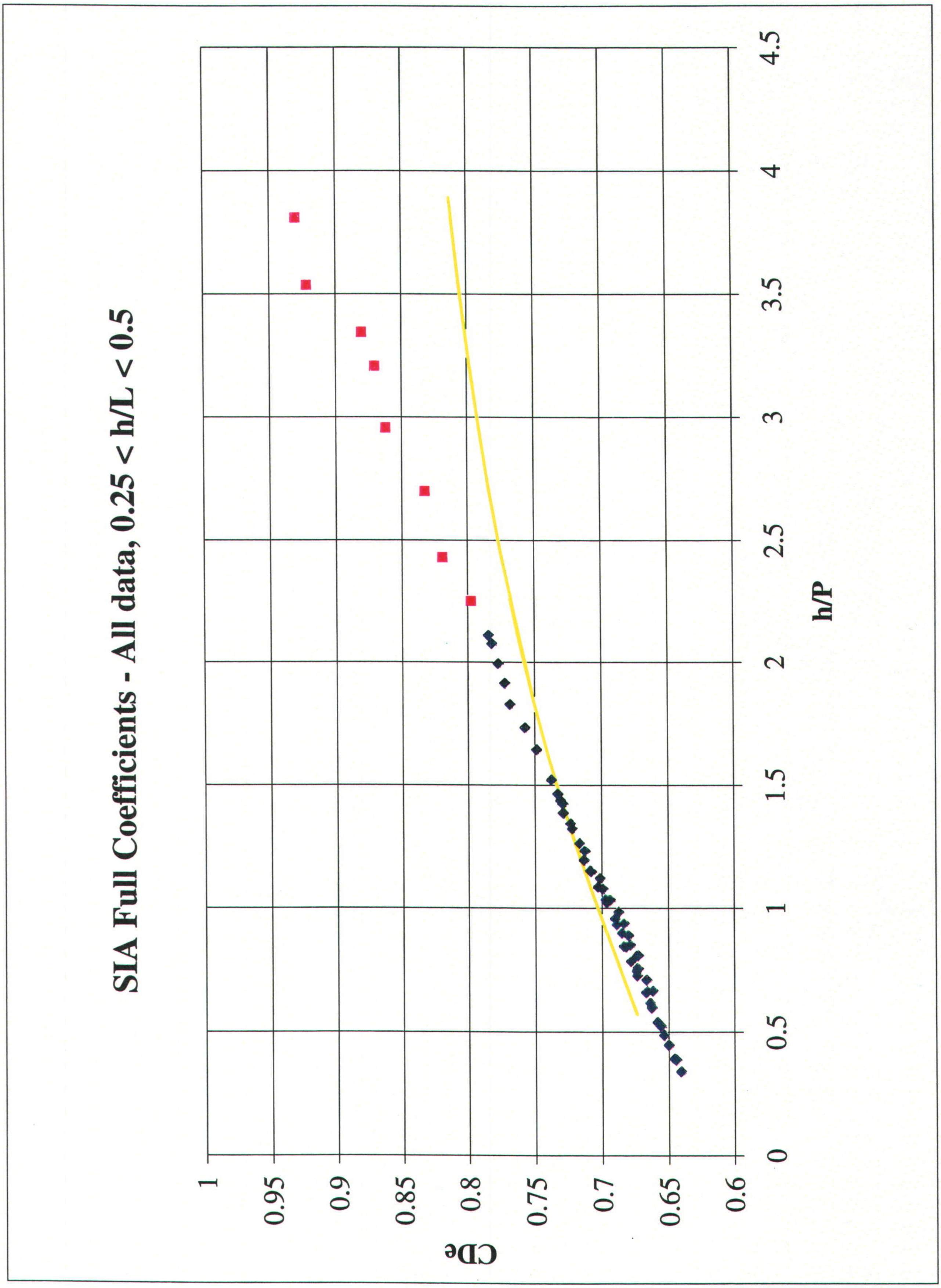


Figure 15 Full coefficient of discharge, S. I. A., 1926 (Switzerland)

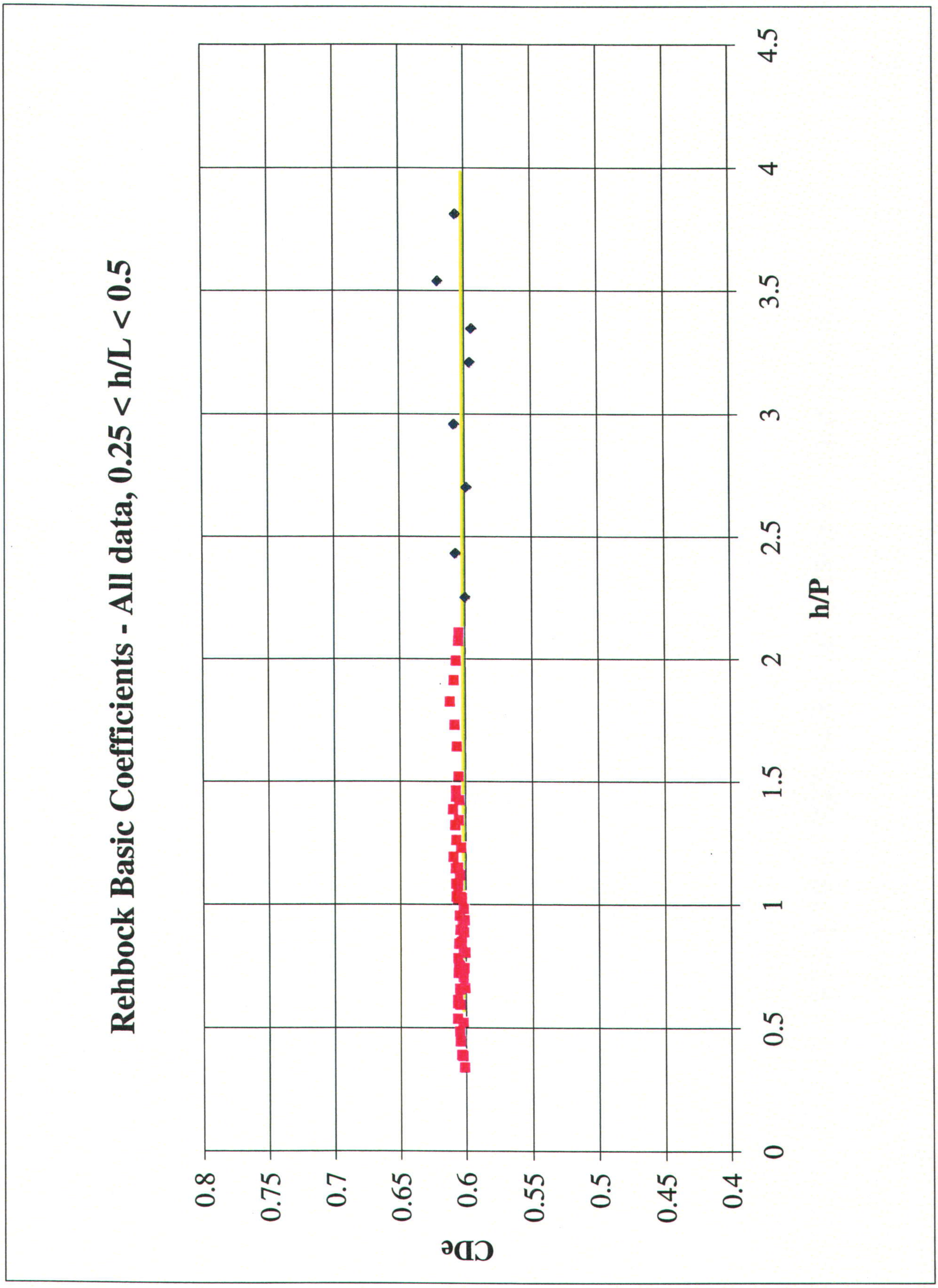


Figure 16 Basic coefficient of discharge, Rehbock, 1929 (Germany)

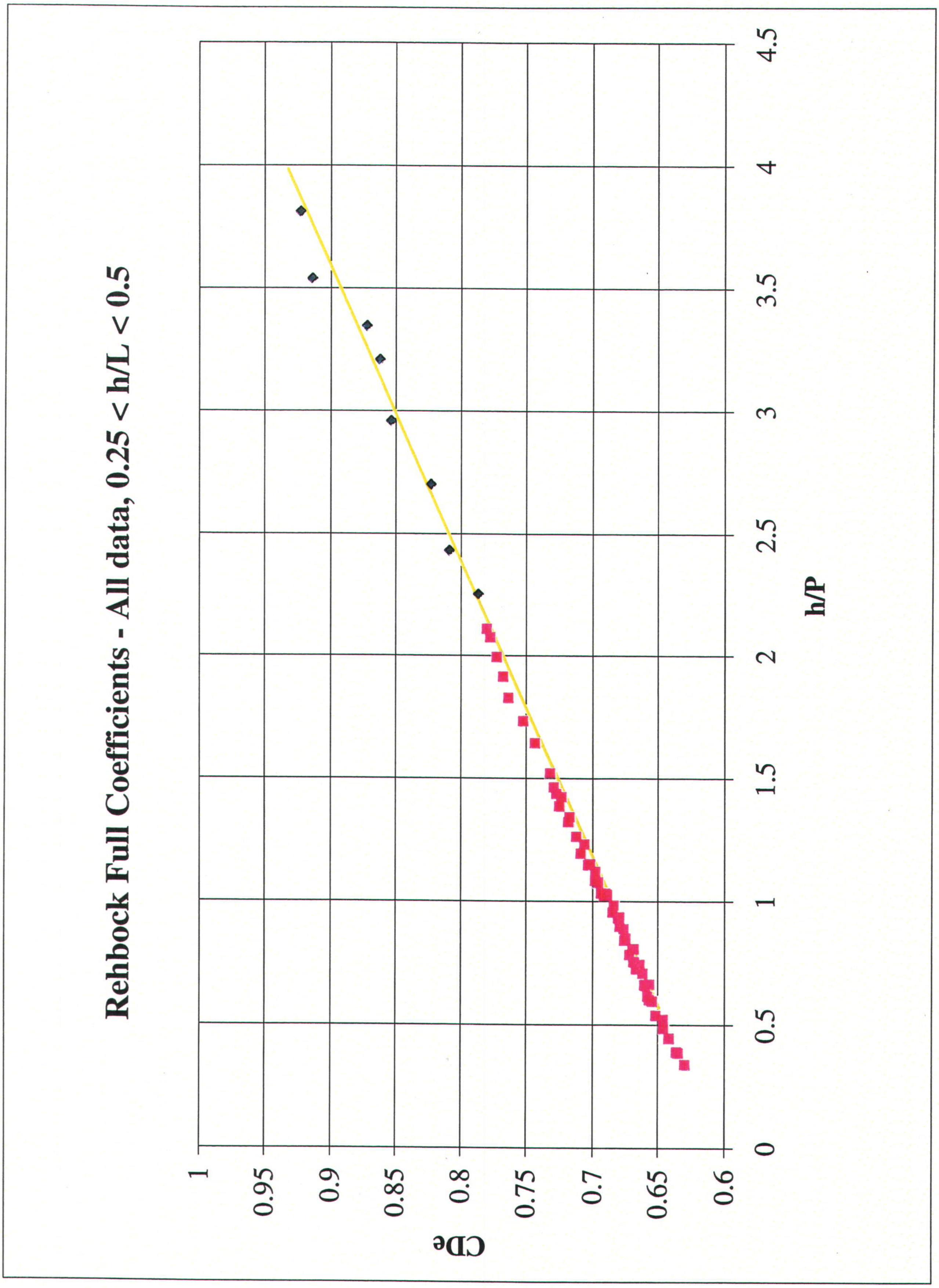


Figure 17 Full coefficient of discharge, Rehbock, 1929 (Germany)

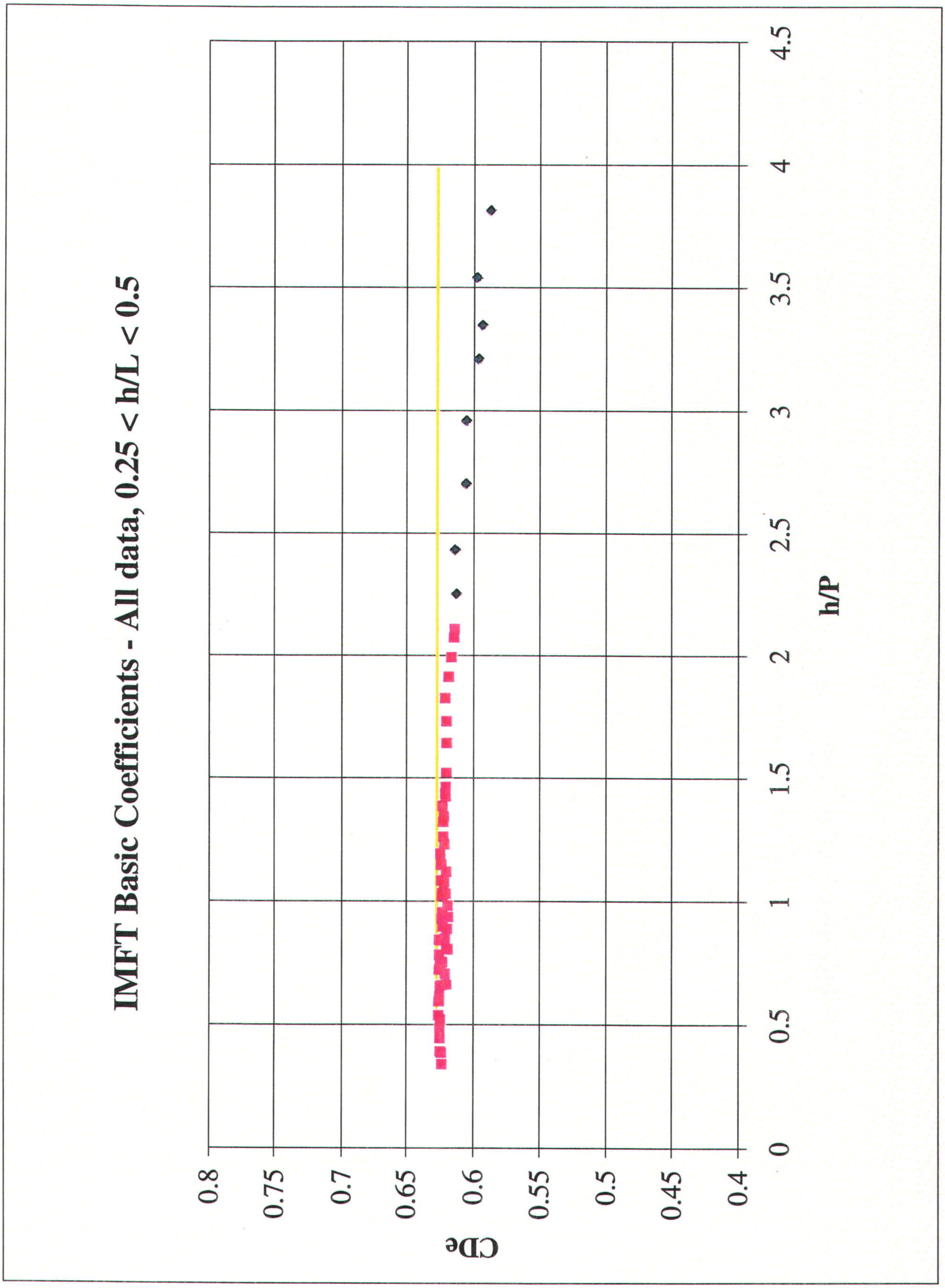


Figure 18 **Basic coefficient of discharge, I. M. F. T., 1969 (France)**

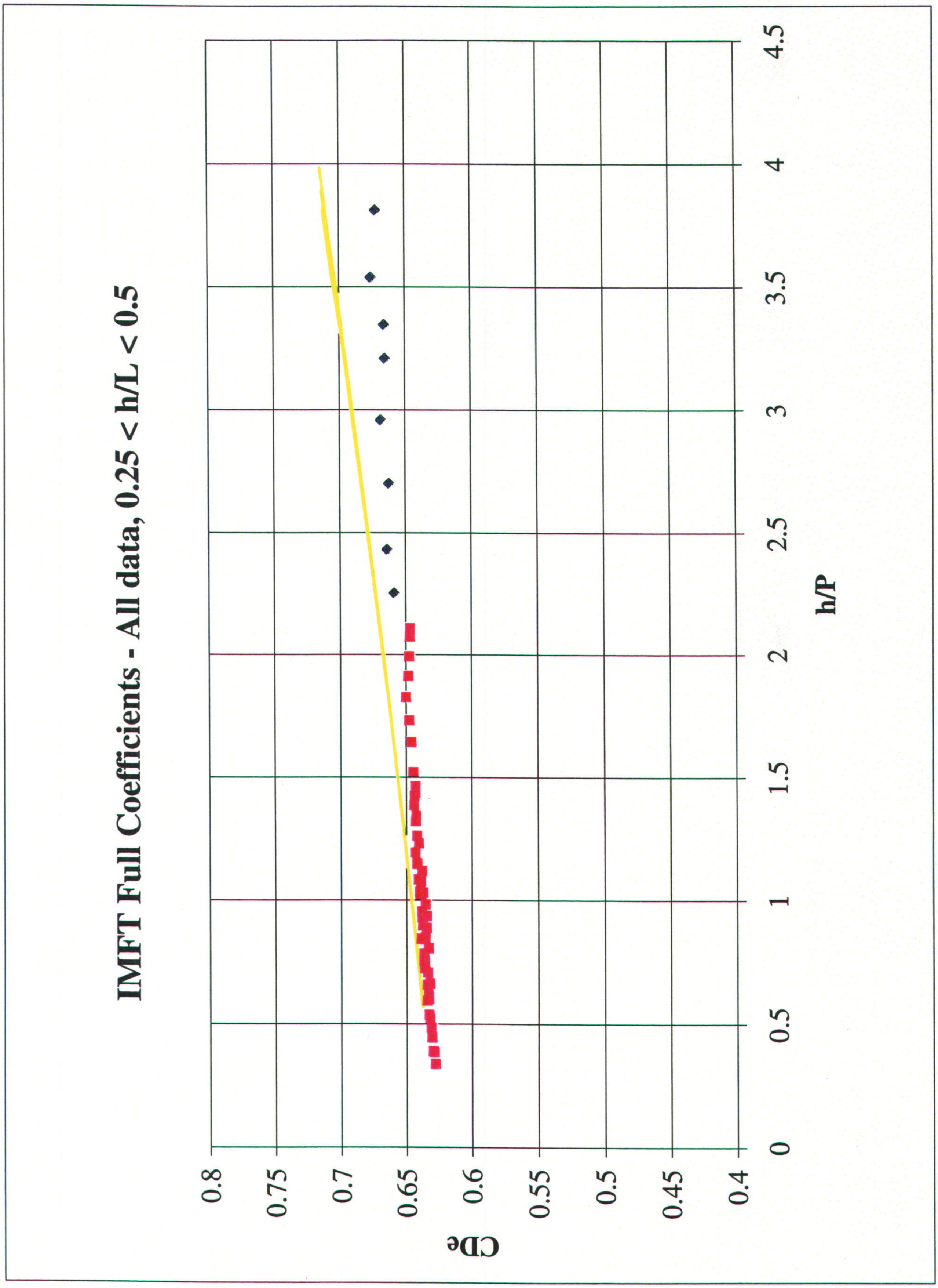


Figure 19 Full coefficient of discharge, I. M. F. T., 1969 (France)

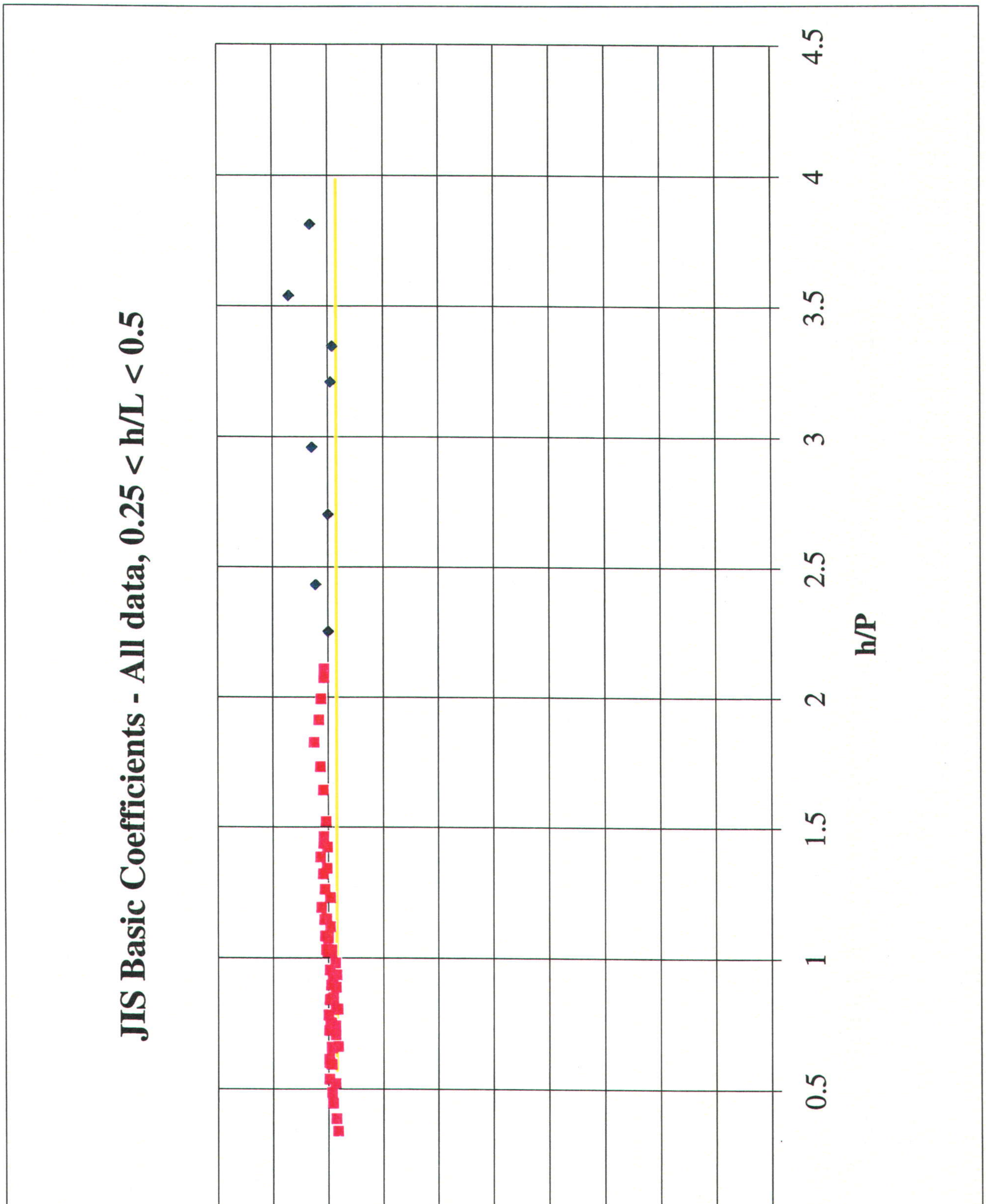


Figure 20 Basic coefficient of discharge, J. I. S., 1990 (Japan)

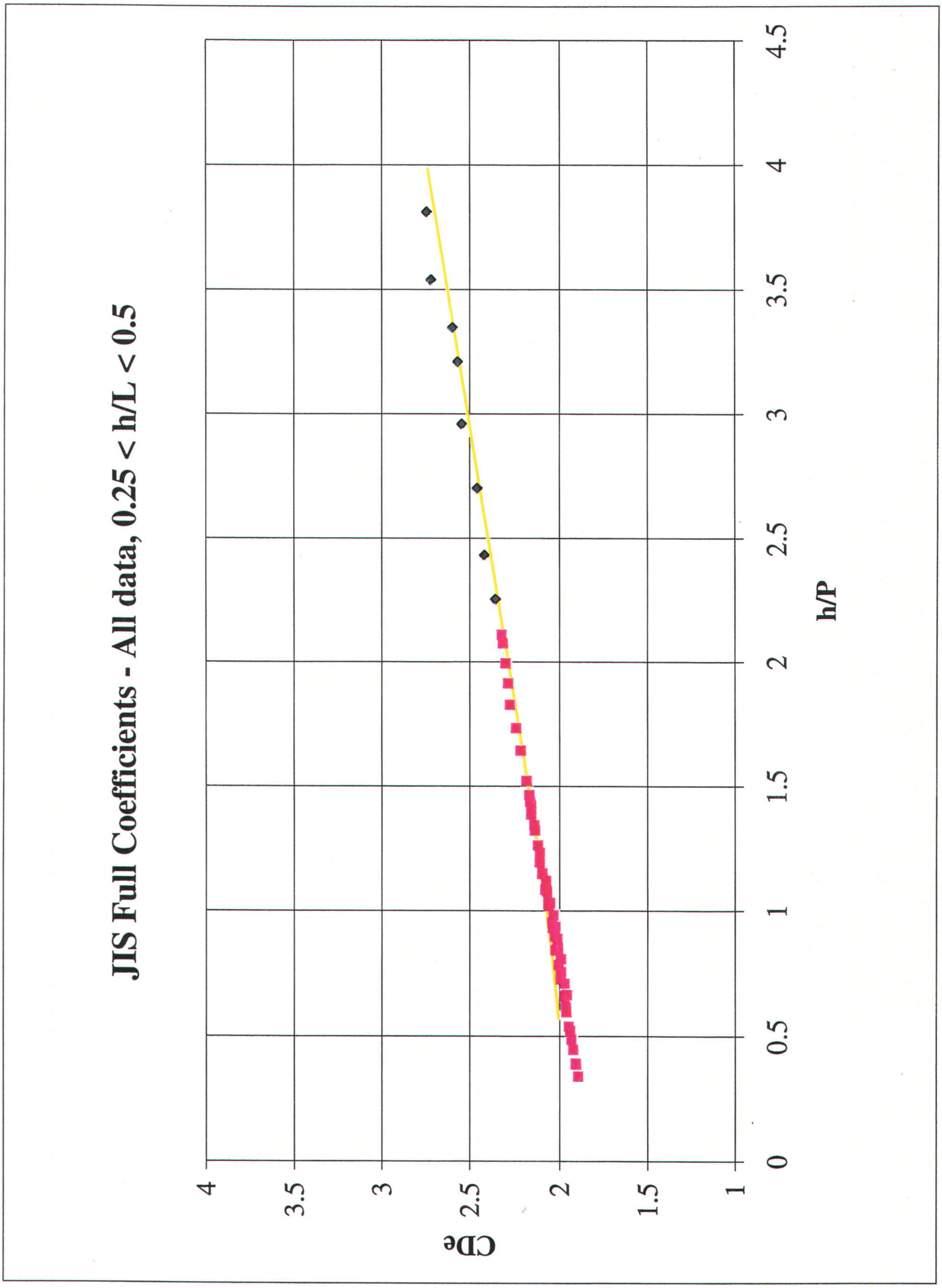


Figure 21 Full coefficient of discharge, J. I. S., 1990 (Japan)

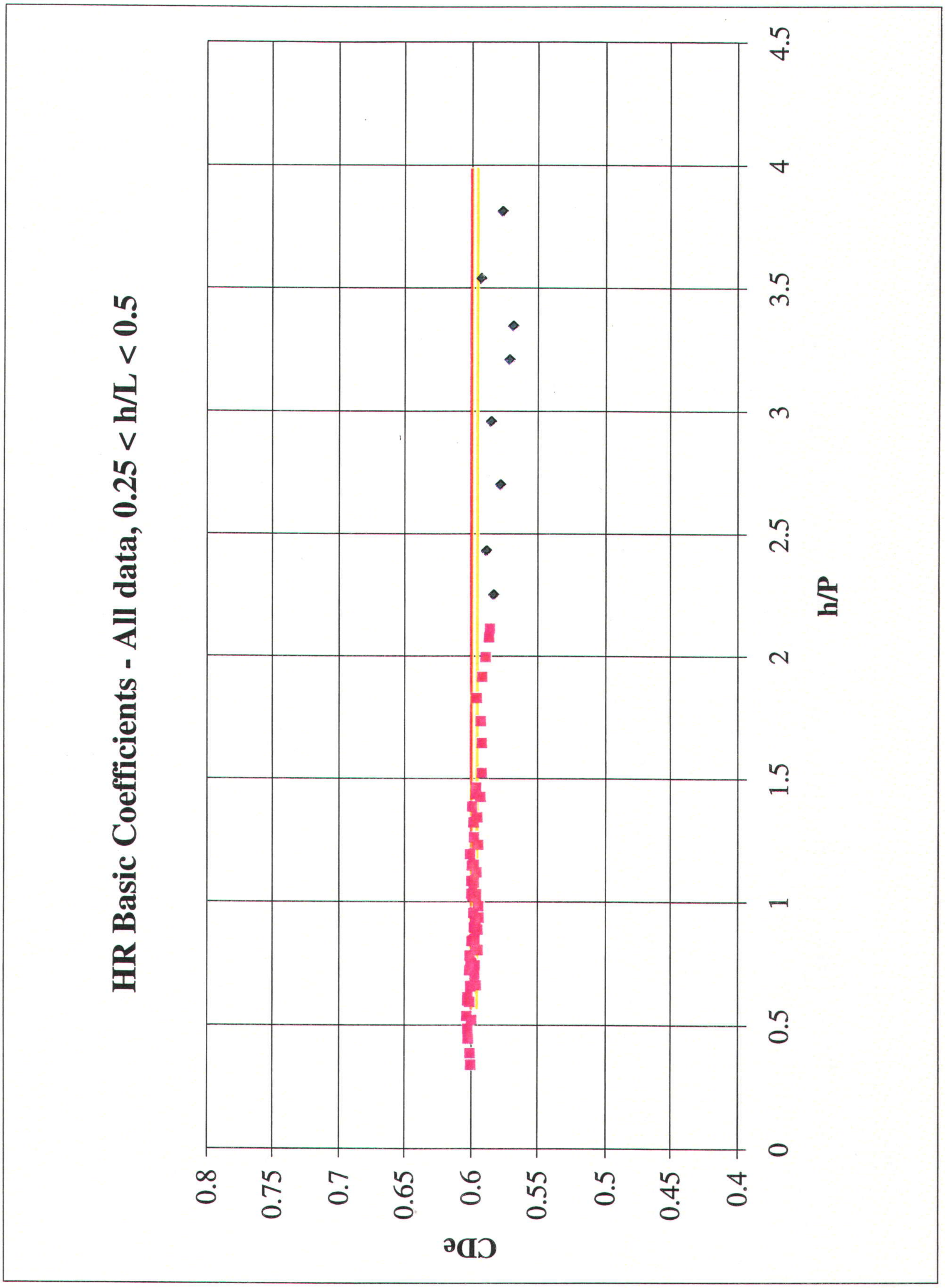


Figure 22 Basic coefficient of discharge, HR Wallingford, 1975, 1999 (UK)

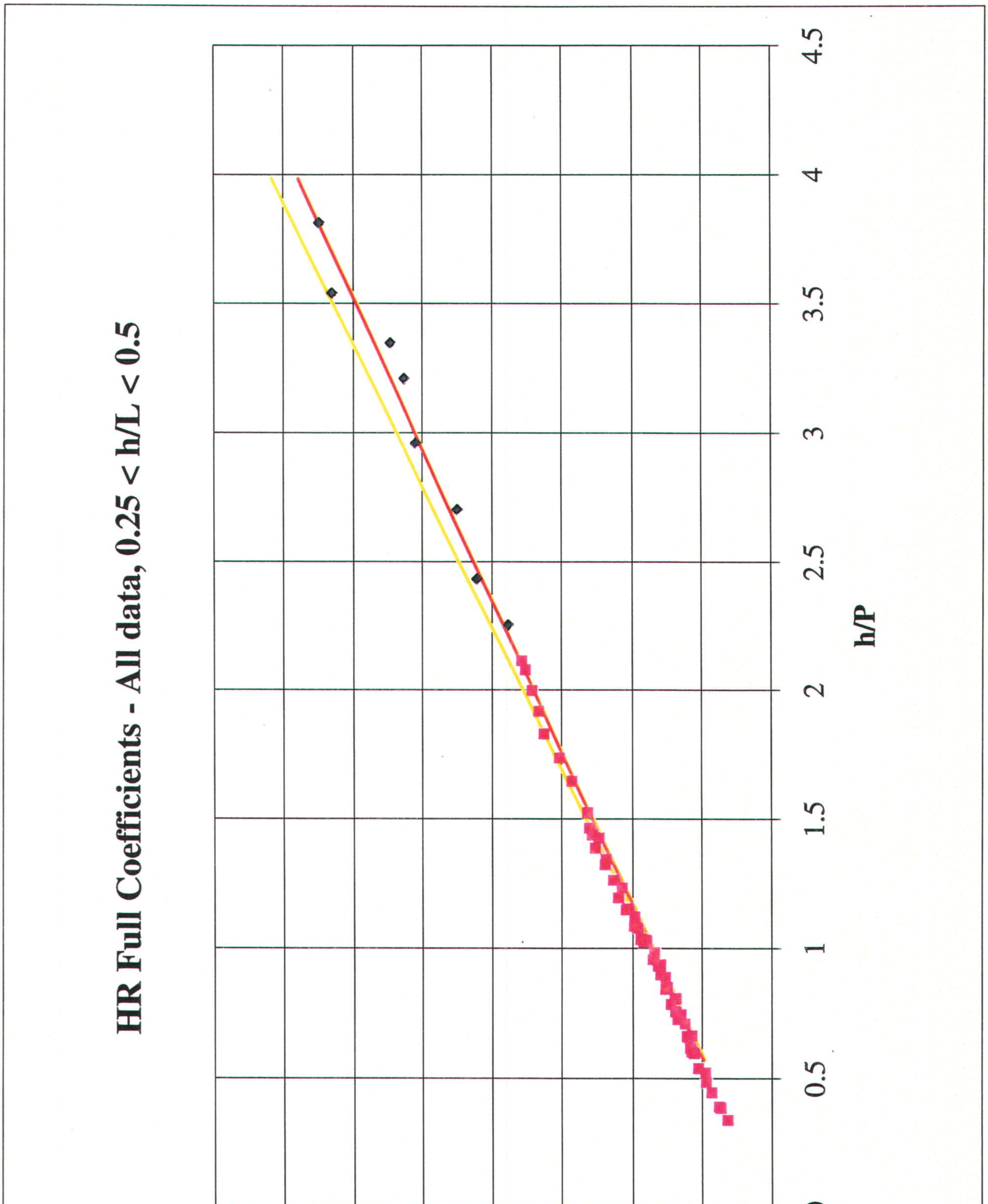


Figure 23 **Full coefficient of discharge, HR Wallingford, 1975, 1999 (UK)**

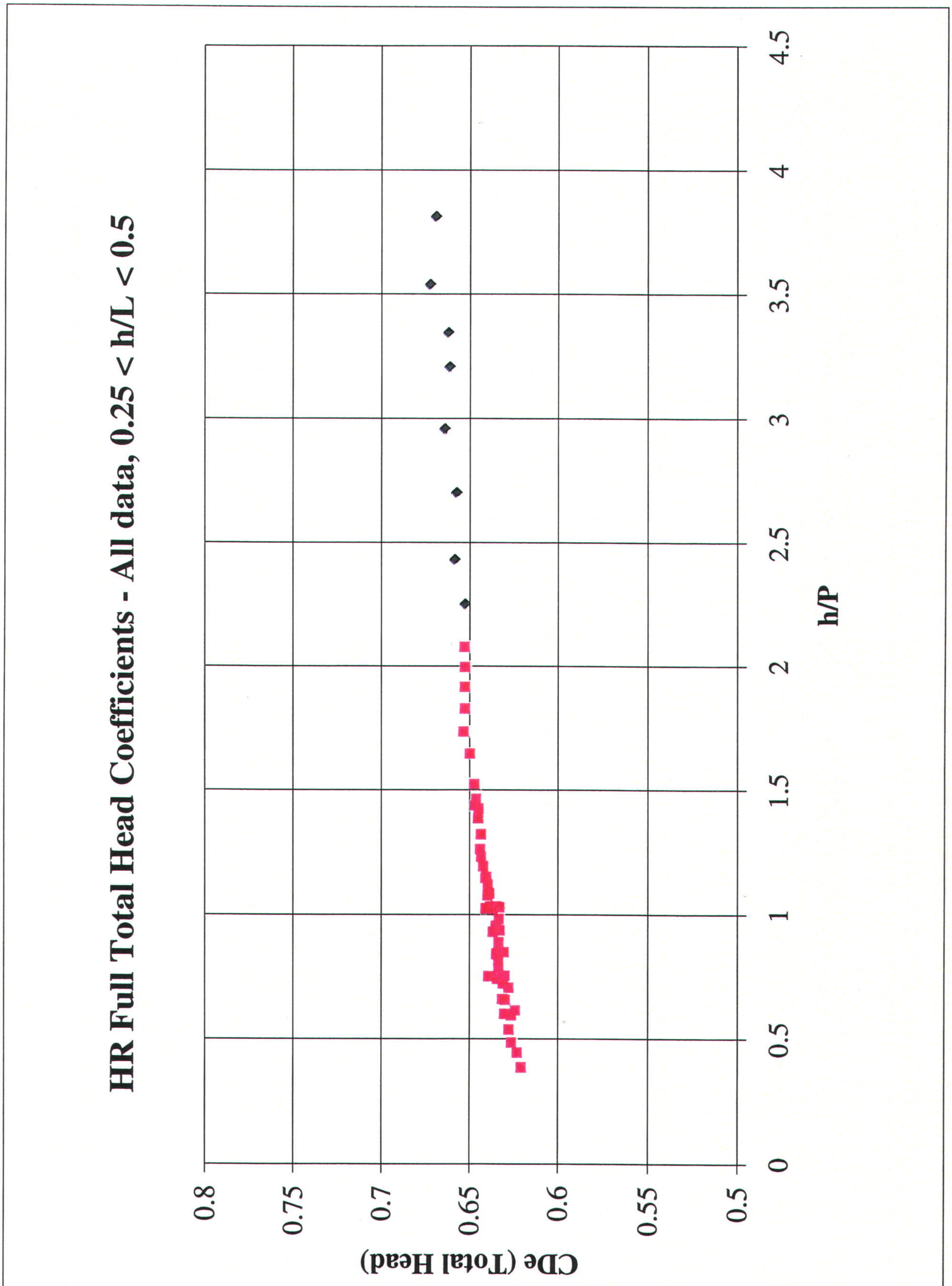


Figure 24 Coefficient of discharge for full width Thin Plate weirs based on total head

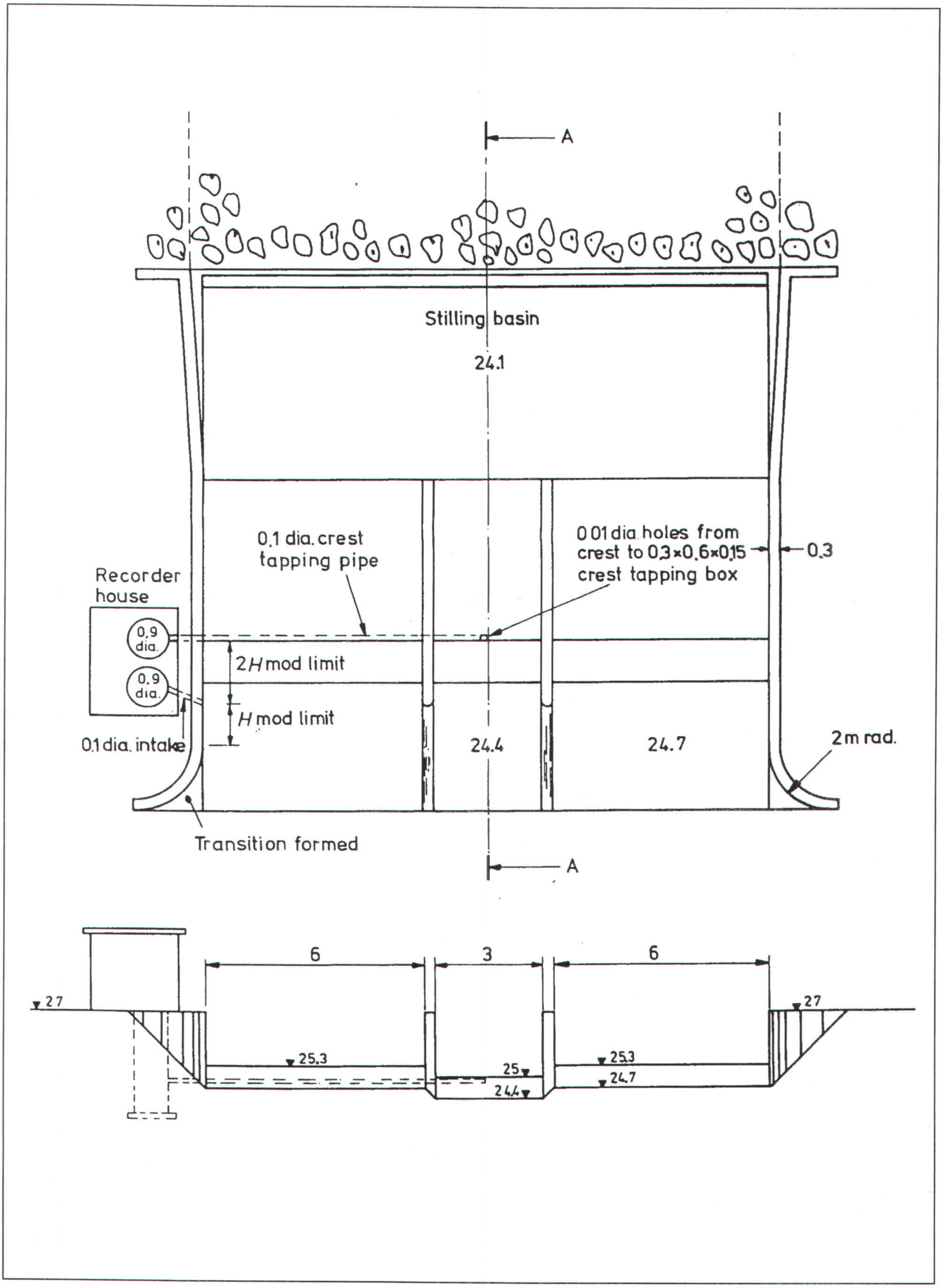


Figure 25 Example of compound weir design

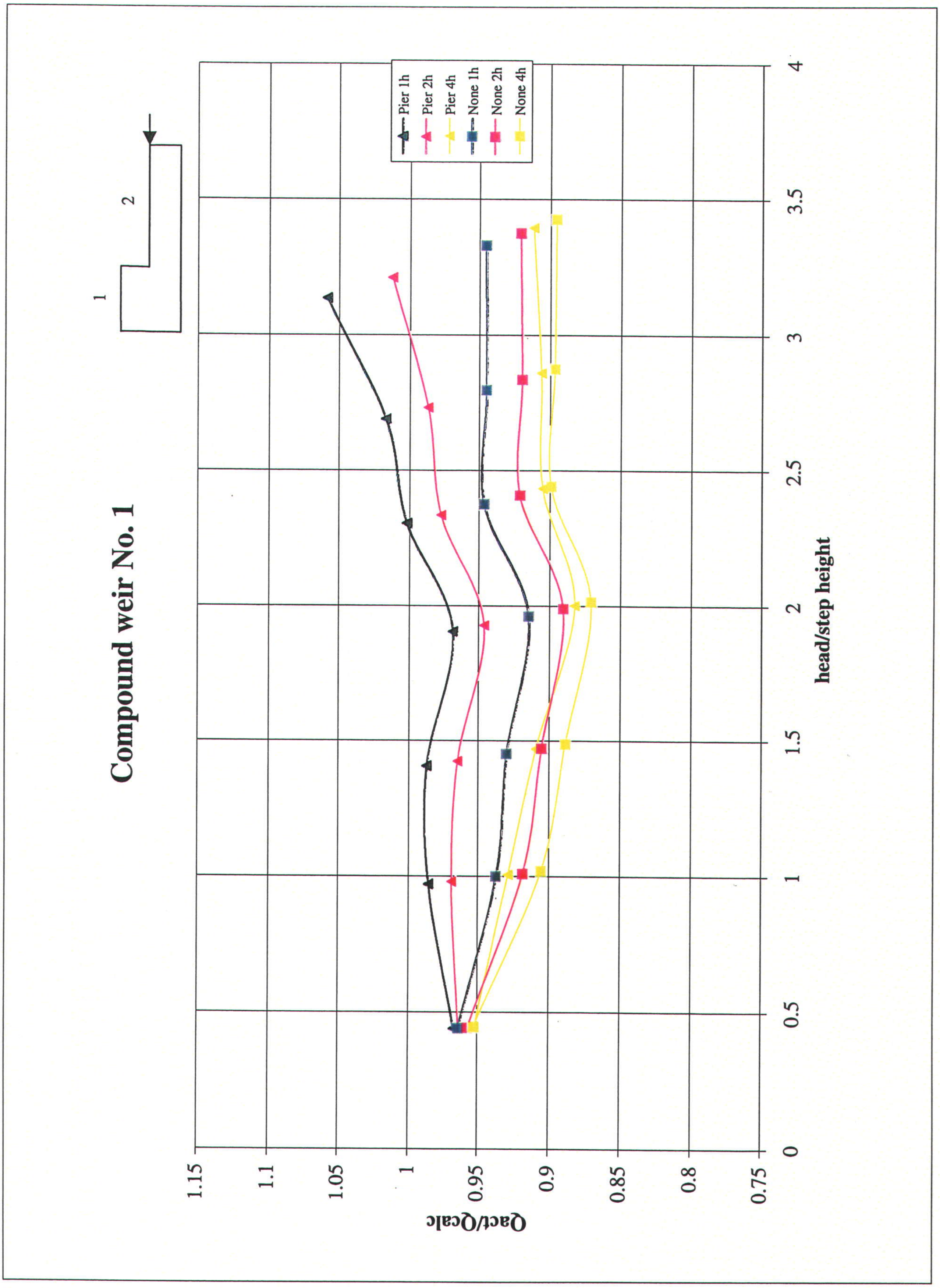


Figure 26 Compound weir No. 1, discharge characteristics based on head measurements at the low crest

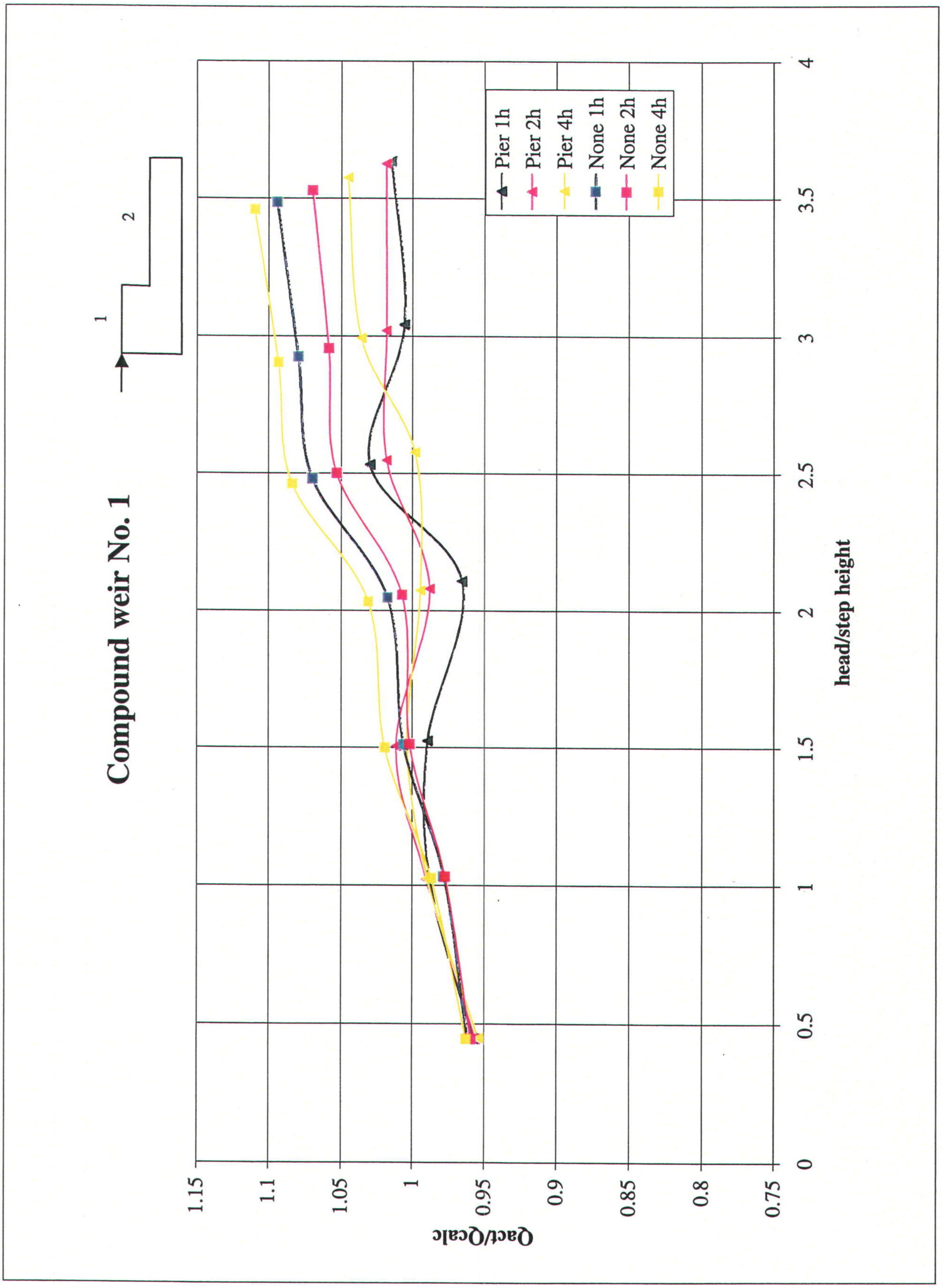


Figure 27 Compound weir No. 1, discharge characteristics based on head measurements at the high crest

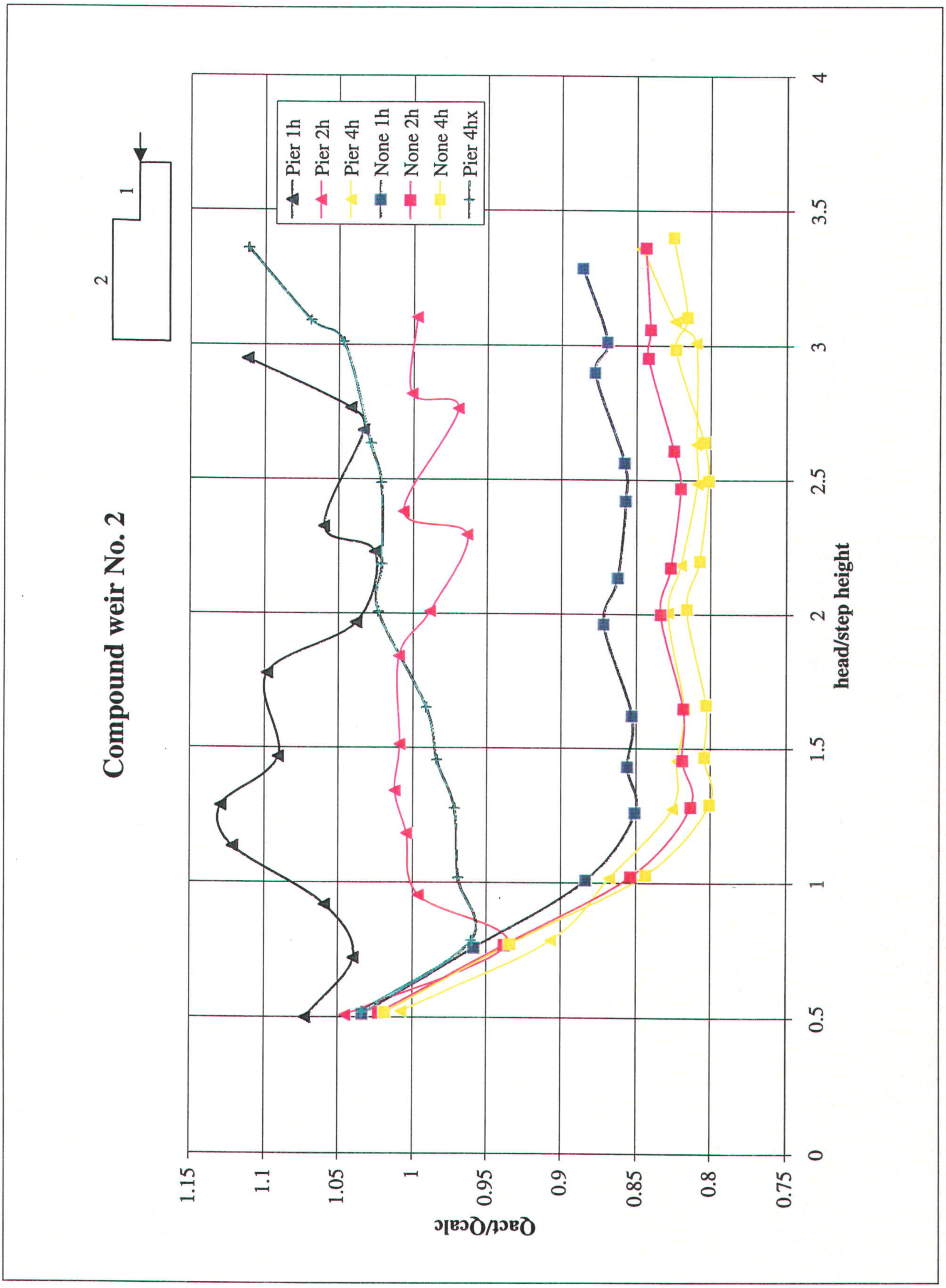


Figure 28 Compound weir No. 2, discharge characteristics based on head measurements at the low crest

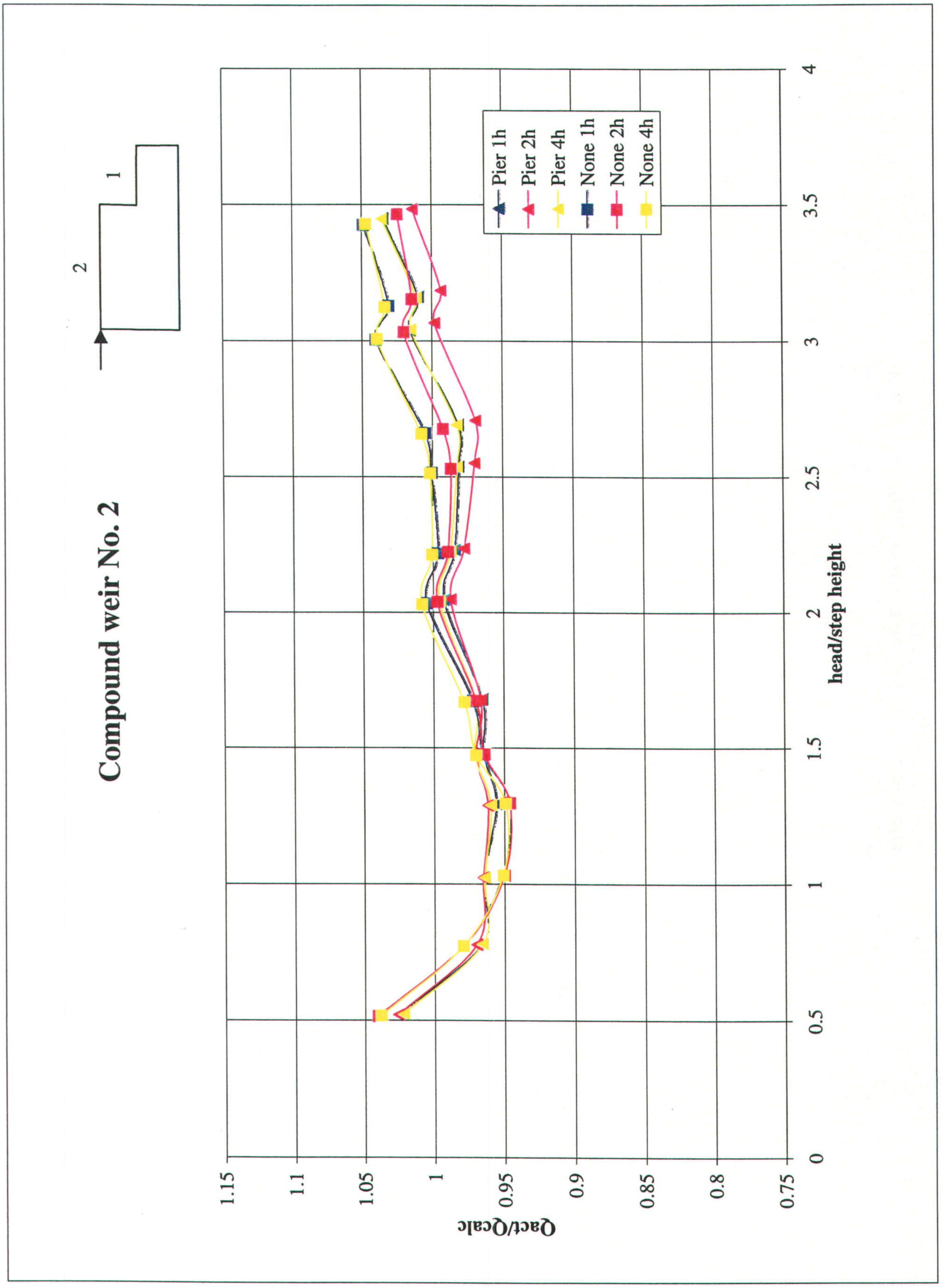


Figure 29 Compound weir No. 2, discharge characteristics based on head measurements at the high crest

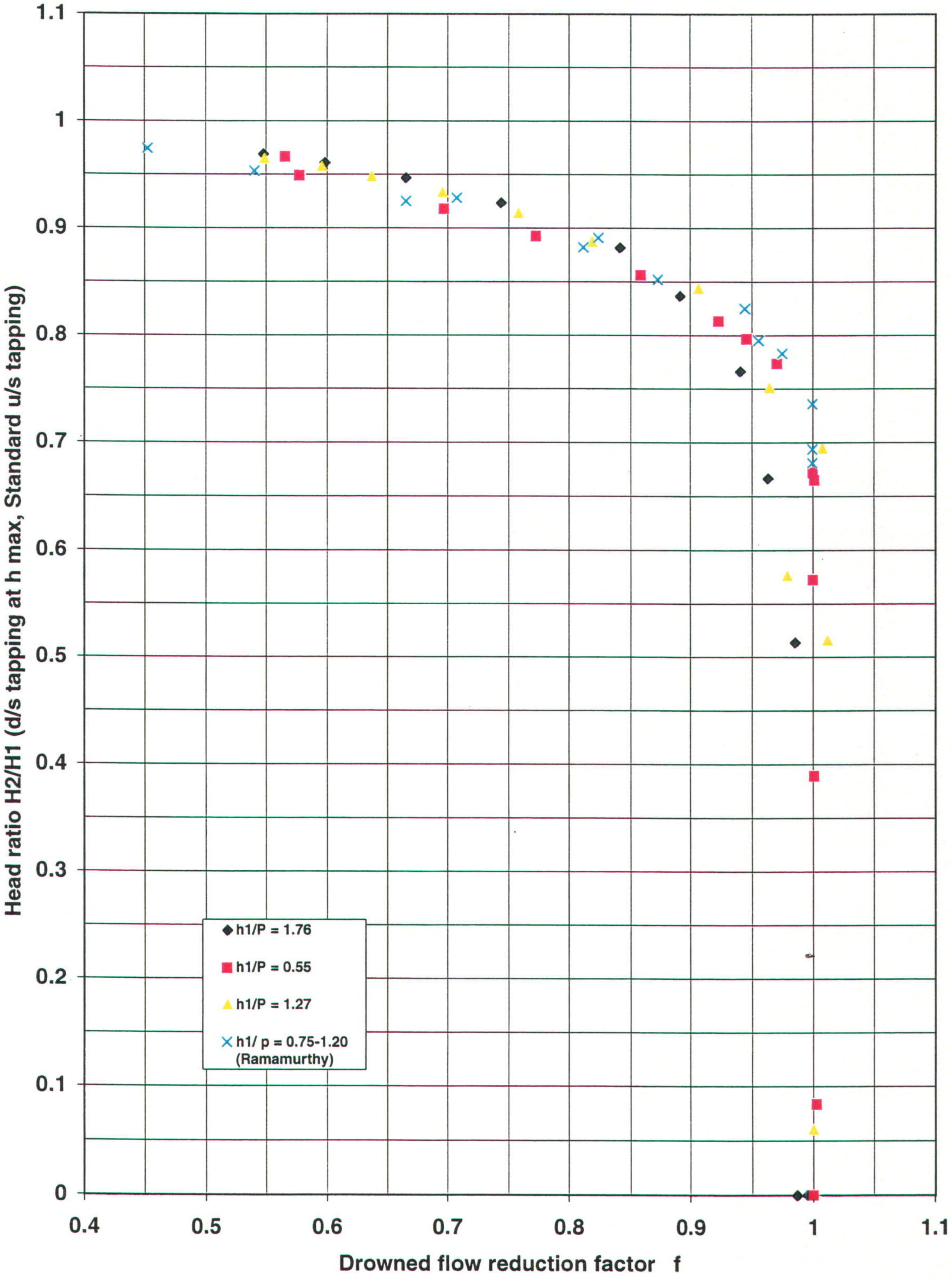


Figure 30 Rectangular Broad Crested weir, drowned flow characteristics based on heads measured h_{max} downstream of the crest

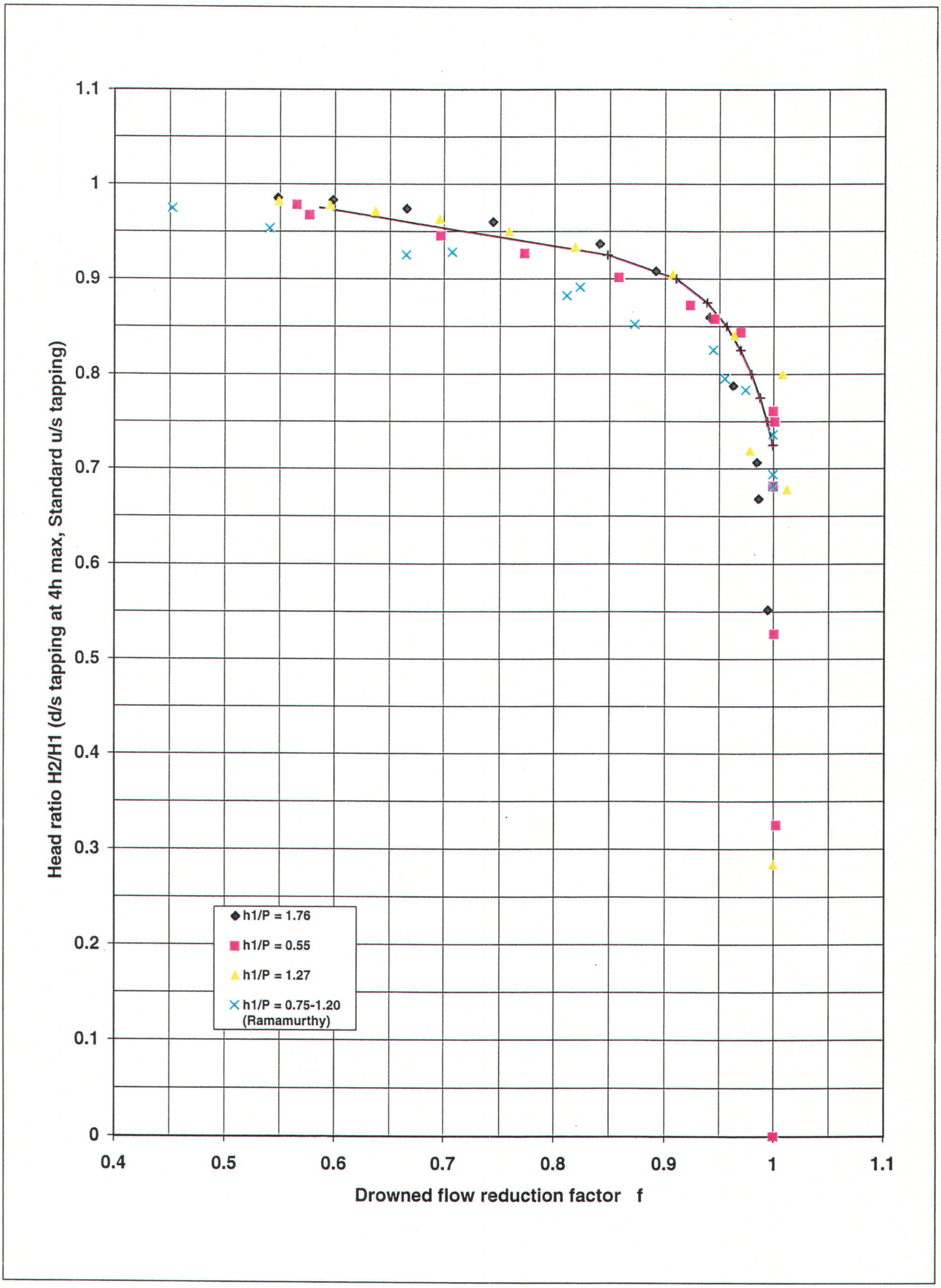


Figure 31 **Rectangular Broad Crested weir, drowned flow characteristics based on heads measured 4 h_{max} downstream of the crest**

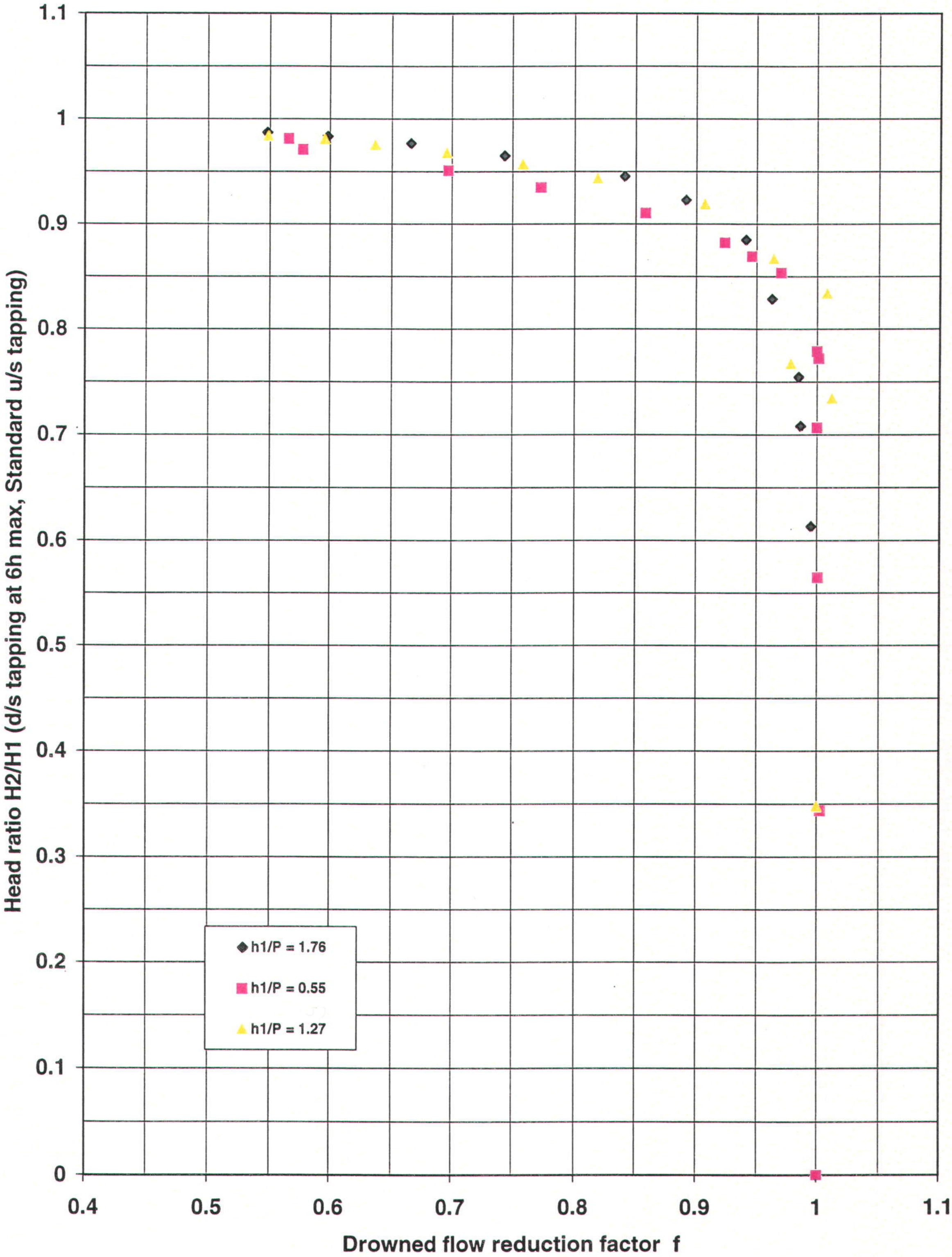


Figure 32 Rectangular Broad Crested weir, drowned flow characteristics based on heads measured 6 h_{max} downstream of the crest

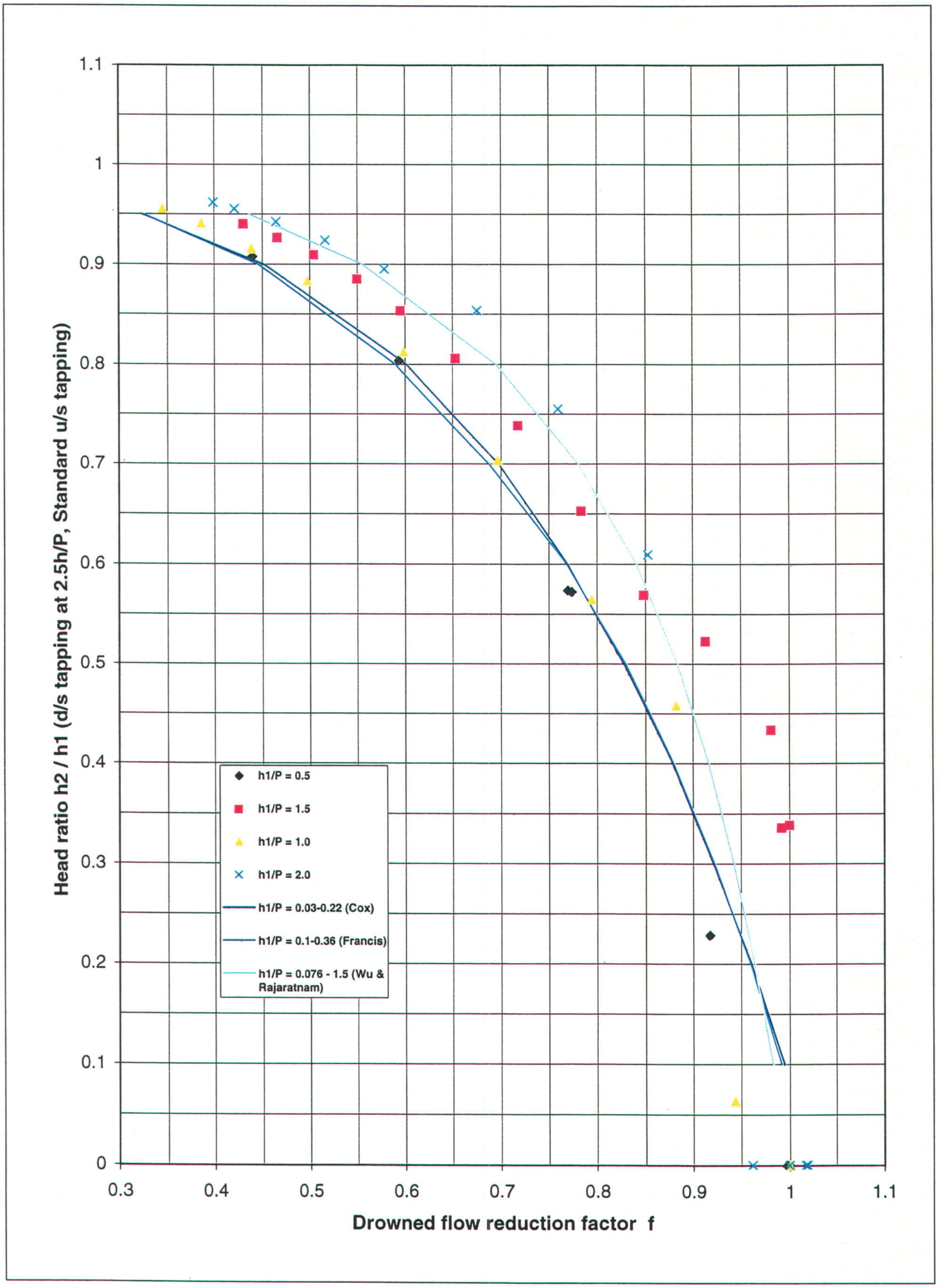


Figure 33 **Full Width Thin Plate weir, drowned flow characteristics based on heads measured 2.5 h / P downstream of the crest**

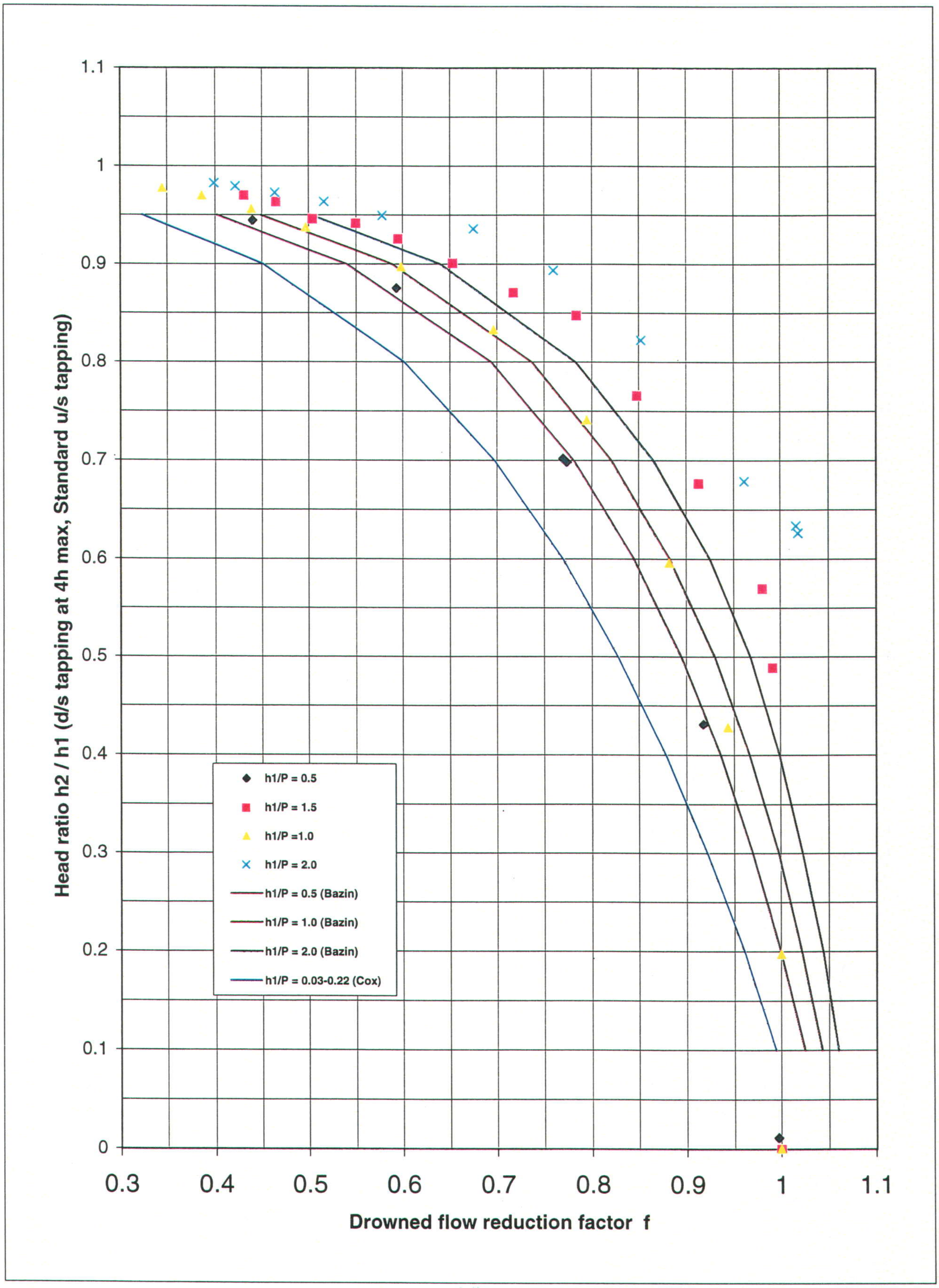


Figure 34 **Full Width Thin Plate weir, drowned flow characteristics based on heads measured 4 h_{max} downstream of the crest**

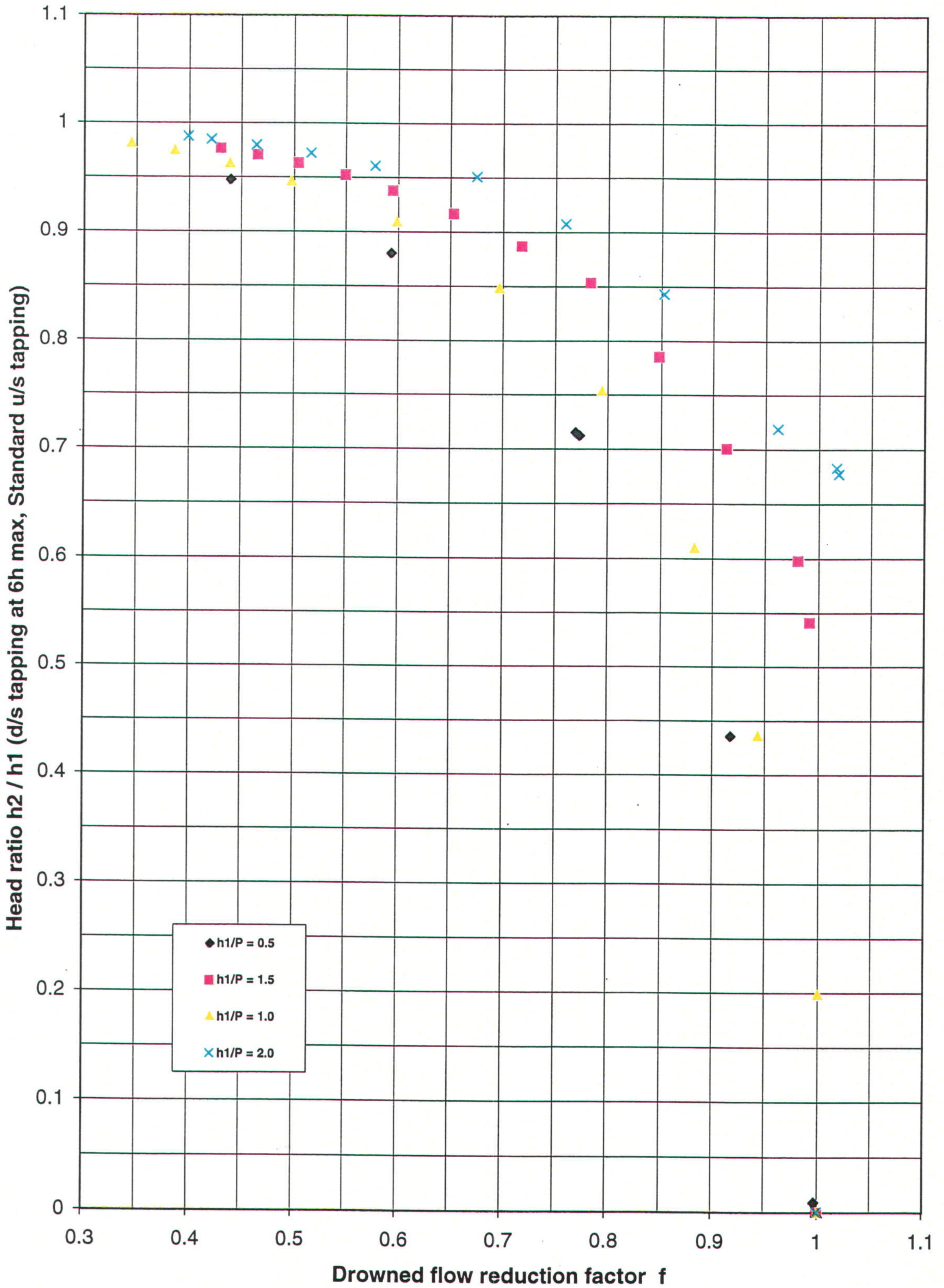


Figure 35 Full Width Thin Plate weir, drowned flow characteristics based on heads measured 6 h_{max} downstream of the crest

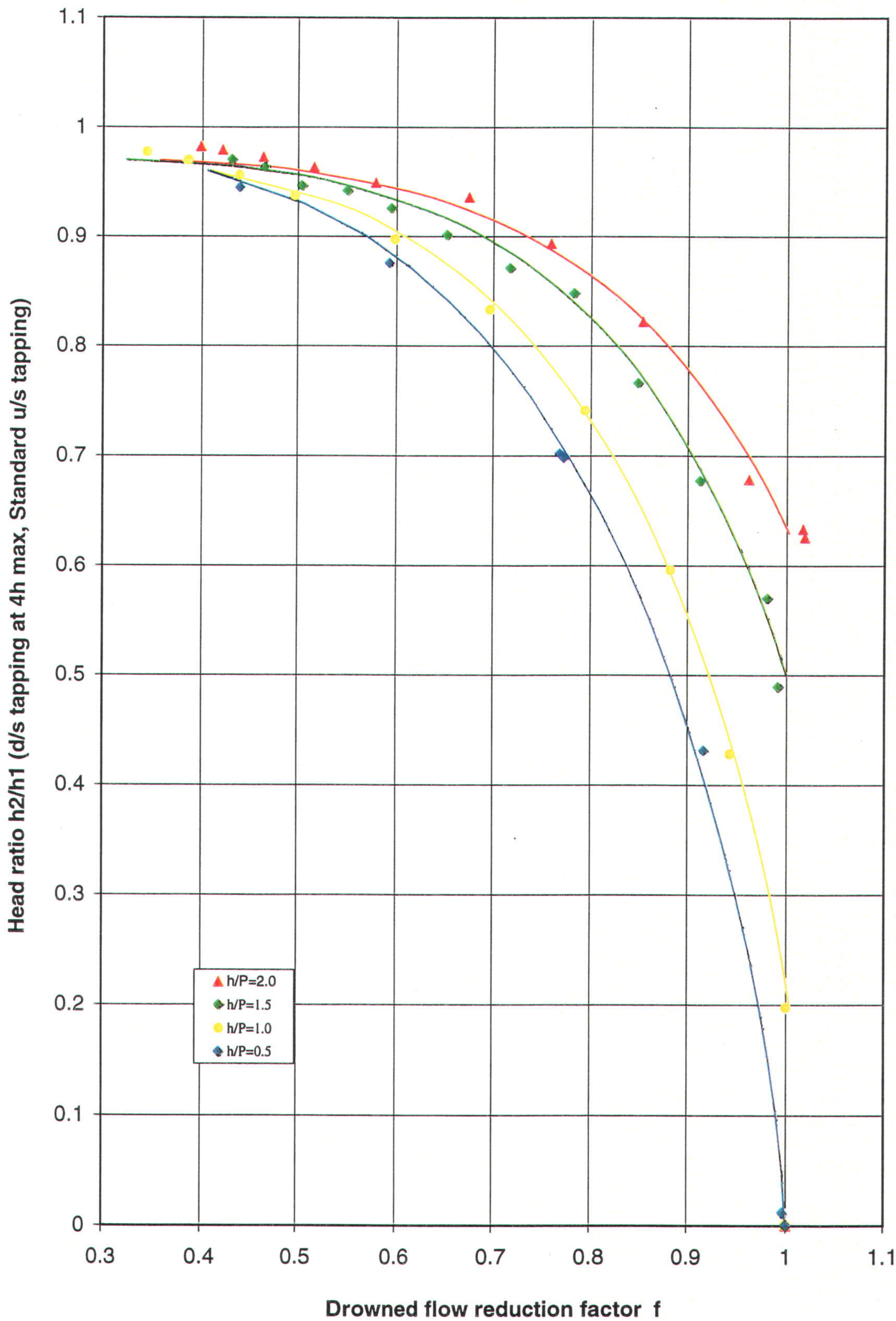


Figure 36 **Full Width Thin Plate weir, drowned flow equations based on heads measured 4 h_{max} downstream of the crest**

Plates

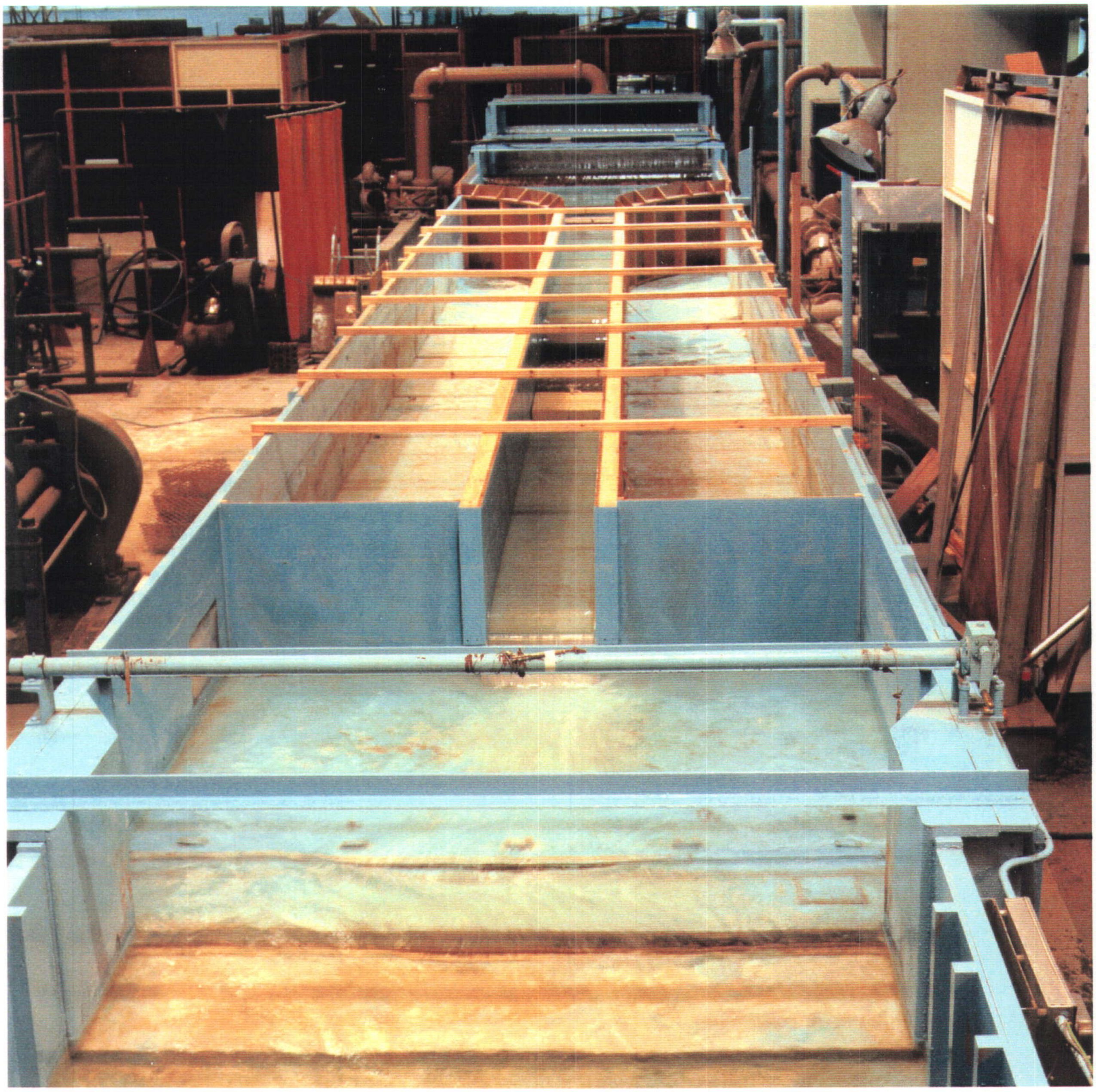


Plate 1 General arrangement of the flume

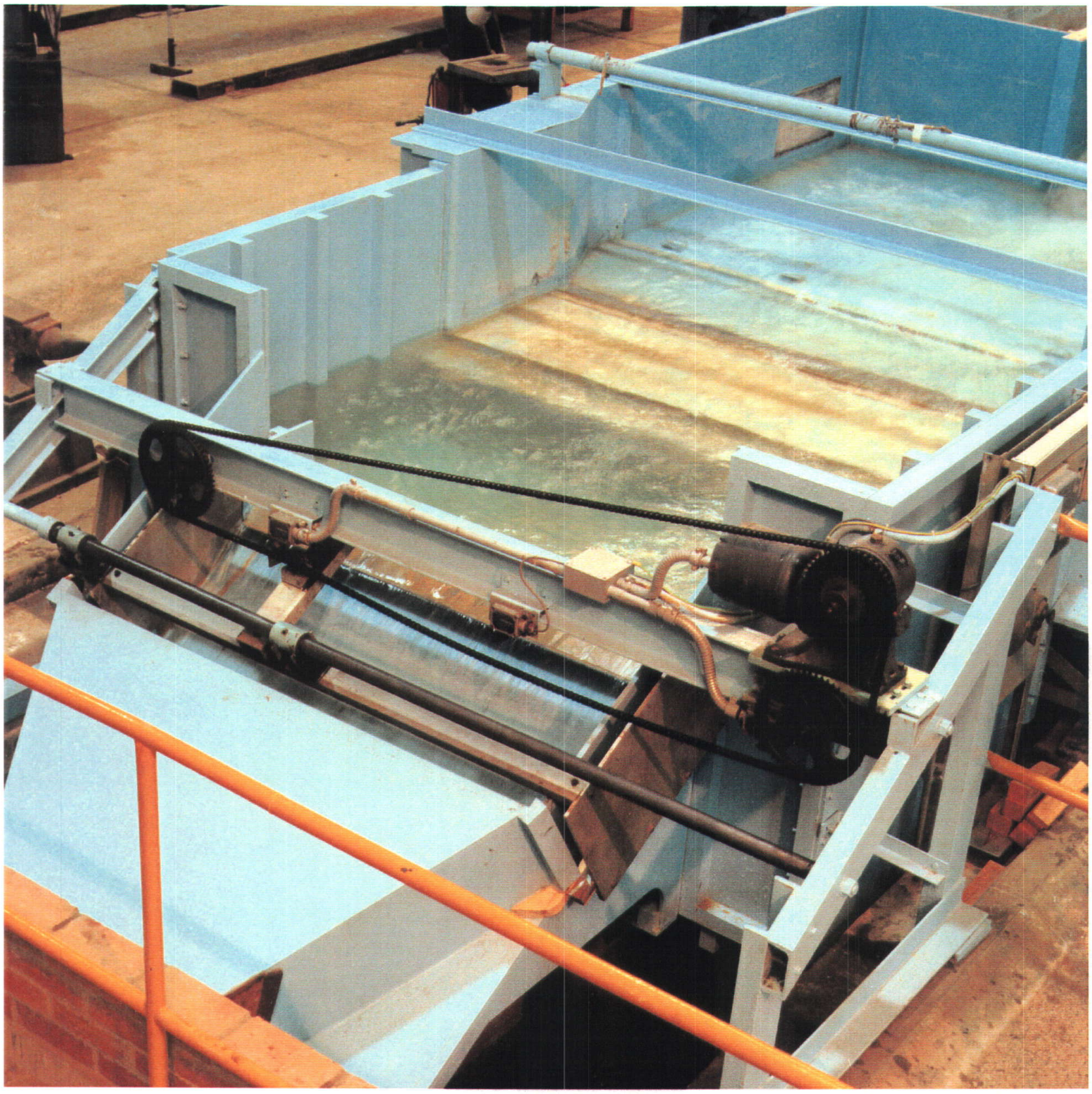


Plate 2 The deflector gear for the volumetric tank

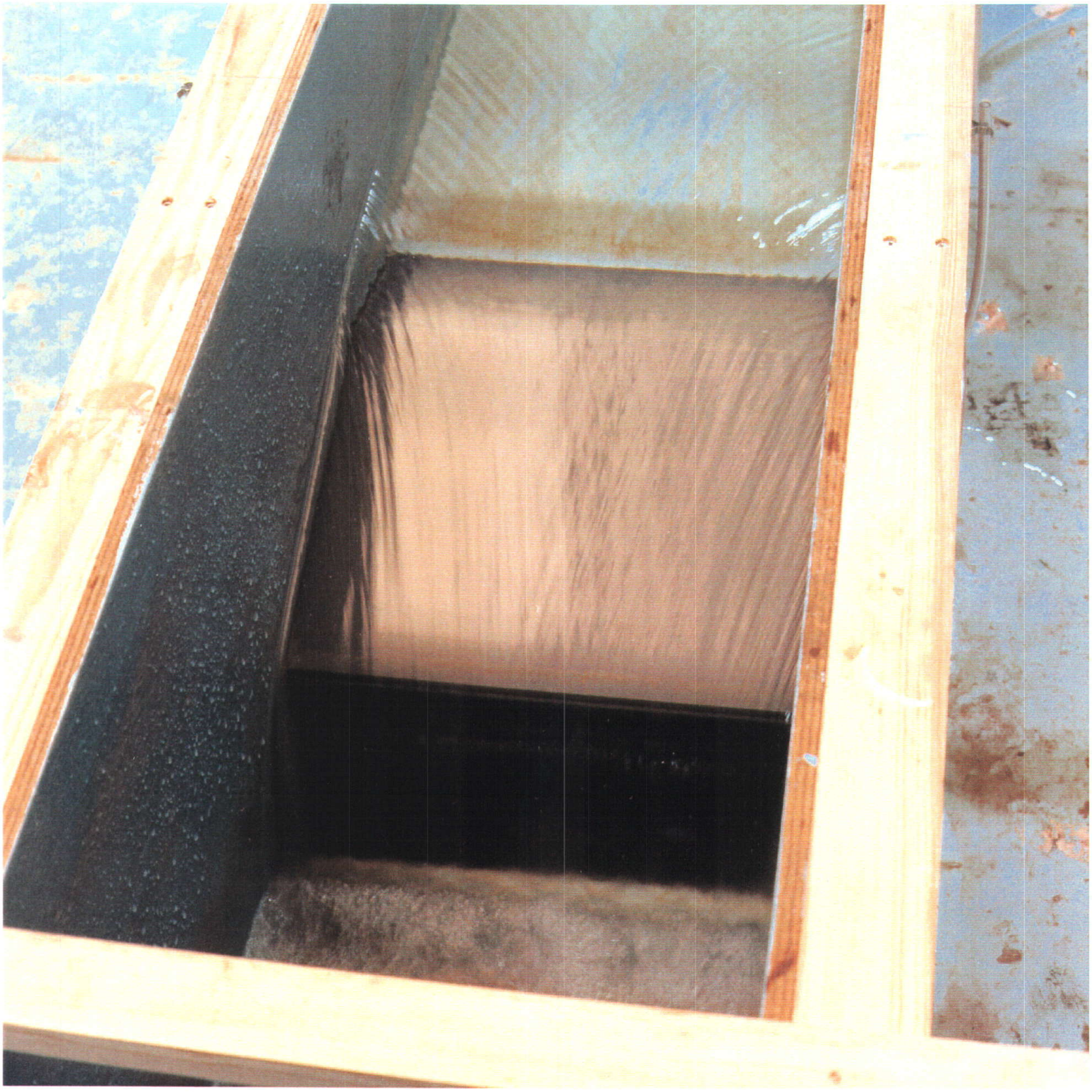


Plate 3 The Crump weir

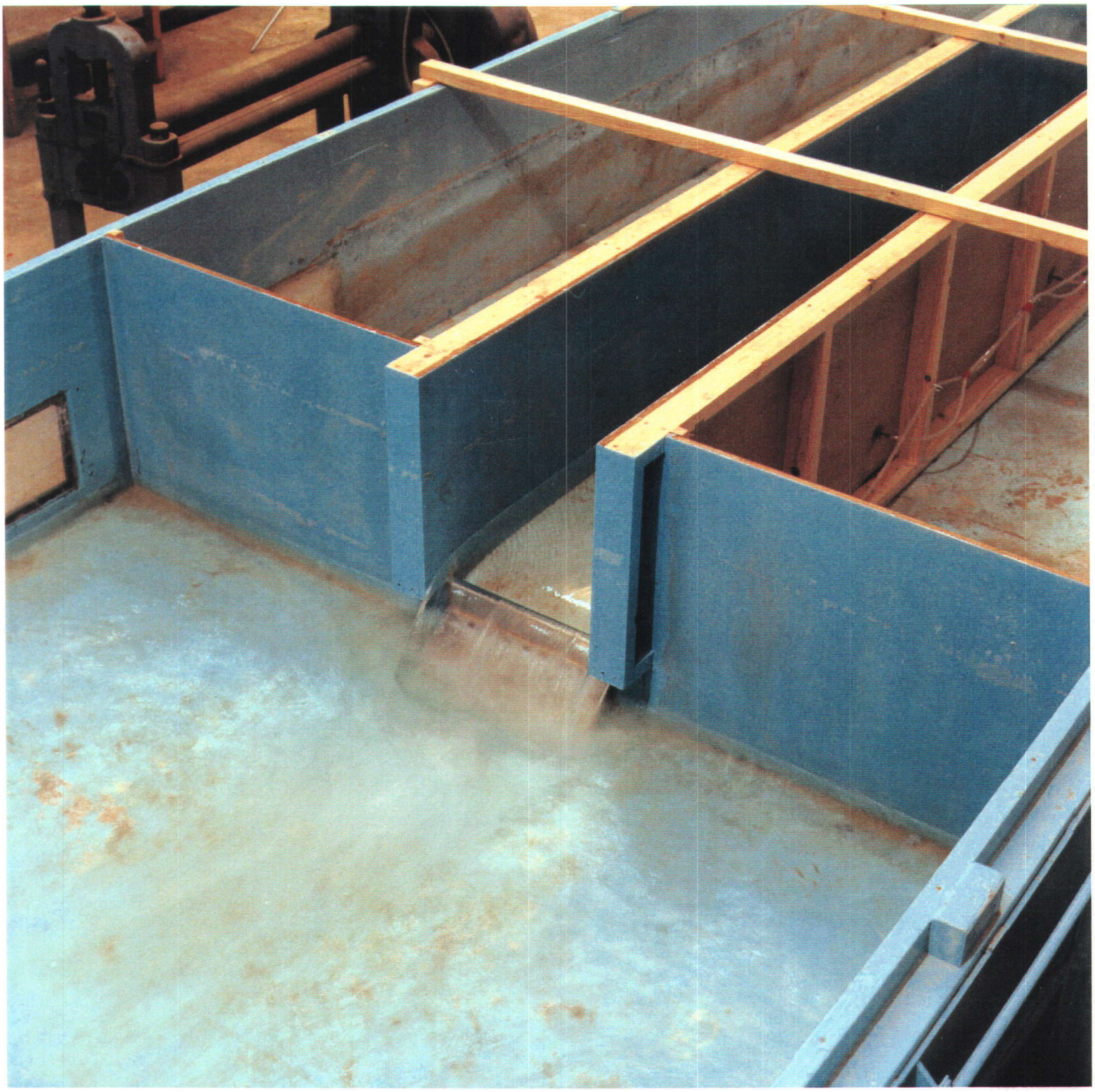


Plate 4 The Thin Plate weir

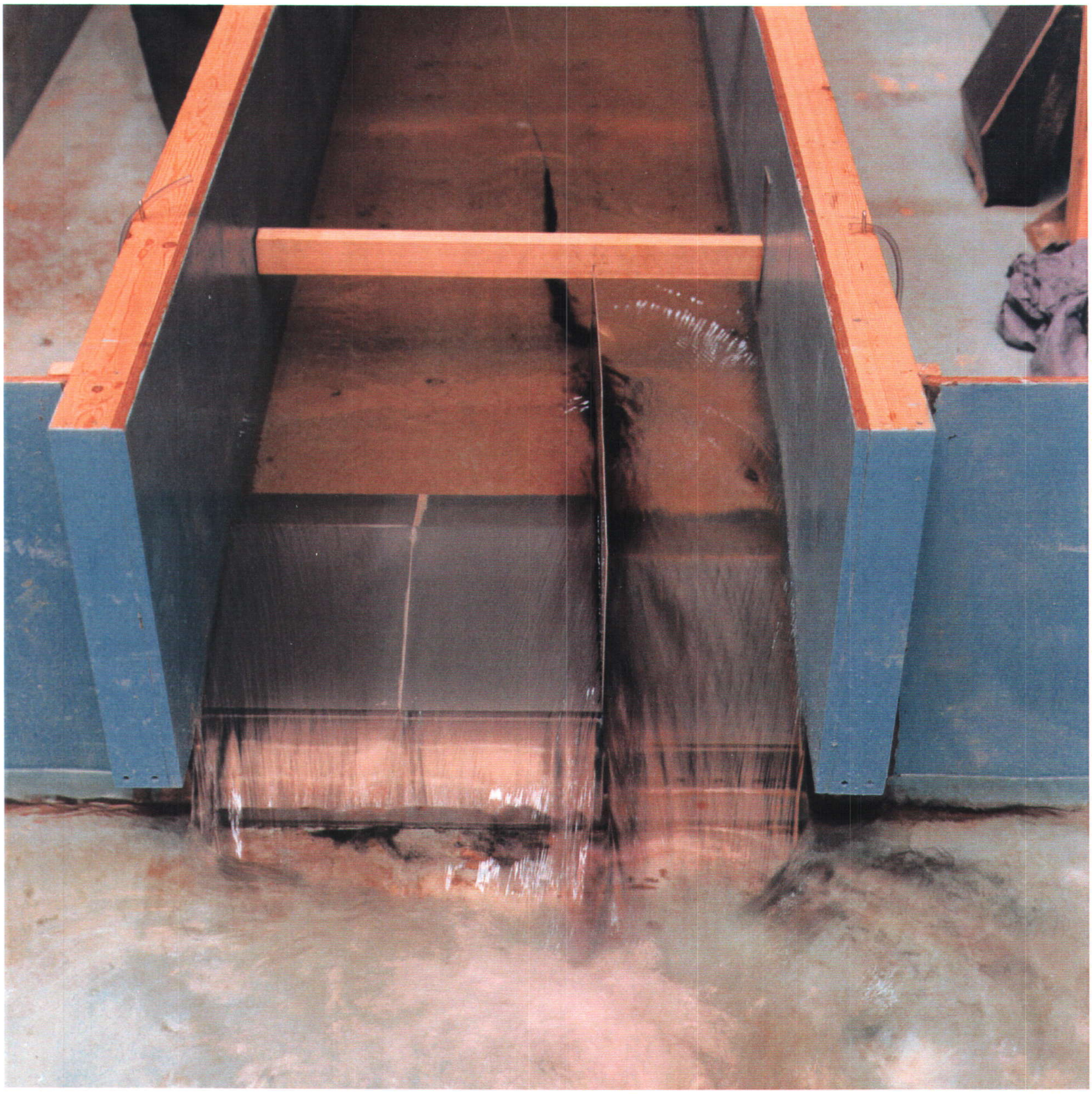


Plate 5 Compound Crump weir with divide piers

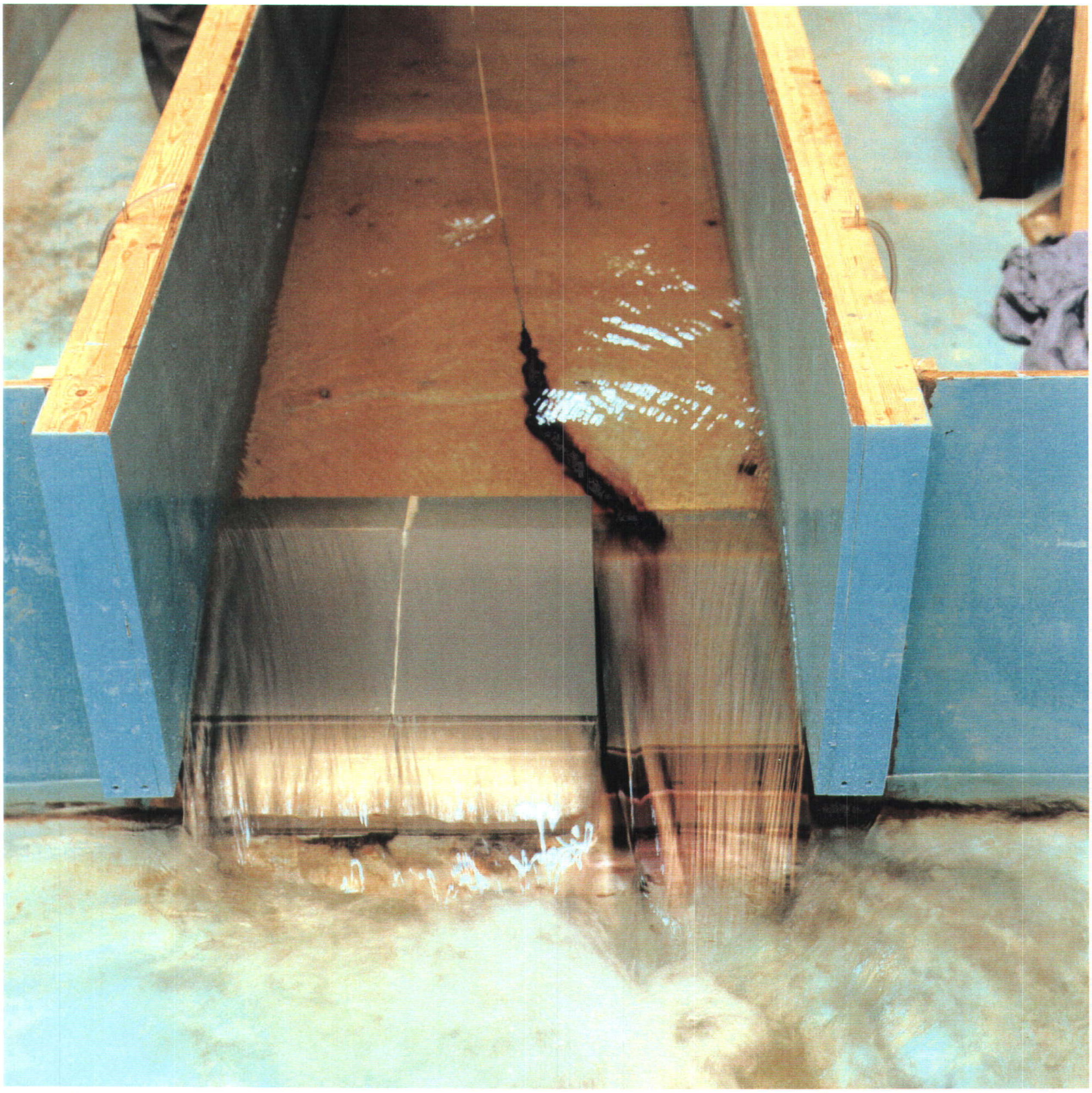


Plate 6 **Compound Crump weir without divide piers**

Appendices

Appendix 1

Summary of Standard specifications for the Crump weir

Appendix 1 Summary of Standard specifications for the Crump weir

1 Triangular Profile Crump weir

Formula:

$$Q = C_{de}\ b\ (g_n)^{0.5}\ H^{1.5}$$

Limitations:

a) $h > 0.03$ for smooth metal crests
b) $h > 0.06$ for fine concrete crests
c) $P > 0.06m$
d) $b > 0.30m$
e) $h / P < 3.5$
f) $b / h > 2.0$

Appendices

Appendix 1

Summary of Standard specifications for the Crump weir

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1 Triangular Profile Crump weir

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b) $h > 0.06$ for fine concrete crests
c) $P > 0.06m$
d) $b > 0.30m$
e) $h / P < 3.5$
f) $b / h > 2.0$

Appendix 2

Summary of Standard specifications for the full width Thin Plate weir

Appendix 2 Summary of Standard specifications for the full width Thin Plate weir

1 Kindsvater-Carter, 1957 (USA) - as applied to full width weirs

Formula:

$$Q = C_e \; 2/3 \; (2 \, g_n)^{0.5} \; b_e \; h_e^{\,1.5}$$

Basic coefficient:

$$C_b = 0.602$$

Full coefficient:

$$C_e = C_b + 0.075 \, (h / P)$$

Limitations:

a) $h / P < 2.5$
b) $h > 0.03m$
c) $b > 0.15m$
d) $P > 0.10m$

2 S. I. A., 1926 (Switzerland) - as applied to full width weirs

Formula:

$$Q = C \; 2/3 \; (2 \; g_n)^{0.5} \; b \; h^{1.5}$$

Basic coefficient:

$$C_b = 0.615$$

Full coefficient:

$$C = \{ C_b + [0.000615 / (h + 0.0016)] \} \{ 1.00 + 0.50 [h / (h + P)]^{2.0} \}$$

Limitations:

a) $h / P < 1.00$
b) $0.025 < h \, (m) < 0.80$
c) $P > 0.3m$

3 Rehbock, 1929 (Germany)

Formula:

$$Q = C_e \; 2/3 \; (2 \; g_n)^{0.5} \; b \; h_e^{\,1.5}$$

Basic coefficient:

$$C_b = 0.602$$

Full coefficient:

$C = C_b + 0.083 (h / P)$

Limitations:

a) $h / P < 1.00$
b) $0.03 < h (m) < 0.75m$
c) $b > 0.30m$
d) $P > 0.10m$

4 I. M. F. T., 1969 (France)

Formula:

$$Q = C\ 2/3\ (2\ g_n)^{0.5}\ \{ h + [V_a^{2.0} / (2\ g_n)] \}^{1.5}$$

Basic coefficient:

$C_b = 0.627$

Full coefficient:

$$C = C_b + 0.018 \{ [h + V_a^{2.0} / (2\ g_n)] / P \}$$

Limitations:

a) $h / P < 2.5$
b) $h > 0.03m$
c) $b > 0.20m$
d) $P > 0.10m$

5 J. I. S., 1990 (Japan)

Formula:

$$Q = C\ b\ h^{1.5}$$

Basic coefficient:

$C_b = 1.785$

Full coefficient:

$$C = C_b + \{ [0.00295 / h] + [0.2367\ (h / P)] \} \{ 1.00 + \varepsilon \}$$

where

$\varepsilon = 0$ for $P < 1.00m$
$\varepsilon = 0.55\ (P - 1.00)$ for $P > 1.00m$

Limitations:

a) $h / P < 0.667$
b) $0.03 < h (m) < 0.80m$
c) $b < 0.50m$

d) $0.30 < P < 2.50$

6 HR Wallingford, 1975 (UK)

Formula:

$$Q = C_e \; 2/3 \; (2 \; g_n)^{0.5} \; b \; h^{1.5}$$

Basic coefficient:

$$C_b = 0.596$$

Full coefficient:

$$C_e = C_b + 0.091 \; (h / P)$$

Limitations:

a) $h / P < 2.5$
b) $h > 0.03m$
c) $b > 0.20m$
d) $P > 0.10m$