PERFORMANCE CHARACTERISTICS OF THE CRITICAL-DEPTH, LONG-THROATED FLUME

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DECLARATION

I hereby declare that this thesis has been written by myself under the supervision of Dr. A. Kuz niar and that it is a record of my own research work at the Ahmadu Bello University. It has not been accepted in any previous application for a higher degree.

All sources of information have been specifically acknowledged in the reference section.



I.O. Emoabino

1986

CERTIFICATION

This thesis entitled "Performance Characteristics of the critical-depth, long-throated Flume" by Isah Osumah EMOABINO meets the regulations governing the award of the degree of Master of Science of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

to my daughter REANET.

and her uncle SUFUYANU.

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ISAH O. EMOABINO
JANUARY 1986

ABSTRACT

The performance characteristics and calibrations of various shapes and sizes of the critical-depth, long-throated flumes have been studied. In this study, four flume models were constructed, two of which were bottom contracted, one side contracted, and the fourth a parshall flume, having side and bottom contractions. The flumes were calibrated. The laboratory result verified a computer model, which in turn was used to generate calibration data and to identify the performance levels of various shapes and sizes of flumes.

The study showed that the critical-depth long-throated flume with bottom sill only which has been termed "Modified broad-crested Weir" is the most promising flume device for irrigation discharge measurement since it combines accuracy, ease of construction and high performance tolerances.

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ABBREVIATIONS AND SYMBOLS

A = Area of flow (m^2)

b = The throat width (m)

β = Coefficient to allow for nonhydrostatic pressure distribution

C = Special corrective Coefficient for losses *of head*

Cd = Coefficient of energy losses or discharge Coefficient

C_F = *drag coefficient*

Cs = shape coefficient

Cv = The approach velocitycoefficient

dx = boundary layer displacement thickness (m)

DE = change in energy head

E = Specific energy head (m)

E1 = Upstream energy head (m)

E2 = Downstream energy head (m)

Fr = Froude number

g = acceleration due to gravity (m/sec^2)

h = depth of flow or gauge height (m)

H = Piezometric head at gauging section (m)

K = absolute roughness height (m)

L = length of throat section

m = Side slope

ML = Modular limit

n = manning's coefficient

P = bottom sill height

Q = Discharge through the channel (m/sec)

R = hydraulic radius

ABBREVIATIONS AND SYMBOLS (*contd.*)

r = narrowing ratio

Re = Reynolds number

S = Correlation Coefficient

SH1 = Simulated gauge heights (m)

μ = Coefficient of outflow

V = velocity of flow (m/s)

vi = Kinematic Viscosity of the fluid

α = Coefficient to allow for nonuniform velocity distribution

y_c = critical head (m)

Z = Side slope in computer simulation

σ_Q = Overall percentage error in the discharge

σ_c = percentage error in combined coefficient Cd Cv

σ_b = percentage error in throat width

σ_h = percentage error in gauge height

Δb = error in throat width

Δh = error in gauge height

ΔH = combined head loss

ΔHa = approach channel head loss

ΔHb = converging transition head loss

ΔHL = throat section head loss

CHAPTER ONE

INTRODUCTION

1.1 Objectives of the Study

Experience has shown that for effective and economical use of available water, reasonably accurate measurements and regulation to the desired discharge rate are essential. Moreover, in irrigated agricultural projects, the crop yield can be enhanced by good water management which requires that irrigation water be accurately measured. Accurate water measurement can also be used to advantage where:-

i. water losses computation along canals is required

ii. water charges estimation is necessary

iii. investigation into soil moisture/crop relationship and other soil properties are required for estimation of design discharges in irrigation areas and for specific crops,

iv. control and regulation of inflow rate into municipal sewers is necessary

This research therefore aims at providing an accurate discharge measuring device. It further aims at ensuring that long-throated flumes are adaptable to field condition rather than the reverse as it has hitherto been the case.

1.2 Scope of the Study

Pre-calibrated critical-depth flumes are often used for measuring and regulating the flow of water in irrigation

canals as the use of current meters to obtain field measurements are either impractical or impossible.

Quite a number of investigations have already been carried out on Flow Measuring Structures, each aiming at either improvement on physical characteristics to ease construction or improvement on hydraulic characteristics to ensure the reliability of discharge calibration equations or both. However, the flow measuring structures currently being incorporated in most irrigation projects (e.g. Bakolori Irrigation Project, S.R.R. B.D.A. in Sokoto State, Nigeria) require specialised skills to construct, install and maintain.

Also the hydraulic properties of these structures are such that the error in the discharge measurement is greatly affected by accuracy of installation and the constructed dimensions.

The scope of this research therefore covers the identification and specification of an easy to construct, install and cheap to maintain discharge measuring critical-depth flume with an acceptable level of discharge measurement accuracy. Those constructed dimensions of the flume which adversely limit the discharge measurement reliability will be indentified, while tolerance limits on dimension to result in reliable discharge rates will be investigated.

CHAPTER TWO

LITERATURE REVIEW

2.1 DEFINITION

Any partially obstructing device in an open channel which changes the hydraulic characteristic in the flowing water such that a relationship can be derived between the discharge and the geometric properties of the obstructing device and/or the channel, can be called a discharge measuring structure. For clear definition, Appendix I presents in great details data on some irrigation measuring and regulating structures in use.

2.2. Classification of Measuring Structures

From available literature, there are mainly three types of measuring structures which are each subdivided depending on various classifications. These are:

(a) The Flume

(b) The Weir

and (c) The Orifice.

In this review, only the flumes and the weirs will be dealt with. An investigative emphasis is further conducted for the flumes. Details about the orifice can be obtained from available literature (Bos, 1976).

2.3 The Weir for Flow Measurement

By definition, any overflow structure extending wholly or partially across a channel and normal to the direction of flow can be referred to as a weir. Weirs may either be sharp-crested or broad-cre sted.

2.4 Flumes for Flow Measurement

A measuring flume by definition is a discharge measuring structure formed by a streamlined construction in an open channel. The constriction, which must be formed at the control section, may be by narrowing of the channel (side contractions only), by a raised channel floor or sill (bottom contractions only) or by a combination of both side and bottom contractions. The term "Broad Crested Weirs" will be used to specify that the control section is formed by a raised channel floor or sill, while the term "Flume" will simply indicate that there exist some streamlined constriction in an open channel.

Measuring Flumes can either be (a) double-gauging or (b) single-gauging.

2.4.1 Double-gauging Flume (Venturi Flume)

Cone (1917) described a flume in which although the streamlined constrictions caused the depth of flow in the constriction to be less than in the channel immediately upstream, but were not sufficiently severe to cause a super-critical flow at the constriction. Flow was therefore sub-critical throughout. This device which can only determine the discharge in the channel using double-gauging system and the principle of Bernoulli energy equation is called a venturi flume.

Ackers et al (1980) derived its discharge equation from the Bernoulli energy equation as

$$Q = C_d \ (2g \ (h_1 - h_2) \ A_1^2 \ A_2^2/(A_1^2 - A_2^2))^{\frac{1}{2}} \ \ldots \quad . \ 2.1$$

where symbols are as defined in "Abbreviations and Symbols" page xv .

What militates against the use of this device is the fact that the operation of a venturi flume is very sensitive to the tailwater conditions and the discharge equation must express discharge as a function not only of the difference $(h_1 - h_2)$ but also of individual h_1 (or h_2). It should be noted that the Bernoulli energy theory requires that these gauging depths (h_1 and h_2) be measured simultaneously. This is usually difficult to attain in the field.

Ackers et al (1980) enumerated further the problems associated with using this device for measuring flow and concluded that though the Venturi flume could be of academic importance, it is seldom used for practical gauging.

2.4.2 Single-gauging Flume (Critical-Depth Flume)

By making the streamlined constriction in the Venturi flume sufficiently severe, critical flow may occur at the constriction, thus producing a device which is insensitive to the effects of tailwater level and ensuring a unique discharge relationship that is a function only of h_1 - the upstream water depth. A device thus produced is called the Critical-depth Flume and it requires only a single gauge upstream of the constriction for discharge measurement. Sufficiently small water level losses occur in this device

when a gentle exit transition is provided.

Citrini (1941) observed that the critical depth Flume satisfies the characteristics outlined by De Marchi which every good measuring device must have. The first and essential characteristic being that the measuring device be a "Semi-modulus". This implies a device in which the upstream water level is independent of the downstream level. This condition among other reasons is to enable derivation of simplified discharge relationship with the upstream water level and the physical properties of the device and hence prevent the obvious complications which may result from relating the discharge to two variable levels.

Also, an efficient measuring device must have minimal water-level loss from the upstream to the downstream water levels, thus enabling long run of canals to be designed within small differences in elevation.

Critical-depth flumes can either be long-throated or short-throated.

2.4.3 Short - throated Critical-depth flume

These are structures in which the curvature of the water surface is large and the streamlines do not run parallel to the invert of the flume. Hydrostatic pressure distribution cannot therefore be assumed and hence the stage-discharge relation can only be obtained reliably by means of field or laboratory calibrations. Examples of such flumes are the Khafagi, Parshall, Cut-throat or throatless, and the H-Flumes.

Khafagi (1942) as reported by Bos (1976) developed a flume with very short, parallel, throat section, with curved transitions upstream and down-stream the throat and having a horizontal floor. The discharge equation for such a flume was developed by Khafagi as

$$Q = 2.295\ L\ bt^{\frac{1}{2}}h^{\frac{1}{2}} \quad \ldots \qquad \ldots \qquad 2.2$$

Parshall (1922) as reported by Bos (1976) developed a flume with a uniformly converging section, followed by a short parallel throat, then a uniformly diverging section. The floor being horizontal in the converging section, downward sloping in the throat section and upward sloping in the diverging section. The control section at which the depth is critical occurs near to the downstream end of the converging section and not at the throat section.

Bos (1976) reported about twenty two (22) standard shapes of the Parshall flume, covering a range of discharge from 0.1 m^3/sec to 93.0 m^3/sec. However, the dimensions of each of these twenty two (22) standard shapes must be carefully and accurately constructed in order to ensure reliability of the calibrated rating curves with the discharge.

Cut-throat flume is a rectangular short-throated flume, with an abrupt entrance and absence of any parallel throat section; the throat being formed by the intersection of a uniformly diverging exit section. The floor of the flume is level with the channel floor throughout its length.

There have been a lot of experimentation on this flume since Harvey (1912) first developed it in Punjab-India.

Skogerboe and Hyatt (1967) proposed and tested rectangular throatless flumes having identical lengths of converging and diverging sections. He developed the equation

$$Q = 3.50\ b^{1.25} H^{1.56} \quad \ldots \quad \ldots \quad 2.3$$

Baunett (1972) as reported by Bos (1976) calibrated a number of cut -throat flumes. He reported large scale effects between geometrically indentical cut-throat flumes.

Devaries and Bos (1976) as reported by Bos (1976) concluded from studies that because of their complex hydraulic behaviour (i.e. curvilinear flow and non-hydrostatic pressure distribution), the use of the cut-throat flumes is not recommended.

H -Flumes

It has been reported by Bos (1976) that the soil conservation service of the United States Department of Agriculture in 1930s ran a number of experiments on a series of flumes starting with the letter 'A', with the sole aim of providing a device for natural streams where it is necessary to measure a wide range of discharges.

Ackers et al (1980) reported that the eight flume (denoted by letter 'H') consisting of a rectangular uniformly converging section with a V - type throat was found suitable, since it provided a wide opening at high flows so that it caused no excessive backwater effects, whereas at low flows, its opening was reduced so that the sensitivity of the flume remained acceptable.

The H-Flume is a calibrated measuring device, which implies that they should be constructed in strict compliance with the specified dimensions.

2.4.4 Long-throated Critical-depth flume

The long-throated flume can be defined as those structures which have a throat section (i.e. the contraction) in which the streamlines run parallel to each other and to the floor of the flume at least over a short distance. Thus allowing an assumption of hydrostatic pressure distribution at the constriction and this in turn allows the stage discharge relationships to be derived analytically with the minimum observable data.

Bos (1984) described the long-throated critical-flow flume as essentially a streamlined contraction built into an open channel where there must be sufficient water surface fall through the contraction to cause within the contraction a "critical flow" involving nearly straight-lined, parallel flow.

Flumes can either be trapezoidal, rectangular, triangular or complex- depending on the shape of the throat, or contraction section. Thus a trapezoidal throat installed in a rectangular channel would still be referred to as a trapezoidal flume. The limiting cases for trapezoidal flumes are the triangular flumes (when the bottom width is zero) and the rectangular flumes (when the side slopes are zero). When the throated section is Parabolic, circular, or any other complex shape, the flume is referred to as a complex flume.

Clemmens and Replogle (1980) developed the "Modified Broad-Crested Weir Flume" which is essentially a combination of the trapezoidal long-throated flume and the rectangular broad-crested weir. Their aim was to produce an easy to construct, simple measuring flume for irrigation canals. This research attempts to improve further the performance characteristics of the long-throated critical-depth flume.

Figure 3.3 shows a definition sketch of the long-throated critical depth flume.

2.5 Theory of the long-throated flume

The total energy of flow in an open channel can be represented by the Bernoulli's energy equation.

This principle is used to advantage in the derivation of stage-discharge relationship for the measuring flumes. It is considered that the specific energy at the throat is the same as the specific energy at some gauging point upstream the throat along the channel. The energy losses, surface-tension and viscosity effects are assumed negligible.

The general specific energy equation is given as

$$E = \beta h + \alpha \frac{V^2}{2g} \quad \ldots \quad \ldots \quad 2.4$$

The general discharge equation of flow through a flume of any shape in an open channel and valid for all conditions of flow has been given by Ackers (1980) as presented in equation 2.5. It involves the measurement of two gauge heights (h_1 and h_2) simultaneously, and hence it is most applicable to the venturi flumes.

$$Q = C_d \left(2g \times A_1^2 \times A_2^2 \times (h_1 - h_2)/(A_1^2 - A_2^2)\right)^{\frac{1}{2}} \quad \ldots \quad 2.5$$

2.6 Discharge in Critical state of flow

Clemmens et al (1984) noted that the operation of flumes in the subcritical state of flow in which two gauge heights are required for discharge estimation is not recommended as it leads to considerably greater error in the discharge measurement. Flumes should therefore be operated in the critical state of flow.

The basic criteria for critical flow is that the specific energy be minimum while the discharge Q is constant. This condition is obtained by differentiating the specific energy equation and equating to zero for the minimum value.

Hence we obtain

$$\frac{Q^2 bc}{gA^3 c} = 1 \quad \ldots \quad \ldots \quad 2.6$$

where subscript 'c' denote critical state of flow.
This can be further represented as a dimensionless expression given as

$$F = Vc/(ghc)^{\frac{1}{2}} = 1 \quad \ldots \quad \ldots \quad 2.7$$

This is a form of the Froude's Number 'F', and it implies that for critical flow, the Froude Number must be equal to one. For super critical flow, the Froude Number 'F', is greater than one as will be seen later.

Note that the term $(gh)^{\frac{1}{2}}$ is the speed of propagation of a small gravity wave in shallow water. Therefore, Froude Number is the ratio of water velocity "V" to the wave velocity" $(gh)^{\frac{1}{2}}$.
When $V < (gh)^{\frac{1}{2}}$ the waves caused by obstruction at the throat can progress upstream with relative velocity $(gh)^{\frac{1}{2}} - V$ and

downstream with relative velocity $(gh)^{\frac{1}{2}} + V$. Hence the gauge height at point (1) can be affected by downstream water level conditions at the throat section (2). This is the condition for subcritical flow and discharge can be obtained with equation 2.5

However, when $V > (gh)^{\frac{1}{2}}$, then the waves caused at the throat can either be stationary (i.e. when $(gh)^{\frac{1}{2}} - V = 0$) or progress downstream with relative velocities

$$(\sqrt{gh})^{\frac{1}{2}} + V) + ((gh)^{\frac{1}{2}} - V)$$

This is the super critical flow condition and there is no wave propagation upstream as $(gh)^{\frac{1}{2}} - V$ is negative upstream. Gauge height at point (1) can not therefore be affected by downstream water level conditions.

Ackers (1980) has derived the stage-discharge relationship for critical flow in a measuring flume as

$$Q = (2/3)^{3/2}\, g^{\frac{1}{2}}\, Cd\, Cv\, bch_c^{3/2} \quad .. \quad ... \quad 2.8$$

The coefficient, Cv, is a function of the ratio

$\sqrt{\alpha c}\, Cd\, A^*/Ac$, in which αc = the approach velocity distribution coefficient (usually approximated by 1.04). Clemmens et al (1980) showed that 'Cv' can further be obtained by the relation

$$(\alpha)^{\frac{1}{2}}\, Cd\, A^*/A = (27/h\,(Cv^{2/3} - 1)/Cv^2)^{0.5} \quad .. \quad 2.9$$

The equation 2.9 can be used to compute Cv for rectangular throated flumes by the method of successive approximation.

For a trapezoidal long-throated, critical - depth Flume, it has been shown by Ackers (1980) that

$$Q = (2/3)^{3/2}\ g^{\frac{1}{2}}\ Cv\ Cs\ Cd\ bh^{3/2} \quad \ldots \quad \ldots \quad 2.10$$

where

$$Cs = (1+2m)\ (he-dx)\ (1+m(hc-dx)/be)/(1+5m\ (hc-dx)/3be) \quad \ldots \quad 2.11$$

2.7 Alternative stage-discharge relation for critical flow

Impersit (1974) used the discharge relation derived by Citrini (1914) which gives the critical state as

$$hc = (Q^2/gbc^2)^{2/3} \quad \ldots \quad \ldots \quad 2.12$$

and $$Q = C\mu\ bH\ (2ghl)^{\frac{1}{2}} \quad \ldots \quad \ldots \quad 2.13$$

From research conducted at the hydraulic laboratory of the "Politecnico di Milano", Italy, the corrective coefficient 'C' was found to be on the average a constant value given as

$$C = 0.98$$

De Marchi (1937) as reported by Impresit (1974) determined an expression for the outflow coefficient μ as

$$\mu = ((hl + p)/rh)^{3/2}\ Cos^{3/2}\{1/3\ (\Pi + a\ rccos\ rh/(hl+p))\} \quad \ldots\ldots \quad 2.14$$

Hence $$\mu = 2(bl\ (hl + P)/b2)^{3/2}\ Cos^{3/2}\ (1/3\ (\Pi+arccos\ b2hl/bl\ (hl+p)) \quad \ldots \quad \ldots \quad 2.15$$

For P = 0

$$\mu = 2(bl/b2)^{3/2}\ Cos^{3/2}\ (\Pi/3 + 1/3\ arccos\ b2/bl) \quad \ldots \quad 2.16$$

Evaluating equation 2.16 for various narrowing ratios, 'r' give the corresponding values of 'μ' given below

r	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
μ	0.336	0.386	0.392	0.400	0.410	0.422	0.440	0.468	0.514

In the case where there is a bottom sill (i.e. P, not equal to zero), Citrini (1941) reported that Gherardelli derived a mathematically simplified expression given as:

$$\mu = 0.385 + 0.108\, r^2\, (h/h+p)^2 \quad \ldots \quad \ldots \quad 2.17$$

i.e. $\mu = 0.385 + 0.108\, (b2/b1)^2\, (h/h+P)^2$

And the head loss through the flume can be obtained by

$$h = 0.895\, (h_2^{7/2}/Q) \quad \ldots \quad \ldots \quad 2.18$$

2.8 Design Criteria and Sensitivity of Flume

The values of Cd, Cv and Cs in equations 2.8 and 2.10 are greatly affected by the shape and dimensions of the Flume. For instance: Cd can be shown as a function of E/L, Cv as a function of $\sqrt{\alpha}$ Cd A^*/A and Cs as a shape factor given by equation 2.11..

The design and operation of a flume is therefore within prescribed limits of the flume dimensions.

Bos (1976) limited the range of the empirical discharge coefficient Cd to

$$0.1 \leq \frac{E}{L} \leq 1.0$$

From equation 2.9, it can be noted that the value of Cv increases rapidly if 'V', increases. However, the approach velocity 'V', should not be allowed to become too large, lest standing waves formed at the gauging point (1) make accurate height reading difficult. To prevent this, the Froude number 'F' in the approach channel defined by equation 2.7 should not exceed about 0.5 (Chow, 1959). Further, a value of the throat length 'L' equals 1.5 h_1 max(h_1 max = maximum gauged height at point (1))

is a reasonable compromise between providing a long enough throat to avoid the effects of streamline curvature and minimizing the size of the structure and the distance between the gauging station (1) and the start of the throat should be between 2 to 3 times h_1 maximum (Bos, et al 1984).

2.9 MODULAR LIMIT

The modular limit sometimes referred to as the limiting submergence ratio is numerically defined as the ratio of the sill referenced energy heads at gauging points located (2) downstream of the flume to that located (1) upstream.

i.e.
$$ML = \frac{E2}{E1} = 1 - \frac{DE}{E1} \quad .. \quad ... \quad 2.19$$

The limiting condition has been defined as the value of DE at the highest tailwater level, such that the flow through the flume is not changed by more than 1% for a given upstream head. Values of 'ML', recommended to satisfy this condition range between 0.70 and 0.80 (Clemmens et al 1984).

Citrini (1941) deduced an equation to ensure modular operation as

$$ML = h_2 (1.5 - D\, h_2/b2) \quad .. \quad .... \quad 2.20$$

where $_D$ = constant = 0.35 for flumes with sill 'P'

± 0.25 for flumes without sill height.

The equation 2.20 is valid only when $h_2 < b_2$.

Impresit (1974) employed Citrini's equation 2.20 to obtain a submergence limit curve, based on which the operational measuring flumes at Bakolori Irrigation Project

were classified.

The effect of non modular operation of a flume on the discharge measurement should be noted. For instance, when the tailwater afflux is reduced, as in a case of lowering a sluice gate downstream, the hydraulic jump is made to advance upstream towards the throat. Undular profile could result as the minimum depth approaches the critical depth. With further reduction of the afflux, a condition is reached when wave velocity "$(gh)^{\frac{1}{2}}$" is not greater than Water velocity 'V' and the wave velocity starts propagating upstream with relative velocity "$(gh)^{\frac{1}{2}} - V$". At this stage, the gauged upstream head 'h_1' is no longer independent of downstream conditions. This is the limiting level referred to as the Modular limit and monitored by the submergence ratio.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Materials and Equipment

The materials used for this research were four models from three classes of the critical-depth flumes. Three of the flumes were rectangular long-throated, while the fourth was rectangular short-throated Parshall flume model. For the long-throated models, one was of side contraction only and the other two with bottom contraction only, were of different throat lengths.

The long-throated models were constructed of wooden material at the carpentery division of the Civil Engineering Laboratories, Ahmadu Bello University, Zaria. These were installed in the concrete lined channels at the hydraulics laboratory of the Water Resources and Environmental Engineering Department, Ahmadu Bello University, Zaria.

The Parshall flume model constructed of a wooden bottom contraction and plastic side contracted walls was installed in a rectangular "Universal Modular Flow glassed channel model TE 36/4420 manufactured by Plint and Partners Ltd, Wokingham, England. The channel is 8.0 metres length, 0.20 metres wide and has 0.30 metres maximum working depth.

Other materials used at one stage or the other during the experiment include two plastic tubes, sticky paste (putty), engine oil, two scale gauges, stop-watch, point gauge recorder and water. There were two sets of equipments. The first consists of two centrifugal pumps and three water tanks arranged in series with the concrete

lined rectangular channel. The tank into which water from the channel discharges directly has a gauge which measures the variation of water depth in the tank. This tank will be referred to as the "Measuring tank" in the text and it has a surface area of $6.6164m^2$.

The second set of equipments consists of one pump and two water tanks arranged in series with the "Universal Modular Flow Channel". Figures 3.1 and 3.2 show the arrangements of the first and second set of equipments respectively. Figure 3.3 illustrate dimensioning terms used on the flume models, whereas, table 4.1 gives the specific dimensions for the long-throated flume models. Plate I and Plate VII show the models as installed in the channels.

3.2 Experimental Procedure

The experimental procedure varied depending upon the set of equipments.

For the first set of equipments, the preparatory work involved lowering the water level in the measuring tank to a predetermined near bottom mark by the use of the pump installed immediately after the tank (Figure 3.1). The water removed from the measuring tank was fed into the underground storage tank, from where the second pump lifts water into the underground storage tank, from where the second pump lifts water into an overhead tank. Water in the overhead tank flows under gravity through a pipe into the concrete lined channels. There are three channels arranged in parallel, each of length 15m, depth 0.46m

and different widths. A regulating valve located at the end of the steel pipe, allows an effective control of the rate of discharge into the channels. The head at the overhead tank is maintained constant during the experiments by continous lifting from the storage tank. The head gauging points upstream and downstream were located at 0.60m to the start of throat and 1.50m from the flume respectively. Scale gauges were fixed at these locations to obtain the heads h_1 and h_2 respectively.

At the start of the experiments, after the preparatory work, the regulating valve is opened slightly to allow water into the channel in which the flume model is installed. Putty was used to fix the flume model in position and to prevent leakage. As water enters the channel, the depth of water varies until steady state conditions (noted by constant gauge head at h_1) are established. The gauge head h_1 and h_2 are then recorded and the variation of water depth in the measuring tank is taken over stipulated time range (usually 1 minute or 2 minutes) with the stop-watch.

The flow rate Q corresponding to the gauge heads h_1 and h_2 is then computed.

The regulating valve opening is then increased stepwise, and for each step the above readings recorded until ten readings were obtained for each flume model.
By re-installing the flume models such that the exit transitions become the entrance transitions, six flume models were tested on the first set of equipments as described above.

For the second set of equipment, the preparatory work involved filling the two tanks with enough water, installing the flume model and the point gauges at pre-determined locations along the flow channel. Putty was used to prevent water leakage through the flume.

At the start of the experiments, the pump was started and the inlet control valve for the channel slightly opened to let in water into the channel. At steady conditions, similar to those in the concrete channel, the gauge heads h_1 and h_2 are recorded, time taken by flow to move through 4.0m (from 7.10m to 3.10m) of the channel, upstream the flume model is taken with the stop-watch and the manometric arrangement. The flow rate Q corresponding to the gauge heads h_1 and h_2 is then computed.

The inlet valve openings is then varied stepwise and similar records taken at each step when steady conditions exist.

Ten of such records were taken. Plates II, III and VI, indicate various stages of the experimentation, while Plates IV and V show an on site operation of a side-contracted prototype in the Bakolori Irrigation Project.

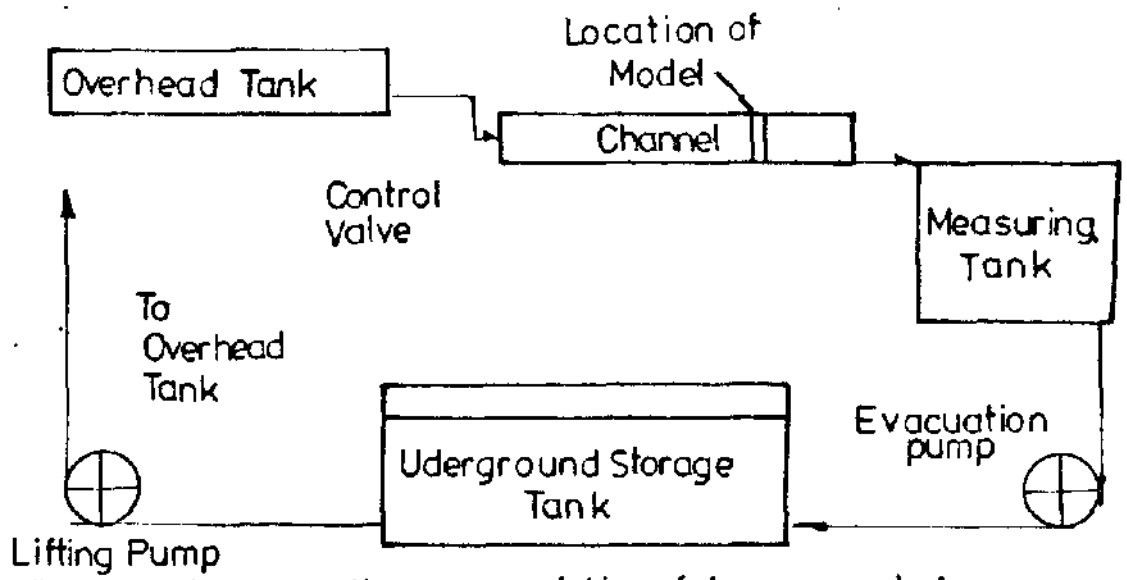


Fig-3.1: Diagrammatic presentation of Arrangement of 1st set of equipments

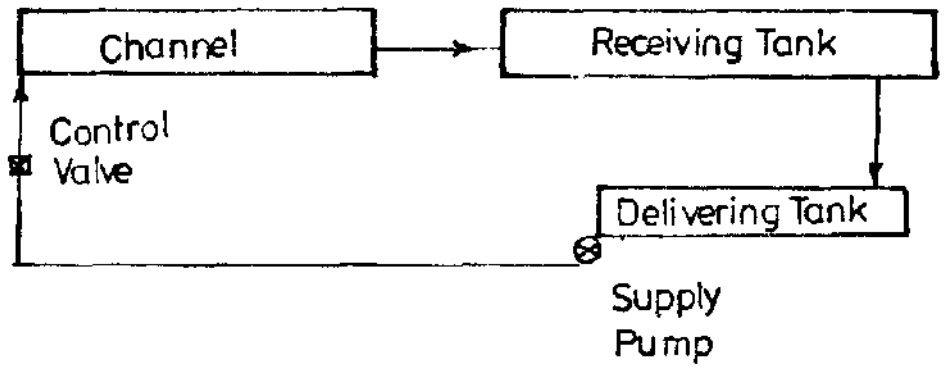


Fig3.2: Diagrammatic presentation of the Arrangement of the 2nd set of Equipments

Fig.3.3: Illustration of Terms Used for the Dimensioning of Models (see Table 4.3 for specific Dimensions)

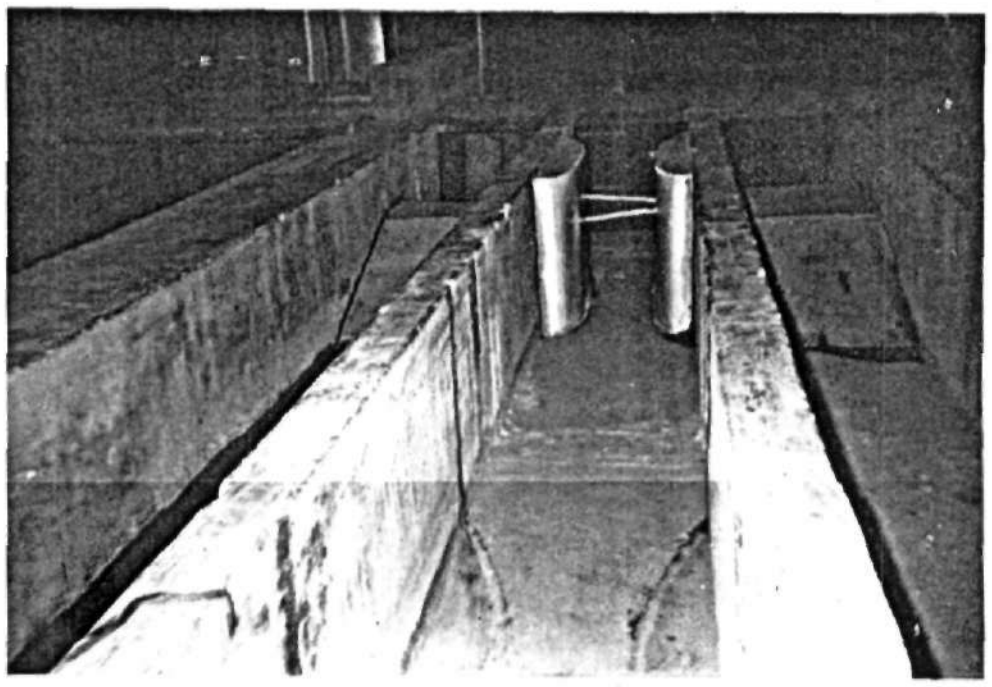


PLATE I: Installation of flume models in the concrete channel at the hydraulic laboratory, A. B. U., Zaria.

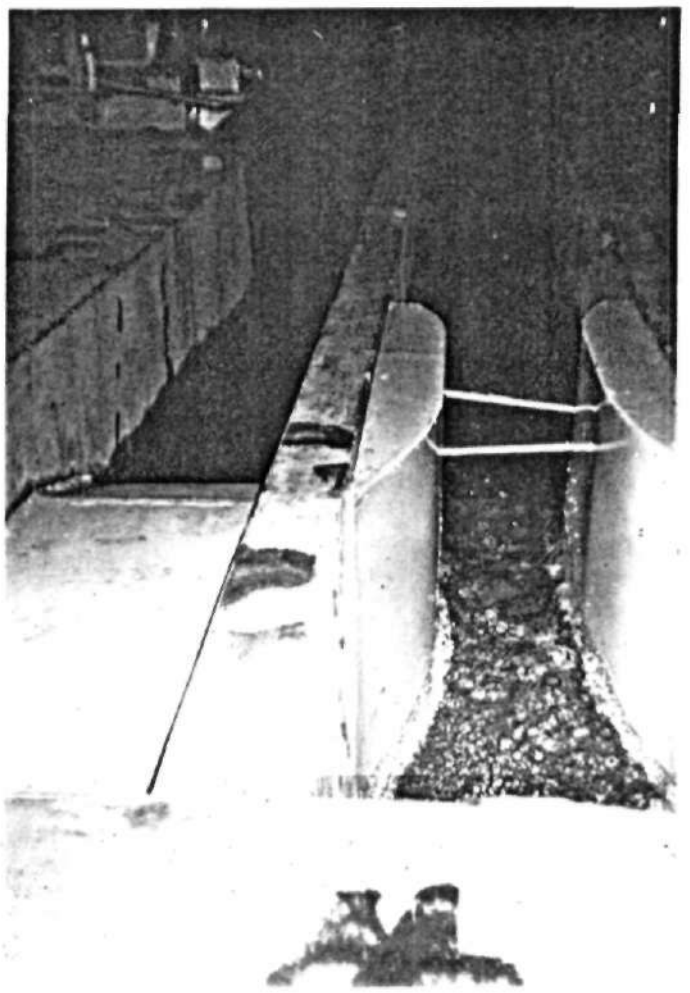


PLATE II: Test run on the flume models Seven days after installation to check leakages.

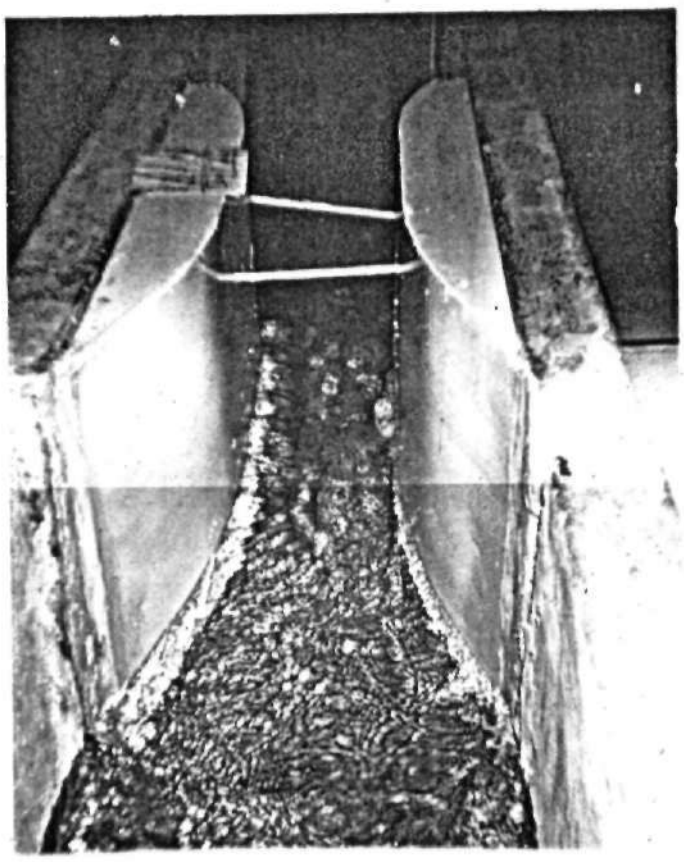


PLATE III: Flow through Model A (Downstream View) in the laboratory.



PLATE IV: Flow through Prototype A at Bakolori Irrigation Project, Sokoto State (Downstream view) Taken on 20-10-85).



PLATE V: Flow through Prototype A at Bakolori Irrigation Project, Sokoto State (Upstream view taken 20-10-85)

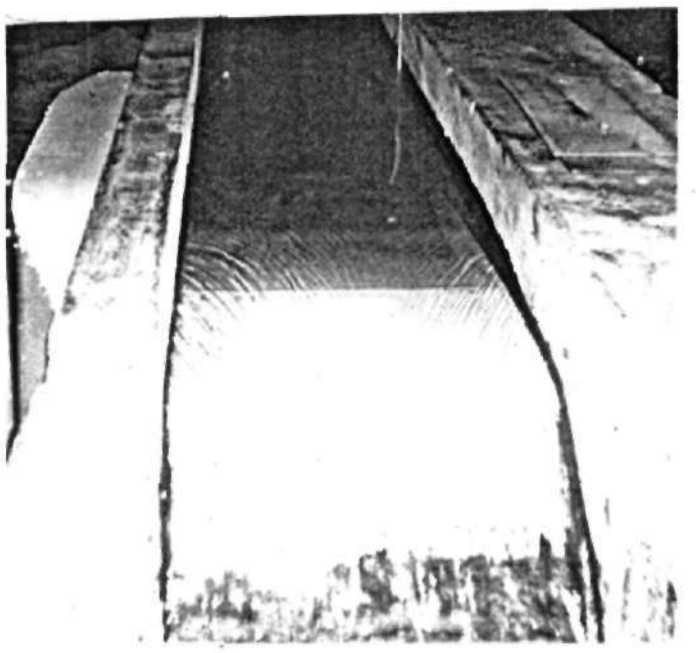


PLATE VI: Flow through Model B at the hydraulic laboratory A.B.U. Zaria (Downstream view).

3.3 Introduction to Computer Modelling

Computerization presents to the engineer a powerful tool for planning, design, data storage, data base analysis and information retrieval. Wright (1984), noted that "Because the expert computer system rapidly and economically conducts numerical and logical data processing, it promises to become the sucessor to the textual version of the engineering standard."

However, this can only materialize if the computer is used to re-think the design process rather than used only as a means to automate old design methods and more importantly, if engineers play a role in the development of computer aids. The use of computers in modelling-simulation, optimization strategies and data analysis has been known to improve considerably job planning and quality control in management, research and construction engineering. In this chapter, it is the aim to present a computer software that will enable considerable flexibility in the measuring flume design such that the measuring flume can be adapted to conditions in the channel rather than the reverse. This is expected to ease the construction of irrigation channels and more importantly to create a procedure whereby the flume can be designed to suit existing site conditions.

3.4 The Computer Model

If a mathematical relationship exists, a computer program can always be developed to simulate a mathematical

model and to generate solutions for various aspects of the prototype to be investigated.

In chapter three, a stage-discharge relationship for critical flow through a long-throated flume was presented in equation 2.8. Use of the equation requires the evaluation of two empirical coefficients Cd and Cv, these coefficients are usually evaluated through laboratory rating curves on models- a process which is very cumbersome and often lead to changing the site conditions to suit the tested laboratory model.

The empirical coefficient Cd is introduced to account for friction or head losses in the approach channel, the converging transition, and throat section. Noting that friction in the diverging transition and tailwater channel do not affect the flume discharge, but affect the tailwater limit for maintaining modular flow.

Several equations have been developed (Bos et al 1984) for estimating friction losses through the flume.

Some of these equations include:-

(a) Manning Function given as

$$\Delta H = L\, v^2\, n^2 / Cu^2\, R^{4/3} \quad \ldots \quad .. \quad 3.1$$

(b) Chezy function given as

$$\Delta H = Lv^2 / C^2\, R \quad \ldots \quad \ldots \quad 3.2$$

and (c) Boundary layer drag function given as

$$\Delta H = Lv^2\, C_f / 2g\, R \quad \ldots \quad \ldots \quad 3.3$$

Although the Manning equation has found many applications in open channel flow, but the use of a constant value of "n"

for a wide range of flow conditions is unacceptable for the precise calibration of measuring flumes. On the other hand, Chezy's "C" and boundary layer drag coefficient "C_f" take into account the absolute roughness height of the flume surface, the Kinematic viscosity of the fluid, and the Reynolds number of the flow.

However, the Chezy equation assumes that the flow is uniform, while the boundary layer theory would indicate a gradual change in flow conditions. Thus the boundary layer drag method is more appropriate because it is more consistant with the energy-based equations used to determine flow rate.

A measuring flume model based on the boundary layer drag method can therefore be developed (Replogle 1985) thus eliminating the use of "Cv".

Values for the turbulent drag coefficients are found from the following relationship which was derived from Granville (1958) as reported by Bos (1976).

$$C_{FL} = 0.544\ D\ C_{FL}^{0.5} /\ 5.61\ C_{FL}^{0.5} - 0.638\text{-In}\ ((Re1C_{FL})^{-1} + 4.84\ C_{FL}^{0.5} L/K)^{-1} \quad .. \quad .. \quad 3.4$$

Equation 3.4 can only be solved by trial and error since C_{FL} appears several times, hence its adaptation to computer solution is beneficial as it will be time saving.

However, for a fully developed turbulent boundary layer, as would be expected in the approach channel, converging transition, diverging transition and tailwater channel, the drag coefficient can be taken as 0.00235

(Bos et al 1984), hence the head losses are computed from equation 3.3. The combined head loss can then be written as

$$DH = DHa + DHb + DHL \quad \ldots \quad \ldots \quad 3.5$$

Hence the energy head at the critical section is obtained from;

$$Ec = EI - DHI \quad \ldots \quad \ldots \quad \ldots \quad 3.6$$

The velocity - distribution coefficient is introduced to account for non uniform velocity profiles. The following equation has been developed to estimate for fully developed flow in wide channels (Chow, 1959);

$$\alpha = 1 + 3\,e^2 - 2\,e^3 \quad \ldots \quad \ldots \quad 3.7$$

where

$$e = \frac{Vm}{V} - 1$$

Vm = maximum flow velocity

However, for fully developed flow e can be approximated Bos et al (1984) by;

$$e = 1.77\,(C_{FL})^{\frac{1}{2}} \quad \ldots \quad \ldots \quad 3.8$$

Whereas at control section the velocity - distribution coefficient α_c can be given as (Bos 1984),

$$\alpha_c = 1 + (3\,e^2 - 2\,e^3)\,(1.5\,D/R - 0.5)\,(0.025L/R - 0.05) \quad \ldots \quad 3.9$$

with the addition of velocity distribution coefficient, equation 2.6 becomes

$$Q = (gAc^3/\alpha c\ bc)^{\frac{1}{2}} \quad \ldots \quad \ldots \quad 3.10$$

3.5 Computer Run

A program to incorporate the velocity - distribution coefficient and to compute the value of the combined energy loss as outlined in section 3.4 has been developed (Replogle 1978). A Basic Version of the program (which can also be presented in FORTRAN) is given in appendix B.

Essentially, the program computes the initial flow rate and uses this as the initial guess for the actual flow rate. Next the friction losses and velocity distribution coefficients are computed for the estimated discharge. Then the actual flow rate is computed from equation 3.10 and the critical depth Yc is computed from

$$Yc = E1 - Ac/2Bc - DH1 \quad .. \quad ... \quad 3.11$$

The trial and error process is continued until Yc converges.

This trial and error process is given as:-

Assume initial value for Yc = 0.70h

Compute $Ac = Yc\ bc + Zc\ Yc$

Compute $Bc = bc + 2\ AZc\ Yc$

Compute $Qi = (gA^3_{c/Bc})^{\frac{1}{2}}$

or $Q = (gA^3_{c/\alpha c\ Bc})^{\frac{1}{2}}$

Compute $E1 = h + Qi^2/2gA1^2$

or

$E1 = h + \alpha\ Q^2/2\ gA1^2$

Compute new $Yc = E1\ Ac/2Bc$

or $Yc = E1 - Ac/2\ Bc - DH1$

Then check if new Yc equals initial Yc and continue otherwise.

Note that Q = actual discharge

Qi = discharge for ideal fluid

Also, the resulting flow rate is checked against the flow rate for the previous values of DH1 and α . If the flow rate has not converged, DH1 and α are computed with the new Q and the process is repeated until the flow rate converges. However, when there is not enough of a contraction in the channel to cause critical flow, the critical depth and flow rate will not converge. A counter has therefore been added to the program so that the computations is stopped if the results are not converging.

The discharge coefficient"Cd" is computed from

$$Cd = Q/Qi$$

where

Qi = discharge for ideal fluid.

The velocity coefficient "Cv" is then computed from equation 2.9 and the Froude Number from equation 2.7..

3.6 Inputs and Outputs

The inputs consist of the channel and flume cross-sectional data, the flume profile data, the material roughness K, initial value of gauge height h and increment for successive values of h and the highest value of h .

The output from the computer program includes a repetition of the input data on flume cross-section and values for Q, SH1, Fr, Cd, Cv, DH, ML and H1/TL.

A total of about fifty models were simulated and values obtained for the above listed terms.

The following classes of flumes were simulated;

(a) the side contracted rectangular flume

(b) the bottom contracted rectangular flume

(c) the parshall flume

(d) the side and bottom contracted trapezoidal flume.

CHAPTER FOUR

ANALYSIS OF RESULTS

4.1 Presentation of Results

The results have been presented in tabular form in appendix A. Tables 4.1 to 4.10 in that appendix refer to the laboratory results whereas tables 4.11 to 4.17 refer to the computer results.

4.2 Calibration of Flume

Data obtained with the computer modelling as presented in chapter four and in the laboratory work as presented in chapter four, were regressed to obtain the calibration curves for each model tested.

Calibration equations obtained have been shown along with tables in appendix A.

A comparison of the rating curves for models A1, A2, B1 and C2 are satisfactorily similar for both the laboratory results and the computer results.

However, the laboratory rating for model B2 shows a substantially high power of 1.69 for gauge height 'h' as compared to 1.54 from the computer results. Also the laboratory rating for model C1 show a relatively high constant value 'C' of 1.318 as against C = 0.837 for the computer rating and a substantially high power of 1.65 as against 1.54 for the computer rating.

These discripancies are attributed to an experimental limitation of maximum pumping time for the lifting pump and variation of control valve during experimentation. The

specific values resulting in these discripancies have been asteriked in tables 4.5 and 4.6.

The rating curves obtained for table 4.1 to table 4.7 are consistent with rating curves obtained by other experimenters (Replogle and Clemmens 1981) and closely related to the discharge equations reported in many literature (Ackers 1980).

For the Parshall flume model D, the laboratory rating present a result consistent with reported discharge equations in literature (Bos 1976). However, the computer rating is way out of the normal, indicating that the computer model, presented in this research cannot be applied to simulate Parshall flume models. However, this is as expected because the computer model is designed for long-throated structures whereas the parshall flume is not long-throated.

Rating curves obtained from tables 4.8 and 4.9 show the implication of operating a long-throated flume above its modular limit. In such a case, the flume can no longer be considered as critical-depth, long-throated, and discharge measurement is better estimated by the constriction siutated downstream of the flume. For model E the downstream constriction was a V - notch weir and the rating curves obtained, are consistent with reported ratings of V - notch in literature where the power of gauge height has been generally reported as 2.5. It should be noted however that the closeness of

the flume to the V - notch in each of Models E1, and E2 is considered to explain the exact form of rating curves obtained for these models E1 and E2.

Comparison of equations in tables 4.2 and 4.3 on one hand and equations in tables 4.4 and 4.5 on the other hand indicate that the discharge constant for a bottom contracted flume is double that for a side contracted flume.

4.3 Shape Factor

The Froude number "Fr", the modular limit "ML", the head loss "DH" and the discharge "Cd" and velocity "Cv" Coefficients vary from shape to shape for identical flow rates.

Figures 4.1, 4.2, 4.3 and 4.4 indicate these variations in each shape and with respect to each performance characteristic of head loss "DH", Modular limit "ML", discharge and velocity coefficients "Cv Cd", and gauge height "SH1" respectively.

Figure 4.1 indicate that the head loss "DH" required to maintain Modular flow is lowest in the trapezoidal-throated flume and highest in the rectangular-throated flume. This clearly vindicates that in the case of head loss for irrigation channels, the trapezoidal flume is recommended especially for flow rates above 0.02 m^3/sec. For low flow rates, of say 0.01m^3/sec and below, the shape factor on head loss is not very pronounced.

Figure 4.2 indicate that the change in specific energy head DE as the water flow from upstream gauging point through the flume to the downstream gauging point is smallest in the triangular flume and highest in the rectangular flume. However, the range of values obtained for Modular limit in all three shapes, are consistent with reported modular limit values to satisfy no more than 1% change in flow through the flume. The trapezoidal flume is indicated in this figure to show more sensitivity to changes in specific energy head and hence modular limit. The rectangular flume is least sensitive to specific energy head changes. It should however be noted from figure 4.4 that the rectangular flume is second to the trapezoidal flume in sensitivity of gauge height to discharge measurements. It implies therefore that the trapezoidal shape is the most sensitive of the three shapes considered. Figure 4.3 which however follow from figure 4.1 further showed the trapezoidal flume model to require a higher value of discharge coefficient and hence higher sensitivity and better discharge characteristic performance to both the triangular and the rectangular flumes. The triangular rank second to the trapezoidal in this interpretation of discharge characteristic performance.

Furthermore, another deduction obtainable from figure 4.4 is that for the same gauge height "SHI", the discharge "Q" from the trapezoidal-throated flume is always equal to the sum of the discharges from the triangular-throated "QT" and the rectangular-throated "QR"

$$Q = QT + QR$$

The above relation has only been proved valid for values of gauge height not exceeding 0.26 metres.

For constant gauge height "SH1", the Froude Number "Fr " per shape showed a variation corresponding to that shown by the discharge.

4.4 Sill height factor

In the case of bottom contracted flumes, the bottom constriction is provided by a sill height on the floor of the throated section. Table 4.18 presents some of the data obtained from simulated models. Details of the computer outputs for the simulated models are presented in appendix C.

The computer output details further showed that the variation in sill height "P_1" has no effect on the discharge coefficient "Cd", the head loss "DH" required to maintain modular flow, the tailwater level "Y_2" and the modular limit "ML" of the flume considered.

Figures 4.5, 4.6 and 4.7 represent the variation of discharge Q, velocity coefficient Cv and Froude Number "Fr" respectively with the sill height P_1. Relations for five gauge heights have been presented in figure 4.5, while figures 4.6 and 4.7 show regulations for three gauge heights. Figure 4.5 indicates that for constant gauge height, less discharge can be measured as the sill height increases. However, the discharge "Q" measurable decreases rapidly only for low values of sill height below 0.25m and remains almost constant for higher values of

Table 4.18: Sensitivity of Performance to sill height Variation

N/B Gauge height 'h' = 0.20m.

Sill height P_1 (m)	Discharge Q m^3/sec	Velocity Coeff. Cv	Froude No Fr	Hl/TL
0.055	0.085	1.21	0.45	0.74
0.105	0.079	1.13	0.32	0.71
0.155	0.076	1.08	0.25	0.69
0.205	0.075	1.06	0.20	0.68
0.237	0.074	1.05	0.17	0.67
0.305	0.073	1.04	0.14	0.67
0.405	0.072	1.02	0.10	0.67
0.805	0.071	1.00	0.05	0.66

sill height P_1. It can be deduced from these relations in figure 4.5 that there is a critical value of sill height "P_1" above which the variations in sill height does not affect the discharge computed per gauge height observed. This critical sill height lies between 0.25 metres to 0.30 metres. However, by the method of bisection of tangents, the critical sill height has been fixed at 0.28 metres for discharges lower than 0.6m^3/s. Figure 4.6 show that as the sill height increases, the velocity coefficient decreases and approaches the value 1.00. It can also be deduced from figure 4.6 that the higher the flow rate "Q" and hence the gauge height "h", the higher the velocity coefficient for constant value of sill height P.

This is as expected from the discharge relation of

$$Q = A.V$$

It should also be noted that the rate of decrease of velocity coefficient "Cv" with sill height P_1 changes rapidly as sill height varies from zero to $P_1 = 0.30m$, then it gradually approaches Cv = 1.00 as P_1 further increases. This again brings in the question of a critical value of sill height P_1 being around "P" = 0.30 metres.

Relations in figure 4.7 of decrease in Froude Number as sill height increases are identical with those in figure 4.6 except that in figure 4.7, the Froude Number approaches zero as the sill height increases.

Bos et al (1984) presented rating tables for broad crested weirs in which the discharge ratings were closely identical for sill height P_1 = 0.05 metres and sill height P_1 of infinitely large value. The above deductions from figure 4.6 therefore seems to be in agreement with observations of previous literature. An additional deduction that can be made with regard to the sill height factor is that for measuring low discharge rates, the sill height effect is very small and can be ignored for all values of sill height. This can be seen in figure 4.1 comparing curves for Q = 0.025m^3/sec and Q = 0.07m^3/s and above. However the higher the discharge rate the more pronounced the sill height effect, and hence the need for a critical sill height.

4.5 Roughness factor

The absolute roughness height K in metres for a number of materials typically used for flume construction

is given in table 4.19. It should be noted that the actual value of the absolute roughness height K for each material though vary with the age of the material, but is always within the range indicated in table 4.19.
An analysis of the sensitivity of the performance characteristics to the absolute roughness height K was made using thirteen simulated models of which nine were

Table 4.19 Absoute Roughness heights for Various Construction Materials

Material	K (mx 10^{-4})
Glass, plastic	0.01 - 0.10
Metal painted	0.20 - 1.00
Galvanized sheet Metal	1.00 - 10.00
Wood sanded to rough saw	2.00 - 10.00
Concrete, smooth troweled	1.00 - 20.00
Concrete, float finished or	
Concrete broomed	5.00 - 50.00

(*Adapted from Clemmens et al, (1984)

A1 side-contracted flume types and the other four were B1 bottom - contracted flume types. Table 4.20 present a summary of the values obtained for the side-contracted rectangular flume. Full output details can be seen in appendix D.

Table 4.20: Sensitivity of Performance to Roughness K

K ($m \times 10^{-4}$)	Q m^3/s	Cd	Cv	DH
0.01	0.03826	0.9906	1.0628	0.0057
0.05	0.03826	0.9906	1.0628	0.0057
0.10	0.03826	0.9906	1.0628	0.0057
0.50	0.03826	0.9906	1.0628	0.0057
1.00	0.03826	0.9906	1.0628	0.0057
5.00	0.03837	0.9904	1.0661	0.0057
10.00	0.03826	0.9906	1.0628	0.0057
50.00	0.03826	0.9906	1.0628	0.0057
100.00	0.03226	0.9906	1.0628	0.0057

*Values presented in this table are for a constant gauge height of SH1 = 0.205m.

This sensitivity analysis showed that a change of several orders of magnitude in the absolute roughness height K produces much less than 0.1% change in discharge indication, discharge coefficient indication and even in the head loss indication. Thus, in the usual range of flows for a particular flume, whether one uses materials as smooth as glass or as rough as troweled concrete, will have relatively no effects on the performance rate of the flume.

4.6 Throat length factor

The length through the throat of a flume has been considered important as it plays a dual purpose in the performance of a flume. It is one of the monitoring

parameters to ensure streamlined parallel flow through the throat and it is a principal parameter for the computation of frictional losses in the flume. The sensitivity of various performance parameters (e.g. Q, Fri, Hl/TL, Cd, Cv, DH and ML) to throat length TL have been analysed using eleven simulated models. A summary of the results obtained for both the type Al and Bl models have been presented in table 4.21 and 4.22 respectively.

Table 4.21: Sensitivity of Performance to throat length TL for the Al side contracted flume

Throat length TL(m)	Discharge $Q(m^3/s)$	Hl/TL	Cd	Head loss DH(m)	Modular limit ML
0.025	0.00389	1.8620	0.990	0.00033	0.9927
0.300	0.00380	0.1549	0.965	0.00091	0.9802
0.600	0.00372	0.0773	0.946	0.00130	0.9720
0.900	0.00360	0.0514	0.914	0.00177	0.9593

These are values for constant gauge height SHl = 0.045m.

Table 4.22 : Sensitivity of Performance to throat length TL for the Bl bottom contracted flume

Throat length TL(m)	Discharge $Q(m^3/s)$	Hl/TL	Cd	Head loss DH(m)	Modular limit ML
0.055	0.0235	1.749	0.9923	0.0246	0.7442
0.155	0.0235	0.620	0.9890	0.0247	0.7431
0.305	0.0234	0.315	0.9841	0.0247	0.7426
0.500	0.0232	0.192	0.9787	0.0248	0.7424
0.900	0.0225	0.106	0.9513	0.0253	0.7358
1.000	0.0224	0.096	0.9454	0.0255	0.7339

*These values are for constant gauge height SHl = 0.095 m.

Both tables 4.21 and 4.22 indicate a less than 0.1% sensitivity for discharge rate "Q" to throat length "TL". There is a very high sensitivity (about 95%) of discharge coefficient Cd to values of H1/TL less than 0.2. However for H1/TL values of between 0.2 to 1.0, the sensitivity of Cd to H1/TL is about 2.5% and in agreement with the observation of Bos, (1976). For throat length TL = 0.50m, the corresponding value of H1/TL for the considered B1 model is about 0.2 (0.192 exact value). Therefore throat length TL $\geq$ 0.50m implies H1/TL $\leq$ 0.20 and figure 4.9 indicate that for this range of TL $\geq$ 0.50, the head loss DH is 100% or even more than 100% sensitive to the throat length. Whereas for TL $<$ 0.5 (i.e. H1/TL $>$ 0.20), the sensitivity of head loss DH to throat length TL is approximately 25%. This leads to the deduction that one of the major reasons for the very high sensitivity of discharge coefficient Cd to low values of H1/TL is friction. Therefore, the throat length TL provided for any flume should be such as to limit the range of H1/TL to within 0.2 and 1.0 in order to minimize the frictional head loss and ensure streamlined parallel flow through the throat.

4.7 Narrowing Ratio Factor

The narrowing ratio factor his hereby defined as the ratio of the throat width Bc to the upstream gauge point width b_1. i.e. Narrowing ratio 'r' = bc/b_1

The value of 'r' is one except in a case where the flume is side-contracted. Six models of the side-contracted rectangular flume has been analysed to find the sensivity of the discharge rating to the narrowing ratio r.

Table 4.23 present a summary of the computer output details for this analysis and figure 4.10 show the sensitivity curve of 'Q' to 'r'.

Table 4.23 Sensitivity of Discharge Q to narrowing ratio 'r'

b_1 (m)	Throat Width bc (m)	Narrowing ratio 'r' % = $\frac{bc}{b_1}$ x 100	Discharge Q m^3/s
1.00	0.150	15.00	0.0073
1.00	0.300	30.00	0.0150
1.00	0.350	35.00	0.0176
1.00	0.467	46.70	0.0241
1.00	0.750	75.00	0.0427
1.00	0.900	90.00	0.0567

*Values for SH1 = C. 095m.

Narrowing ratio of 50% and below, indicate about 50% sensitivity of 'Q' to 'r' whereas narrowing ratios above 50% show much higher sensitivity of say 80% as 'r' approaches 90%, it should be recalled that the severeness of the constriction provided at the throat ensures the occurance of critical flow at the throat section. The narrowing ratio should therefore be such as to ensure critical flow at the throat section.

4.8 Position of Constriction

A measuring flume is formed by the introduction of a constriction to either the bottom of the channel , the sides of the channel, or both bottom and sides of the channel. The position of such a constriction determines the name or description for the flume. The effect of the position of the constriction on performance has been analysed. The analysis showed that for defined throat width BC and throat length TL, the discharge rate Q obtained in the bottom contracted flumes is within 98.6% the same as the discharge rate Q obtained in the side contracted flumes; provided that the throat width BC, throat length TL and the gauge height SH1 are the same in both flumes. Therefore, the location of a constriction has very little effect on the accuracy of the flume. The analysis further showed that the discharge rates Q obtained from the bottom-contraction are always lower. The bottom-contracted flume can therefore be recommended if this difference is considered as a safety margin. One major effect of the location of the constriction is that the side-contracted flumes have relatively high modular limits, whereas the bottom-contracted flumes have low modular limits for the same gauge height and flows.

4.9 Other factors

Flume performance sensitivity to other factors such as inlet, exit and submergence conditions were also analysed. Deductions from such analysis are herein presented, while the output details are in appendix H.

4.9.1 Flume inlet factor

The analysis showed that the discharge rate Q is less than 1% sensitive to the entrance transition. However, the head loss DH is about 29% sensitive as the entrance transition becomes more suddenly severe. Although the entrance transition has shown less than 1% effect on the discharge rate, it should however be such as to satisfy the following requirements which aim to ensure adequate performance of the flume. (1) production of a smooth, predictable water surface (2) minimization of head loss in the transition (3) prevention of channel scour in the vicinity of the contraction and (4) simple and economical to design and construction.

4.9.2 Flume outlet factor

In this case the discharge rate Q was completely insens itive to the exit transition and the head loss was only about 9.6% sensitive.

4.9.3 Submergence factor

A submerged flow show increase in discharge Q for same gauge height.

However, in submerged conditions, the flume no longer behave as the Critical-depth flumes and this condition is not covered by this research.

4.10 Criteria for hydraulic Similarity

Flow through the critical-depth long-throated flumes are either critical or supercritical, thus implying turbulent or shooting flows respectively. In both cases of flows, viscosity forces are of negligible influence, gravity forces being dominant, and hence Froude number "Fr" is the criterion for dynamic similarity.

$$Fr = V^2/gL \quad \ldots \quad \ldots \quad 4.1$$

The scale ratio can therefore be shown to be as follows:-

(1) Velocity scale ratio = $(Lr)^{\frac{1}{2}}$

(2) Discharge scale ratio = $(Lr)^{5/2}$

(3) Length scale ratio = Lr

and (4) Roughness scale ratio = $(Lr)^{1/6}$

In research studies where the computer simulated models are not possible, the above ratios can therefore be used to scale the laboratory model to site prototype.

4.11 Sources of errors

The generalized discharge equation for a measuring flume can be written as:

$$Q = X\ Cd\ Cv\ S_f\ (g)^{\frac{1}{2}}.b.h^y \quad \ldots \quad \ldots \quad 4.2$$

where

$X = (\frac{2}{3})^{3/2}$; a numerical constant not subjected to errors

$(g)^{\frac{1}{2}}$ = root of acceleration due to gravity, its variation from place to place can be neglected in this case.

$y = 3/2$ numerical value, subject to errors due to experimental limitations.

The discharge coefficient "Cd", velocity coefficient "Cv", shape coefficient "Cs", submerged flow reduction factor "S_f", the throat width 'b' and the gauge height 'h' are all subjected to errors in measurement or estimation.

4.12 Computation of errors

D_e Varies, (1975) as reported by Bos (1976) showed that for critical flows, the submerged flow reduction factor S_f is constant (S_f = 1.0) and therefore not subjected to experimental errors.

Ackers, et al (1980) has shown that errors in coefficient estimation within the 95% confidence level is given as

$$\sigma_c = \pm (1 + 20 (Cv - Cd))\% \quad .. \quad ... \quad 4.3$$

DeVaries, (1975) as reported by Bos (1976) further showed that from standard normal distribution of propagation of errors,

$$\sigma Q = (\sigma^2 + \sigma b + \mu^2 \sigma_h^2)^{\frac{1}{2}} \quad .. \quad ... \quad 4.4$$

where

$$\sigma_b = 100\Delta b/b \quad ... \quad ... \quad 4.5$$

and σ_h = 100 (Δh_1 x Δh_2 x .... x (2 h)$^{2})^{1/2}$/h .. 4.6

y = 1.5

Analysing Model B1 for the overall percentage error in discharge gave the results in table 4.24 for the low and high flows respectively. Reference to table 4.24 show that when the gauge height on a structure is 0.195m, the overall error in the discharge measurement is + 4.4%.

At this discharge, the percentage error in combined coefficient"C_d" dominates the overall error "σ_Q", but at a lower gauge height of 0.045m, percentage error in gauge height "σ h" becomes a more important factor. This illustrates the difficulties encountered in accurate measurement of low flows and emphasizes the need to take great care in the measurement of gauge height. The analysis further showed that for very low flows, the side-contracted flumes provide more accurate devices for flow measurement. However, for high flows, the bottom-contracted flumes are about as accurate as the side-contracted flumes. This can be verified by comparing data in tables 4.24 and table 4.25. It should be remembered however, that the bottom-contracted flumes are much easier to construct.

Table 4.24 Computation of errors in Model B1

	Low flow $Q= 0.007\ m^3/s$	High flow $Q=0.071 m^3/s$	Reference
Gauge height h (m)	0.045	0.195	
Cv	1.00557	1.05157	
Cd	0.96736	0.992088	
σc	+ 7.7%	+ 2.2%	equation 4.3
σ_h	+ 11.1%	+ 2.5%	eq. 4.6
σ_b	+ 0.43%	+ 0.43%	eq. 4.5
σ_Q	+ 18.3%	+4.4%	eq. 4.4
Δh	0.005m	0.005m	
Δb	0.002m	0.002m	

Table 4.25: Computation of errors in Model A1

	low flow $Q=0.00067 m^3/s$	High flow $Q= 0.071 m^3/s$
Gauge height h(m)	0.065	0.35
C_v	1.05438	1.04622
Cd	0.975281	0.97224
σ_c	+ 2.58%	+2.48%
σ_h	+ 7.69%	+1.42%
σ_b	+0.87%	+1.00%
σ_Q	+ 11.8%	+ 3.4%
Δh	0.005m	0.005m
Δb	0.002m	0.002m

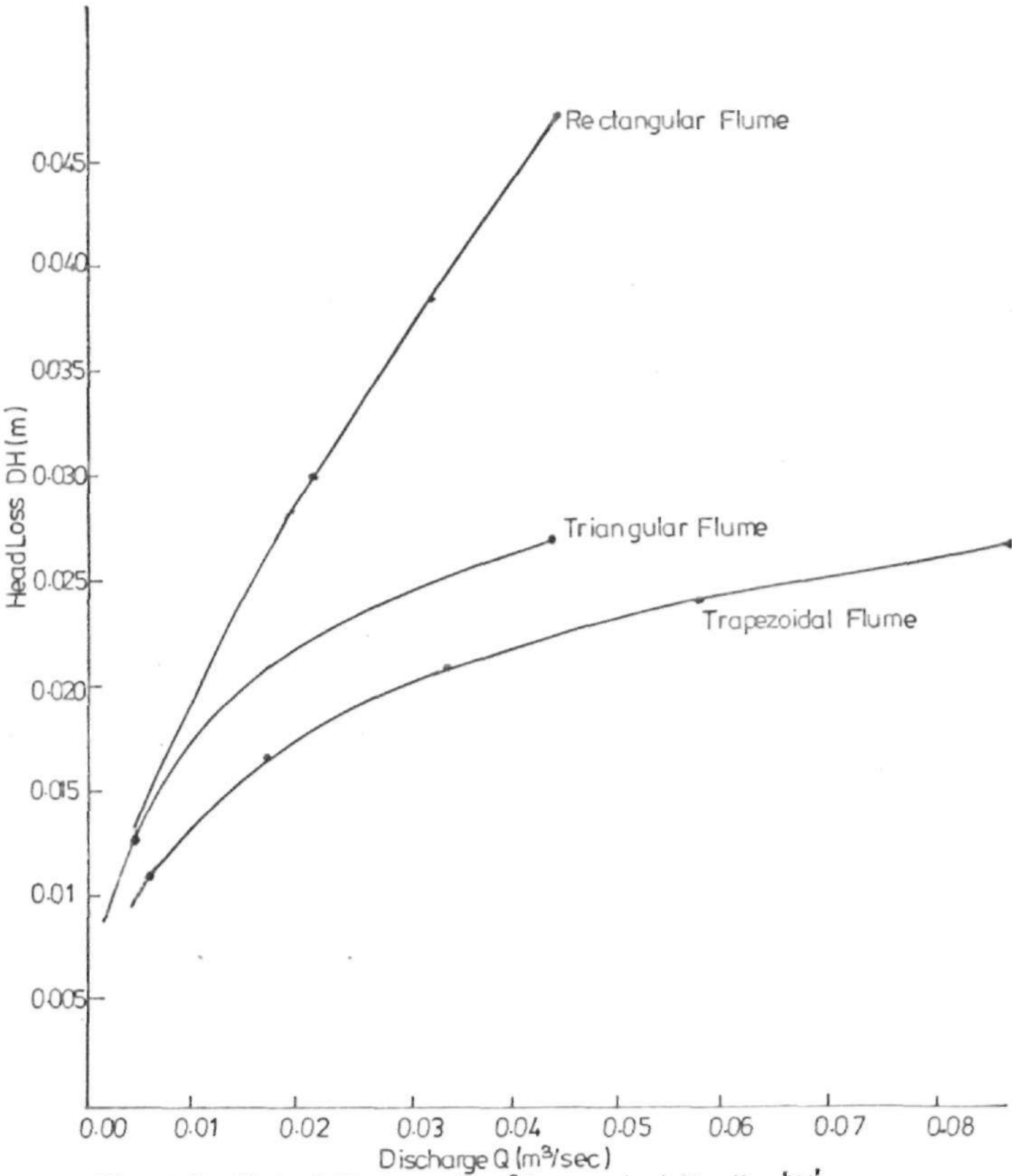


Fig. 4.1: Plot of Discharge Q m^3/sec against Headloss 'DH' m

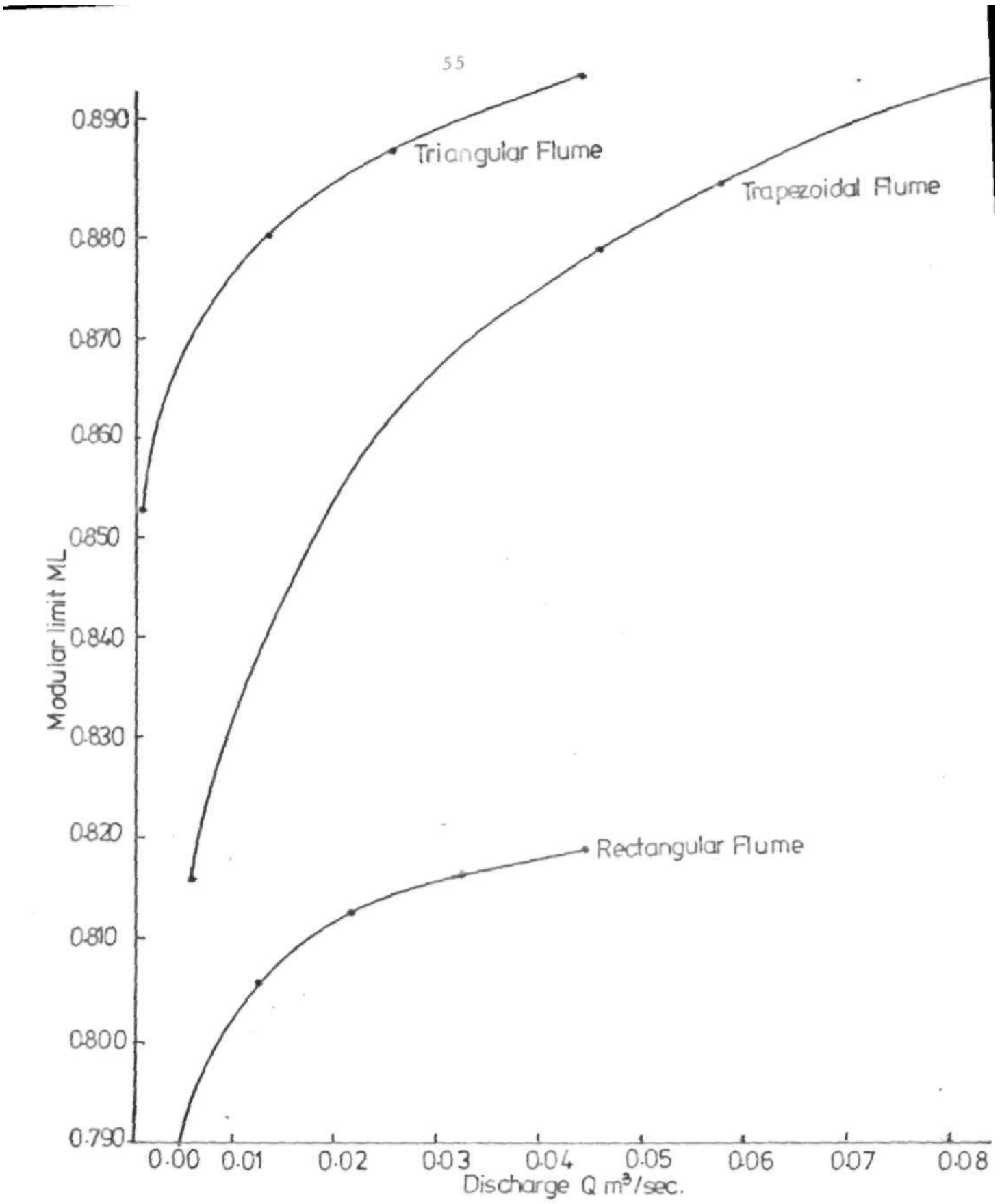


Fig. 4.2: Plot of discharge Q against Modular limit ML

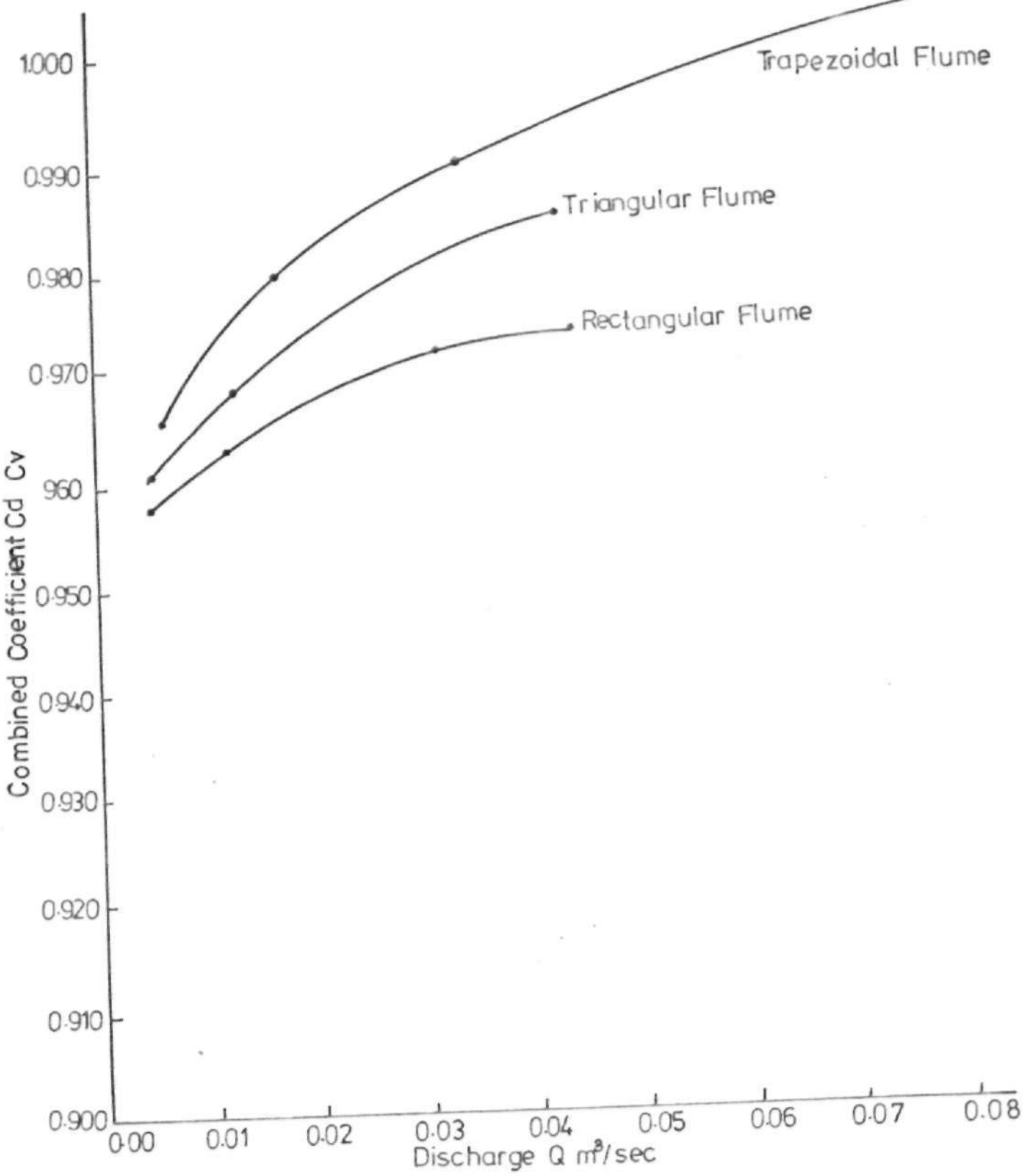


Fig. 4.3: Plot of Discharge Q against Combined Coefficients Cd Cv

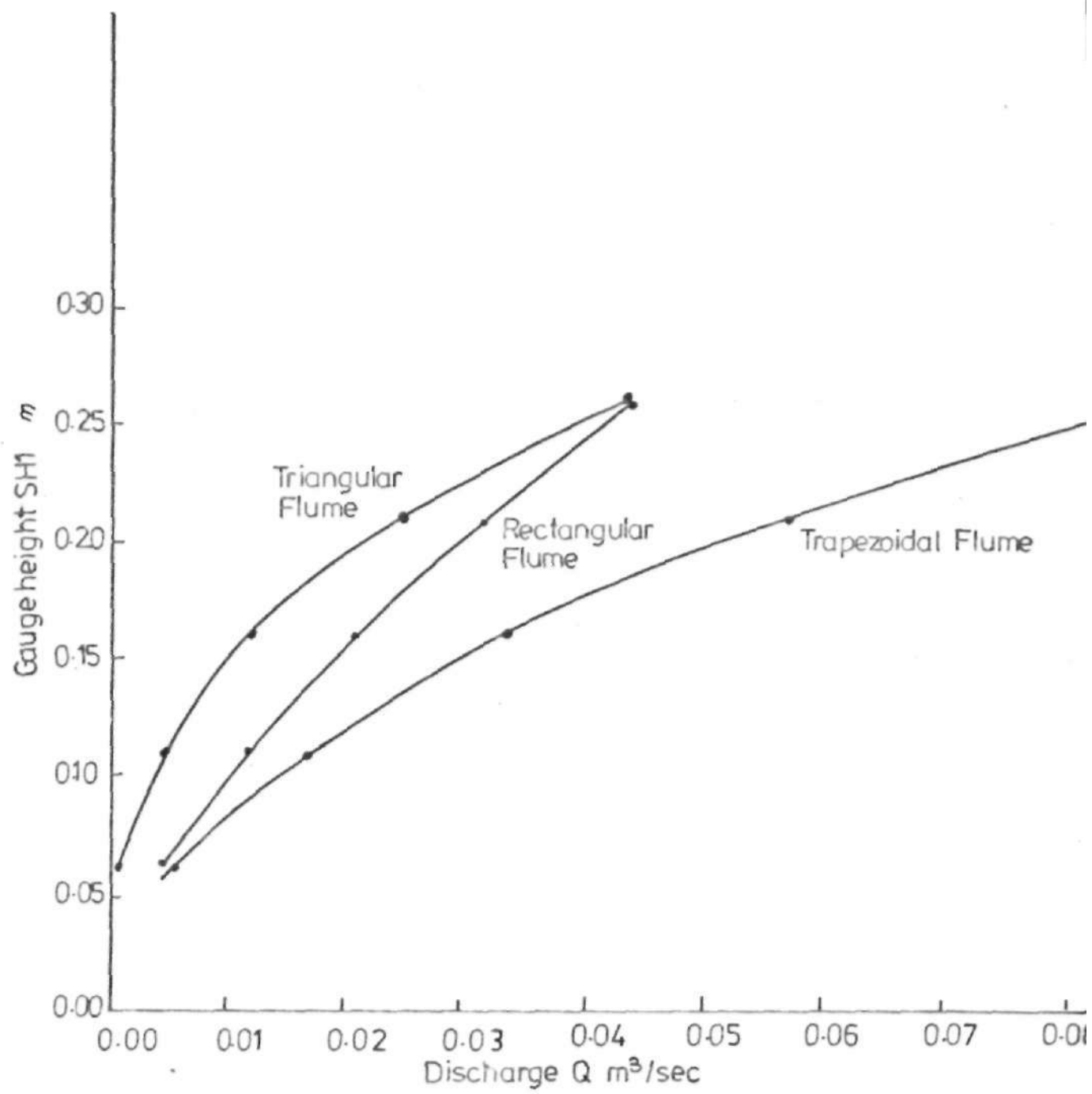


Fig. 4.4: Plot of Discharge Q against gauge height SH1

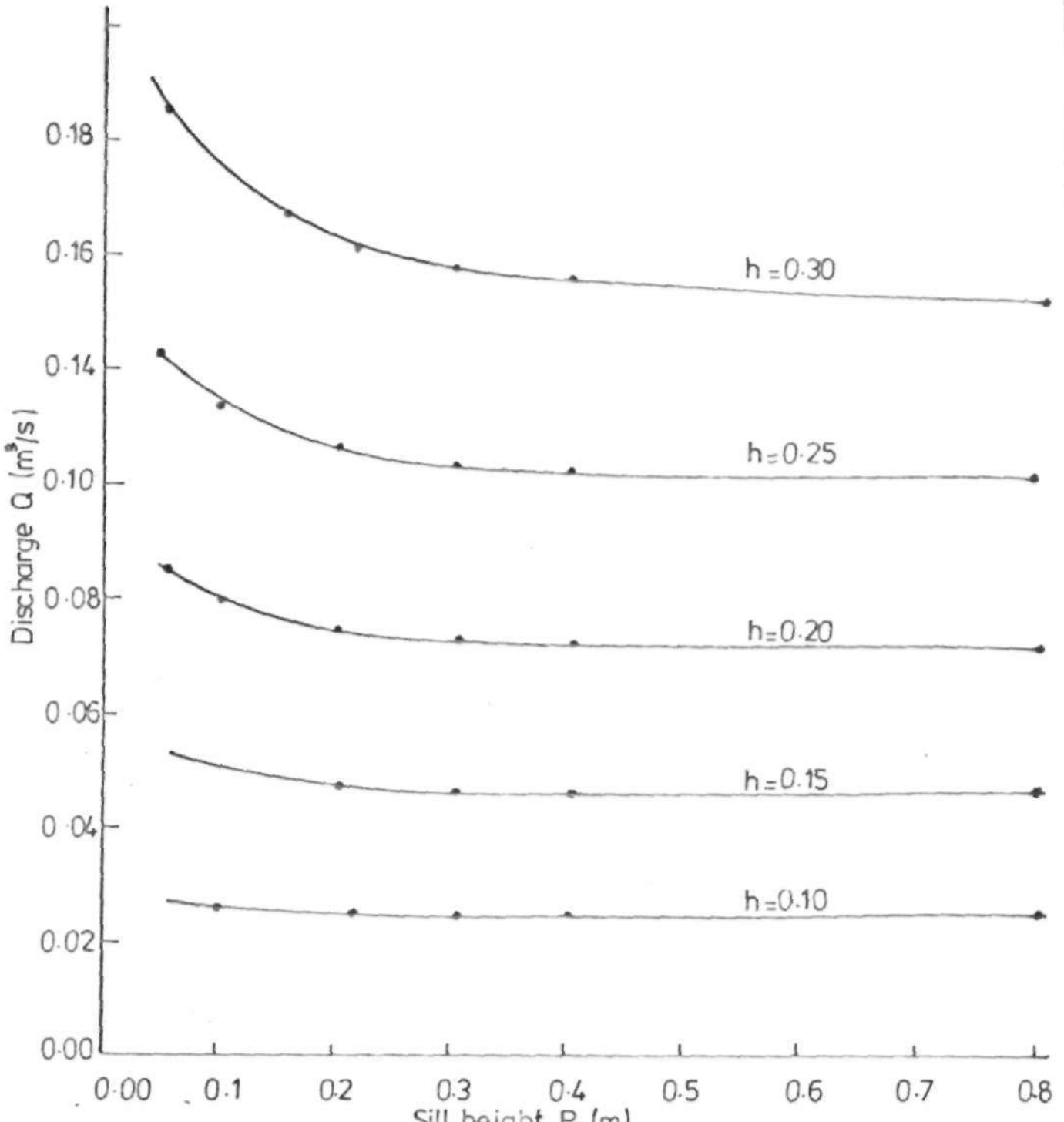


Fig. 4.5: Plot of Discharge Q against sill height P_1.

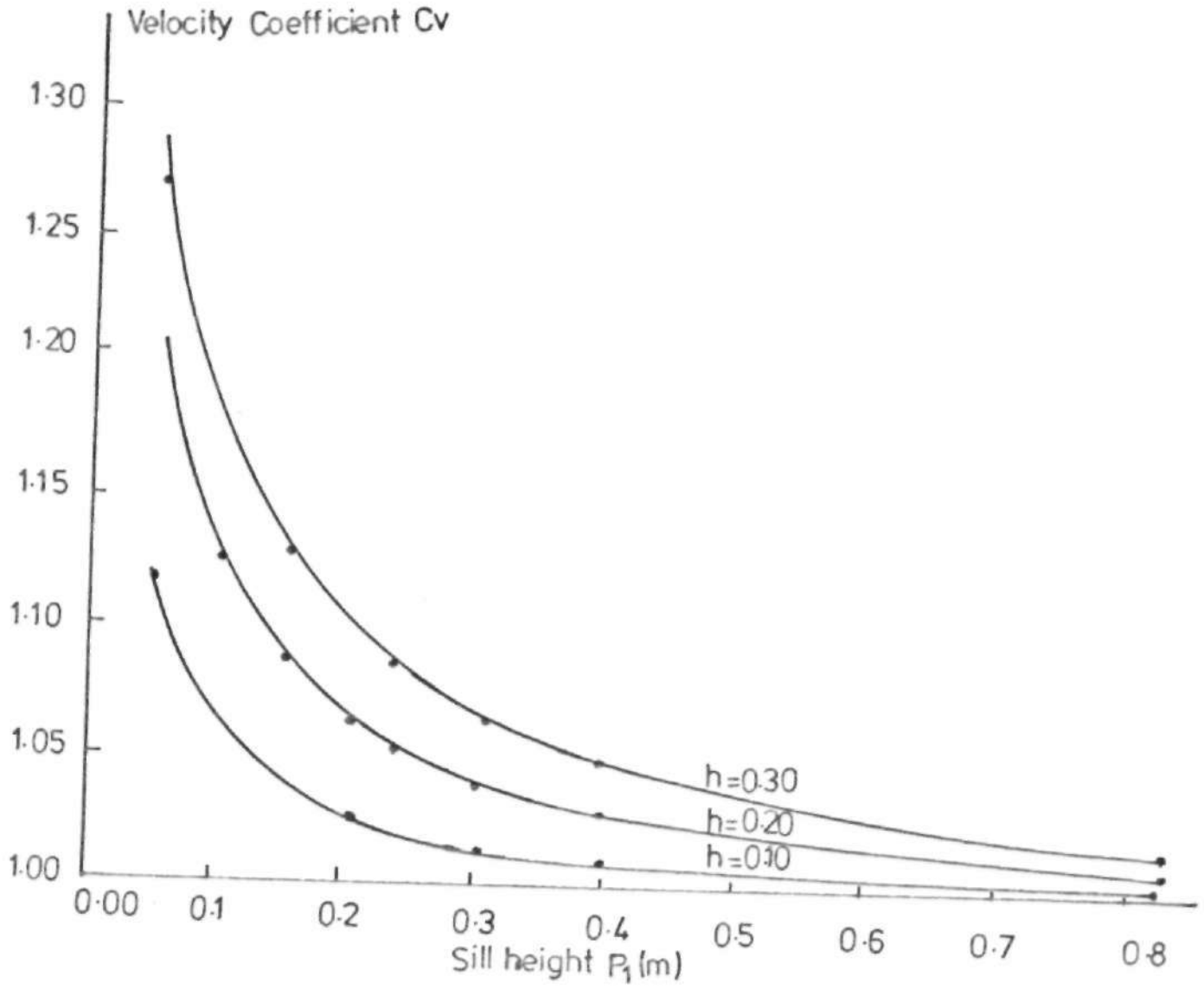


Fig. 4.6: Plot of velocity Coefficient Cv against sill height P_1 m

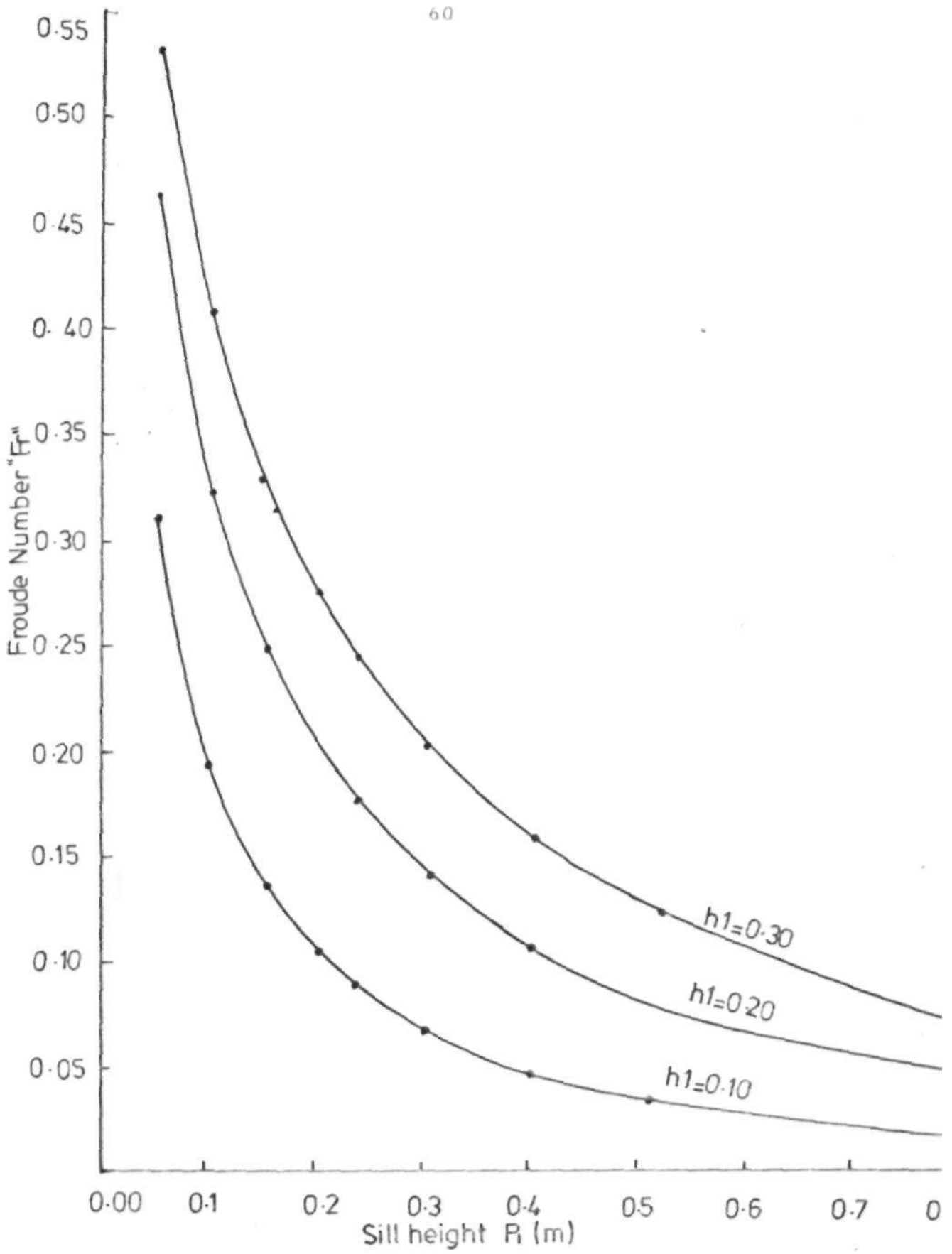


Fig. 4.7: Plot of Froude No "Fr" against sill height P_1

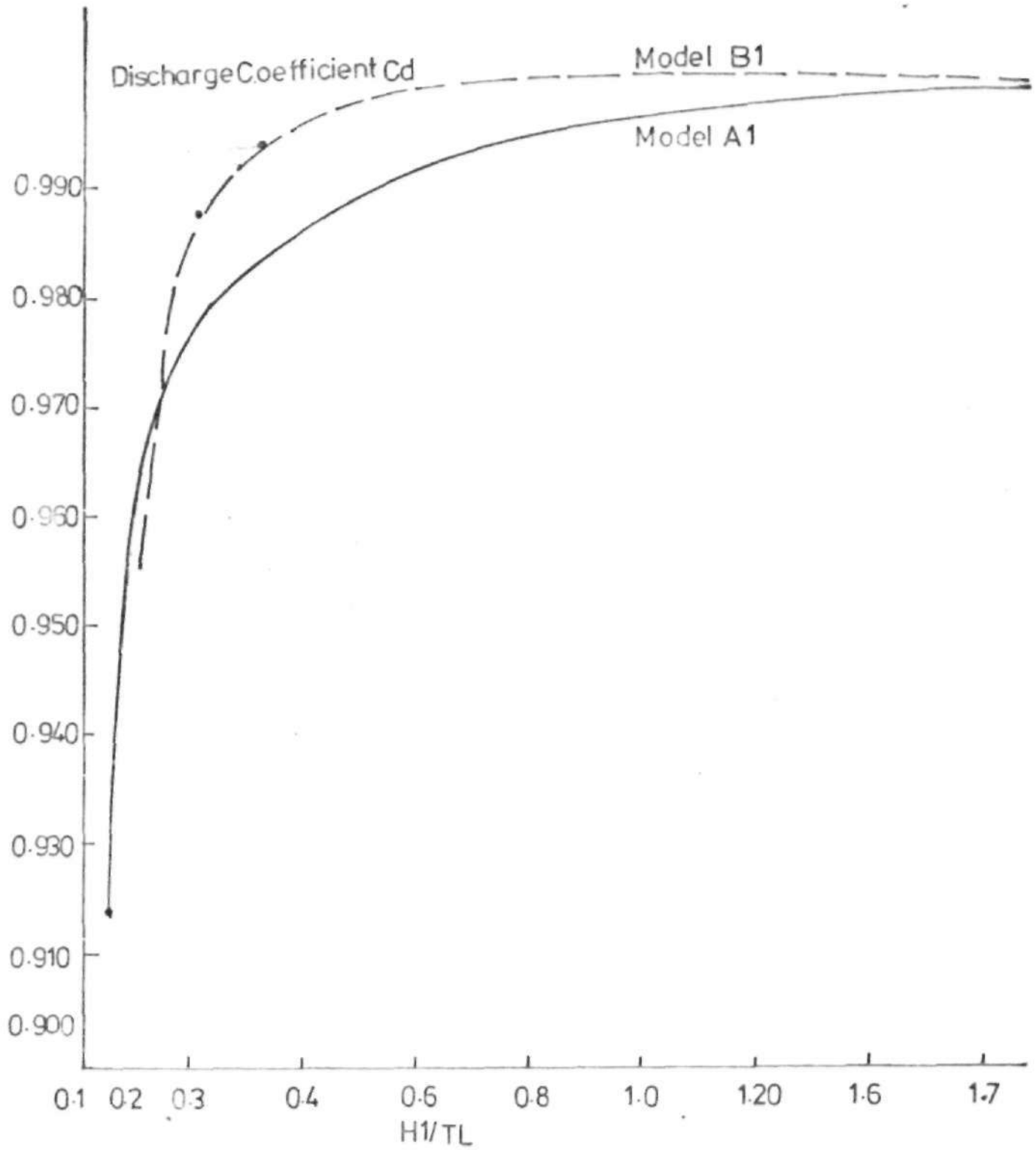


Fig. 4.8: Plot of Discharge Coefficient Cd against H1/TL

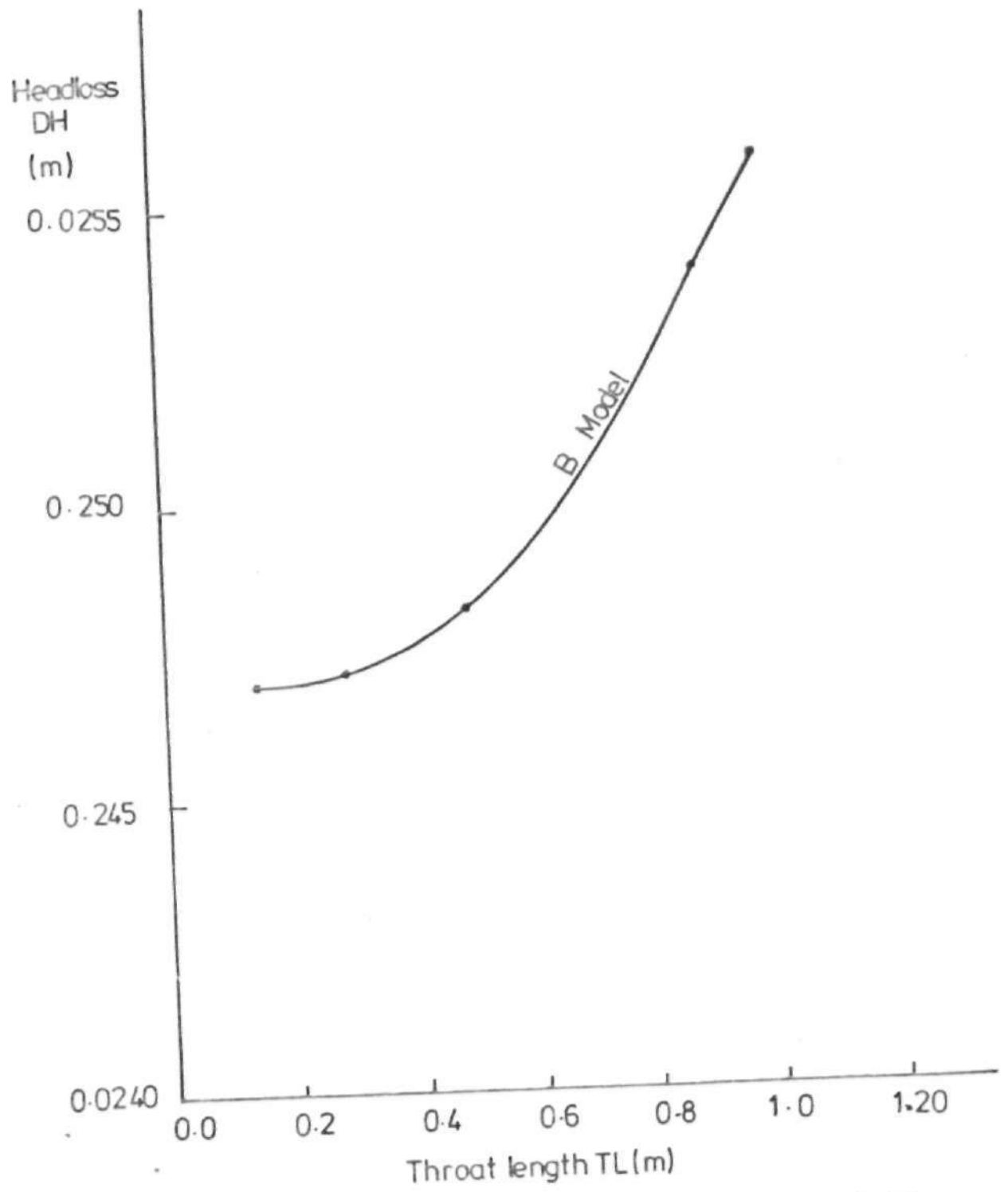


Fig. 4.9: Plot of Headloss DH against throat length TL

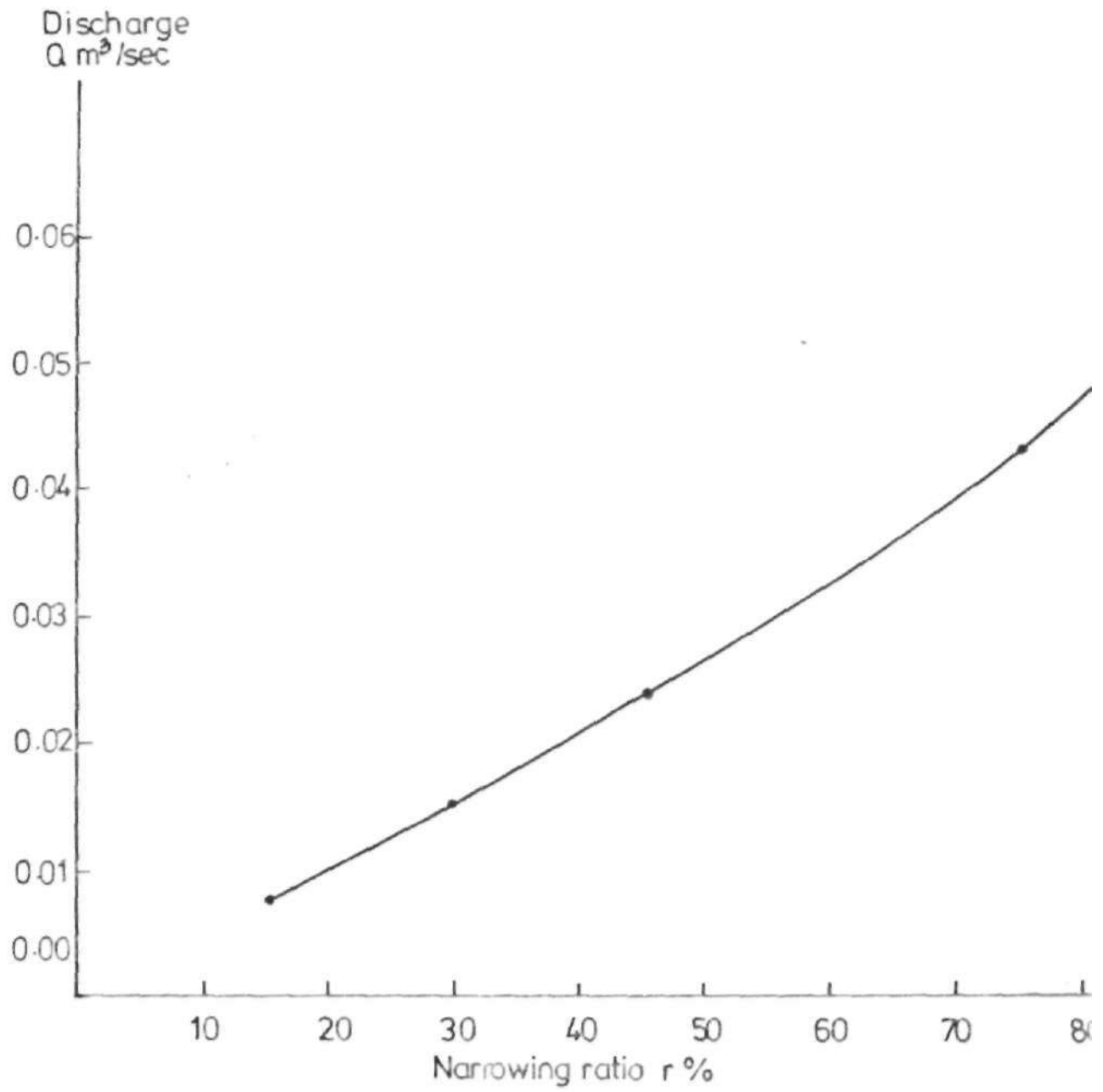


Fig. 4.10: Plot of Discharge Q against Narrowing ratio r

CHAPTER FIVE

SUMMARY AND RECOMMENDATION

5.1 Summary

The performance characteristic of the critical-depth long-throated flume has been studied. The work involved the preparation of about eight flume models for laboratory investigation in addition to the generation or simulation of more than fifty flume models by the aid of a computer for detailed analysis.

Although the calibration relationships obtained are not exactly in agreement with already established discharge rates, the differences are sufficiently small and can only be considered to be due to experimental limitations. Analysis showed that discharge is more sensitive to gauge height in the trapezoidal shape relatively insensitive to sill height above a certain critical value of 0.28 metres. Also that discharge rate is insensitive to the absolute roughness height. It has been further shown that discharge rate is less than 0.1% sensitive to the throat length, whereas it is about 50% or even more than 50% sensitive to the throat narrowing. Other deductions obtained from the studies are that neither the location of the restriction, nor the suddenness of the inlet transition or the outlet transition has any adverse effect on the discharge measureable from the flume. These parameters however

affect other characteristics of the flume such as stability and ease in construction.

Finally, the research showed that only about 4.4% overall errors are expected from the measurement of flows through an average irrigation canal carrying 71 L/sec.

5.2 Recommendation

The results from this analysis combined with previous experience in Bakolori Irrigation Project in Sokoto State with measuring flume constructions, lead to the following recommendations. That:

(1) the bottom contracted flume be adopted for discharge measurements in irrigation canals

(2) the shape of the flume be the same as the shape of the canal to prevent constructional problems and minimize costs

(3) the calibration curve be that presented in table 4.4.

(4) the sill height be between 0.20 metres and 0.30 metres

(5) the throat length be such as to limit H1/TL to between 0.2 and 1.0

(6) the narrowing ratio be 60% or less

(7) the inlet and outlet transitions be gradual enough to prevent local scour in the vicinity of the contraction or throat of the flume.

REFERENCE

ACKERS, P. (1961) Comprehensive formulae for critical-depth flumes. Journal of Water and Wastewater Engineering Vol. 65 pp. 121 - 137.

ACKERS, P., WHITE, W.R., PERKINS, J. A. and HARRISON, A.J.M. (1980). Weirs and Flumes for Flow Measurements. John Wiley and Sons, New York pp 87 - 211.

BOS, M.G. (Ed.) (1976) Discharge Measurement Structures. International Institute for land reclamation and Improvement, Publication 20, The Netherlands.

BOS, M.G., REPLOGIE, J. A. and CLEMMENS, A.J. (1984) Flow Measuring Flumes for Open Channel Systems. John Wiley and Sons, New York. pp 115 - 301.

CHOW, V.T. (1959) Open Channel Hydraulics McGraw-Hill Book Coy. pp. 45 - 171.

CITRINI, D. (1941) Measuring Flumes, a guide for design, Centre of studies for the application of engineering techniques in agriculture. Milan. pp. 10 - 44.

CLEMMENS, A. H., REPLOGIE, J. A. and BOS, M.G. (1984) Rectangular Measuring Flumes for lined and earthen channels. Journal of Irrigation and drainage A.S.C.E. Vol. 110 No. 2 pp 121 - 137.

CLEMMENS, A.J. and REPLOGLE A.J. (1980) Constructing Simple Measuring Flumes for Irrigation Canals. U S D A farmers bulletin No. 2268, Phoenix, USA.

CONE, V.M. (1917) The Venturi flume. Journal of Agricultural Research, 9 (4), pp 115 - 123.

HARVEY, W.B. (1912) Harvey's Irrigation outlet, Punjab Irrigation branch paper HMSO

IMPRESIT SPA (1974) Hydraulic Calculations for Irrigation land reclamation works. Unpublished detailed Design, Milan - Rome.

REPLOGLE, A.J. (1978). Flumes and broadcrested Weirs, Mathematical Modelling and laboratory ratings In: Dijstelbergen and Spencer E.A. (Eds) flow measurement of fluids. Nor-Holland Publishing Company pp 321-328.

REPLOGLE, A.J. and CLEMMENS A.J. (1981) Measuring Flume of Simplified Construction. Transactions of the American Society of Agricultural Engineers 24(2) pp 362-366.

REPLOGLE, J.A., CLEMMENS, A.J. and BOS, M.G. (1985) Program Computing flume rating tables. Unpublished research work, U.S., Water conservation laboratory Phoenix, Arizona, pp 1-5.

SKOGERBOE, V.G. and HYATT, M.L. (1967) Analysis of submergence in flow Measuring flumes. Joutnal of the Hydraulics Division A S C E No. 4. pp. 183 - 200.

WRIGHT, (1984) On the Forum page of Civil Engineering Journal of A S C E May 1984 p.6.

APPENDIX A

PRESENTATION OF RESULTS

TABLE 4.1: SPECIFIC DIMENSIONS FOR THE LONG-THROATED FLUME MODELS

Notation	Description	Model A Side Contraction only		Model B Bottom Contraction only		Model C Bottom Contraction	
		A1	A2	B1	B2	C1	C2
AL	Length to Gauge (Section 1) (m)	0.600	0.600	0.50	0.50	0.50	0.50
BL	Converging transition length (m)	0.255	0.465	0.7111	0.00	0.771	0.00
TL	Throat length (m)	0.300	0.30	0.305	0.305	0.610	0.610
DL	Diverging transition length (m)	0.475	0.225	0.00	0.731	0.00	0.711
EL	Tail water length to section 2 (m)	3.00	3.00	3.895	3.163	5.35	
P1	Upstream height of ramp (m)	0.00	0.00	0.237	0.237	0.237	0.237
P2	Downstream height of ramp (m)	0.00	0.00	0.237	0.237	0.237	0.237
r	Throat narrowing ratio	0.50	0.50	1.0	1.0	1.0	1.0
EN	Slope for converging transition	3.00	4.20	3.00	0.00	3.09	0.0
EM	Diverging transition slope	4.20	3.00	0.00	3.09	0.0	3.09
B1	Bottom width at section 1 (m)	0.460	0.460	0.467	0.455	0.455	0.455
Z1	Side slope at section 1	0.00	0.00	0.00	0.00	0.00	0.00
Bc	Bottom width at throat (m)	0.230	0.230	0.467	0.467	0.455	0.455
Zc	Side slope at throat	0.00	0.00	0.00	0.00	0.00	0.00
B2	Bottom width at section 2 (m)	0.460	0.460	0.467	0.467	0.455	0.455
Z2	Side slope at section 2	0.00	0.00	0.00	0.00	0.00	0.00

Note: Model D is the Parshall flume model
Model E is an arrangement of model A1 and a vee-notch weir
See Figure 3.3 for illustration of terms.

APPENDIX A

Table 4.2 Laboratory results for side contracted flume A1

Test Date: 11 - 9 - 85

h(m) x 10^{-2}	Q(m^3/sec) x 10^{-3}	log h	log Q	$(\log h)^2$	log h x log Q	h2(m) x10^{-2}
4.6	3.31	-1.34	-2.48	1.80	3.32	2.00
575	5.62	-1.24	-2.25	1.54	2.79	2.00
6.30	5.73	-1.20	-2.24	1.44	2.69	2.00
6.60	6.51	-1.18	-2.19	1.39	2.58	2.20
6.70	7.11	-1.17	-2.15	1.37	2.52	2.30
7.80	8.22	-1.11	-2.09	1.23	2.32	2.50
8.30	8.82	-1.08	-2.05	1.17	2.21	2.50
8.50	9.76	-1.07	-2.01	1.15	2.15	2.90
9.50	11.25	-1.02	-1.95	1.04	1.99	3.20
10.20	12.57	-0.99	-1.90	0.98	1.88	3.40
11.50	13.78	-0.94	-1.86	0.88	1.75	3.50
12.50	16.87	-0.90	-1.77	0.81	1.59	3.60
13.00	17.75	-0.89	-1.75	0.79	1.56	4.00
14.00	19.63	-0.85	-1.71	0.72	1.45	4.20
13.20	18.42	-0.88	-1.73	0.77	1.52	4.00
14.00	20.95	-0.85	-1.68	0.72	1.43	4.20
15.40	23.93	-0.81	-1.62	0.65	1.31	5.00
16.00	24.59	-0.80	-1.61	0.64	1.29	5.40
		-18.32	-36.36	19.11		

*Regression analysis of log h1 on log Q gave

B = 1.517

S = 0.402

C = 0.396

Hence the regression equation

$Q = 0.396h^{1.517}$

APPENDIX A

Table 4.3 Laboratory Results for Side Contraction A2

Test Date: 24 - 10 - 85

h (m) $\times 10^{-2}$	Q(m^3/sec) $\times 10^{-3}$	log h	log Q	$(\log h)^2$	log h x log Q	$h^2 \times 10^{-2}$ (m)
5.50	2.757	-1.26	-2.56	1.59	3.22	2.00
5.00	4.962	-1.30	-2.30	1.69	2.99	2.00
6.00	5.514	-1.22	-2.26	1.49	2.76	2.00
6.20	5.514	-1.21	-2.26	1.46	2.73	2.10
6.20	5.514	-1.21	-2.26	1.46	2.73	2.20
6.60	5.514	-1.18	-2.26	1.39	2.67	2.30
6.80	5.514	-1.17	-2.26	1.37	2.64	2.30
6.80	6.616	-1.17	-2.18	1.37	2.55	2.30
7.40	6.065	-1.13	-2.22	1.28	2.51	2.40
8.00	8.271	-1.10	-2.08	1.21	2.29	2.50
8.30	8.822	-1.08	-2.05	1.17	2.21	2.50
8.30	8.822	-1.08	-2.05	1.17	2.21	2.50
11.00	10.752	-0.96	-1.97	0.92	1.89	3.00
11.50	11.578	-0.94	-1.94	0.88	1.82	3.30
11.40	14.336	-0.94	-1.84	0.88	1.73	3.40
11.40	15.990	-0.94	-1.80	0.88	1.69	3.40
11.40	13.23	-0.94	-1.88	0.88	1.77	3.40
12.50	15.438	-0.90	01.81	0.81	1.63	3.50
12.60	17.092	-0.90	-1.77	0.81	1.59	3.50
14.00	19.298	-0.85	-1.71	0.72	1.45	3.80
14.00	19.739	-0.85	-1.70	0.72	1.45	3.80
14.00	19.849	-0.85	-1.70	0.72	1.45	3.80
13.90	20.401	-0.86	-1.69	0.74	1.45	3.70
14.50	21.503	-0.84	-1.67	0.71	1.40	4.20
		-24.88	-48.22	26.3328	50.83	

Regression Analysis gave

B = 1.557

S = 0.394

C = 0.4026

Hence the regression equation

$Q = 0.403h^{1.56}$

APPENDIX A

Table 4.4 Laboratory Results for bottom contraction B1

h (m) x 10^{-2}	Q m^3/sec x 10^{-3}	log h	log Q	$(\log h)^2$	log h x log Q	h2
*3.85	6.00	-1.42	-2.22	2.00	3.14	1.00
4.60	7.99	-1.34	-2.10	1.79	2.80	1.10
*5.30	11.58	-1.28	-1.94	1.69	2.47	1.20
6.30	11.303	-1.20	-1.95	1.44	2.34	1.50
7.30	14.61	-1.14	-1.84	1.29	2.09	1.90
8.00	18.47	-1.10	-1.73	1.20	1.90	2.00
8.50	19.57	-1.07	-1.71	1.15	1.83	2.00
8.30	19.30	-1.08	-1.74	1.17	1.85	2.30
8.70	19.85	-1.06	-1.70	1.12	1.80	2.50
		-7.984	-12.737	9.166	14.617	

Asterisked values were neglected as error was noticed in the records.

Regression analysis gave

B = 1.50

S = 0.108

C = 0.779

Hence the regression equation

$$Q = 0.779\ h^{1.50}$$

APPENDIX A

Table 4.5 Laboratory results for Bottom contraction B2

h m x 10^{-2}	Q m3/s x 10^{-3}	log h	log Q	$(\log h)^2$	log h x log Q	h2 x 10^{-2}(m)
*3.30	4.96	-1.48	-2.3045	2.19	3.41	0.90
*4.50	7.168	-1.35	-2.1446	1.82	2.89	1.00
4.50	6.947	-1.35	-2.1582	1.82	2.91	1.10
5.30	8.82	-1.28	-2.0545	1.64	2.63	1.10
6.30	10.145	-1.200	-1.994	1.44	2.39	1.20
*6.60	12.68	-1.18	-1.897	1.39	2.34	1.20
6.70	11.58	-1.1739	-1.936	1.38	2.27	1.30
*7.80	17.09	-1.1079	-1.767	1.23	1.96	1.40
*7.80	16.54	1.060	-1.781	1.23	1.97	1.40
8.70	16.54	1.060	-1.781	1.12	1.89	1.60
8.80	13.195	-1.055	-1.740	1.11	1.84	1.60
9.30	19.298	-1.0315	-1.714	1.06	1.77	1.90
9.30	17.09	-1.0315	-1.767	1.06	1.82	1.90
9.30	19.297	-1.0315	-1.714	1.06	1.77	1.90
9.30	19.849	-1.0315	-1.702	1.06	1.76	1.90
		-17.4707	-28.4508	20.63	33.62	

The asteriked values have been approximated since some error were observed in them during the experiment. Regression analysis gave

$B = 1.69$

$S = 0.0615$

$C = 0.867$

Hence the regression equation

$$Q = 0.867\ h^{1.69}$$

APPENDIX A

Table 4.6 Laboratory results for bottom contraction C1

Date 18 - 9 - 85

h m $\times 10^{-2}$	Q m^3/s $\times 10^{-3}$	log h	log Q	(log h)	log h x log Q	h2 $\times 10^{-2}$
4.30	7.17	-1.37	-2.14	1.87	2.93	1.10
4.80	8.33	-1.32	-2.08	1.74	2.74	1.30
5.30	10.23	-1.28	-1.99	1.63	2.54	1.50
6.05	12.13	-1.22	-1.92	1.48	2.33	1.90
6.80	13.23	-1.17	-1.88	1.36	2.19	2.10
7.70	17.04	-1.11	-1.75	1.24	1.95	2.30
*8.60	20.95	-1.07	-1.68	1.14	1.79	2.40
7.70	18.75	-1.06	-1.66	1.12	1.74	2.50
*8.80	22.05	-1.06	-1.73	1.12	1.83	2.50
8.80	20.95	-1.06	-1.68	1.11	1.77	2.50
		13.337	20.8061	16.4963	25.608	

Regression analysis gave

B = 1.65

S = 0.12

C = 1.318

Hence regression equation

$$Q = 1.318\ h^{1.65}$$

N/B The asteriked values are only some approximations due to experimental limitations.

APPENDIX A

Table 4.7 Laboratory results for bottom contraction C2

Date: 25 - 10 - 85

$h \times 10^{-2}$ (m)	$Q \times 10^{-3}$ m^3/s	log h	log Q	$(\log h)^2$	log h x log Q
3.00	4.00	-1.6229	-2.3979	2.31922	3.65176
4.30	7 .30	-1.3665	-2.136677	1.86732	2.919769
4.90	8.30	-1.3098	-2.08092	1.71558	2.72559
5.50	9.50	-1.2596	-2.02228	1.58659	2.54726
6.20	11.80	-1.2076	-1.9281	1.45830	2.32837
7.70	16.9	-1.1135	-1.7721	1.23988	1.97323
8.50	19.30	-1.07058	-1.7144	1.14614	1.8354
8.70	19.80	-1.06048	-1.70333	1.1246	1.8063
8.90	21.10	-1.0506	-1.6757	1.10376	1.76049
9.20	21.50	-1.0362	-1.66756	1.0737	1.72793
		-11.9978	-19.0991	14.6351	23.27615

Regression analysis gave

$B = 1.503$

$S = +0.1283$

$C = 0.744$

Hence the regression equation becomes

$$Q = 0.744h^{1.50}$$

APPENDIX A

Table 4.8 Laboratory results for side contraction
Combined with V-notch weir Model E1

Date_ 30 - 8 - 85

h m $\times 10^{-2}$	Q m3/s $\times 10^{-3}$	log h	log Q	$(\log h)^2$	log h x log Q
2.0	0.551	-1.699	-3.259	2.887	5.537
4.0	1.948	-1.398	-2.710	1.944	3.788
4.50	3.804	-1.347	-2.420	1.814	3.260
4.72	4.19	-1.326	-2.378	1.758	3.153
4.90	4.41	-1.310	-2.356	1.716	3.086
5.08	5.51	-1.294	-2.259	1.674	2.923
5.12	5.789	-1.291	-2.237	1.667	2.888
5.30	4.96	-1.276	-2.304	1.628	2.940
6.06	7.69	-1.217	-2.144	1.481	2.573
6.32	9.08	-1.199	-2.042	1.438	2.448
6.40	8.82	-1.194	-2.055	1.425	2.454
6.41	11.027	-1.193	-1.957	1.423	2.335
6.41	11.027	-1.193	-1.957	1.423	2.335
		-16.937	-30.048	22.29	39.72

Regression analysis gave

$B = 2.557$

$S = 1.02$

$C = 10.48$

Hence the regression equation

$$Q = 10.48\ h^{2.56}$$

APPENDIX A

Table 4.9 Laboratory results for side contracted flume combined with V-notch weir model E2

Date: 5 - 9 - 85

h m $\times 10^{-2}$	Q m 3/s $\times 10^{-3}$	log h	log Q	$(\log h)^2$	log h x log Q
*9.8	0.919	-1.02	-3.04	1.0404	3.101
14.55	7.168	-0.84	-2.14	0.706	1.797
16.9	14.336	-0.80	-1.90	0.64	1.52
19.2	18.011	-0.77	-1.84	0.59	1.417
19.8	18.38	-0.72	-1.74	0.52	1.253
21.2	19.114	-0.70	-1.74	0.49	1.218
*20.8	29.67	-0.68	-1.54	0.46	1.047
16.0	12.50	-0.67	-1.72	0.45	1.152
		-4.5	-11.08	3.396	8.357

*The asteriked values were neglected because some errors were noticed during experimentation. Regression analysis gave

$B = 2.30$

$S = 0.136$

$C = 0.73$

Hence the regression equation

$$Q = 0.73\ h^{2.30}$$

APPENDIX A

Table 4.10: Laboratory results for Parshall Flume Model

Date: 27 - 9 - 85

h (m) x 10^{-2}	Q m 3/s x 10^{-3}	log h	log Q	$(\log h)^2$	log h x log Q
6.7	4.32	-1.17	-2.37	1.378	2.78
6.7	3.93	-1.17	-2.41	1.38	2.82
7.5	4.86	-1.13	-2.31	1.26	2.60
10.0	7.59	-1.00	-2.12	1.10	2.12
11.6	9.81	-0.94	-2.01	0.88	1.88
11.6	9.05	-9.94	-2.04	0.88	1.91
13.6	11.83	-0.87	-1.93	0.75	1.67
18.6	14.87	-0.81	-1.83	0.65	1.48
19.5	20.92	-0.71	-1.68	0.50	1.19
19.5	19.20	-0.71	-1.70	0.50	1.21
		-9.54	-20.49	9.43395	20.0318

Regression analysis gave

$B = 1.5006$

$S = 0.6227$

$C = 0.238$

Hence the regression equation

$$Q = 0.238\ h^{1.5}$$

APPENDIX A

TABLE 4.11: Computer Simulation of Parshall Flume

Date: September 30 - 1985

h x 10^{-2} (m)	Q x 10^{-3} m^3/s	log h	log Q	$(\log h)^2$	log h x log Q
2.5	0.68	-1.602	-3.201	2.566	5.128
4.5	1.57	-1.347	-2.804	1.8144	3.777
6.5	2.76	-1.187	-2.559	1.409	3.0375
8.5	4.17	-1.0706	-2.380	1.1462	2.548
10.5	5.76	-0.979	-2.240	0.958	2.193
12.5	7.52	-0.9031	-2.124	0.8156	1.918
14.5	9.44	-0.8386	-2.025	0.7032	1.698
16.5	11.50	-0.7825	-1.939	0.6123	1.517
17.5	12.58	-0.7570	-1.9003	0.573	1.4385
18.5	13.70	-0.7328	-1.8633	0.5370	1.365
19.5	14.84	-0.7100	-1.8286	0.5041	1.2983
		-10.909	-22.4837	11.640	25.9194

Regression analysis of data gave

$B = 4.41$

$S = 2.67$

$C = 473.8$

Hence $Q = 473.8h^{4.41}$

APPENDIX A

TABLE 4.12: Comupter Simulation of Model A1

$h \times 10^{-2}$ (m)	$Q \times 10^{-3}$ m^3/s	log h	log Q	$(\log h)^2$	log h x log Q
2.5	1.52	-1.602	-2.818	2.566	4.514
*4.5	3.80	-1.347	-2.420	1.8144	3.260
6.5	6.68	-1.187	-2.175	1.409	2.582
8.5	10.07	-1.0706	-1.997	1.1462	2.138
10.5	13.88	-0.979	-1.8576	0.958	1.8186
12.5	18.09	-0.9031	-1.7425	0.8156	1.5736
14.5	22.66	-0.8386	-1.6447	0.7032	1.3792
16.5	27.56	-0.7825	-1.5597	0.6123	1.2205
17.5	30.13	-0.7570	-1.5210	0.573	1.1514
19.5	35.49	-0.7100	-1.450	0.5041	1.0295
		-7.2275	-13.9475	6.7223	12.8928

Regression analysis gave

$B = 1.5715$

$S = 0.3737$

$C = 0.422$

Hence $Q = 0.42h^{1.515}$

APPENDIX A

TABLE 4.13: Computer Simulation of Model A2

$h \times 10^{-2}$ (m)	$Q \times 10^{-3}$ (m^3/s)	log h	log Q	log h x log Q	$(\log h)^2$
2.5	1.51	-1.602	-2.821	2.566	4.519
4.5	3.78	-1.347	-2.4225	1.8144	3.263
6.5	6.66	-1.187	-2.1765	1.409	2.5835
8.5	10.04	-1.0706	-1.998	1.462	2.139
10.5	13.85	-0.979	-1.8586	0.958	1.8196
12.5	18.06	-0.9031	-1.7433	0.8156	1.5744
14.5	22.62	-0.8386	-1.6455	0.7032	1.3799
16.5	27.51	-0.7825	-1.5605	0.6123	1.221
17.5	30.08	-0.7570	-1.5217	0.573	1.1519
19.5	35.43	-0.7100	-1.4506	0.5041	1.0299
		-10.1765	-19.1985	11.1027	20.6815

Regression analysis gave:

$B = 1.53$

$S = 0.365$

$C = 0.43$

Hence $Q = 0.43h^{1.53}$

APPENDIX A

TABLE 4.14 : Computer Simulation of Model B1

h x 10^{-2} (m)	Q x 10^{-3} (m^3/s)	log h	Log Q	$(\log h)^2$	log h. × log Q
2.5	2.96	-1.602	-2.5287	2.566	4.0510
4.5	7.37	-1.347	-2.1314	1.8144	2.8710
6.5	13.03	-1.187	-1.885	1.409	2.2375
8.5	19.69	-1.0706	-1.7057	1.1462	1.8261
10.5	27.28	-0.979	-1.564	0.958	1.5311
12.5	35.73	-0.9031	-1.447	0.8156	1.3068
14.5	44.99	-0.8386	-1.3469	0.7032	1.1295
116.5	55.01	-0.7825	-1.2596	0.6123	0.9856
17.5	60.31	-0.7570	-1.2196	0.573	0.9232
19.5	71.43	-0.7100	-1.1461	0.5041	0.8137
		-10.1765	-16.2341	11.1027	17.6756

Regression analysis gave

B = 1.54

S = 0.0504

C = 0.89

Hence $Q = 0.890h^{1.54}$

APPENDIX A

table 4.15 Computer Simulation of Model B2

$h \times 10^{-2}$ m	$Q \times 10^{-3}$ m^3/s	log h	log Q	$(\log h)^2$	log h x log Q
2.5	3.00	-1.602	-2.52-9	2.566	4.0417
4.5	7.45	-1.347	-2.1278	1.8144	2.8661
6.5	13.10	-1.187	-1.8827	1.409	2.2348
8.5	19.78	-1.0706	-1.70377	1.146	1.8241
10.5	27.39	-0.979	-1.5624	0.958	1.5296
12.5	35.86	-0.9031	-1.4454	0.8156	1.3053
14.5	45.14	-0.8386	-1.3454	0.7032	1.12825
16.5	55.19	-0.7825	-1.2581	0.6123	0.98446
17.5	60.50	-0.7570	-1.2182	0.573	0.92218
19.5	71.66	-0.7100	-1.447	0.5041	0.8127
		-10.1765	-16.21156	11.1027	17.6492

Regression analysis gave

B = 1.54

S = 0.052

C = 0.887

Hence $Q = 0.89h^{1.54}$

APPENDIX A

Table 4.16 Computer Simulation of Model C1

$h \times 10^{-2}$ m	$Q \times 10^{-3}$ m^3/s	log h	log Q	$(\log h)^2$	log h x log Q
3.5	4.77	-1.4559	-2.3215	2.1196	3.3798
4.5	7.06	-1.347	-2.1512	1.8144	2.8976
6.5	12.50	-1.187	-1.9031	1.409	2.2589
8.5	18.83	-1.0706	-1.7251	1.1462	1.8468
10.5	26.08	-0.979	-1.5837	0.958	1.5504
12.5	34.16	-0.9031	-1.4665	0.8156	1.3244
14.5	43.03	-0.8386	-1.3662	0.7032	1.14569
16.5	52.63	-0.7825	-1.2788	0.6123	1.0006
17.5	57.70	-0.7570	-1.2388	0.573	0.9378
19.5	68.37	-0.7100	-1.1651	0.5041	0.8272
		-10.0304	-16.2000	10.656	17.16959

Regression analysis of log on log Q gave

$B = 1.54$

$S = 0.0773$

$C = 0.837$

Hence $Q = 0.837h^{1.54}$

APPENDIX A

Table 4.17 Computer Simulation of Model C2

$hx\ 10^{-2}$ (m)	$Q \times 10^{-3}$ m^3/s	log h	log Q	$(\log h)^2$	log h x log Q
3.5	4.8	-1.4559	-2.3187	2.1196	3.3757
4.5	7.11	-1.327	-2.1481	1.8144	2.8934
6.5	12.57	-1.187	-1.9006	1.409	2.256
8.5	18.91	-1.0706	-1.7233	1.1462	1.8449
10.5	26.18	-0.979	-1.582	0.958	1.5487
12.5	34.29	-0.9031	-1.4648	0.8156	1.32286
14.5	43.17	-0.8386	-1.3648	0.7032	1.1445
16.5	52.81	-0.7825	-1.2773	0.6123	0.999
17.5	57.89	-0.7570	-1.23739	0.573	0.9367
19.5	68.58	-0.7100	-1.1638	0.5041	0.8263
		-10.0304	-16.1879	10.656	17.1489

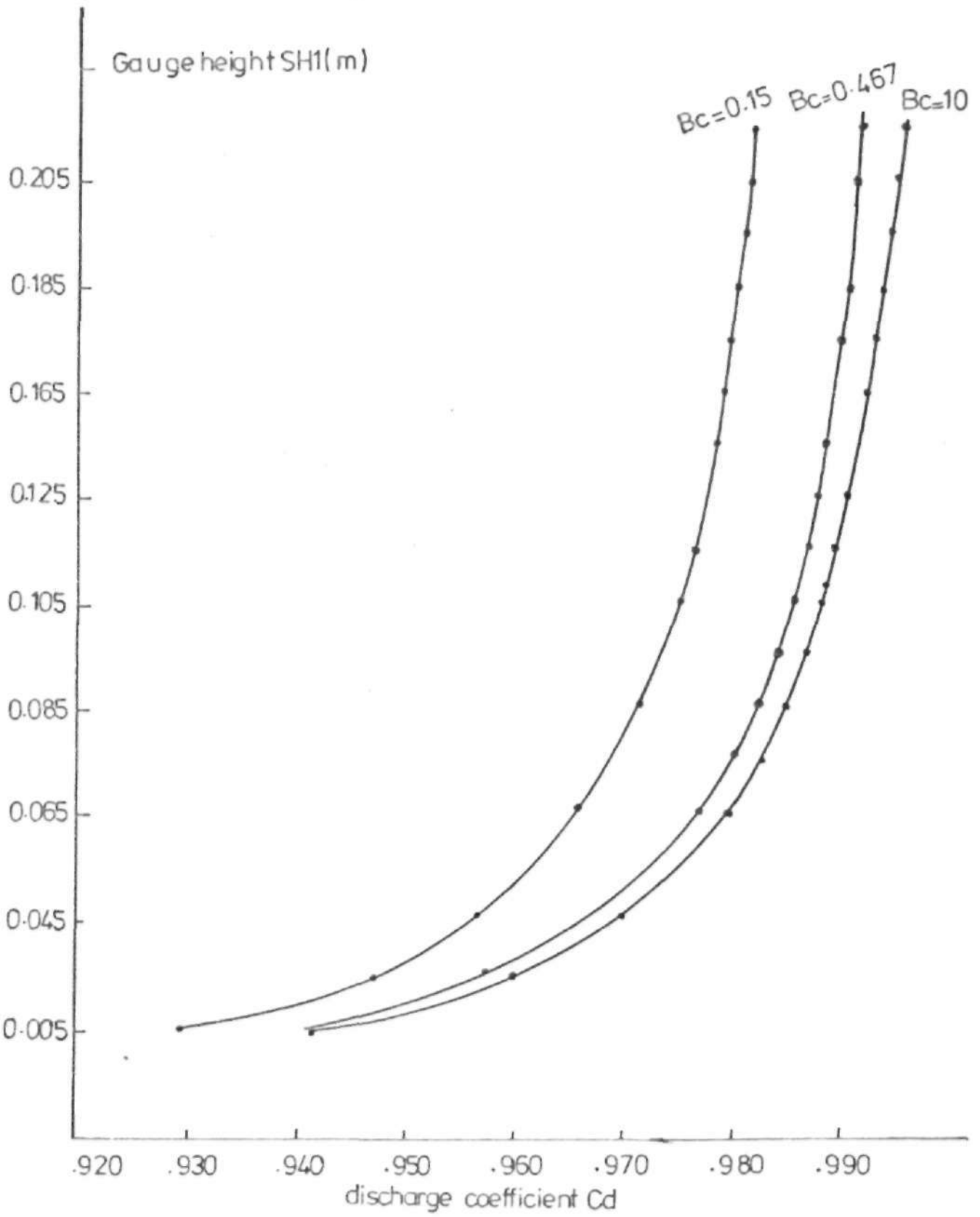
Regression analysis gave

$B = 1.53$

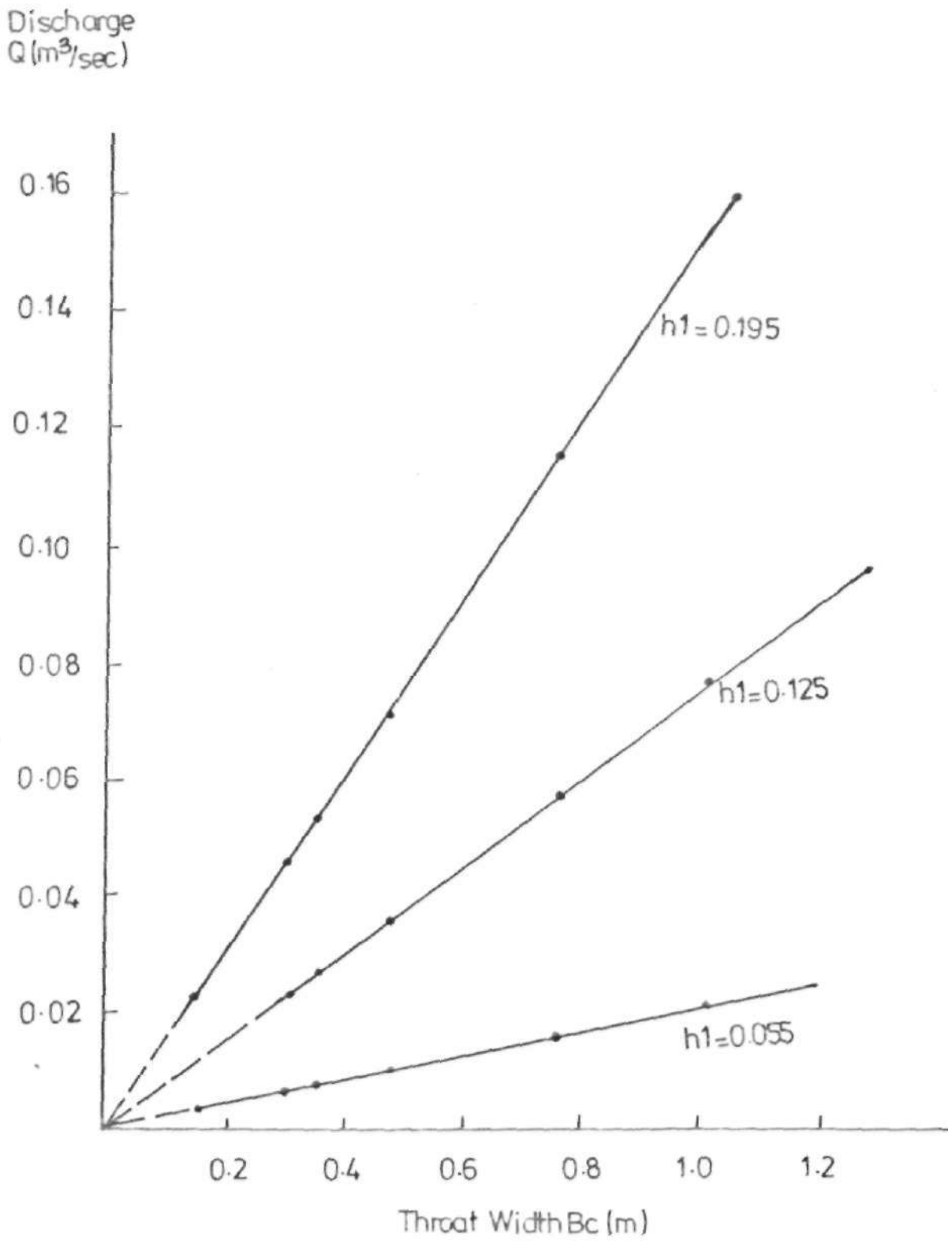
$S = 0.081$

$C = 0.829$

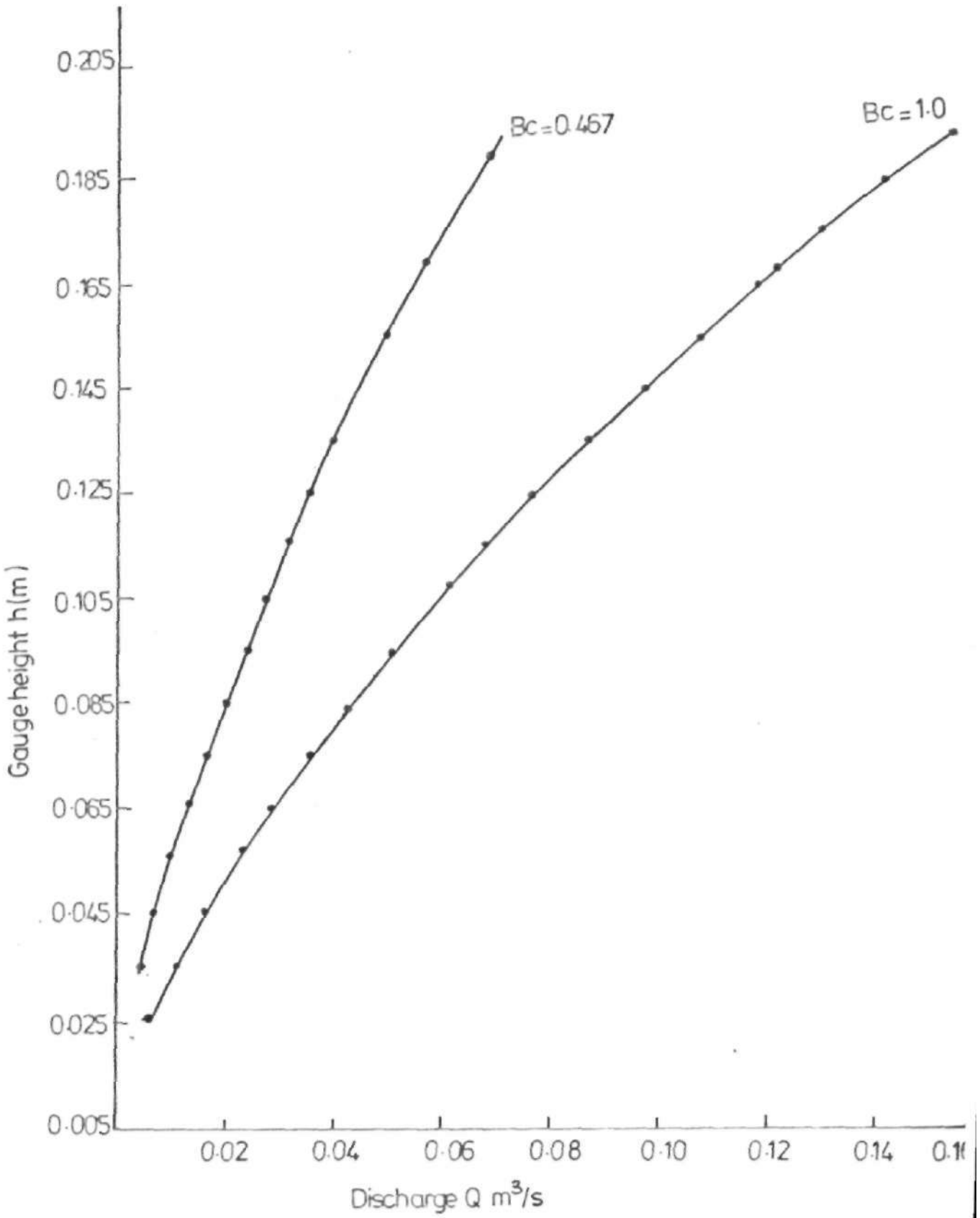
Hence $Q = 0.829h^{1.53}$



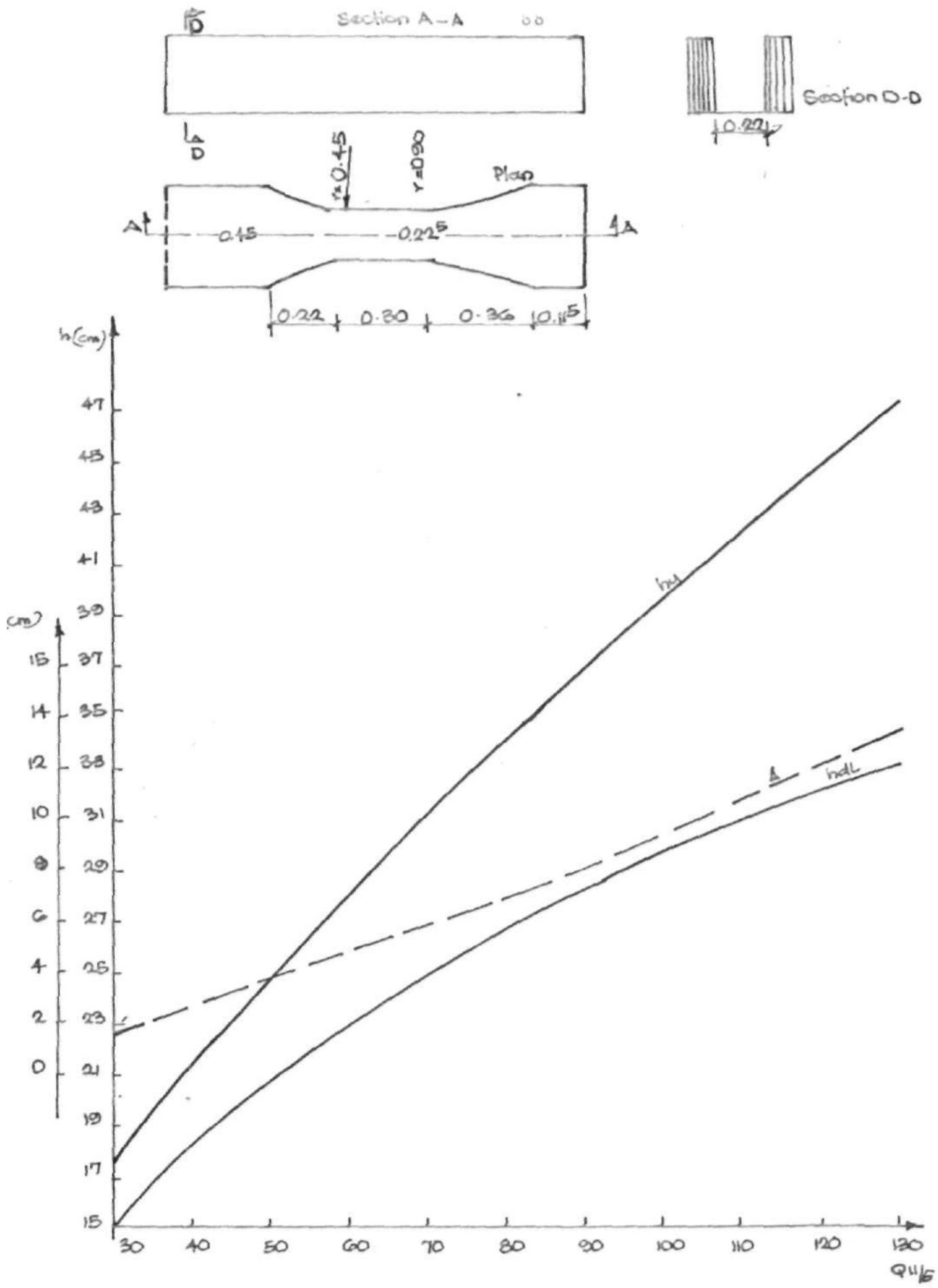
Appendix A1 Plot of gauge height h against Discharge coeff. Cd
* valves are for the bottom contracted Flume



Appendix A2: Plot of Discharge Q against throat width Bc

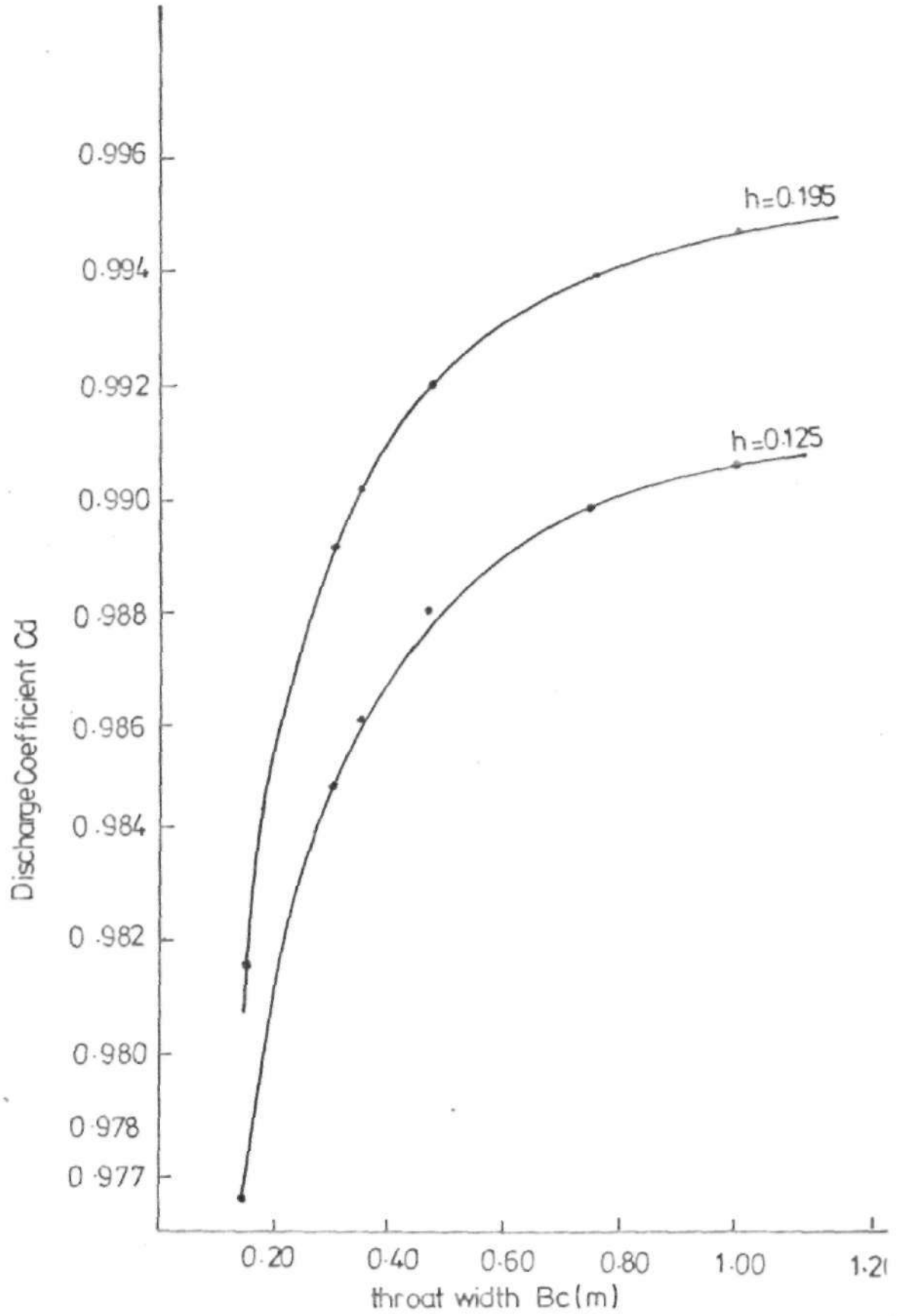


Appendix A3 Plot of gauge height h against Discharge Q



APPENDIX A4: Measuring Flume Calibration

hn = rating curve
A = Submergence Limit Curve
hdl. = downstream total height



Appendix A5 Plot of discharge coefficient Cd against throat width Bc

SOFT WARE FOR SIMULATING FLUME MODELS

```
LIST   Appendix B

1 WIDTH 255
2 POKE 4163,(INT(255/10)-1)*10
3 GOSUB 2240:REM PRINTER IS OFF
4 CLS:CLEAR 3000
20 N1$="PERFORMANCE CHARACTERISTICS OF LONG-"
30 N2$="THROATED FLUMES"
40 N1$=N1$+N2$:PRINT N1$:N2$="":PRINT:PRINT
50 INPUT"LOCATION ";N2$:INPUT"DATE     ";N3$
54 INPUT"TYPE OF FLUME";N6$
55 PRINT"DESCRIBE THE "N6$" FLUME"
56 INPUT N7$:N7$="       "+N7$
60 INPUT"IDENTIFICATION ";N4$
61 CLS:PRINT"N/P ** THIS PROGRAM USES METRIC";
63 PRINT" UNITS."
64 PRINT"DO YOU WISH TO CHANGE TO";
65 INPUT" ENGLISH UNITS";U$:CLS
70 GOSUB 2400:REM PRINT TITLE
100 REM
110 REM
130 REM    AREA FUNCTIONS
140 DEF FNA(X)=(B1+Z1*X)*X
150 DEF FNB(X)=(B4+Z0*X)*X
160 DEF FNC(X)=(B2+Z2*X)*X
170 REM *** TOP WIDTH FUNCTIONS
180 DEF FND(X)=B1+2*Z1*X
200 DEF FNF(X)=B2+2*Z2*X
210 REM *** WETTED PERIMETER FUNCTIONS
220 DEF FNG(X)=B1+2*X*(1+Z1*Z1)^.5
230 DEF FNH(X)=B0+2*X*(1+Z0*Z0)^.5
240 DEF FNI(X)=B2+2*X*(1+Z2*Z2)^.5
250 REM    *** INPUT DATA
255 GOSUB 2400:REM KEYBOARD DATA INPUT
257 IF LEFT$(N6$,1)<>"U" THEN 300
260 REM    *** INPUT B1,Z1,B0,Z0,B2,Z2
270 READ B1,Z1,B0,Z0,B2,Z2
280 DATA .5,1,.2,1,.5,1
290 REM    *** INPUT N1,B1,Z1,F1,F2,E0,K
300 READ N1,Z1,Z0,F1,F2,E0,K
310 DATA .5,.45,.6,.15,.5,.6,.0002
320 REM  *** INPUT START, INCREMENT, LIMIT ON Q*1
330 READ S7,S8,S9
340 DATA .01,.01,.2
350 N=0
351 LET Q=S7:GOSUB 2260:REM PRINTER IS ON
352 GOSUB 2400:REM  PRINT TITLE
354 PRINT:PRINT
355 LPRINT"
```

```
354 GOSUB 2400:REM  PRINT TITLE
356 PRINT:PRINT
360 L4=E2*P2
370 L5=10*(P2+L0/2)-L4
380 E1=0
390 IF P1>0 THEN E1=L2/P1
400 REM  **** PRINT HEADINGS
410 PRINT"CROSS SECTION DATA ","PROFILE DATA"
420 REMT B1,L1
430 PRINT "B1=";B1;TAB(25);"AL=";L1;TAB(35);
440 REMNT P1
450 PRINT "P1=";P1
460 REMNT Z1,L2
470 PRINT "Z1=";Z1;TAB(25);"BL=";L2;TAB(35);
480 REMNT E1
490 PRINT"EN=";E1
500 REMNT B0,L0
510 PRINT "BC=";B0;TAB(25);"TL=";L0
520 PRINT"ZC=";Z0
530 REM
540 PRINT "B2=";B2;TAB(25);"DL=";L4;TAB(35);
550 REM
560 PRINT"P2=";P2
570 REM
580 PRINT "Z2=";Z2;TAB(25);"EL=";L5;TAB(35);
590 REM
600 PRINT"EM=";E2:PRINT
610 REM
620 PRINT"ROUGHNESS K = ";K:PRINT:PRINT
630 PRINT"N/B  Z1,ZC,Z2,EN, and EM are Slopes"
640 PRINT"     B1,BC,B2,AL,BL,TL,DL,EL,P1,";
650 PRINT"and P2 are in Meters":PRINT
660 PRINT "    *  NOT USER INPUT"
670 PRINT:PRINT CHR$(15)
680 PRINT"SH1","Q","FF1","H1/TL",
690 PRINT"CD","CV","DH","Y2","ML"
700 PRINT:REM INSERT UNITS
710 REM *** FOR ENGLISH UNITS SET G=32.16
720 REM *** & V = 1.22*E-05
722 G=32.16:V=1.22&E-05
725 IF LEFT$(U$,1)= "Y" THEN 750
730 G=9.807
740 V=1.14000E-06
750 REM ***INCREMENT UPSTREAM HEAD***
760 FOR S1=67TO 69STEP 88
770 I=0
780 C=0
790 A9=1
800 A8=1
810 B1=S
```

```
820 D9=0
830 D5=0
840 Y1=P1+S1
850 A1=FNA(Y1)
860 T1=FND(Y1)
870 Y0=.7*S1
880 REM *** ITERATION LOOP FOR IDEAL D
890 Y9 = Y0
900 A0 = FNB(Y0)
910 T0 = FNE(Y0)
920 D= (8*A0^3/(T0*A8))^.5
930 H1 = S1+A9*( D/A1 )^2/ (2*G)
940 Y0 = H1-A0 / (2*T0) - D1
950 R9 = ABS((Y0-Y9) / Y0)
960 C  = C+1
970 IF C<100 THEN1030
980 IF R9 > .005 THEN2130
990 Y0 = (Y0+Y9) / 2
1000 D  = (D + D5) / 2
1010 D5 = D
1020 GOTO1040
1030 IF R9 > .0001 THEN890
1040 IF I = 1 THEN1090
1050 D9 = D
1060 IF H1 / L0 < .05 THEN2170
1070 I = 1
1080 GOTO1110
1090 R9 = ABS((D-D5) / D)
1100 IF R9 < .0001 THEN1670
1110 D5 = D
1120 REM *** COMPUTE FRICTION LOSSES
1130 A0 = FNB(Y0)
1140 V0 = D/A0
1150 R  = V0 * L0 / V
1160 R5 =350000.0* L0/K
1170 L9 = R5*V / V0
1180 C6 = 1.328 /((R5)^.5)
1190 C4 = .005
1200 IF R5 <= R THEN1230
1210 C3 = 1.328 /((R)^.5)
1220 GOTO1390
1230 C9 = C4
1240 J1 = .544 *  C4^.5
1250 J2 = 5.61 *  C4 ^.5 - .628
1260 J3 = 1 / (R * C4) + 1 / (4.84* C4 ^.5*L0/D
)
1270 C4 = J1 / (J2-LOG(J3))
1280 R9 = (C4-C9)/C4
1290 IF ABS(R9) > .0001 THEN1230
1300 C5 = .005
```

```
1310 C9 = C5
1320 J1 = .544 * (C5)^.5
1330 J2 = 5.61 * (C5)^.5 - .638
1340 J3 = 1/(R5*C5)+1/(4.84*L9*(C5)^.5/K)
1350 C5 = J1/(J2-LOG(J3))
1360 R9 = (C5-C9)/C5
1370 IF ABS(R9) > .00001 THEN1310
1380 C3 = C4 - L9*(C5-C6)/L0
1390 W0 = FNH(Y0)
1400 R0 = A0/W0
1410 D6 = C3*L0*V0*V0/(2*R0*G)
1420 V1 = 0/A1
1430 W1 = FNG(Y1)
1440 R1 = A1/W1
1450 D4 = .00235 * L1 *V1*V1/(2*R1*G)
1460 Y4 = Y0+5*(S1-Y0)/8
1470 A4 = FNB(Y4)
1480 W4 = FNH(Y4)
1490 V4 = 0/A4
1500 R4 = A4/W4
1510 D5 = .00235*L2*(V1*V1/R1+V4*V4/R4)/(4*G)
1520 D1 = D4+D5+D6
1530 REM *** COMPUTE ENERGY DIST. COEFF.
1540 E = 1.77* C4 ^.5
1550 T0 = FNE(Y0)
1560 D0 = A0/T0
1570 W = 1.5*(D0/R0)-.5
1580 IF W<1 THEN W = 1
1600 F = .025*(L0/R0)-.05
1610 IF F<0 THEN F=0
1620 IF F>1 THEN F=1
1630 A8 = 1 +((3*E*E)-(2*E^3))*W*F
1640 A9 = 1.04
1650 GOTO890
1660 REM *** MODULAR LIMIT CALCULATIONS ***
1670 W0 = FNH(Y0)
1680 R0 = A0/W0
1690 V0 = 0/A0
1700 E9 = 1.2
1710 IF E2 = 0 THEN1740
1720 E9= (LOG(114.59*ATN(1/E2))*.43429448)
1730 E9=(E9-.168)/1.742
1740 Y2 = Y0+P2
1750 E=0
```

```
1760 REM *** ITERATION LOOP ON Y2
1770 A2 = FNC(Y2)
1780 W2 = FNI(Y2)
1790 R2 = A2/W2
1800 V2 = Q/A2
1810 H9 = Y2-P2+V2*V2/(2*G)
1820 D8 = .00235*L4*(V0*V0/R0+V2*V2/P2)/(4*B)
1830 D7 = .00235*L5*V2*V2/(2*R2*B)
1840 D9 = E9*(V0-V2)^2/(2*G)
1850 D2 = D7+D8+D9
1860 H2 = H1-D1-D2
1870 R9 = (H2-H9)/H2
1880 IF ABS(R9) < .001 THEN1960
1890 Y2 = Y2 * (H2+P2)/(H9+P2)
1900 C  = C + 1
1910 IF C > 100 THEN1930
1920 GOTO1770
1930 H2 = (H2+H9)/2
1940 PRINT "MODULAR LIMIT CALCS DID NOT ";
1950 PRINT "CONVERGE"
1960 M = H2/H1
1970 D = H1 - H2
1980 T1 = FND(Y1)
1990 D1 = A1 / T1
2000 F1 = Q / A1/(G*D1)^.5
2010 Y9 = Y0*S1 / H1
2020 C1 = Q/09
2030 C2 = (H1/S1)^.5 * FNE(V0)/SQR(Y9)
2040 H9=H1/L6
2050 REM *** PRINT OUTPUT
2060 PRINT S1,Q,F1,H9,C1,C7,D,Y2,F
2070 REM
2080 IF H1/L0 > 1 THEN2100
2090 IF F1>.5 THEN2210
2100 NEXT S1
2110 STOP
2120 REM *** ERROR / INTERMEDIATE MESSAGES
2130 PRINT"SUPPLY AND DISCHARGE DID NOT CONVERGE
"
2140 PRINT " L= "V0" Y9= "Y9" P= "P2" D= "D
2150 STOP
2160 ST 2
2170 PRINT"H1/L < 0.05"
2180 GOTO2000
2190 PRINT"H1/L > 1.0"
2200 STOP
2210 PRINT"F1 > .5"
2220 STOP
2230 END
2240 REM printer OFF
2250 POKE 53505,162
```

```
2260 DOKE 3187,1919
2270 RETURN
2280 REM printer ON
2290 DOKE 3189,1921
2300 DOKE 3187, 1918
2310 RETURN
2400 REM *** PRINT TITLES
2410 PRINT N1$:PRINT
2412 PRINT"TYPE: "N6$" FLUME"
2414 PRINT N7$
2420 PRINT"IDENTIFICATION: ";N4$,
2430 PRINT"DATE: ";N3$:PRINT
2435 PRINT          "LOCATION: ";N2$:PRINT:PRINT
2440 RETURN:REM from title
2500 REM *** INPUTS
2510 INPUT"SUPPLYING DATA FROM KEYBOARD ";N5$
2520 IF LEFT$(N5$,1)<>"Y" THEN 2800
2530 INPUT"       Value of B1          ";B1
2540 INPUT"       Value of Z1          ";Z1
2550 INPUT"       Value of BC          ";BC
2560 INPUT"       Value of ZC          ";ZC
2570 INPUT"       Value of B2          ";B2
2580 INPUT"       Value of Z2          ";Z2
2590 CLS:GOSUB 2400:REM PRINT TITLE
2600 INPUT"       Value of AL          ";L1
2610 INPUT"       Value of BL          ";L2
2620 INPUT"       Value of TL          ";LC
2630 INPUT"       Value of P1          ";P1
2640 INPUT"       Value of P2          ";P2
2650 INPUT"       Value of EM          ";E1
2660 INPUT"       Value of  N          ";F
2670 CLS:GOSUB 2400:REM PRINT TITLE
2680 INPUT"       START ?              ";S7
2690 INPUT"       INCREMENT?           ";S8
2700 INPUT"       LIMIT ON SH1         ";S9
2710 CLS:PRINT "HAND YOU ";N5$
2800 RETURN:REM input
OK
```

APPENDIX C

Sensitivity to sill height variation

Sill height P_1 (m)	Discharge Q (m^3/sec)	Velocity Coeff. Cv	Froude No Fr	H1/TL
0.055	0.028	1.12	0.31	0.35
0.105	0.026	1.06	0.19	0.34
0.155	0.026	1.04	0.14	0.34
0.205	0.025	1.03	0.10	0.33
0.237	0.025	1.02	0.09	0.33
0.305	0.025	1.01	0.07	0.33
0.405	0.025	1.01	0.05	0.33
0.805	0.025	1.00	0.02	0.33

*Above values were obtained for Gauge height 'SH1' = 0.10m.

0.055	0.122	1.24	0.50	0.95
0.105	0.114	1.15	0.37	0.90
0.155	0.109	1.11	0.29	0.88
0.205	0.107	1.08	0.24	0.86
0.237	0.106	1.06	0.21	0.85
0.305	0.104	1.05	0.17	0.84
0.405	0.102	1.03	0.13	0.83
0.805	0.100	1.01	0.06	0.83

*Above values were obtained for Gauge height 'SH1' = 0.25m

APPENDIX C (Contd)

Sensitivity to sill height variation

Sill height P_1 (m)	Discharge $Q(m^3/sec)$	Velocity Coeff. Cv	Froude No Fr	H1/TL
0.055	0.165	1.27	0.63	1.16
0.105	0.153	1.18	0.41	1.09
0.155	0.146	1.13	0.33	1.07
0.205	0.143	1.11	0.27	1.05
0.237	0.141	1.08	0.24	1.03
0.305	0.138	1.06	0.20	1.02
0.405	0.136	1.04	0.16	1.01
0.805	0.132	1.02	0.08	1.00

*Above values were obtained for Gauge height

'SH1' = 0.30m.

APPENDIX D

Sensitivity to Roughness factor k

K ($m \times 10^{-4}$)	Q m^3/sec	Cd	Cv	DH m
0.01	0.01388	0.9818	1.0588	0.0034
0.05	0.01388	0.9831	1.0588	0.0034
0.50	0.01388	0.9831	1.0588	0.0034
1.00	0.01388	0.9831	1.0588	0.0034
5.00	0.01395	0.9828	1.0647	0.0034
10.00	0.01388	0.9831	1.0588	0.0034
50.00	0.01388	0.9831	1.0588	0.0034
100.00	0.01388	0.9831	1.0588	0.0034

*Above values were obtained for Gauge height 'SH1' = 0.105m

0.01	0.02507	0.9881	1.0615	0.0046
0.05	0.02507	0.9881	1.0615	0.0046
0.50	0.02507	0.9881	1.0615	0.0046
1.00	0.02507	0.9881	1.0615	0.0046
5.00	0.02517	0.9879	1.0606	0.0046
10.00	0.02507	0.9881	1.0615	0.0046
50.00	0.02507	0.9881	1.0615	0.0046
100.00	0.02507	0.9881	1.0615	0.0046

*Above values were obtained for Gauge height 'SH1' = 0.155m

APPENDIX D (CONTD.)

Sensitivity to Roughness factor K

k ($m \times 10^{-4}$)	Q M^3/sec	Cd	Cv	DH m
0.01	-	-	-	-
0.05	0.06970	0.9932	1.0644	0.0081
0.50	0.06961	0.9919	1.0642	0.0082
1.00	0.06960	0.9916	1.0641	0.0082
5.00	0.06961	0.9897	1.0661	0.0083
10.00	0.06930	0.9887	1.0638	0.0083
50.00	0.06910	0.9846	1.0632	0.0084
100.00	0.06891	0.9818	1.0629	0.0085

Above values were obtained for Gauge height

'SH1' = 0.305m.

APPENDIX E

Sensitivity to throat length variation

Throat length TL(m)	Discharge (m^3/sec)	Hl/TL	Cd	Head loss DH (m)	Modular limit ML
0.055	0.0075	0.8213	0.9845	0.0146	0.6769
0.155	0.0075	0.2914	0.9764	0.0147	0.6755
0.305	0.0074	0.1481	0.9674	0.0147	0.6749
0.50	0.0073	0.0903	0.9576	0.0147	0.6750
0.90	0.0071	0.0501	1.0051	0.0146	0.6756
1.00	-	-	-	-	-

*The above value were obtained for gauge height 'SH' = 0.045m in the Bl bottom contracted flume.

APPENDIX F

Sensitivity to narrowing ratio factor

Narrowing ratio 'r' %	Discharge Q m^3/s	H1/TL	DH m
15.00	0.0024	0.1479	0.0027
30.00	0.0048	0.1492	0.0023
35.00	0.0057	0.1497	0.0022
46.70	0.0077	0.1517	0.0020
75.00	0.0133	0.1600	0.0018
90.00	0.0173	0.1685	0.0018

Above values were obtained for Gauge height
'SH1' = 0.045m

15.00	0.0073	0.3124	0.0046
30.00	0.0150	0.3154	0.0038
35.00	0.0176	0.3169	0.0036
46.70	0.0241	0.3216	0.0031
75.00	0.0427	0.3432	0.0024
90.00	0.0567	0.3675	0.0023

Above values were obtained for Gauge height
'SH1' = 0.095m

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APPENDIX G

Performance responses to the Position of the Constriction

Position of constriction	SHJ m	Discharge Q m^3/sec	HI/TL	Head loss DH m x 10^{-4}
Side	0.025	0.0015	0.0855	9.907
Bottom	0.025	0.0015	0.0821	91.518
Side	0.055	0.0052	0.1896	8.839
Bottom	0.055	0.0040	0.1813	171.112
Side	0.105	0.0139	0.3636	7.391
Bottom	0.105	0.0134	0.3493	264.539
Side	0.155	0.0251	0.5376	6.015
Bottom	0.155	0.0244	0.5210	324.727
Side	0.195	0.0355	0.6769	4.932
Bottom	0.195	0.0350	0.6609	369.865

*Above values were obtained for constant throat length (0.30m) and throat width (0.23m) for both flumes.

APPENDIX H

Sensitivity to entrance and exit conditions

Flume type	SHI m	Discharge Qm m^3/sec	HI/TL	DH (m)	ML
B1	0.055	0.0098	0.1813	0.0171	0.6912
B2	0.055	0.0101	0.1813	0.0171	0.6912
B3	0.055	0.0101	0.1813	0.0120	0.7832
B4	0.050	0.0087	0.1647	0.0157	0.6865
B1	0.155	0.0486	0.5211	0.0326	0.7947
B2	0.155	0.0499	0.5211	0.0326	0.7947
B3	0.155	0.0501	0.5211	0.0228	0.8564
B4	0.150	0.0476	0.5038	0.0318	0.7931

Only the Bottom-contracted flume has been considered and the following notations apply

B1 = Gradual entrance and Sudden exit

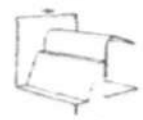
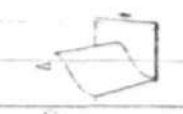
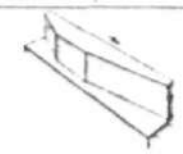
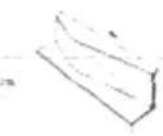
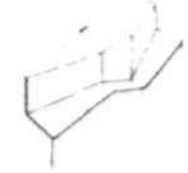
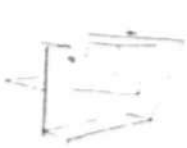
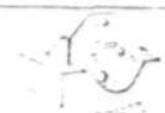
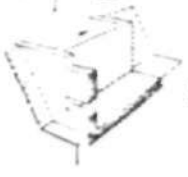
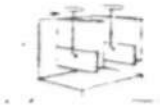
B2 = Gradual entrance and Gradual exit

B3 = Sudden entrance and Gradual exit

B4 = Sudden entrance and Sudden exit.

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APPENDIX I: Various Irrigation Measuring and Regulating Structures

1 Name of structure and section number in which structure is described	2 Sketch of structure	3 Shape of control section perpendicular to flow and μ-value	4 M = measuring MR = measuring & regulating	5 H_1 min or Sh_1 min	6 H_1 max or Sh_1 max	7 minimum crest height above approach channel bottom p	8 minimum size of control b or B, w and D_p	9 range of notch angle θ degrees
Triangular profile flat-vee weir (6.6)		(truncated) triangular μ = 1.7 to 2.5	M	0.03 m steel 0.06 m concrete	1.00 m 3.0 p	0.06 m 0.33 H_1	0.30 m 2 H_1	158°36' 114°36'
Thacher's movable standing vane weir (6.5)		rectangular μ = 1.6	MR	0.05 m	1.00 m	1.4 h_1 max	0.30 m 2 h_1	-
USBR-Standard spillway (6.6)		rectangular μ = 1.5	M	0.06 m	depends* on h_d 3.0 p	0.15 m 0.2 h_1	0.30 m 2 H_1	-
Cylindrical crested weir (6.7)		rectangular μ = 1.5	MR	0.06 m 0.1 r	depends* on r 3.0 p	0.15 m 0.33 h_1	0.30 m 2 H_1	-
Long-throated flumes (5 basic shapes) (7.1)		rectangular μ = 1.5	M	0.06 m 0.1 L	1.0 L 1.0 B	0 but Fr≤0.3	0.30 m*	-
		(truncated) triangular μ=1.7 to 2.5	M - -	for all flumes	for all flumes	for all flumes	B≥0.10 m*	30 to 150
		trapezoidal μ=1.6 to 2.4	M		Take: in general $B_1 \geq 2$ m		B≥0.30 m*	side slope variable**
		parabolic μ = 3.0	M				$B \geq 0.10$ m*	-
		Semi-circular μ is variable but ≤ 2.0	M			↓	4 x 0.20 m*	-
Throatless flumes with rounded transition (7.2)		rectangular μ = 1.5	M	0.06 m	2.00 m 1.5 h	0	0.30 m H_1 max	-
Throatless flumes with straight slope transition (7.3)		rectangular μ = 1.5	M	0.06 m	1.80	0	0.105 m only	-
Parshall flumes (22 types) (7.4)		rectangular μ = 1.15 and 1.60	M	0.015 m to 0.03 m	0.21 m to 0.33 m	0 level floor	0.0254 m to 0.0762 m	-
		μ = 1.522 to μ = 1.607	M	0.03 h_1 0.045 h_1 and 0.076 h_1	0.45 m to 0.76 m		0.1524 m to 2.438 m	-
		μ = 1.60	M	0.09 m	1.07 m to 1.83 m		1.346 m to 15.24 m	-
Cutthroat flumes (3 types) (7.5)		also: trapezium μ = 1.0 to 2.4	M	0.06 m to 0.24 m 0.05 m to 0.09 m 0.05 m	0.61 m to 3.00 m 0.24 m to 1.06 m 1.06 m to 1.20 m	0	see Figure 7.21	-
Circular sharp-crested orifice (8.1)		circular μ = 0.5	M	$Sh \geq 0.03$ m $h_1 \geq d$	-	0.3 d	$h_1 \geq 0.3 h_1$ $d \geq 0.2$ m	-
Rectangular sharp-edged orifice (8.2)		rectangular μ = 0.5	M but MR if suppressed	$Sh \geq 0.03$ m $h_1 \geq 0.15$ m	-	0	$b \geq 0.10$ m $w \geq 0$ m	-
Constant head orifice (8.3)		rectangular μ = 0.5	MR	$Sh \geq 0.06$ m $h_1 \geq 2.5$ w	$Sh \geq 0.06$ m	0	usually* b=1.40 m and w=1.5 m	-

Source: Adapted from reference Bos (Ed) (1976).