THE RATING OF SLUICING FLUMES IN COMBINATION WITH SHARP - CRESTED AND CRUMP WEIRS UNDER MODULAR AND NON-MODULAR FLOW CONDITIONS

H Bruce • J Rossouw • A Rooseboom

WRC Report No 980/2/00

Water Research Commission

THE RATING OF SLUICING FLUMES IN COMBINATION WITH SHARP-CRESTED AND CRUMP WEIRS UNDER MODULAR AND NON-MODULAR FLOW CONDITIONS

by
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PREFACE

This report is one of five which were produced under Water Research Commission contract No. 980, and which are listed below.

The first three reports contain results which may be regarded as conclusive, whilst the last two contain the results of exploratory research which may serve as the basis of further research.

WRC Report No. 980/1/00
The rating of compound sharp-crested weirs under modular and non-modular flow conditions.

WRC Report No. 980/2/00
The rating of sluicing flumes in combination with sharp-crested and Crump weirs under modular and non-modular flow conditions.

WRC Report No. 980/3/00
Discharge measurements in terms of pressure differences at bridge piers.

WRC Report No. 980/4/00
Flow gauging in rivers by means of natural controls.

WRC Report No. 980/5/00
The application of Doppler velocity meters in the measurement of open channel discharges.

EXECUTIVE SUMMARY

As part of a previous WRC project, three types of sluicing flumes were developed for use in compound weirs in combination with sharp-crested and Crump weirs, (Rossouw et al., 1998). These sluicing flumes have several advantages which make them ideal structures for flow measurement in South African rivers. These are a high modular limit, stable modular flow characteristics, an ability to measure a wide range of flows accurately, as well as good sediment handling characteristics. These three flumes have been calibrated under modular or free flow conditions in combination with sharp-crested and Crump weirs.

There is a high degree of variability of flow in South African rivers. Flood discharges are part of this variability, and can form an important part of the mean annual runoff. Measuring weirs cannot always be built so that they do not become submerged during floods, but it is nevertheless important that flood discharges be recorded. It is therefore important that these compound weirs be calibrated for flow measurement under non-modular or submerged conditions.

The purpose of the research undertaken for this WRC project is to find a method to calculate the non-modular discharge over compound weirs consisting of sluicing flumes in combination with sharp-crested and Crump weirs.

By analysis of existing data from the previous WRC project, as well as data from laboratory tests undertaken as part of this project, the submergence effect of sluicing flumes has been quantified. A range of configurations of sharp-crested weirs as well as Crump weirs in combination with the sluicing flume have been tested. A new method has been developed to calculate the submerged discharge over these compound weirs. This method is suitably accurate, and can be recommended to the DWAF for use.

The calculation procedure that must be followed in order to calculate the submerged discharge over these compound weirs becomes rather complicated due to the iterations that must be carried out. In order to clarify these procedures, flow charts are provided which set out the steps that must be followed.

Calibration curves for all the combinations of compound weirs analysed in this report are also provided. These can be used to obtain estimates of the discharge in the field, and can also be used as a check on any calculations carried out.

The principal goal of this project, namely that of finding a suitably accurate method to calculate the non-modular discharge over these compound weirs has therefore been achieved.

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Dr M J Shand

Mr S van Biljon

Mr J van Heerden

Dr P Wessels

Miss U Wium (Secretary)

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Thanks are also due to all undergraduate and postgraduate students involved with this project, as well as the personnel in the workshops and hydraulics laboratory of the Civil Engineering Department at the University of Stellenbosch who assisted with implementing a successful test program.

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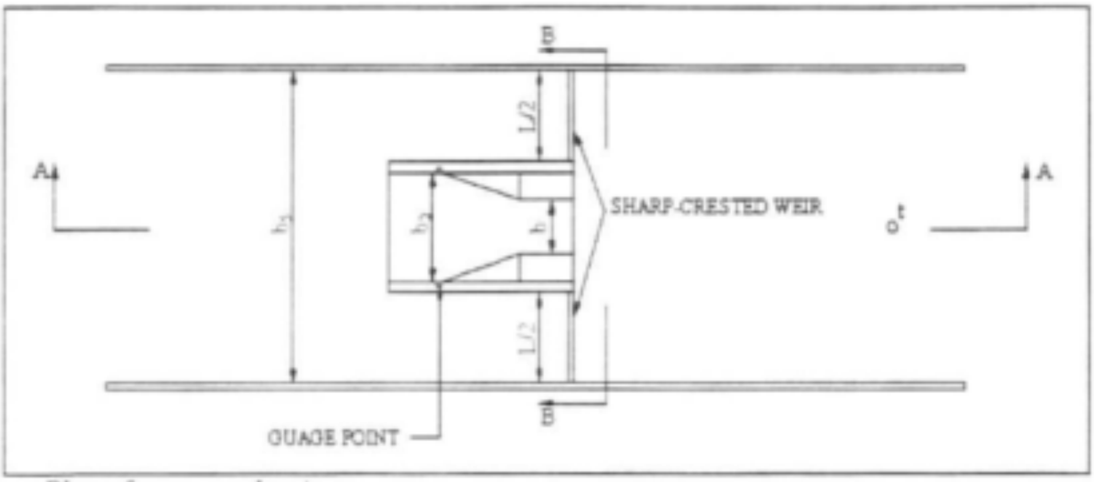
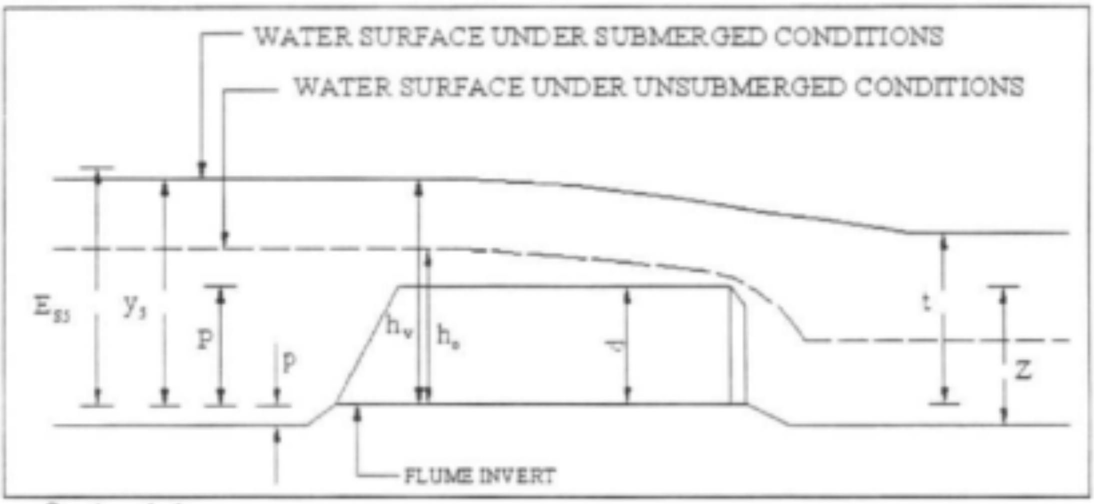


Plan of compound weir



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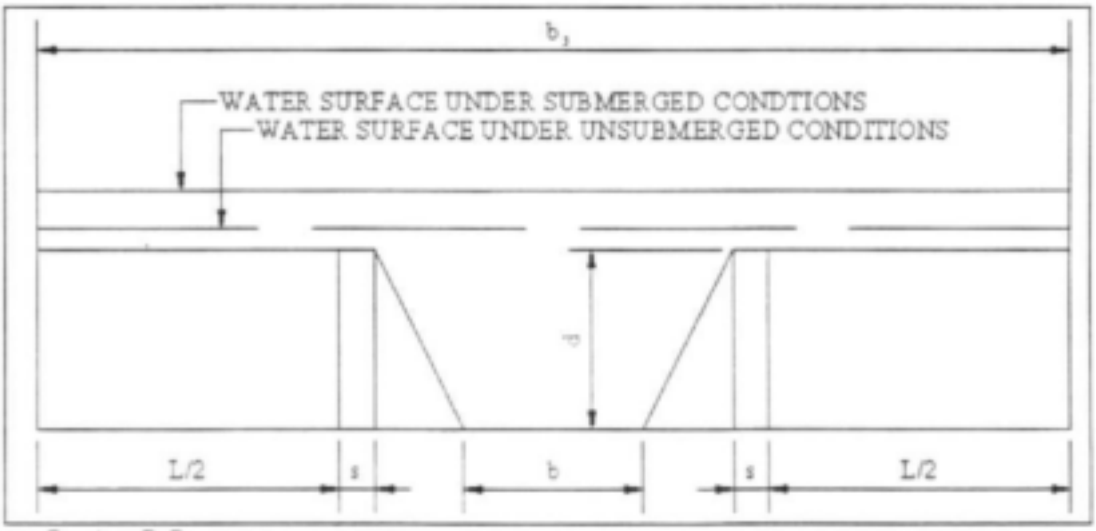

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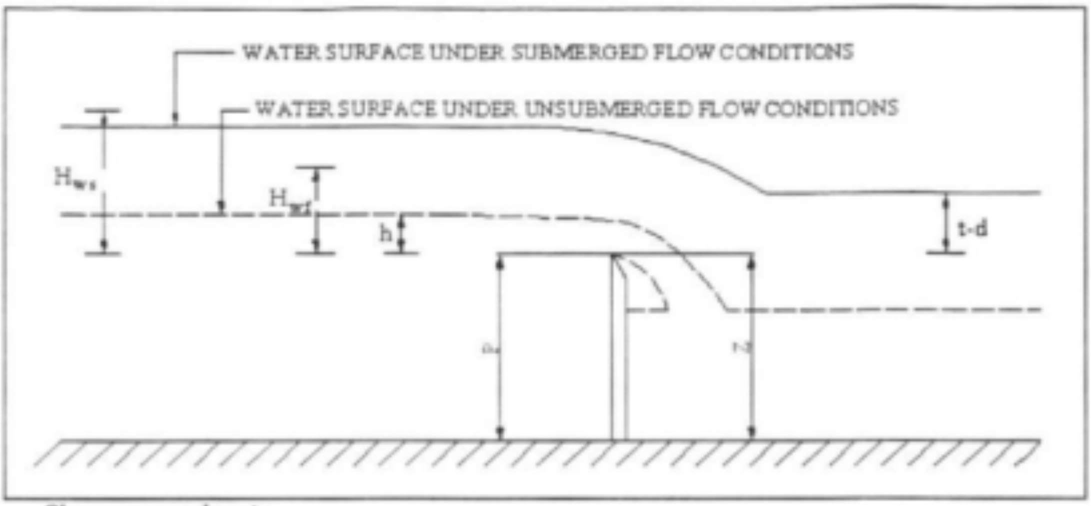
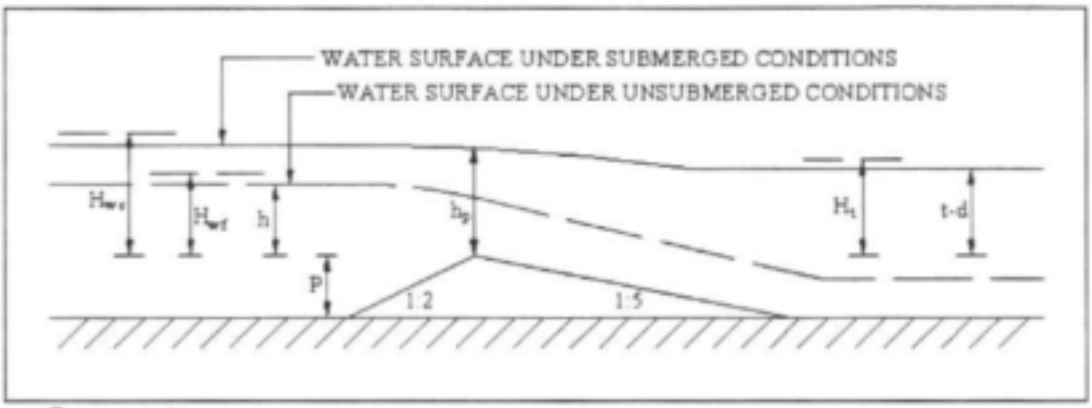


Sharp-crested weir



Crump weir

Symbol	**Meaning of symbol**
b	bottom width of flume outlet (m)
b_2	width of flume at gauge position (m)
b_5	width of upstream pool (equal to channel width) (m)
d	height of flume walls (m)
E_{s5}	specific energy in upstream pool, relative to flume invert (m)
H_t	submerged, downstream energy head over Crump weir (m)
H_{wf}	unsubmerged energy head over side, sharp-crested or Crump weirs (m)
H_{ws}	submerged energy head over side, sharp-crested or Crump weirs (m)
h	head over side, sharp-crested or Crump weirs (m)
h_o	water depth at gauge point under modular flow conditions (m)
h_v	water depth at gauge point under non-modular flow conditions (m)
L	length of side weirs (m)
P	pool depth upstream of sharp-crested or Crump weir (m)
p	pool depth upstream of sluicing flume (m)
s	width of flume walls (m)
t	tail water level relative to flume invert (m)
y_5	water depth relative to flume invert in upstream pool (m)
Z	height of structure on downstream side (m)

Symbols not indicated in the above figures:

Symbol	**Meaning of symbol**
A_o	flow area above crest of sharp-crested weir under free flow conditions (m^2)
A_{co}	flow area of vena-contracta under free-flow conditions (m^2)
A_{to}	area of downstream section when the downstream water level just reaches the sharp-crest (i.e. t – d =0) (m^2)
A_c	area of critical section at control (for flume only) (m^2)
B_c	top width of critical section (for flume only) (m)
C_{d2}, C_{d5}	coefficients of discharge for flow through flume
C_w	coefficient of discharge for sharp-crested weirs
E_{sc}	specific energy at control (flume outlet) (m)
E_{s2}	specific energy at the gauge point (m)
g	gravitational acceleration (taken as 9.81 m/s^2)
Q_{ff}	free discharge through flume (m^3/s)
Q_{fs}	submerged discharge through flume (m^3/s)
Q_{lab}	discharge recorded in laboratory (m^3/s)
Q_t	total discharge over compound weir (m^3/s)
Q_{wf}	free discharge over side, sharp-crested or Crump weirs (m^3/s)
Q_{ws}	submerged discharge over side, sharp-crested or Crump weirs (m^3/s)
S_c	degree of submergence of Crump weir
S_f	degree of submergence of flume (= t/h_v)
$S_{s/c}$	degree of submergence of sharp-crested weirs
y_c	critical depth (m)

Acronyms

BSI	British Standards Institute
DWAF	Department of Water Affairs and Forestry
IMFT	Institut de Mécanique des Fluides de Toulouse
WRC	Water Research Commission

1. INTRODUCTION

1.1 GENERAL BACKGROUND

Water is essential to most forms of life, and is therefore the most precious natural resource. As population grows and industry develops, so the availability of water becomes increasingly important. A knowledge of the quantity available is the first step in the efficient management of this vital resource (Ackers and White, 1978). Furthermore, river discharge measurement provides essential data for the design of hydraulic structures and the management of water resources and water quality (Herschy, 1978).

The Directorate of Hydrology in the Department of Water Affairs and Forestry, (DWAF) in Pretoria, has the responsibility of gathering hydrological data in South Africa. In order to obtain this data , the DWAF maintains and operates a network of roughly 800 flow gauging stations throughout the country.

A flow gauging station may be defined as follows:-

"*A gauging station is a site on a river which has been selected, equipped and operated to provide the basic data from which systematic records of water level and discharge may be derived. Essentially it consists of a natural or artificial river cross-section where a continuous record of stage can be obtained and where a relation between stage and discharge can be determined.*" (Herschy, 1978)

The challenges involved in river discharge measurement in South Africa are severe. River flow is highly variable (DWAF, 1986) and high sediment loads are transported especially in the former Eastern and Western Cape, the Free State and Natal (Rooseboom et al., 1992). In addition to these constraints, only limited manpower and financial resources are available for the implementation and maintenance of river discharge measurement networks.

1.2 HIGH FLOW MEASUREMENT

South Africa experiences large floods on a fairly regular basis. Examples are the September 1987 floods in Natal, the 1988 floods in the Orange River, and the recent floods in Mpumalanga and the Northern Province. These floods are important, both in terms of their destructive capacity and their contribution to the mean annual runoff – especially in dry parts of the country (Lotriet, Rooseboom, 1995). Records of floods are required for the design of river structures such as bridges, dams and flood banks and for the operation of flood warning systems (Herschy, 1978).

There are various methods used to estimate high river discharges, as shown below:

Use of measurement methods during the Natal floods:

Method of flow measurement	No. of measurements	No. of flood peaks with T > 50 years
Slope-Area	43	14
Weirs	44	5
Reservoir spillways	18	5
Bridge contractions	1	1

Table 1.1: *Measurement methods used during 1987 Natal floods (van Bladeren and Burger, 1989)*

It can be seen that weirs do provide valuable data on flood discharges. For this reason, the DWAF continues to strive for higher degrees of accuracy and improved methods of discharge estimation at weirs.

High discharges in rivers normally submerge measuring weirs, since due to economic, physical as well as ecological constraints, these weirs cannot be built large enough to prevent submergence. In order to measure these high discharges therefore, it is necessary that weirs be calibrated for flow measurement under submerged or non-modular flow conditions.

1.3 SLUICING FLUMES

As part of this continued drive, the DWAF initiated extensive, WRC sponsored research at the University of Stellenbosch, which over the last few years has led to the development of a new type of gauging structure; the sluicing flume, (Rossouw et al., 1998).

These flumes have three major advantages for use in South Africa, namely that they possess good characteristics with respect to handling heavy sediment loads, they can accurately measure a wide range of flows, and they have a high modular limit.

These sluicing flumes are used in combination with sharp-crested and Crump weirs to form compound weirs, which are well suited to flow measurement in South African conditions.

1.4 PURPOSE OF THIS STUDY

These flumes had been calibrated under free flow conditions in combination with sharp-crested and Crump weirs. It had been found that this calibration can be done theoretically, and that the calibration characteristics of the flumes are stable (Rossouw et al., 1998)

As part of the research conducted for free flow calibration of these weirs, (Rossouw et al., 1998), attempts had been made to calibrate these compound weirs under submerged flow conditions. Their report concluded that further research was required in this field.

The purpose of the further research to find a method to accurately calculate the discharge over these compound weirs under submerged or non-modular flow conditions. This was therefore an extension of the work done previously, and had been made possible by new findings on the submergence characteristics of sharp-crested weirs, resulting from research conducted in that field (Canto, 2000).

2. SLUICING FLUMES AND COMPOUND WEIRS

2.1 SLUICING FLUMES

Three different sluicing flumes had been developed for use in compound weirs (Rossouw et al., 1998). These flumes were developed to comply with international standards as stated in BSI 1981, part 4C, (Loubser, 1997). Several characteristics of these flumes make them well suited for use in South African rivers:

- The flumes possess stable calibration characteristics, insensitive to variations in the adjacent weir structures. This allows the combination of the flumes with a wide variety of adjacent sharp-crested and Crump weir configurations.
- The flume makes use of a horizontal rather than a vertical contraction and thus it possesses good characteristics with respect to handling heavy sediment loads.
- The gauging position is inside the flume wall, and remains largely sediment free. The flume will therefore be able to provide accurate flow measurements even if some sediment deposits are present in the flume.
- The flume possesses good submergence characteristics, with a high modular limit.
- The flumes are able to accurately measure a wide range of discharges.

(after Lotriet, Rooseboom, 1995 and Rossouw et al., 1998)

The flume inlet had a rectangular cross-section, which narrowed to a trapezoidal cross-section at the flume outlet. The three flumes developed all have this basic layout, differing only in their dimensions. Flume 1 was a narrow, deep flume, with a height/width (d/b) ratio equal to 1 (Fig. 2.1). Flume 3 was a wide, shallow flume, with a ratio of d/b of 0.25 (Fig. 2.3). Flume 2 had a shape between that of flumes 1 and 3, with a ratio d/b equal to 0.5 (Fig 2.2). This was the flume most favoured in the prototype.

2.2 COMPOUND WEIRS

The geometry of the compound weirs, consisting of flumes in combination with sharp-crested weirs are shown in Figures 2.1, 2.2, 2.3 and 2.4:

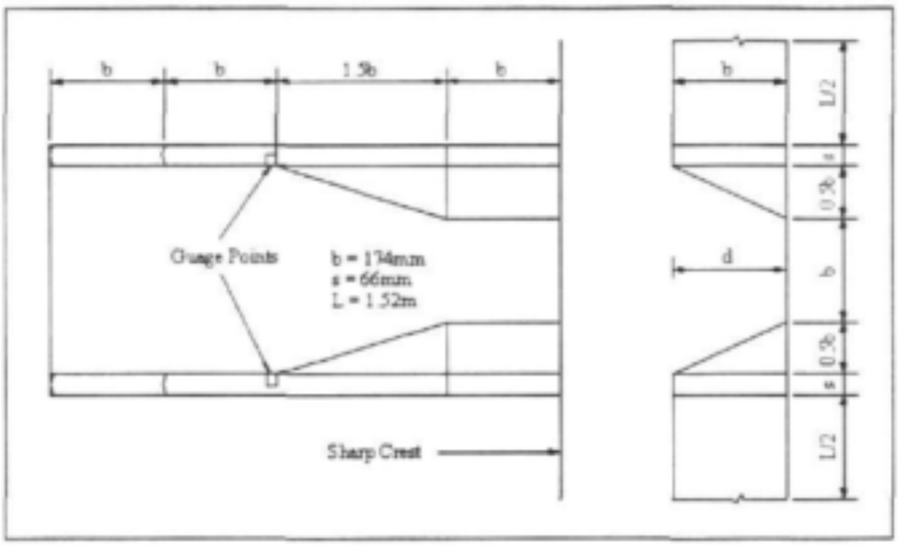


Figure 2.1: *Flume 1 (d/b = 1) with sharp –crested weirs*

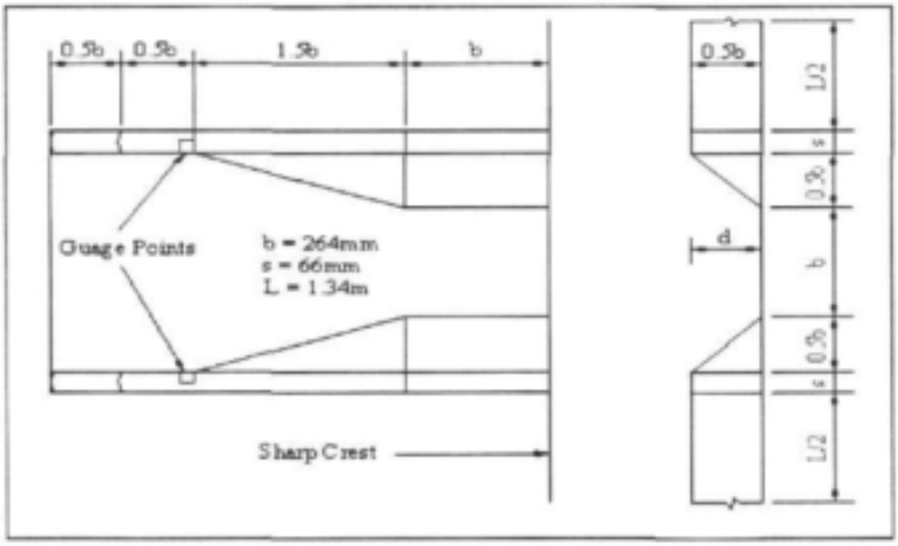


Figure 2.2: *Flume 2 (d/b = 0.5) with sharp-crested weirs*

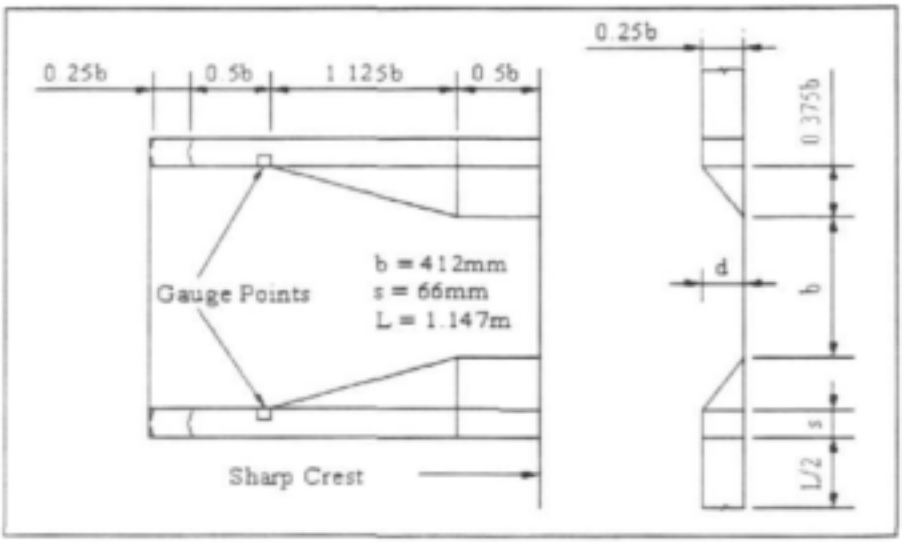


Figure 2.3: *Flume 3 (d/b = 0.5) with sharp-crested weirs*

A summary of the weir dimensions is given below:

	b (m)	d (m)	b_2 (m)	b_5 (m)	L (m)	p (m)	s (m)
Flume 1	0.174	0.174	0.348	2.000	1.520	0.027	0.066
Flume 2	0.264	0.132	0.528	2.000	1.340	0.025	0.066
Flume 3	0.412	0.103	0.721	2.000	1.147	0.025	0.066

Table2.1: *Weir dimensions for flumes with sharp-crested weirs*

Flume 2 (d/b = 0.5) in combination with Crump weirs is shown below:

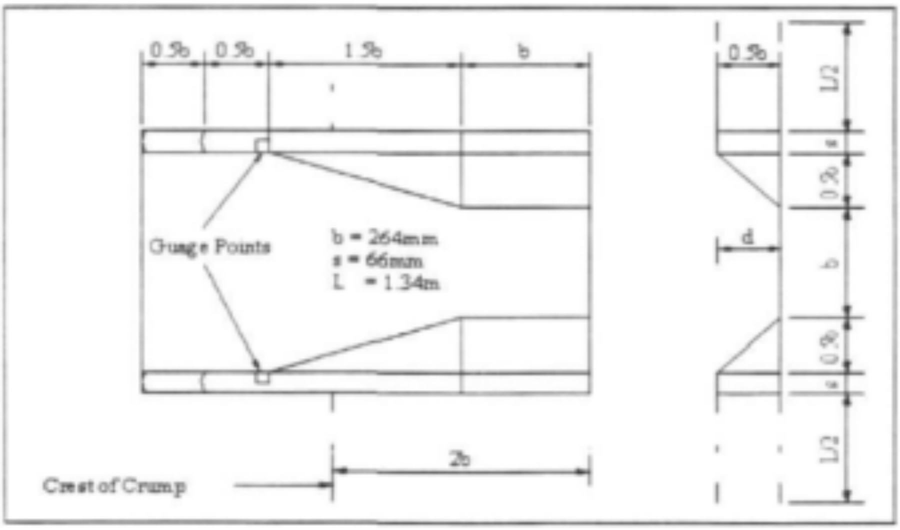


Figure 2.4 : *Flume 2 (d/b= 0.5) with Crump weirs*

The basic dimensions for the compound weir remain the same as per Table 2.1.

Figures 2.5 and 2.6 shown below are two compound weir configurations as built in the prototype:

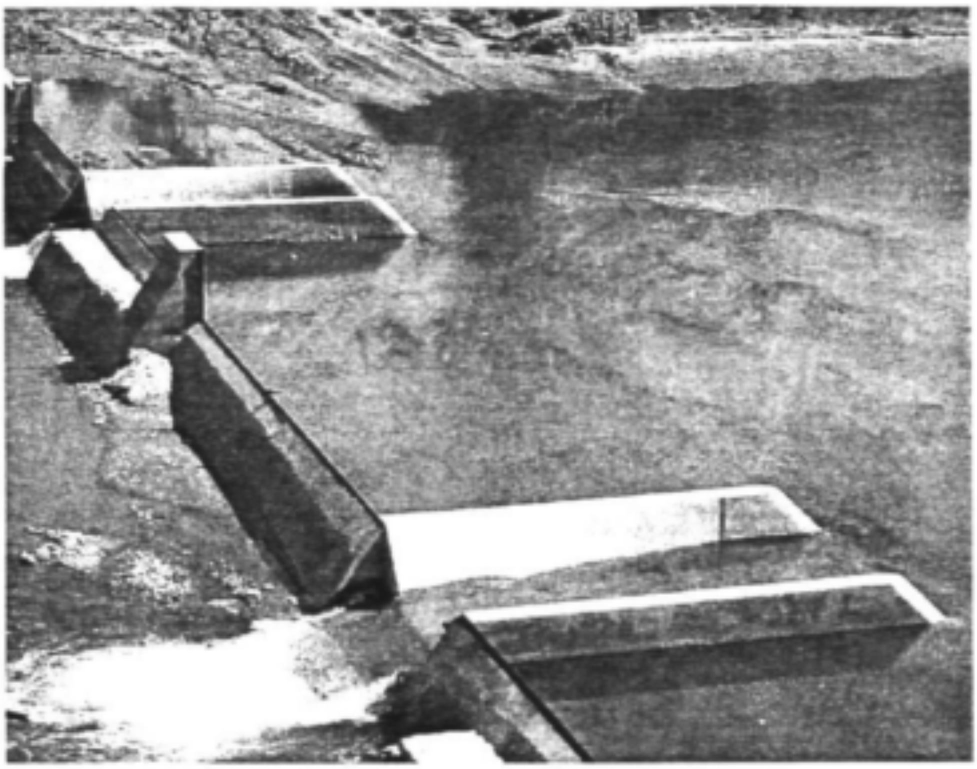


Figure 2.5: *Photograph showing sluicing flumes in combination with sharp-crested weirs (Olifants River, Northern Province)*

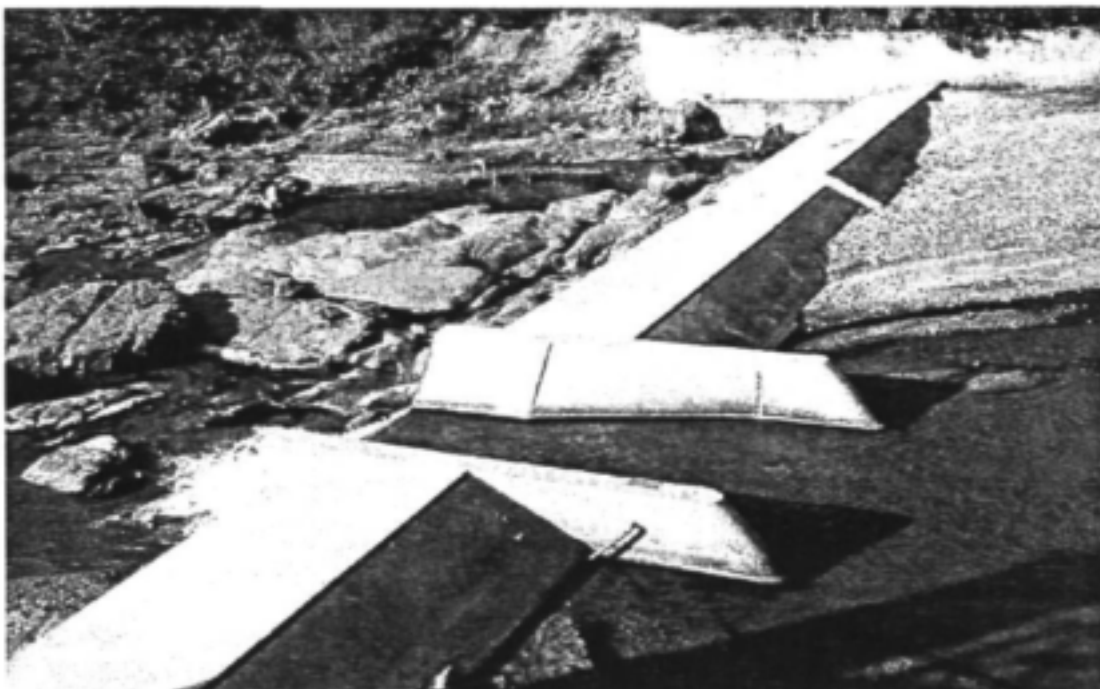


Figure 2.6: *Photograph showing sluicing flume in combination with Crump weirs (Mpambanyoni River, Kwa-Zulu Natal)*

3. DATA ANALYSED

3.1 EXISTING DATA

As previously mentioned, some submergence tests had been conducted along with the modular calibration of the sluicing flumes which have been developed (Rossouw et al., 1998). These tests had featured full-length side sharp-crested or Crump weirs. Data from these tests had been used in the initial analyses, in order to find a suitable method to calculate the submerged discharge over the compound weirs. The extent of the submergence data available for each flume in combination with either sharp-crested or Crump weirs is summarised below:

	h_o/d	h_v/d	S_f	$S_{v/c}$	Q (m^3/s)
Min. value	0.532	0.536	0.341	0.057	0.010
Max. value	1.848	2.121	0.994	0.971	0.303

Table 3.1: *Range of data available for flume 1 (d/b = 1.0) with sharp-crested weirs*

	h_o/d	h_v/d	S_f	$S_{v/c}$	Q (m^3/s)
Min. value	1.678	1.689	0.640	0.133	0.151
Max. value	2.489	2.744	0.928	0.856	0.451

Table 3.2: *Range of data available for flume 2 (d/b = 0.5) with sharp-crested weirs*

	h_o/d	h_v/d	S_f	S_c	Q (m^3/s)
Min. value	1.133	1.138	0.588	0.203	0.050
Max. value	2.390	2.722	1.025	0.996	0.454

Table 3.3: *Range of data available for flume 2 (d/b = 0.5) with Crump weirs*

	h_o/d	h_v/d	S_f	$S_{v/c}$	Q (m^3/s)
Min. value	0.513	0.517	0.466	0.114	0.011
Max. value	2.823	3.604	1.019	0.966	0.355

Table 3.4: *Range of data available for flume 3 (d/b = 0.25) with sharp-crested weirs*

3.2 NEW DATA

Flume 2 (d/b = 0.5) was the flume layout with most potential application in the prototype, but the one for which there is the least data available as far as submergence of the flume in combination with sharp-crested weirs was concerned. For this reason, further laboratory tests were conducted on this flume in combination with sharp-crested weirs, to expand the range of data currently available.

The downstream structure height, Z, was needed in the calculation of the submerged discharge over Crump weirs. This value was not available for the tests conducted as part of the previous WRC project, and consequently, the submerged discharge through the compound weirs could not be calculated. Hence additional tests were conducted on flume 2 in combination with Crump weirs.

A wooden model of the flume with Perspex sharp-crested weirs (and wooden Crump weirs) were installed in a 2m wide glass canal in the Hydraulics Laboratory of the Civil Engineering Department at the University of Stellenbosch. The laboratory configuration and a description of the tests conducted are described in detail in a following Chapter.

To begin with, flume 2 (d/b = 0.5) was tested with full-width sharp-crested weirs, in an identical configuration to the tests conducted previously. In subsequent tests, symmetrical and asymmetrical end-contractions were introduced on the sharp-crested weirs. This was done to simulate the configurations used by DWAF in the prototype weirs, where end contractions occur due to compounding of the sharp-crested weirs, or were introduced for aeration purposes.

Flume 2 was then tested with full width Crump weirs, in a configuration identical to that of the previous tests.

The configurations of sharp-crested weirs tested are shown in Figures 3.1, 3.2, 3.3 and 3.4:

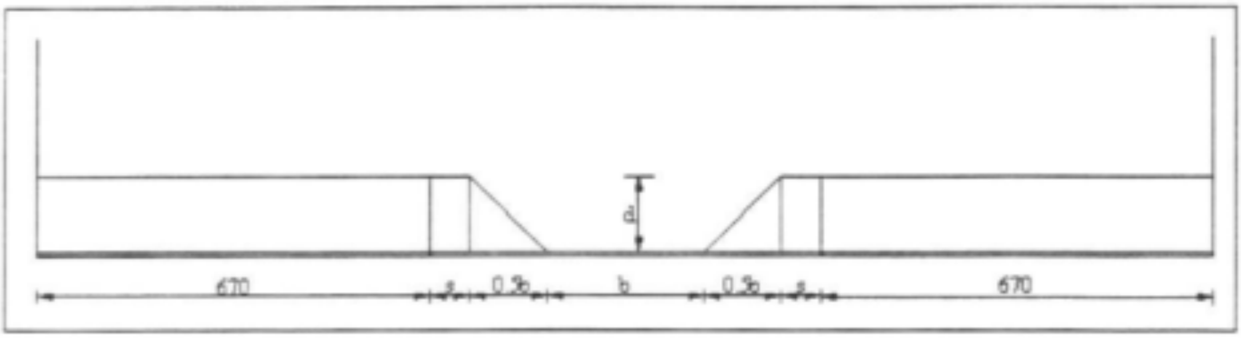


Figure 3.1: *Flume 2 (d/b = 0.5) with full-width sharp-crested weirs (Tests A, B, C, D)*

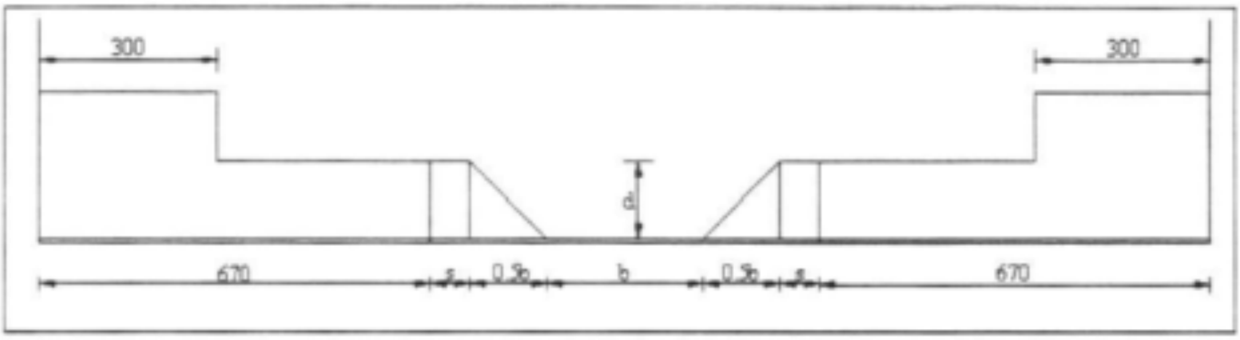


Figure 3.2: *Flume 2 (d/b = 0.5) with symmetrically 300mm end-contracted sharp-crested weirs (Tests E, F)*

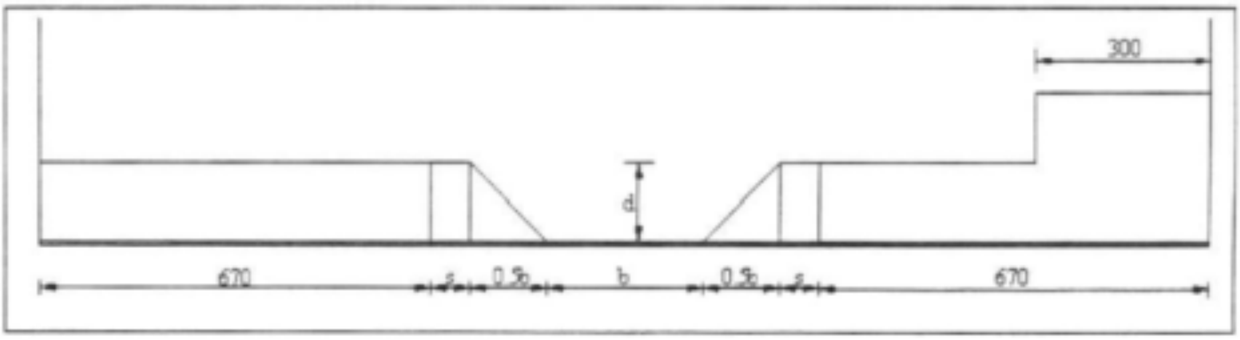


Figure 3.3: *Flume 2 (d/b = 0.5) with left sharp-crested weir 300mm end-contracted (Tests G, H)*

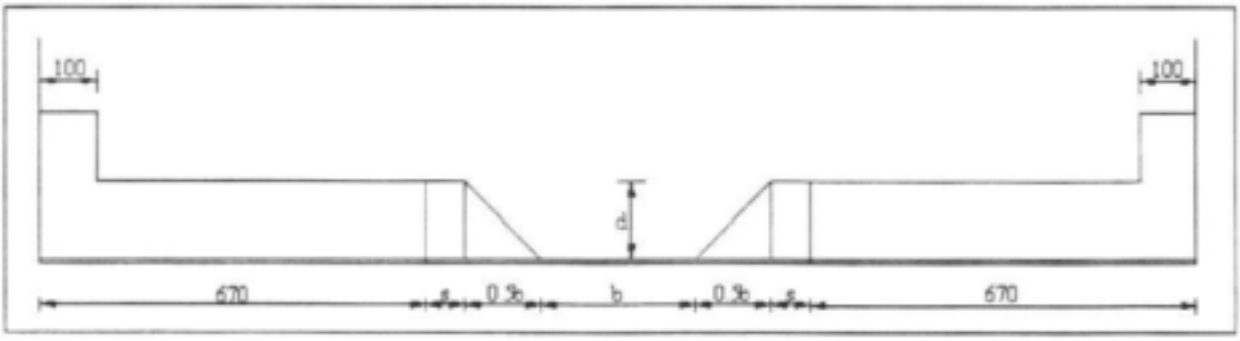


Figure 3.4: *Flume 2 (d/b = 0.5) with symmetrically 100mm end-contracted sharp-crested weirs (Tests I, J)*

The nomenclature of tests, both new and existing, is defined as below:

		Modular flow:		Non-modular flow:	
Tests	**Compound weir configuration**	**Test name**	**Number of tests**	**Test name:**	**Number of tests**
Existing	Flume 1, sharp-crested weirs (full-width)	A1S	36	B1S	63
	Flume 2, sharp-crested weirs (full-width)	A2S	35	B2S	13
	Flume 2, Crump weirs	A2C	14	B2C	27
	Flume 3, sharp-crested weirs (full-width)	A3S	35	B3S	58
New	Flume 2, sharp-crested weirs (full-width)	C2S	14	D2S	49
	Flume 2, s/c weirs. 300mm symmetrical end contractions	E2S	27	F2S	31
	Flume 2, s/c weirs. LHS crest with 300mm end contraction	G2S	12	H2S	22
	Flume 2, s/c weirs. 100mm symmetrical end-contractions	I2S	15	J2S	27
	Flume 2, Crump weirs	C2C	21	D2C	31

Table 3.5: *Nomenclature of existing and new laboratory tests, with number of tests for each*

3.2.1 Free flow tests

3.2.1.1 Sharp-crested weirs

Free flow tests were conducted on all four configurations of flume 2 with sharp-crested weirs. It was found that the results from the new tests (test C2S) compare sufficiently well with those performed previously (test A2S) for it to be assumed that the model had been accurately installed in the laboratory. A summary of the modular tests conducted is provided in Table 3.6:

			h_o/d	Q (m^3/s)
Previous tests:	**A2S**	Min. value	0.385	0.006
		Max. value	2.555	0.481
New tests:	**C2S**	Min. value	0.561	0.011
		Max. value	1.625	0.144
	E2S	Min. value	1.139	0.041
		Max. value	1.803	0.142
	G2S	Min. value	1.160	0.046
		Max. value	1.695	0.141
	I2S	Min. value	1.089	0.040
		Max. value	1.677	0.143

Table 3.6: *Range of modular data available for flume 2 (d/b = 0.5) with sharp-crested weirs*

3.2.1.2 Crump weirs

Free flow tests were also conducted on flume 2 in combination with full width Crump weirs. A summary of the new and old tests is provided in Table 3.7:

			h_o/d	Q (m^3/s)
Previous tests:	**A2C**	Min. value	0.407	0.006
		Max. value	2.462	0.488
New tests:	**C2C**	Min. value	0.543	0.011
		Max. value	1.544	0.137

Table 3.7: *Range of modular data available for flume 2 (d/b = 0.5) with Crump weirs*

The data from all free flow tests are presented in Appendix B.

3.2.1 Submergence tests

3.2.1.1 Sharp-crested weirs

From Table 3.2 it can be seen that the existing data for the weir configuration of flume 2 with sharp-crested weirs (tests B2S) cover only higher degrees of submergence. The recent laboratory tests (series D2S) have been conducted to supply data for lower degrees of submergence, so that the additional data cover a wider range of conditions. A summary of the old and new tests is provided in Table 3.8:

			h_o/d	h_v/d	S_f	$S_{s/c}$	Q (m^3/s)
Previous tests:	**B2S**	Min. value	1.678	1.689	0.640	0.133	0.151
		Max. value	2.489	2.744	0.928	0.856	0.451
New tests:	**D2S**	Min. value	0.745	0.746	0.246	0.017	0.020
		Max. value	2.227	2.744	0.960	0.907	0.347
	F2S	Min. value	1.726	1.735	0.138	0.032	0.125
		Max. value	1.796	2.548	0.947	0.911	0.140
	H2S	Min. value	1.643	1.692	0.128	0.890	0.128
		Max. value	1.695	2.213	0.941	0.078	0.141
	J2S	Min. value	1.612	1.656	0.159	0.099	0.127
		Max. value	1.663	2.077	0.942	0.885	0.139

Table 3.8: *Range of non-modular data available for flume 2 (d/b = 0.5) with sharp-crested weirs*

3.2.1.2 Crump weirs

A summary of the existing and additional submergence tests on Crump weirs is provided in Table 3.9:

			h_o/d	h_v/d	S_f	S_c	Q (m^3/s)
Previous tests:	**B2C**	Min. value	1.133	1.138	0.588	0.203	0.050
		Max. value	2.390	2.722	1.025	0.996	0.454
New tests:	**D2C**	Min. value	1.086	1.087	0.171	0.153	0.045
		Max. value	1.523	1.692	0.976	0.941	0.130

Table 3.9: *Range of non-modular data available for flume 2 (d/b = 0.5) with Crump weirs*

Data from all the submergence tests are presented in Appendix C.

3.3 LABORATORY TESTS

As previously mentioned, the model tests were conducted in the Hydraulics Laboratory of the Civil Engineering Department of the University of Stellenbosch.

3.3.1 Model configuration

The model of the flume was made of wood. The side, sharp-crested weirs had lower portions of wood, with the upper parts of perspex. The Crump weirs were also wooden. The two parts of the weir (flume and sharp crests or flume and Crumps) were carefully levelled in the 2m glass canal before being sealed and fixed in place.

In accordance with the previous tests on sluicing flumes, as well as the method used by the DWAF in practice, the water levels in the flume were recorded at cavities in the flume wall (Rossouw et al., 1998). These cavities were connected to 5mm plastic tubes, which lead to 100mm stand pipes, in which the water levels were recorded. The DWAF prefered to record the water levels in cavities in the flume walls to reduce the risk of sediment blocking the recording apparatus in the prototypes. An additional water level recording was made at a point on the flume invert between the cavities in the side walls as a control recording. This point was also connected to a stand pipe via plastic tubing.

The downstream water levels were also measured in stand pipes due to the fact that the downstream water level was too turbulent to allow direct recordings of the water surface. 10mm plastic pipes were placed at the recording positions on the bed of the canal, and so aligned that the openings are orientated 90° to the flow direction. These tubes were connected to 100mm stand pipes. Water levels at positions 2.1, 2.2, 2.3, 7, 8, and 9 were recorded in stand pipes. The water levels are recorded directly on the water surface at points 1, 3, 4, 5, and 6. All recordings were made with a needle gauge accurate to a tenth of a millimetre. (With Crump weirs, recordings at points 1 and 3 were not possible, as the Crumps were positioned above these points). The positions of the gauge points are indicated in Figure 3.5:

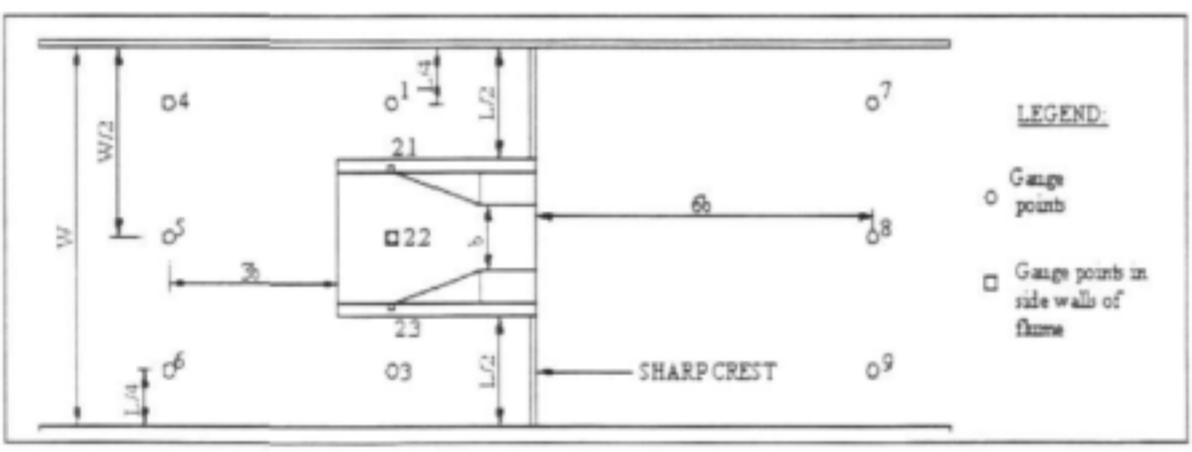


***Figure 3.5**: Layout of model in canal, showing position of gauge points*

Figures 3.6 and 3.7 show photographs of the weir, under modular and non-modular flow conditions, while Figures 3.8 and 3.9 show photographs of Crump weirs under similar conditions:

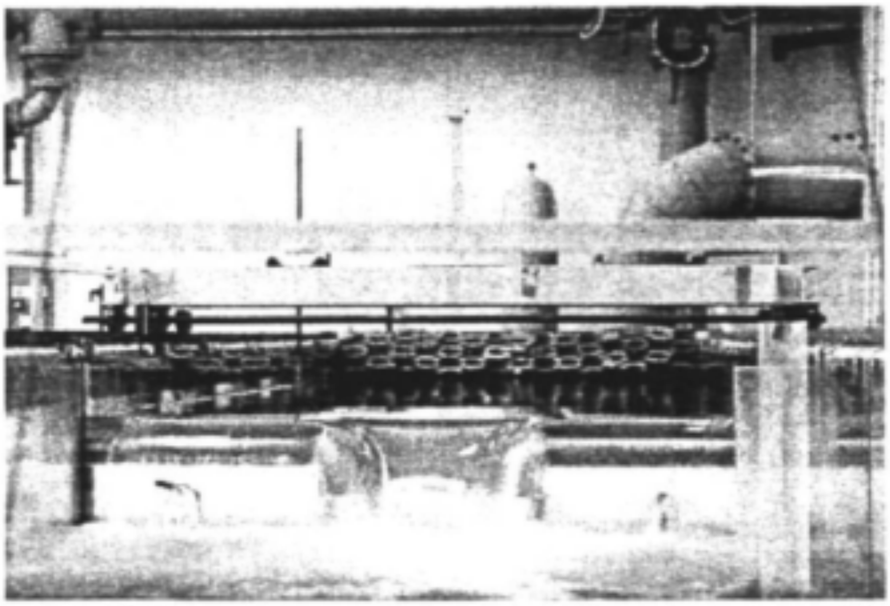


Figure 3.6: *Photograph of flume with sharp-crested weirs under modular flow conditions (Tests I2S)*

The splitters referred to in the next section can be seen in Figure 3.6, as can the stand pipes on the right, in which the downstream water levels were recorded. Also shown, is the needle used to record the water levels. At the rear of the photograph, the flow straighteners, also referred to later, can be seen.

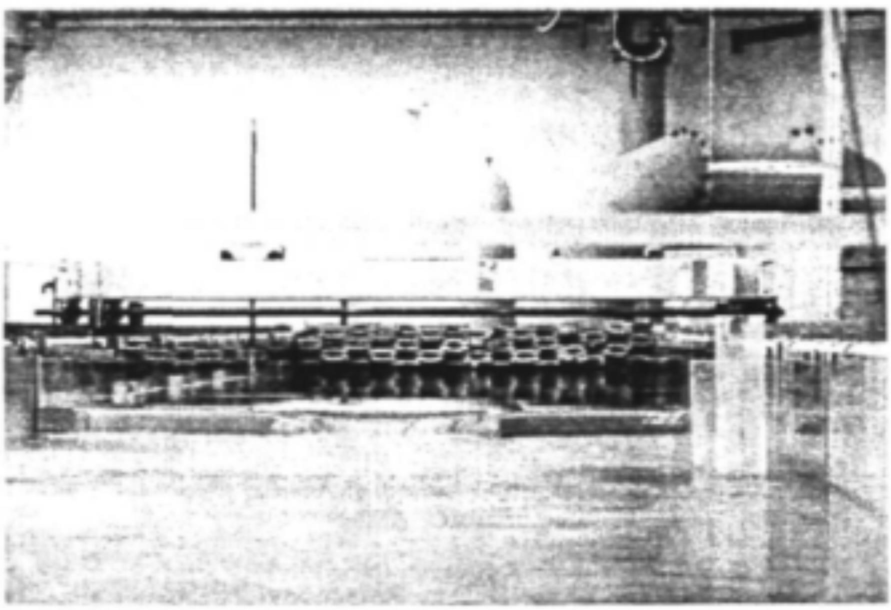


Figure 3.7: *Photograph of flume with sharp-crested weirs under non-modular flow conditions (Test J2S)*

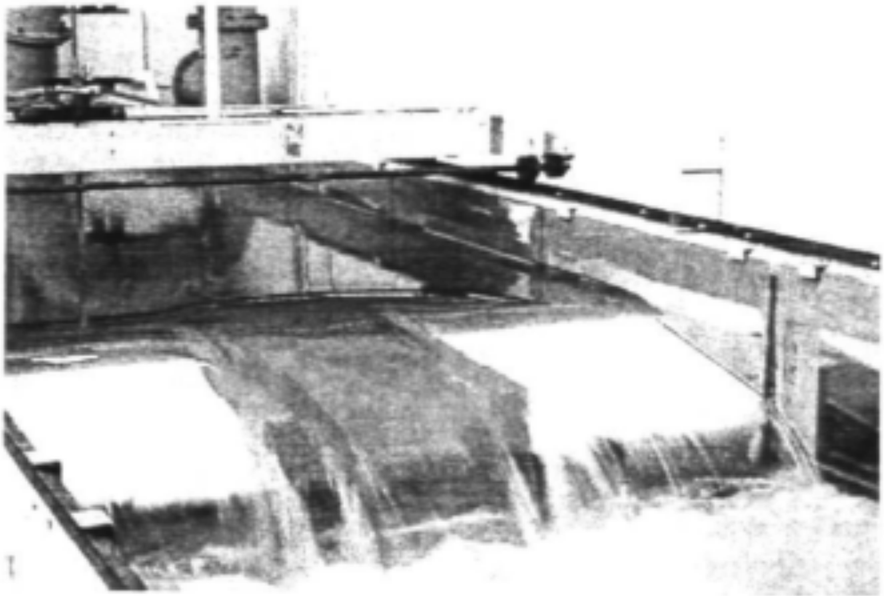


***Figure 3.8**: Photograph of flume with Crump weirs under modular flow conditions (Test D2C)*

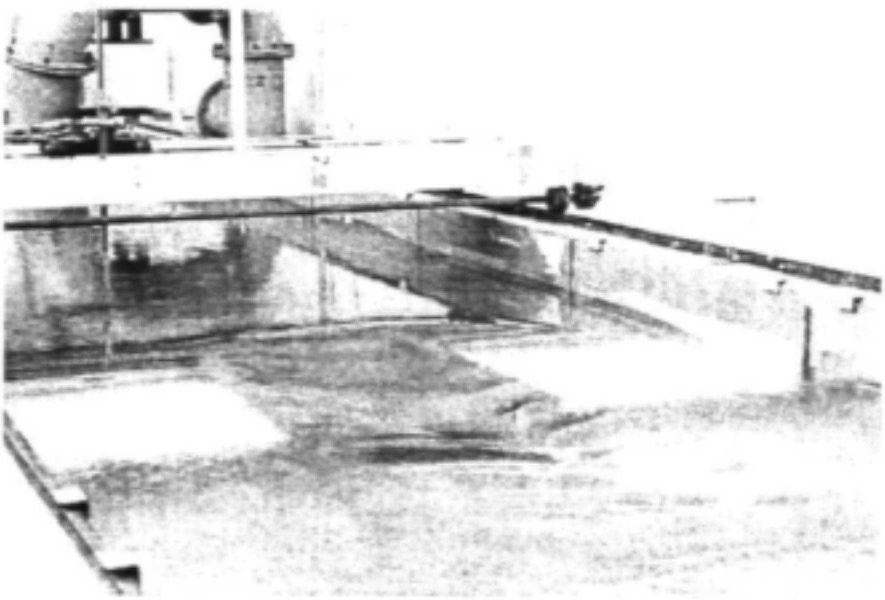


***Figure 3.9**: Photograph of flume with Crump weirs under non-modular flow conditions (Test D2C)*

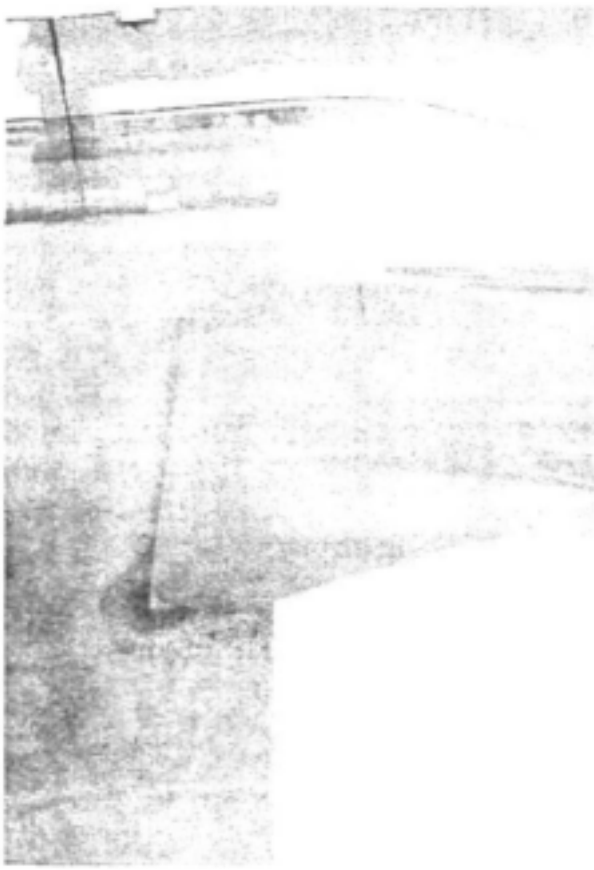


***Figure 3.10:** Photograph of flume with Crump weirs under modular flow conditions (Test C2C)*

Figure 3.10 shows the cavity in the left hand side flume wall where the water level in the flume was recorded.

3.3.2 Laboratory configuration

Water was supplied to the canal from a constant head tank, which ensured a constant rate of flow. This water was delivered through a 300mm internal diameter steel pipe. Important features of the delivery pipe were a steel orifice plate fitted in the pipe, and an adjustable valve. The pressure differential created by this orifice plate was measured by a water and/or mercury manometer. This pressure difference was used in a simple formula to calculate the flow rate in the delivery pipe (Featherstone and Nalluri, 1995):

$$Q_{lab} = C_d . a_1 . \sqrt{\frac{2gh}{(a_1 / a_2)^2 - 1}} \tag{3.1}$$

where: Q_{lab} = flow rate in delivery pipe (m^3/s)
C_d = discharge coefficient
a_1 = internal cross sectional area of delivery pipe (m^2)
a_2 = internal cross sectional area of orifice plate (m^2)
h = measured pressure difference (m)

A C_d value of 0.604 from previous calibrations was used for the 213mm orifice plate in the 300mm delivery pipe (Canto, 2000).

Flow in the delivery pipe was regulated with the valve. Water from the pipe entered a large basin, from where it flowed into the canal through flow straighteners, whose function was to create uniform flow upstream of the weir. The degree of submergence of the weir was controlled by adjustment of the sluice gate at the downstream end of the canal. The laboratory configuration is shown schematically Figure 3.11:

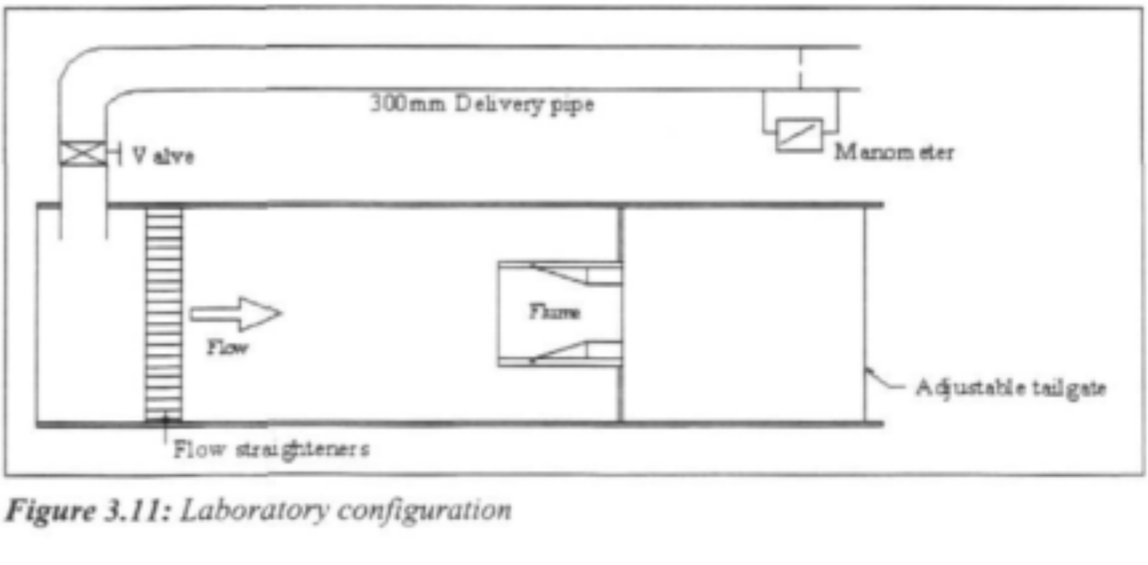


***Figure 3.11:** Laboratory configuration*

3.3.3 Testing procedure

At the start of all tests, the manometer was bled of all air, and re-zeroed. Reference readings of all weir dimensions were checked.

3.3.3.1 Free-flow tests

A rate of flow in the canal was established by opening the valve in the delivery pipe. This flow was given time to stabilise.

- The pressure difference at the manometer was recorded, and the flow rate in the delivery pipe calculated
- The water levels at points 1, 2.1, 2.2, 2.3, 3, 4, 5 and 6 were recorded with the needle gauge (recordings at 1 and 3 not possible with Crump weirs)
- The flow rate over the weir was calculated, and compared to that measured in the delivery pipe, and the error calculated
- The flow rate was altered and the above process repeated

3.3.3.2 Submergence tests

A rate of flow was established in the canal, and allowed to stabilise.

- The pressure difference at the manometer was measured, and the flow rate in the delivery pipe calculated
- The water levels at points 1, 2.1, 2.2, 2.3, 3. 4, 5 and 6 were recorded, whilst the weir was still unsubmerged (recordings at 1 and 3 not possible with Crump weirs)
- The sluice gate at the end of the canal was raised, causing the downstream water level to rise, which submerges the weir. The water levels were allowed to stabilise, and recordings of the levels were made at all points 1 to 9.
- The sluice gate was raised some more, and the process repeated.

At the end of the submergence tests, the sluice gate was lowered, and the weir allowed to become unsubmerged. The water level was again allowed to stabilise, and the unsubmerged water levels recorded once again. These were compared to those taken at the start of the test to ensure that conditions remained constant throughout the test. The valve was then adjusted in the delivery pipe to provide a different flow rate, and the procedure repeated.

3.3.4 Observations

It was found that there was insufficient aeration of the nappe from the sharp-crested weirs during the submergence of the weir. If a sharp-crested weir was not sufficiently aerated, the air underneath the nappe got drawn out which caused the nappe to 'cling' to the weir. The lowering of the pressure underneath the nappe in turn led to a drop in the upstream water level. Since the upstream water head was used to calculate the discharge, poor aeration can have a significant impact on the accuracy of the discharge calculation (Canto, 2000). Splitters were used to aerate the nappe of each sharp-crested weir in exactly the same way that they were used by Canto. These splitters split the nappe to allow sufficient air underneath it, whilst not affecting the upstream water level. As mentioned by Canto, (Canto, 2000), where end-contractions were present on the sharp-crested weirs, it was found that these provided sufficient aeration of the nappe, such that the use of splitters was not necessary.

It was found that cross flow occurred into the flume when sharp-crested side weirs were used adjacent to the flume. The effect of this was more pronounced the larger the end contractions on the sharp-crested weirs. Conversely, cross flow occurred out of the flume in the case of Crump weirs. The crest of the sharp-crested weirs was at the same level as the top of the flume walls. Head above the level of the sharp-crests also means head over the flume walls, and hence cross flow occured into the flume over the side walls of the flume. End contractions increased the head over the sharp-crested weirs, since the flow width was restricted. This increased head created more cross flow into the flume.

In the case of Crump weirs, the crest level of the Crump was at the same level as the flume walls. Downstream of the Crump crest, the surface of the Crump fell away at a 1:5 slope. Hence, when the critical depth at the flume outlet exceeded the flume depth, cross flow occured over the side walls of the flume onto the Crump weir. These different cross flow patterns probably affected the calibration of the flume.

As found by Canto, (Canto, 2000), two flow regimes could be identified downstream of the sharp-crested weirs during submergence. These were a plunging nappe which occured at the lower degrees of submergence, and a surface nappe which occured at higher degrees of submergence. In the second flow regime, standing waves were formed downstream of the sharp-crested weirs, producing very turbulent conditions in the tailwater basin, up to degrees of submergence (in the flume) of about 85%. For degrees of submergence greater than this, these standing waves dissipated, giving way to a smoother transition of flow over the compound weir. For degrees of submergence (in the flume) of 95% and greater, very little disturbance of flow over the compound weir was observed.

With Crump weirs, no plunging nappe was observed. As the tailwater level encroached on the downstream level of the Crump weir, standing waves were formed, creating very turbulent flow downstream of the weir. As the tailwater level rose further, these soon dissipated, giving way to a smoother transition of flow over the compound weir. As with sharp-crested weirs, at very high degrees of submergence, very little disturbance of the flow over the compound weir was observed (Figure 3.9).

Horizontal eddies downstream of the compound weir were observed, as mentioned by Canto (Canto, 2000). These were more pronounced in the case of sharp-crested weirs than was the case with Crump weirs.

4. MODULAR LIMIT AND SUBMERGED FLOW

4.1 THE MODULAR LIMIT

A weir normally creates a transition between sub critical flow and supercritical flow in a channel. Under the condition of free flow downstream of this transition, a control is created. Under these conditions, the downstream water level has no influence on the water level upstream of the weir. This allows an explicit relationship between stage (measured upstream of the control at the gauge point) and discharge to be developed for the particular type of weir. This is termed unsubmerged or modular flow.

Under submerged or non-modular flow conditions however, this is no longer the case. When the water level downstream of the weir rises to the point where it starts influencing the stream lines of flow over the structure, the modular limit has been reached. Submergence is initiated when the modular limit of the structure is exceeded. When this occurs, the control at the weir is cancelled out since the tail water level now influences the upstream water level. This invalidates the modular relationship between stage and discharge, and dictates that another such relationship be determined for submerged flow conditions.

The modular limit is often defined as the point where a 1% reduction in equivalent modular discharge is experienced (Featherstone and Nalluri, 1995).

4.2 SUBMERGENCE OF COMPOUND WEIR

Since the compound weirs analysed here consisted of two different types of gauging structures with very different submergence characteristics and modular limits, it was essential that a distinction be made between them as far as the onset and treatment of submergence was concerned.

The sharp-crested weirs and the sluicing flume were treated separately as far as discharge calculation under modular conditions was concerned. The submergence of these two systems was likewise treated separately. The modular limits and submergence of the sharp-crested weirs and sluicing flume are covered in detail in the following Chapters.

5. LITERATURE REVIEW

A literature review was conducted in order to determine what methods are available for the calculation of submerged flow over sluicing flumes, sharp-crested and Crump weirs.

5.1 FLUMES

5.1.1 Modular flow

The calculation of the modular or unsubmerged discharge through the sluicing flumes, Q_{ff}, is covered in detail in the following Chapter.

5.1.2 Modular limit

The submergence of sluicing flumes is not covered in great detail in the WRC report which details the development of the flumes. (Rossouw et al., 1998). For this reason, an investigation was made into the methods available for the quantification of submergence and the modular limit of other flumes.

The modular limit for long-throated flumes is defined as the value of the submergence ratio, t/h_v, at which the real discharge deviates by 1% from the modular discharge (Bos and Reinink, 1981).

The modular limit of the sluicing flumes is defined as a degree of submergence ($S_f = t/h_v$) of 80% (Rossouw et al., 1998). This was done on the grounds that the ratio of the unsubmerged to submerged water depths (h_o/h_v), started to deviate at a point of 80% submergence. This is illustrated in Figure 5.1:

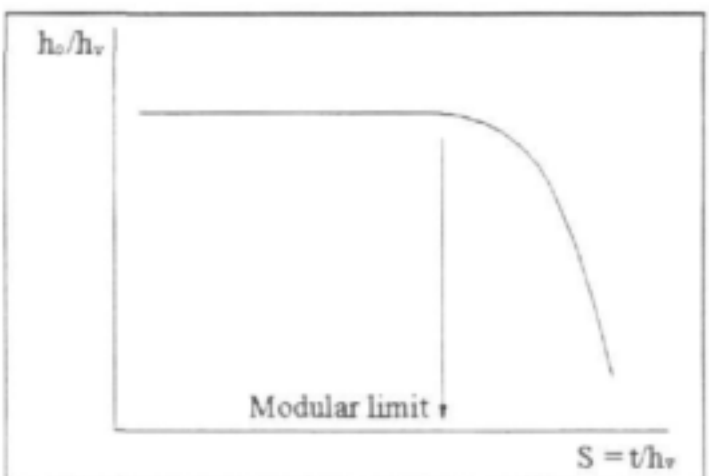


Figure 5.1: *Modular limit of sluicing flumes (Rossouw et al., 1998)*

5.1.3 Non-modular flow

The British Standard for flumes, BSI 1981, part 4C, does not provide for submergence of any of the flumes covered. Only the submergence of long-throated flumes is covered in any detail in the literature.

5.1.3.1 Long-throated flumes

The submerged discharge through long-throated flumes is obtained by multiplying the free discharge with a drowned flow reduction factor, f (Bos and Reinink, 1981).

The free or unsubmerged discharge through the long-throated flume is calculated. This is then multiplied with a drowned flow factor, f, of less than unity to give the submerged discharge. The value of this factor is dependant on the degree of submergence of the flume, and is read off the graph derived by Bos and Reinink. The form of the graph is shown in Figure 5.2:

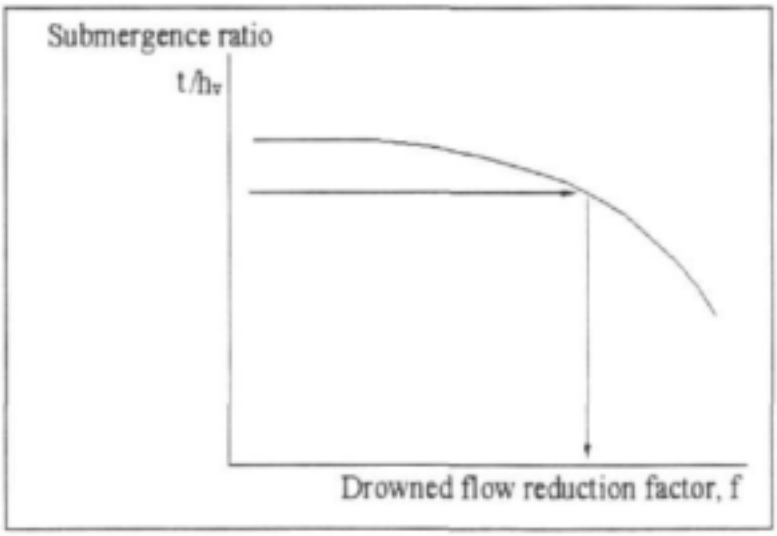


Figure 5.2: *Drowned flow reduction factor, f, for long-throated flumes (Bos and Reinink, 1981)*

Submerged flow is calculated as:

$$Q_{fs} = f.Q_{ff} \qquad (5.1)$$

5.1.3.2 Sluicing flumes

The submergence of the newly developed sluicing flumes entails correction of the submerged water depth to an equivalent unsubmerged water depth. (Rossouw et al., 1998). A graph similar to Figure 5.1 was developed for each flume, which allows conversion of the recorded (submerged) water depth, h_v, to an equivalent unsubmerged water depth, h_o. This value of h_o can then be used to calculate the discharge through the flume as if it were unsubmerged. This "unsubmerged" discharge is then the actual (submerged) discharge through the flume.

This method works well, but has the limitation that it is only applicable for the specific case for which it has been derived. Because a plot is made of the water levels, for example, Figure 5.1, the derived relationship between h_o/h_v and S_f is only applicable for the geometry of weir for which it has been derived. This means that each type of weir layout must be calibrated in a laboratory model. This is both expensive and impractical, as many different weir configurations are used in the prototype. A more generally applicable method is therefore desired.

5.2 SHARP-CRESTED WEIRS

A comprehensive study of sharp-crested weirs conducted by R. Canto (Canto, 2000) recommends the following methods for discharge calculation under modular and non-modular flow conditions.

5.2.1 Modular flow

The IMFT formula (BSI, 1981) is used as the basis for discharge calculation, with modifications for end contractions and H/P ratios (Canto, 2000). The formula and modifications are given below:

$$Q_{wf} = C_w . 2/3 . \sqrt{2g}\, L_e H_{wf}^{3/2} \qquad (5.2)$$

$$C_w = 0.627 + 0.018\, H_{wf}/P \qquad \text{for } H_{wf}/P \leq 1.867 \qquad (5.3)$$

$$C_w = 0.689\left[\frac{P}{P+H_{wf}}\right]^{-0.04} \qquad \text{for } 1.867 < H_{wf}/P \leq 15 \qquad (5.4)$$

$$H_{wf} = h + v^2/(2g) \qquad (5.5)$$

For a full-width weir, $L_e = L$. For end contractions on both sides, L_e is calculated as follows:

$$L_e = L - nh \qquad (5.6)$$

$$n = 0.2 \qquad \text{for } H_{wf}/L < 0.35 \qquad (5.7)$$

$$n = 0.174(L/H_{wf})^{0.517} - 0.1 \qquad \text{for } 0.35 < H_{wf}/L \leq 2.00 \qquad (5.8)$$

$$n = 0.0216 \qquad \text{for } H_{wf}/L > 2.00 \qquad (5.9)$$

(L is the overflow length of the sharp-crest.)

If only one side of the notch is contracted, then half of the above correction is applied:

$$L_e = L - ½.nh \qquad (5.10)$$

5.2.2 Modular limit

The modular limit for a rectangular sharp-crested weir is defined as the point where a 1% reduction in equivalent modular discharge is experienced. A sharp-crested weir effectively becomes submerged when the downstream water level rises above the crest level of the weir. This reduces the discharge over the weir (Featherstone and Nalluri, 1995).

5.2.3 Non-modular flow

Two methods exist to calculate the non-modular discharge over sharp-crested weirs. The Villemonte method, corrects the "free" discharge calculated with the submerged energy head to give the actual submerged discharge. The Wessels method corrects the submerged water level, to give the unsubmerged water level, which is then used in the free flow formulae to calculate the discharge (Canto, 2000).

It has been found (Canto, 2000) that the Villemonte method works best under the conditions of low discharge and high energy losses over the sharp-crested weir. The method of Wessels works best under the conditions of higher discharge, and lower relative energy losses. Canto identified a point of transition between these methods by means of the ratio A_{co}/A_{to}. This ratio gives an indication of the relative flow areas and therefore velocities at the vena contracta and downstream sections. Canto found that the submergence process is dependant on the difference between the velocities at the vena contracta and the downstream section (Canto, 2000). The terms required are defined in Figure 5.3:

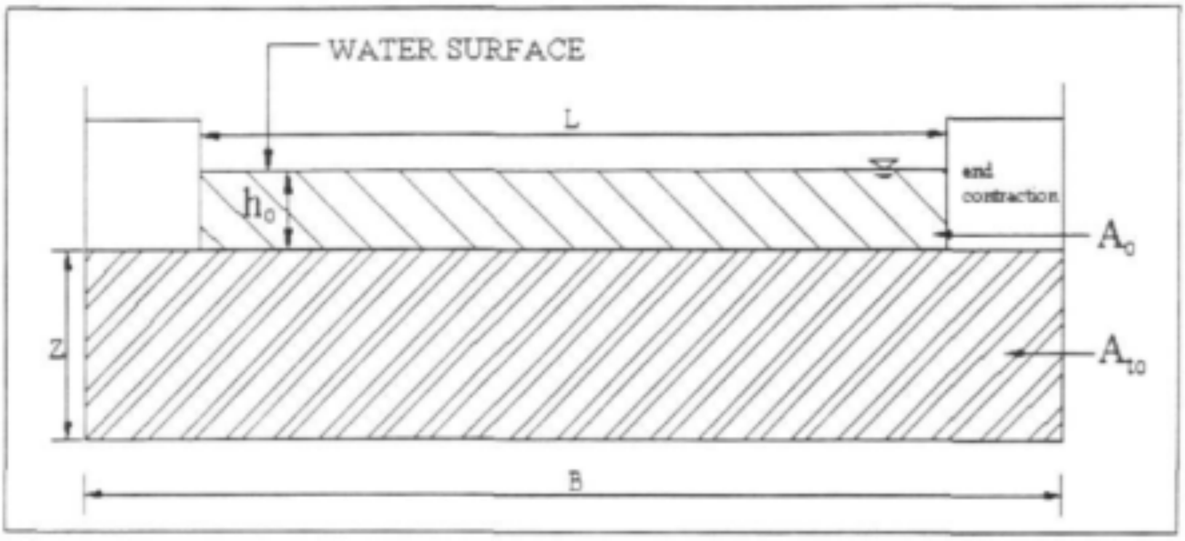


Figure 5.3: *Definition of A_o, and A_{to}, (after Canto, 2000)*

The upstream area which will occur under modular flow conditions, A_o, is given by:

$$A_o = h_o.L \tag{5.11}$$

(where h_o is the equivalent unsubmerged head over the weir, which will give the submerged discharge, Q_{ws}, as explained in the next section.)

The area of the vena contracta, A_c, is given by:

$$A_c = C_d.½.(h_v + t).L \tag{5.12}$$

(where the value of C_d can be taken as 0.6 for single notch weirs: Canto, 2000)

If the weir is just at the point of becoming submerged, then $t - d = 0$, and $h_v = h_o$. The area of the vena contracta then becomes A_{co}, defined below:

$$A_{co} = C_d.½.h_o.L \tag{5.13}$$

The area downstream of the weir, when the weir is on the point of becoming submerged, denoted A_{to}, is given as:

$$A_{to} = B.Z \tag{5.14}$$

The value of the ratio A_{co}/A_{to} is then used to determine whether the Villemonte or Wessels correction should be used to calculate the submerged discharge over the weir.

5.2.3.1 Villemonte Method

The Villemonte method is recommended in the following range (Canto, 2000):

$$0.02 \leq A_{co}/A_{to} \leq 0.130 \tag{5.15}$$

The "free" discharge, Q_{wf}, is calculated using the non-modular flow formulae (equations 5.2 to 5.10) with the submerged energy level over the weir, H_{ws}, instead of the unsubmerged energy level, H_{wf}. This so-called "free" discharge, is corrected to give the actual submerged discharge over the weir with the use of the Villemonte equation:

$$Q_{ws} = Q_{wf}\left[1-\left[\frac{t-d}{y_5-d}\right]^{1.5}\right]^{0.385} \tag{5.16}$$

Since the value of h_o needed to calculate A_{co} is not known at the start of the calculation, the Villemonte correction can be assumed initially. Once the submerged discharge has then been calculated, an estimate of the unsubmerged water level upstream of the weir can be made. The following is assumed;

$$Q_{ws} = C_w.2/3.\sqrt{2g}\,L_e.h_o^{3/2} \tag{5.17}$$

h_o = equivalent unsubmerged head over the sharp-crested weir (m)

Since a rough estimate will suffice, h_o is solved for with the value of C_w taken as 0.6 (Canto, 2000). The value of the ratio A_{co}/A_{to} can then be determined, and it can be verified whether the use of the Villemonte correction was in fact correct.

5.2.3.2 Wessels' Method

For values of A_{co}/A_{to} much greater than 0.130, Canto found that the Villemonte correction underestimated the discharge, and that the Wessels correction proved more accurate. The Wessels' method calculates an equivalent unsubmerged water level from the recorded submerged water level, and Canto recommended that this method be used when the ratio of A_{co}/A_{to} exceeds 0.130. This method is described below:

$$h_o = \frac{h_v\sqrt{1-(t/h_v)^2}}{\alpha} \tag{5.18}$$

$$\alpha = \frac{-b+\sqrt{b^2+4c}}{2} \tag{5.19}$$

$$b = -0.34074 - 0.30623(t/h_v) \tag{5.20}$$

$$c = 0.62879(t/h_v)^2 + 0.10159(t/h_v) - 01.6096 \tag{5.21}$$

The corrected value, h_o, is used in the free-flow formulae and the discharge over the weir calculated.

5.3 CRUMP WEIRS

In 1956 E. S. Crump published the details of a weir with a triangular profile, which had been developed at the Hydraulics Research Station, Wallingford. This was claimed to have a wider modular range, and also to give a more predictable performance under submerged flow conditions (Chadwick and Morfett, 1986). The 1:2/1:5 upstream/downstream profile is based on sound hydraulic principles. The upstream slope of 1:2 was chosen as the steepest slope which would avoid sediment build-up in the vicinity of the crest. This means that the coefficient of discharge will not be affected by upstream sedimentation. The 1:5 downstream slope was chosen so that a stable hydraulic jump would be formed under modular conditions, which provides sufficient energy dissipation. (Ackers and White, 1978).

The high modular limit and good sedimentation characteristics of the Crump weir should make it ideal for use as a flow measuring device in South African rivers.

5.3.1 Modular flow

The modular discharge over the Crump weir is calculated as follows:

$$Q_{wf} = C_w.(2/3)^{1.5}\sqrt{g}\,L.H_{wf}^{\ 1.5} \qquad (5.22)$$

$$C_w = 1.163(1\text{-}0.0003/h)^{1.5} \qquad (5.23)$$

where h = free head over Crump weir (m)

(After Ackers and White 1978, BSI 1981, and Rossouw et al. 1998)

The Department of Water Affairs (Delport and Le Roux, 1990) uses a formula based on the above two:

$$Q_{wf} = 1.982.L.H_{wf}^{\ 1.5} \qquad (5.24)$$

The value of C_w can be set to 1.163 for values of h > 0.1m (BSI, 1986). Thus the value of the constant terms in equation 5.22 approximates to the value of 1.982 used in equation 5.24.

5.3.2 Modular limit

The modular limit is defined as the submergence ratio (H_t/H_{ws}) where a 1% reduction in the equivalent modular discharge takes place. For the above ratio, this is in the range of 0.74 to 0.78 (Ackers and White, 1978).

Chadwick and Morfett (Chadwick and Morfett, 1986) define the modular limit at a value of $(t - d)/(h_v - d) = 0.75$.

5.3.3 Non-modular flow

Most references give the non-modular discharge over the Crump weir as the modular discharge multiplied by a flow reduction factor of some sort:

$$Q_{ws} = f.Q_{wf} \tag{5.25}$$

The British Standards provides a graph, from which the value of f can be obtained (BSI, 1981).

Ackers and White, and Chadwick and Morfett give a more convenient mathematical expression for this factor:

$$f = 1.04[0.945 - (h_p/H_{ws})^{1.5}]^{0.256} \tag{5.26}$$

This expression has the disadvantage of requiring the value of h_p, which is the water level measured at the crest tapping. The Department of Water Affairs does not build crest tappings into the Crump weirs they use in the field, as they have found that these become silted up too easily. Alternative expressions for the flow reduction factor, f, are therefore used by them (Ackers and White, 1978 and Delport and Le Roux, 1990):

$$f = 1.035[0.817 - (H_t/H_{ws})^4]^{0.0647} \quad \text{for } 0.75 < H_t/H_{ws} \leq 0.93 \tag{5.27}$$

$$f = 8.686 - 8.403(H_t/H_{ws}) \quad \text{for } 0.93 < H_t/H_{ws} \leq 0.985 \tag{5.28}$$

6. DISCHARGE CALCULATION OVER COMPOUND WEIRS FOR MODULAR FLOW CONDITIONS

6.1 FLOW THROUGH THE FLUME

Flow is accelerated through the flume, which narrows from a rectangular cross-section at the inlet, to a trapezoidal cross-section at the outlet. This creates a critical control at the flume outlet, which means that the following relationship can be used to calculate the discharge through the flume:

$$\frac{Q^2 B_c}{gA^3} = 1 \qquad (6.1)$$

The terms A_c, and B_c are defined in Figures 6.1 and 6.2, depending on whether the critical depth, y_c, is greater than or less than the flume depth, d:

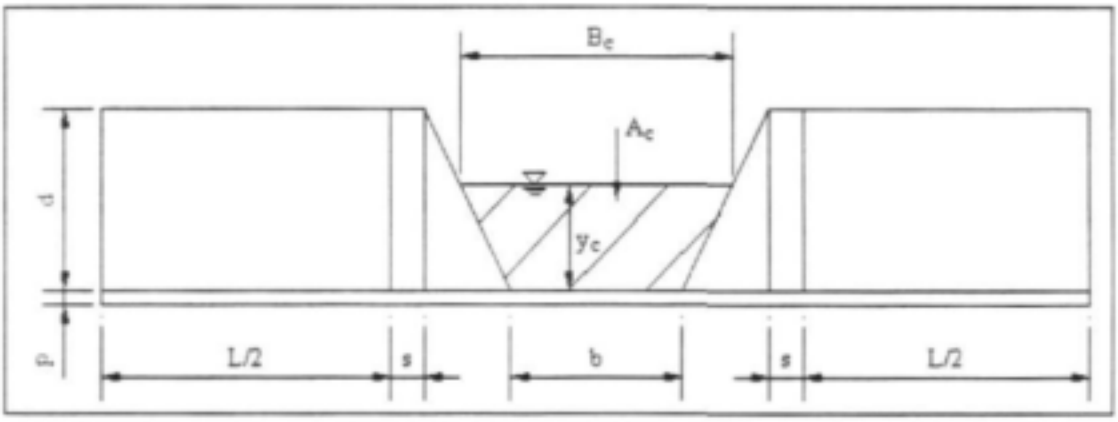


Figure 6.1: *Control section for* $y_c<d$

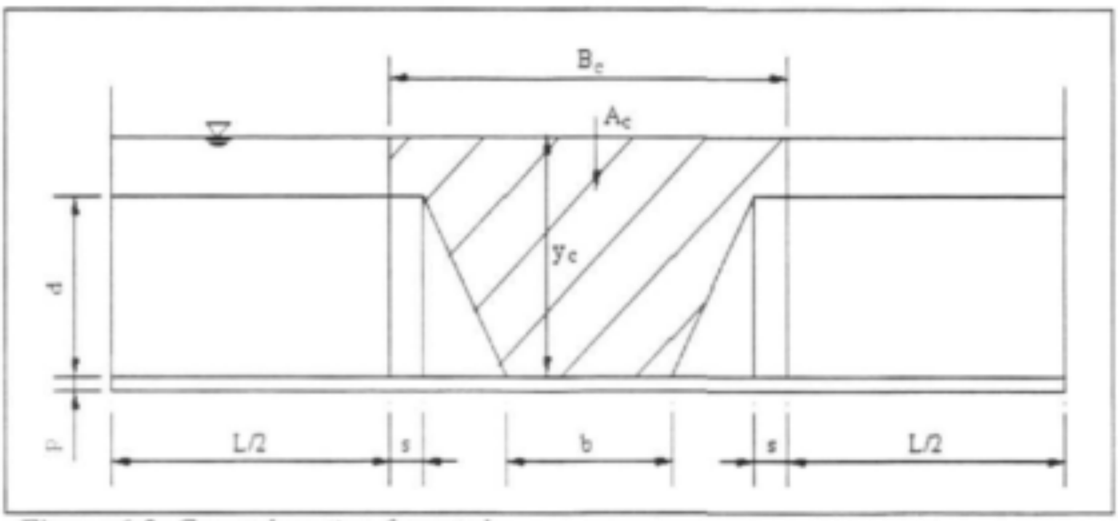


Figure 6.2: *Control section for* $y_c>d$

As an example, A_c and B_c are defined for flume 1 (d/b = 1.0):

If y_c<d:		If y_c>d:	
$A_c = by_c + 0.5y_c^2$	(6.2)	$A_c = 1.5bd + B_c(y_c - d)$	(6.4)
$B_c = b + y_c$	(6.3)	$B_c = 2(b + s)$	(6.5)

To calculate the discharge, Q, A_c and B_c and therefore the critical depth must be known. The critical depth is not measured in the prototype, which means that equation 6.1 cannot be used to calculate the flow rate directly.

To overcome this, one of two assumptions needs to be made. If the flow is contained within the flume walls, it is assumed that the specific energy at the gauge point (point 2, E_{s2}) is equal to the energy at the control section (E_{sc}). In other words:

$$E_{s2} = E_{sc} \qquad (6.6)$$

It was found that when the flow depth in the flume reaches 90% of the height of the flume walls, (i.e. $h_o/d = 0.9$, but 0.85 for flume 3)*, that overtopping of the flume walls and flow over the adjacent weirs commences (Rossouw et al., 1998). Due to the draw-down curve created by the adjacent weirs, the water level at the gauge point, h_o, cannot be used to calculate the flow over the side weirs, as the gauge point is too close to the crest of the side weirs. To calculate the flow rate over the side weirs, a water level further upstream than that of the gauge point must be used. The water level in the pool upstream of the weir is used for this purpose. This water level, designated y_5, is the average of the water level readings taken at points 4, 5 and 6, as shown in Figure 3.5. In the calibrations done previously, (Rossouw et al., 1998), expressions for the energy level in the upstream pool relative to the flume invert, E_{s5}, were derived for each flume. The expression derived for flume 1 (d/b = 1.0) used in combination with sharp-crested weirs is given below as an example:

$$E_{s5}/d = 0.525 + 0.335(h_o/d) + 0.232(h_o/d)^2 \quad \text{for } 0.9<h_o/d<2.0 \qquad (6.7)$$

The derived expressions for the other flumes in combination with sharp-crested as well as Crump weirs are similar.

The second assumption is made when flow overtops the flume walls and adjacent side weirs. Under these conditions, it is assumed that the energy level in the upstream pool is equal to the energy level at the control section. In other words:

$$E_{s5} = E_{sc} \qquad (6.8)$$

In each case, a coefficient of discharge (C_{d2} or C_{d5} respectively) is included to allow for any losses between the measuring point and the control section.

* It is very important to note that henceforth in this report, reference will be made to h_o/d and h_o/d values being greater or less than 0.9, and this being used to distinguish between flow contained in the flume, and flow over the side weirs. This watershed value of 0.9 applies to flumes 1 and 2. The value of 0.85 is used for flume 3. Whenever 0.9 is used in this context, it may be taken as 0.85 for flume 3.

The above two assumptions lead to:

If $h_o/d<0.9$:

$$E_{s2} = E_{sc}$$

$$\Rightarrow \quad h_o + v_2^2/(2g) = y_c + v_c^2/(2g)$$

$$\Rightarrow \quad h_o + \frac{C_{d2}.Q^2}{b_2^2.h_0^2.2g} = y_c + \frac{A_c}{2B_c} \tag{6.9}$$

If $h_o/d>0.9$:

$$E_{s5} = E_{sc}$$

$$E_{s5} = y_c + A_c/(2B_c) \tag{6.10}$$

Expressions have been obtained for C_{d2} and C_{d5} (as well as for E_{s5}) for all three sluicing flumes in terms of the value h_o/d (Rossouw et al., 1998). For the purposes of illustration, these are given below for flume 1 ($d/b = 1.0$) in combination with sharp-crested weirs. The expressions derived for the other two flumes in combination with both sharp-crested and Crump weirs are similar.

$$C_{d2} = 0.811 + 0.275(h_o/d) \qquad \text{for } 0<h_o/d<0.9 \tag{6.11}$$

$$C_{d5} = 0.845 + 0.081(h_o/d) \qquad \text{for } 0.9<h_o/d<1.5 \tag{6.12}$$

$$C_{d5} = 0.094 + 0.887(h_o/d) - 0.203(h_o/d)^2 \qquad \text{for } 1.5<h_o/d<2. \tag{6.13}$$

$$C_{d5} = 1.06 \qquad \text{for } 2.0<h_o/d<3.0 \tag{6.14}$$

These expressions have been derived from fits of plotted data measured in the laboratory. Due to the fact that the crests of the sharp-crested and Crump side weirs are in different positions relative to the flume, the flow patterns over the compound weirs differ slightly in the two cases. Also, as mentioned previously, cross flow occurs into the flume in the case of sharp-crested weirs, and out of the flume in the case of Crump weirs. This is why the derived expressions for C_{d2}, C_{d5} and E_{s5} differ slightly in the two cases. All the expressions referred to are given in Appendix A.

Discharge calculation now proceeds in an iterative manner depending on whether flow is contained within the flume or not.

6.1.1 Discharge Calculation for $h_o/d<0.9$

It can be seen that when equation 6.9 is used for discharge calculation, the critical depth, y_c, and therefore A_c, and B_c are unknown. The solution is found by estimating a value of the critical depth at the control section, and checking whether equation 6.6 holds true. If not, the initial estimate of y_c must be adjusted, and the process repeated. This process is detailed below:

1. Estimate a value of y_c
2. Calculate A_c, B_c, and $E_{sc} = y_c + A_c/(2.B_c)$ (6.9b)
3. Calculate $Q = \sqrt{g.A_c^3 / B_c}$ (6.15)

   With the recorded value of h_o known, calculate:

   $$E_{s2} = h_o + \frac{C_{d2}.Q^2}{b_2^2.h_o^2.2g} \qquad (6.9a)$$

4. Compare E_{s2} and E_{sc} (the two sides of equation 6.9)

   If the value of E_{s2} is greater than E_{sc}, then the estimated value of y_c is too low, and a second value of y_c greater than the first must be chosen, and vice-versa.

5. Continue adjusting the value of y_c until $E_{s2} = E_{sc}$. Use the most recent value of y_c, and calculate A_c and B_c. The free discharge through the flume, Q_{ff}, follows from:

   $$Q_{ff} = C_{d2}\sqrt{g.A_c^3 / B_c} \qquad (6.16)$$

An example calculation is provided in Appendix D.

6.1.2 Discharge calculation for $h_o/d > 0.9$

When flow overtops the flume walls and adjacent weirs, equation 6.10 is used for discharge calculation. The value of E_{s5} is calculated from the relevant expression, for example equation 6.7 for flume 1. As before, a value for y_c is estimated such that equation 6.8 holds true. This process is detailed below:

1. Estimate a value for y_c
2. Calculate A_c, B_c and E_{sc} (equation 6.10b) according to whether y_c is less than or greater than the flume depth, d.
3. Calculate E_{s5} from the relevant expression.
4. Compare E_{s5} and E_{sc}. If $E_{s5}>E_{sc}$, then estimate a second value of y_c greater than the first, and vice-versa.
5. Continue iteration until $E_{s5}=E_{sc}$. Calculate A_c and B_c with the most recent value of y_c used.
6. Calculate C_{d5} using the relevant expression.

The discharge through the flume, Q_{ff}, follows from:

$$Q_{ff} = C_{d5}\sqrt{g.A_c^3 / B_c} \tag{6.17}$$

An example calculation is given in Appendix D.

To avoid laborious iteration, a solver solution or spreadsheet can be used.

6.2 FLOW OVER SIDE WEIRS

When the value of h_o/d exceeds 0.9, flow over the side weirs commences. Flow over the side weirs is calculated separately to that through the flume.

6.2.1 Sharp-crested weirs

Discharge over the sharp-crested weirs is calculated as per Chapter 5.1.1, using the IMFT formula. The pool depth and unsubmerged energy level are defined below:

$$P = p + d \quad (6.18)$$

$$H_{wf} = E_{s5} - d \quad (6.19)$$

6.2.1.1 End contractions

When end contractions are present on the sharp-crested weirs, an additional iteration loop must be included in the calculation process. This is because the calculation of the effective length of the sharp crest requires that y_5 be known, although this is not recorded in the prototype. This value can be estimated initially, and iterated for, since the value of E_{s5} is known, from which y_5 can then later be obtained. An example calculation (for test E_{s2}) is given in Appendix D, and this process is detailed below:

1. Following the steps detailed in Chapter 6.1.2, calculate the free discharge through the flume, Q_{ff}. The third step in this process calculates the value of E_{s5}, which remains unchanged.
2. Calculate $H_{wf} = E_{s5} - d$ (equation 6.19)
3. Calculate C_w, using the relevant equations (5.3 or 5.4, depending on the value of (H_{wf}/P)

For each contracted weir crest:

First Iteration:

4. Estimate the value of $y_5 \approx h_o$
5. Calculate $h = y_5 - d$ (6.20)
6. Calculate the value of n, using the relevant equations (5.7 to 5.9 depending on the value of H_{wf}/L)
7. Calculate the effective length of the sharp crest (equations 5.6 or 5.10)
8. Calculate the free discharge over this crest, using equation 5.2

Steps 4 to 8 are carried out for each contracted sharp-crest. If the sharp-crest is not contracted, then only step 8 needs to be carried out, with $L_e = L$.

9. Add the discharge contributions from each sharp-crested weir, whether contracted or not, to obtain the total modular discharge over the side weirs, Q_{wf}
10. The total discharge over the compound weir follows from section 6.3.2, equation 6.23: $Q_t = Q_{ff} + Q_{wf}$

Second Iteration:

1. Calculate y_5 from:

$$y_5 = E_{s5} - \frac{Q_t^2}{\left(y_5^* + p\right)^2 . b_5^2 .2g} \tag{6.21}$$

(* y_5 from previous iteration)

2. Repeat the steps 5 to 10 from the previous iteration.

Continue iteration until the value of y_5 converges. Calculate the (final) modular discharge with this value.

6.2.2 Crump weirs

Discharge over the Crump weirs is calculated as per Chapter 5.3.1, using equation 5.24. The unsubmerged energy level upstream of the Crump weir is calculated as per equation 6.19 above.

6.3 TOTAL FLOW OVER THE COMPOUND WEIR

6.3.1 Flow contained in the flume

When flow is contained in the flume (h_o/d), the flow through the flume is the total discharge past the weir:

$$Q_t = Q_{ff} \tag{6.22}$$

6.3.2 Flow over the side weirs

In the case where flow overtops the flume walls and adjacent weirs ($h_o/d>0.9$), the total discharge over the compound weir is the sum of the free discharges through the flume as well as over the adjacent weirs:

$$Q_t = Q_{ff} + Q_{wf} \tag{6.23}$$

6.4 ACCURACY OF DISCHARGE CALCULATION UNDER MODULAR FLOW CONDITIONS

6.4.1 Sharp-crested weirs

6.4.1.1 Comparison of new and previous tests

The previous WRC tests were conducted on full-width sharp-crested weirs. The new tests on flume 2 with full width sharp-crests (series C2S) can be compared with the previous tests, as indicated in Table 6.1:

	Previous tests (A2S)	New tests (C2S)
Average Error (%)	0.74	-2.87
Ave abs Error (%)	1.81	3.20
Std Deviation (%)	2.46	2.35
Max. Error (%)	6.33	1.84
Min. Error (%)	-7.73	-8.25
Number of tests	35	19

Table 6.1: *Comparison of previous and new tests for flume 2 (d/b = 0.5) with full width sharp-crested weirs*

The errors in the total discharge for the two series of tests are shown in Figure 6.3:

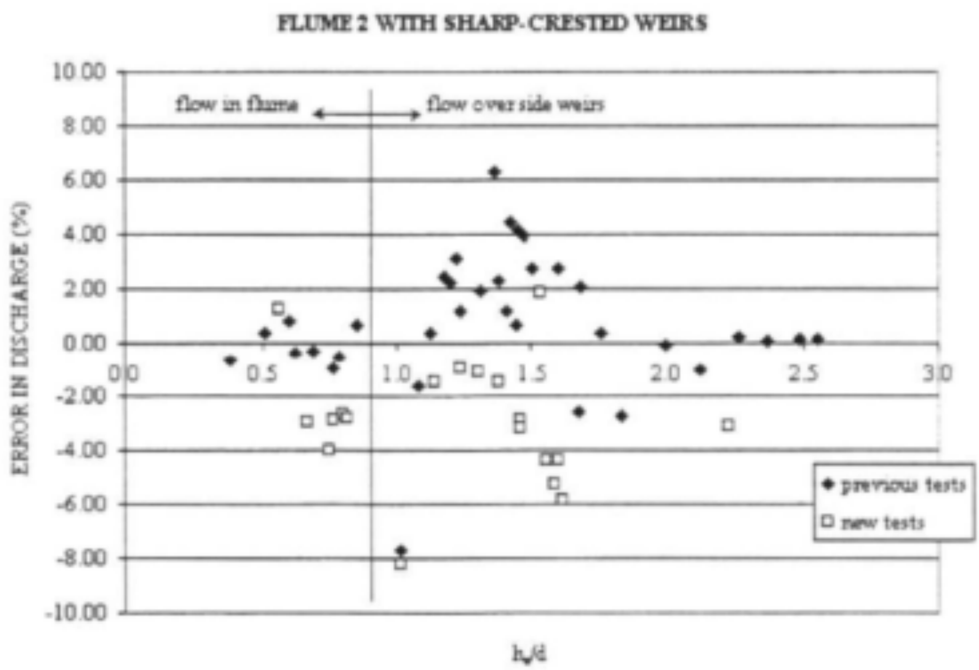


Figure 6.3: *Errors in modular discharge vs h_o/d for new and old tests with flume 2 and full width sharp-crested weirs*

From the above comparisons, it can be seen that the new and old test results compare well. The error in the discharge from the previous tests is 0.74%, whilst the same error in the discharge for the new tests is –2.87%. Hence there is a difference of 2.13% in the average errors. This is within the range of experimental error. There are two possible explanations for the difference though. Firstly, it is possible that a different orifice plate was used in the delivery pipe for the tests conducted in the previous WRC project, or that a slightly different C_d value was used even if the same orifice plate was used. (Neither the orifice plate dimensions nor the applicable C_d value is quoted in the WRC report (Rossouw et al., 1998). This would affect the accuracy with which the discharge in the delivery pipe is calculated. A second possible explanation is that a slightly different set-up may have been used in the solver solution which calculated the discharges from the previous tests. This would affect the accuracy with which the discharge past the compound weir is calculated. Either of these explanations could account for the difference between the average errors in the discharges when the new and old tests are compared.

6.4.1.2 Summary for full width sharp-crested weirs

The new and old tests on flume 2 (d/b = 0.5) with full width sharp-crested weirs have been combined. With the use of the calculation methods described above, on the three configurations of weirs shown in Figures 2.1 to 2.3, the errors as indicated in Table 6.2 are made:

	Flume 1, s-c weirs	Flume 2, s-c weirs	Flume 3, s-c weirs
Average Error (%)	0.03	-0.53	0.20
Ave abs Error (%)	1.07	2.30	2.01
Std Deviation (%)	1.41	2.97	2.91
Max. Error (%)	3.14	6.33	8.31
Min. Error (%)	-3.41	-8.25	-8.92
Number of tests	36	54	35

***Table 6.2**: Errors associated with modular discharge calculation on flumes with full width sharp-crested weirs*

It can be seen that in all cases, the errors are within ±9%. The standard deviation of these errors are in all cases less than 3%. The average errors are less than 0.6%. The average errors indicate the value around which the data are spread, whilst the average absolute errors give a better indication of the actual magnitude of the errors. With the largest absolute error at 2.30%, it can be seen that the method works well under modular conditions.

The spread of the errors is shown in Figure 6.4:

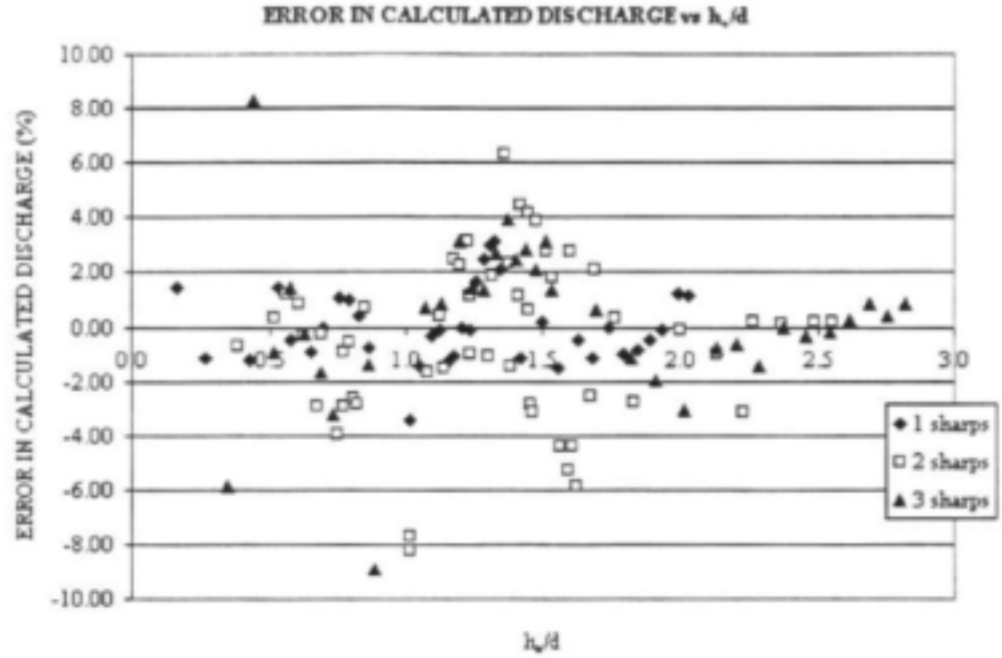


Figure 6.4: *Errors in modular discharge vs h_o/d for flumes with full width sharp-crested weirs*

6.4.1.3 End contractions

Results from the new tests conducted on flume 2 in combination with end-contracted sharp-crested weirs are summarised in Table 6.3:

	Tests E2S	Tests G2S	Tests I2S
Average Error (%)	-1.56	-2.99	-3.52
Ave abs Error (%)	1.56	2.99	3.52
Std Deviation (%)	0.67	0.82	0.86
Max. Error (%)	-0.12	-0.88	-1.93
Min. Error (%)	-2.95	-4.13	-4.80
Number of tests	27	12	15

Table 6.3: *Errors associated with modular discharge calculation for flume 2 with end-contracted sharp-crested weirs*

The spread of these errors is illustrated in Figure 6.5:

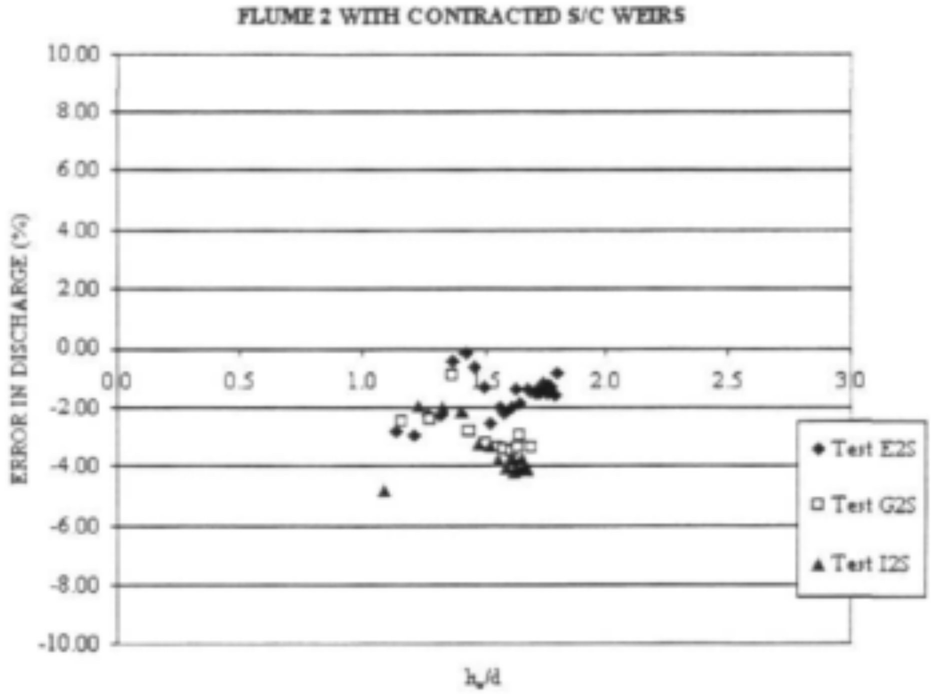


***Figure 6.5**: Errors in modular discharge vs h_o/d for flume 2 with end-contracted sharp-crested weirs*

As can be seen, the end contractions cause the flow to be underestimated slightly. However, the standard deviation of the errors is small, less than 1% in all cases, meaning that the calculation process is reliable.

When end contractions are present, the value of y_5 must also be calculated in order for the effective width of the sharp-crested weirs to be calculated. The accuracy of the calculation process for y_5 as described in 6.2.1.1 is given in Table 6.4:

	Tests E2S	Tests G2S	Tests I2S
Average Error (%)	0.42	0.07	-0.03
Ave abs Error (%)	0.44	0.18	0.26
Std Deviation (%)	0.22	0.23	0.40
Max. Error (%)	0.81	0.47	0.51
Min. Error (%)	-0.15	-0.25	-1.18
Number of tests	27	12	15

***Table 6.4:** Errors in y_5 for flume 2 with end-contracted sharp-crested weirs*

It can be seen that the value of y_5 can be calculated very accurately, even with the use of the formulae derived for compound weirs utilising full width sharp-crested weirs as given in the WRC report 442/3/98 (Rossouw et. al., 1998). Since y_5 can be calculated so accurately, the contribution of the error in y_5 to the error in the discharge will be small. The end contractions reduce the effective width of the sharp-crested weirs. This increases the head over the whole weir, due to the restriction of the flow. Hence, a given flow will have a higher head over the weir when end contractions are present, than the same flow when end contractions are not present. The H/L correction incorporated into the IMFT formula for the calculation of the flow over the sharp-crested weirs compensates for this as far as the sharp-crested weirs are concerned. However, as the head is increased over the whole weir, the flow through the sluicing flume is also affected by the end-contractions. The increased head over the weir, and the narrower sharp-crested weirs increase the cross flow over the flume side walls. The flumes were calibrated with full width side weirs, and hence the formulae for flow through the flume cannot compensate for the effect of the end contractions. Given that flows over two very different types of structure are calculated separately and then added to give the total discharge over the compound weir, and the somewhat idealised assumptions made in this regard, the errors made in the discharge calculation are placed in perspective. Given the magnitude of the errors, the assumptions made in the calculation process can be regarded as reasonable. This is important, as the modular calculation of the discharge forms the basis for the calculation under non-modular conditions.

6.4.2 Crump weirs

6.4.2.1 Comparison of new and previous tests

The previous WRC tests, as well as the new tests on Crump weirs have been conducted on full width Crump weirs in combination with flume 2 (d/b = 0.5). The new and old tests are compared in Table 6.5:

	Previous tests (A2C)	New tests (C2C)
Average Error (%)	-0.11	-2.20
Ave abs Error (%)	0.62	1.94
Std Deviation (%)	0.86	1.45
Max. Error (%)	1.56	0.17
Min. Error (%)	-2.24	-4.91
Number of tests	14	19

Table 6.5: *Comparison of previous and new tests for flume 2 (d/b = 0.5) with full width Crump weirs*

Again, a difference can be seen between the new and old tests, as was the case with the sharp-crested weirs. The possible explanations for this are given in section 6.4.1.1.

These errors are illustrated in Figure 6.6:

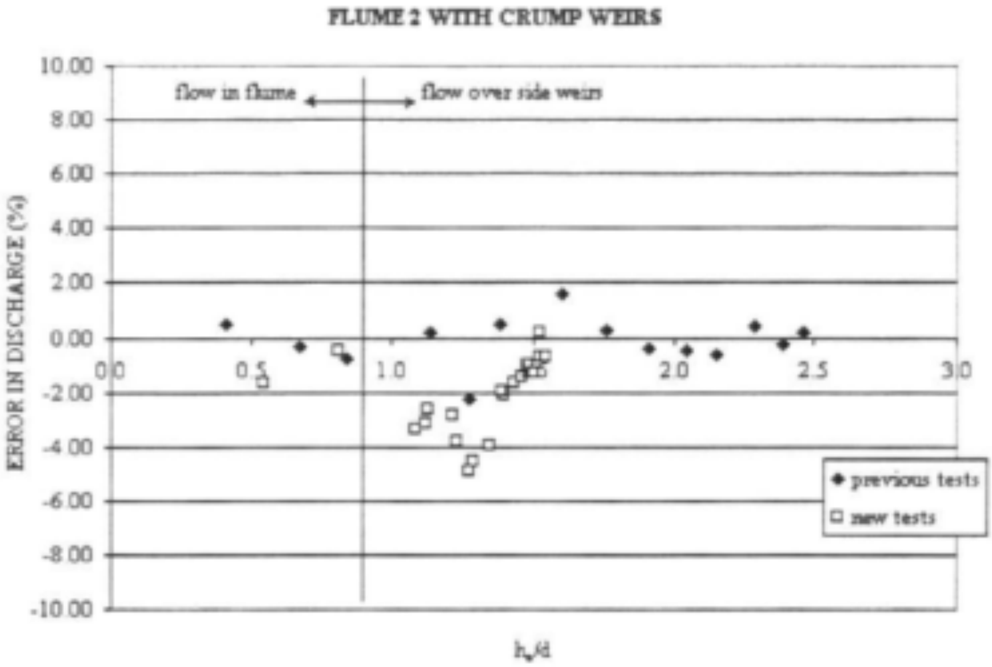


Figure 6.6: *Errors in modular discharge vs h_o/d for new and old tests with flume 2 and full width Crump weirs*

6.4.2.2 Summary for full width Crump weirs

The new and old tests combined give the errors for full width Crump weirs in Table 6.6:

	Flume 2, Crump weirs
Average Error (%)	-1.32
Ave abs Error (%)	1.54
Std Deviation (%)	1.60
Max. Error (%)	1.56
Min. Error (%)	-4.91
Number of tests	33

Table 6.6: *Errors associated with modular discharge calculation on flumes with full width Crump weirs*

Although, in total, fewer tests have been conducted on flume 2 with Crump weirs, it can be seen that the Crump weirs are on the whole more accurate than the sharp-crested weirs. The average error in the modular discharge is greater in the case of Crump weirs, but the average absolute error, the standard deviation, as well as the maximum and minimum errors are smaller in the case of the Crump weirs. The average absolute error gives a better indication of the actual magnitude of the errors, which are smaller in the case of the Crump weirs. The standard deviation of the errors gives an indication of the spread of the errors, which is significantly smaller in the case of the compound weir incorporating Crumps. Hence, it can be said that the Crump weirs in combination with the sluicing flume form a more accurate combination for modular discharge estimation than the combination of the sluicing flume and sharp-crested weirs.

7. SUBMERGENCE OF SLUICING FLUMES

As mentioned in Chapter 5.1, the existing method for the analysis of the submergence of sluicing flumes entails the correction of the submerged water level to the equivalent unsubmerged water level, according to the degree of submergence of the flume. Since the water levels are used, this method has the disadvantage that it is only applicable for the specific case for which it has been derived. If a more generally applicable method is desired, such a method must entail the use of discharges as opposed to water levels.

In describing the submergence of long-throated flumes, Bos and Reinink (Bos and Reinink, 1981) introduced a flow reduction factor, f, which when multiplied with the free discharge yields the submerged discharge for the flume. This factor is dependant on the degree of submergence of the flume, and is read off a graph supplied by them (Figure 5.2). By manipulation of equation 5.1, it can be seen that this flow reduction factor can be expressed as the ratio of the submerged to unsubmerged discharges. The curve derived by Bos and Reinink (Figure 5.2) then becomes a plot of this ratio of the discharges against the degree of submergence of the flume. If this graph is then rotated so that the degree of submergence is plotted on the horizontal axis, its form is as shown in Figure 7.1:

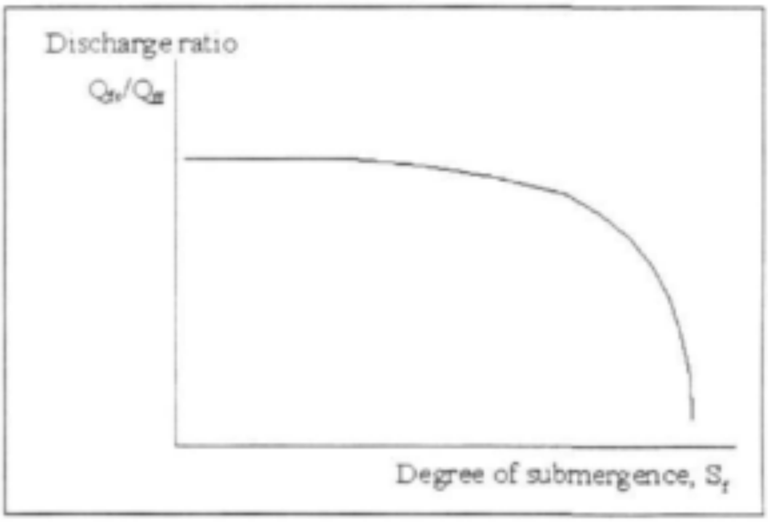


***Figure** 7.1: Ratio of discharges vs degree of submergence*

From this relationship, with the degree of submergence known, the value of Q_{fs}/Q_{ff} can be read off, from which the submerged discharge can be determined. Using existing as well as new data from laboratory tests, this relationship is derived for the three sluicing flumes. This process is detailed in the following paragraphs.

7.1 DETERMINATION OF THE SUBMERGED DISCHARGE THROUGH THE FLUME, Q_{fs}

In the submergence tests conducted, the flow measured in the laboratory, Q_{lab}, is the actual submerged discharge for the whole compound weir. The "free" discharge is calculated over the sharp-crested weirs, and then corrected to give the submerged discharge, Q_{ws}, in accordance with the methods laid out in Chapter 5.2 This submerged flow over the side, sharp-crested weirs is then subtracted from the discharge measured in the laboratory, to give the submerged discharge through the flume, Q_{fs}:

$$Q_{fs} = Q_{lab} - Q_{ws} \tag{7.1}$$

In order to obtain the most accurate values possible, the laboratory values of y_5 were used in the calculation of H_{ws}, and therefore Q_{ws}. This has been done on all the configurations of compound weirs; all three flumes, with sharp-crested (all combinations of full width and end-contracted sharp-crested weirs), and Crump weirs.

7.2 DETERMINATION OF THE "FREE" DISCHARGE THROUGH THE FLUME, Q_{ff}

The Villemonte correction for the submergence of sharp-crested weirs was derived from a ratio between the submerged and "free" discharges. This led to the Villemonte equation, as in equation 5.16. In the calculation of the "free" discharge in the relationship, Villemonte used the modular flow formulae, but the submerged water level. This is because only one water level recording is made upstream at a gauging station. Hence if the weir is submerged, the submerged water level is the only value available, and must therefore be used in the calculation process.

The same is true of the compound weirs analysed here, and therefore a similar process is followed. The "free" discharge through the sluicing flume, Q_{ff}, is calculated using the submerged water level, h_v, so that a similar relationship can be derived for the flume. Discharge calculation proceeds in a manner identical to that described in Chapter 6.1, with the single exception that the submerged water level, h_v, is substituted for h_o, the unsubmerged water level, throughout.

7.3 RELATIONSHIP BETWEEN Q_{ff} AND Q_{fs}

Villemonte plotted the ratio of the submerged to unsubmerged discharges against the degree of submergence of the sharp-crested weirs he worked on. A similar approach is followed here. The ratio Q_{fs}/Q_{ff} is plotted against the degree of submergence of the sluicing flume, S_f.

7.3.1 Sharp-crested weirs

The compound weirs featuring sharp-crested and Crump weirs are analysed separately. It was found during the modular calibration of these compound weirs (Rossouw et al., 1998), that due to the fact that the crests of the Crump and sharp-crested weirs were at different locations relative to the flume, differences between the two configurations of compound weirs were evident. Under non-modular conditions, the same is likely to be true.

The new and old data for flume 2 (d/b = 0.5) in combination with sharp-crested weirs have been combined and analysed simultaneously. It has been found that the correlation between the new and old data is good.

7.3.1.1 Full width sharp-crested weirs

In the case of the compound weirs featuring full width sharp-crested weirs, the Q_{fs}/Q_{ff} vs S_f relationship follows similar patterns, as illustrated in Figures 7.2, 7.3, and 7.4:

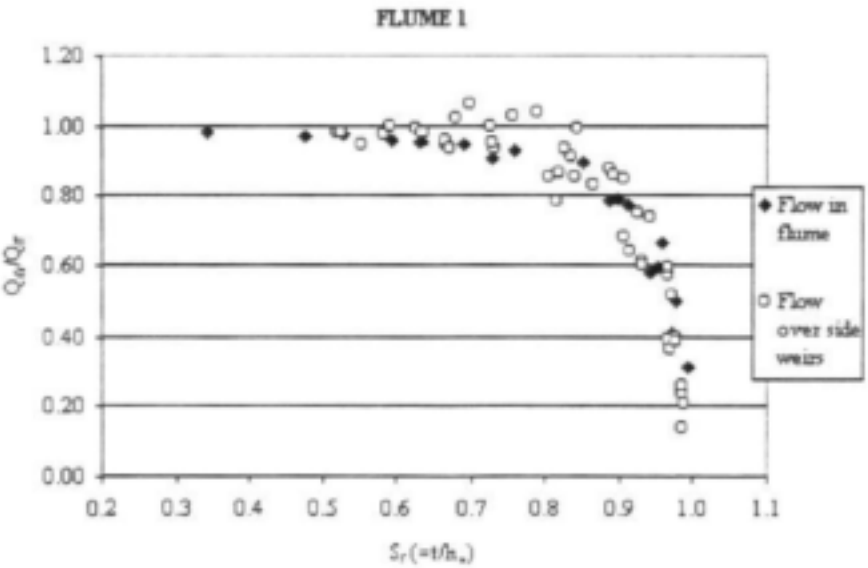


Figure 7.2: *Q_{fs}/Q_{ff} vs S_f for flume 1 (d/b = 1.0) with sharp-crested weirs (data from test B1S, page C2)*

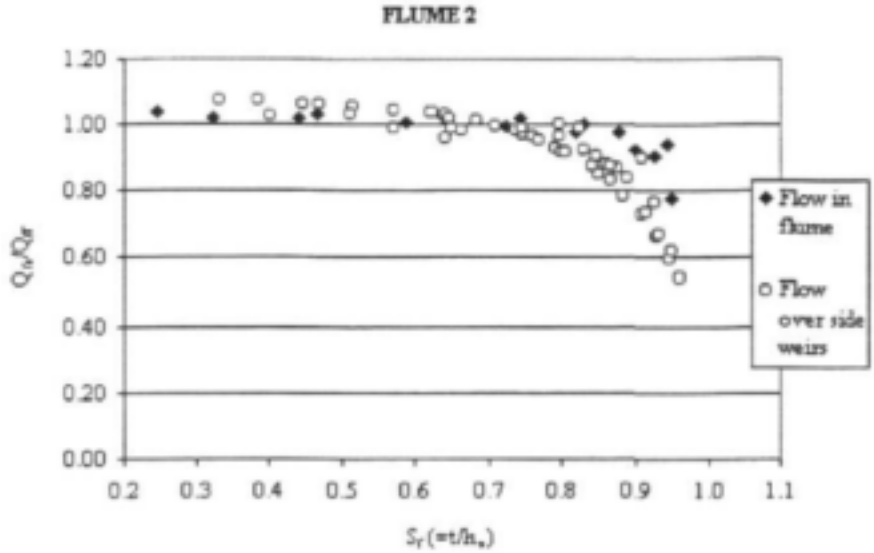


***Figure** 7.3: Q_{fs}/Q_{ff} vs S_f for flume 2 (d/b = 0.5) with sharp-crested weirs (data from tests B2S and D2S; pages C4 and C8)*

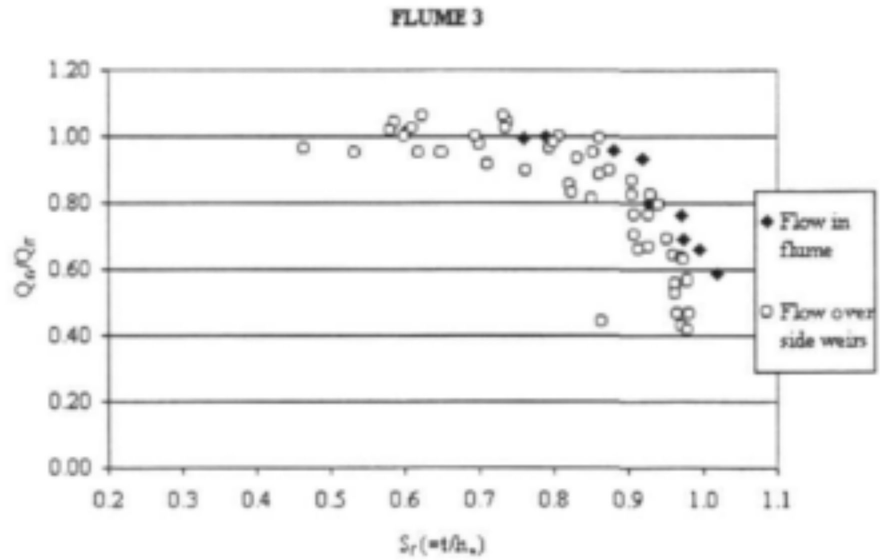


***Figure** 7.4: Q_{fs}/Q_{ff} vs S_f for flume 3 (d/b = 0.25) with sharp-crested weirs (data from test B3S, page C6)*

The trend of all three graphs shows that as the degree of submergence increases, the ratio Q_{fs}/Q_{ff} decreases, meaning that the discharge through the flume, Q_{fs}, is reduced. This is to be expected as submergence reduces the discharge over a weir.

It is interesting to note that this relationship is slightly different, depending on whether the initial, unsubmerged, flow is contained in the flume or not. If these two cases are separated, it can be seen that when flow is contained in the flume, the modular limit of the

flume is slightly higher than when flow overtops the flume and side weirs.
In the case where flow occurs over the side weirs, this submerged discharge is calculated and then subtracted from the discharge recorded in the laboratory. The remaining discharge is attributed to the flume, and used in the Q_{fs}/Q_{ff} vs S_f relationship. Hence, the submerged discharge in the flume, Q_{fs}, is dependent on the accuracy with which the submerged discharge over the sharp-crested weirs is calculated. Since this cannot be done with absolute accuracy, some error is inherent in the value of Q_{fs}. The effect of the sharp-crested weirs being much more susceptible to submergence, and hence becoming submerged to a greater degree before the sluicing flume, is reflected in the calculation of the submerged discharge over these weirs, and hence on the value of submerged discharge through the flume, Q_{fs}. This is in turn reflected in the Q_{fs}/Q_{ff} vs S_f relationship. The flume appears more robust w.r.t. submergence when flow is contained in the flume, with a modular limit of 0.8. By contrast, the flume seems slightly more susceptible to submergence when flow occurs over the side weirs, with a modular limit of 0.7.

This apparent contradiction is due to the influence of the sharp-crested weirs, which become submerged to a greater extent before the flume does, and the fact that this effect is then attributed to flow through the flume. For this reason, it has been decided that two separate curves will be fitted to the data; one for when flow is contained in the flume, and one for when flow occurs over the side weirs. In the former case, and in line with what was obtained previously, (Rossouw et. al., 1998), the modular limit of the sluicing flume has been set at 0.8. In the case where the initial unsubmerged flow occurs over the side weirs, the modular limit has been set at 0.7.

Where submergence takes place in flume flow only, no correction of the flow is made up to the modular limit of 0.8. Thereafter, correction is done according to a curve fitted to all the data for degrees of submergence of greater than 0.8. Where submerged flow occurs once the side weirs have been overtopped, no correction is made for submergence up to the modular limit of 0.7. For degrees of submergence greater than this, correction is applied in two ranges: for degrees of submergence between 0.7 and 0.95, and for degrees of submergence of greater than 0.95. In this latter region, it can be seen that the effect of submergence on the flume is very marked, in that there is a significant deviation of the Q_{fs}/Q_{ff} ratio. Due to this marked effect, it is considered unlikely that discharge calculation with a sufficient degree of accuracy is possible in this region.

7.3.1.1.1 Flow in the flume

In the case where the initial unsubmerged flow is contained in the flume, the fits are made to the data for each flume as shown in Figures 7.5, 7.6, and 7.7:

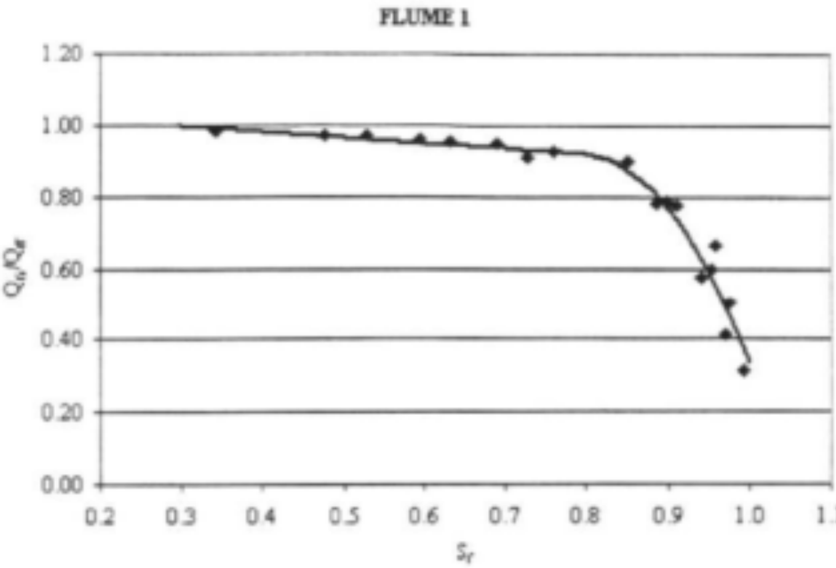


***Figure** 7.5: Submergence of flow in flume: flume 1 (b/d = 1.0) with sharp-crested weirs*

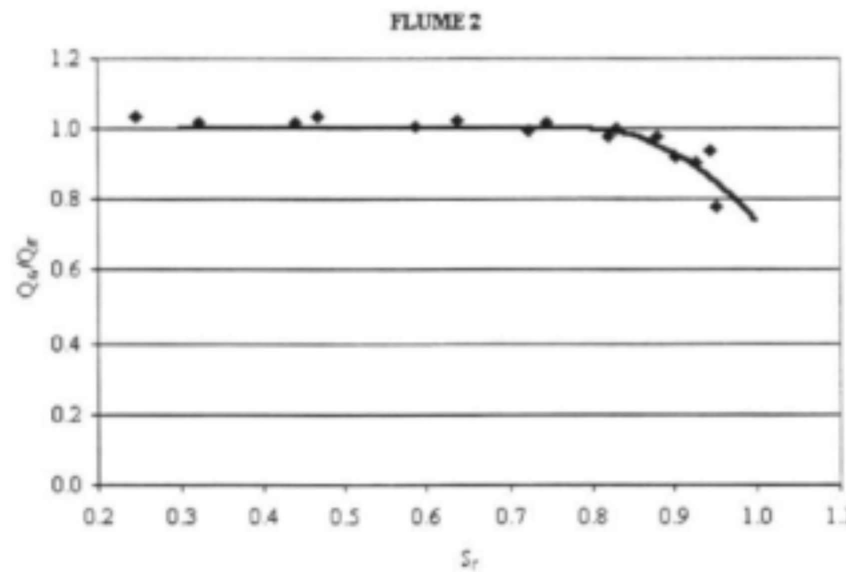


***Figure** 7.6: Submergence of flow in flume: flume 2 (b/d = 0.5) with sharp-crested weirs*

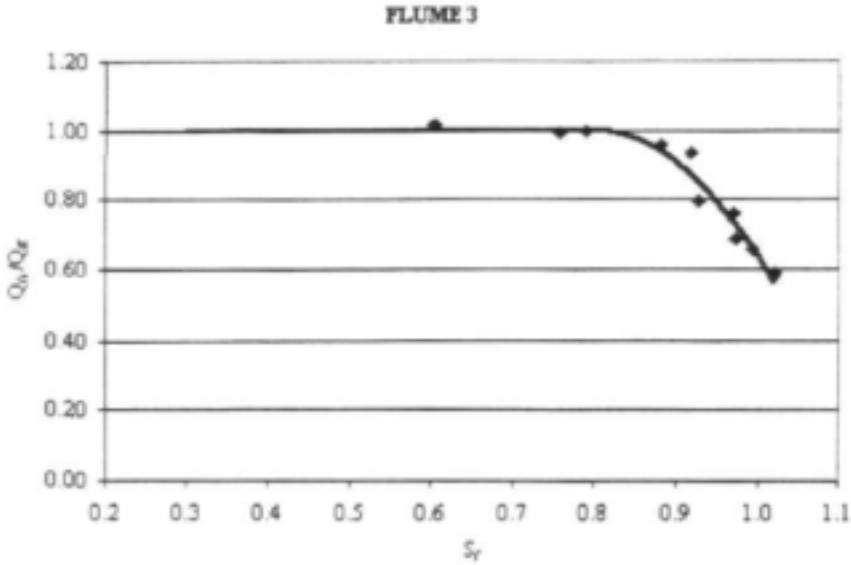


***Figure** 7.7: Submergence of flow in flume: flume 3 (b/d = 0.25) with sharp-crested weirs*

The curves have been fitted to the data such that the curves break away from the modular limit tangentially.

The correction for submergence of the sluicing flumes uses the following fitted curves:

Flume 1 (d/b = 1.0):

$$Q_{fs}/Q_{ff} = 1 \qquad \text{for } S_f < 0.30 \qquad (7.2)$$

$$Q_{fs}/Q_{ff} = -0.154.S_f + 1.043 \qquad \text{for } 0.30 \leq S_f \leq 0.80 \qquad (7.3)$$

$$Q_{fs}/Q_{ff} = -13.852.S_f^2 + 22.009.S_f - 7.822 \qquad \text{for } 0.80 < S_f \leq 0.99 \qquad (7.4)$$

Flume 2 (d/b = 0.5):

$$Q_{fs}/Q_{ff} = -6.539.S_f^2 + 10.462.S_f - 3.185 \qquad \text{for } 0.80 < S_f \leq 0.95 \qquad (7.5)$$

Flume 3 (d/b = 0.25):

$$Q_{fs}/Q_{ff} = -9.011.S_f^2 + 14.417.S_f - 4.767 \qquad \text{for } 0.80 < S_f \leq 1.02 \qquad (7.6)$$

For flumes 1 and 2:

$$Q_{fs}/Q_{ff} = 1.0 \qquad \text{for } S_f \leq 0.80 \qquad (7.7)$$

The above formulae are only applicable within the limits of S_f specified above and extrapolation of these formulae beyond these limits should be avoided

For flumes 2 and 3 the modular limit of the flume has been set at a degree of submergence of 80% when flow is contained in the flume. This has not been applied to flume 1. This is because for degrees of submergence of less than 80%, the Q_{fs}/Q_{ff} points for flume 1 lie below unity. In order to be able to calculate the flow accurately, it has been decided to fit a curve to the data points, rather than apply a modular limit of 0.8 in this case. The reason for the Q_{fs}/Q_{ff} points lying below unity for flume 1 can be explained as follows.

If flume 1, which is a narrow, deep flume, and flume 3, which is a shallow, wide flume are compared, it can be seen that when the sharp-crested weirs adjacent to the two flumes are to be submerged to the same extent, that flume 1 would be submerged to a much greater degree than would be flume 3. This is because flume 1 is much deeper. In order to obtain the fits described here, the submerged discharge over the side weirs is calculated, and subtracted from the discharge recorded in the laboratory to give the submerged discharge through the flume. This is compared to the "free" discharge calculated through the flume with h_v in the place of h_o. However, flume 1 is submerged to a greater extent by the time the sharp-crested weirs are submerged, and are corrected for submergence, than flume 3 is. This is not allowed for, and the results are evident in Figure 7.5: the Q_{fs}/Q_{ff} points lie below unity, even for degrees of submergence of less than 0.8. This means that the submerged discharge should be smaller than the "free" discharge through the flume. In order to allow for this, a different fit has been applied to the data from flume 1.

7.3.1.1.2 Flow over side weirs

When the initial unsubmerged flow overtops the flume walls and side weirs, the fits to the data as shown in Figures 7.8, 7.9, and 7.10, for each flume are made:

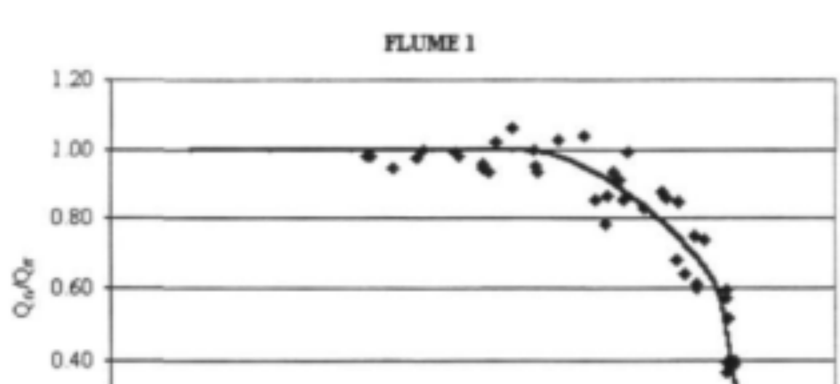


***Figure 7.8:** Submergence of flow over side weirs: flume 1 (b/d = 1.0) with full width sharp-crested weirs*

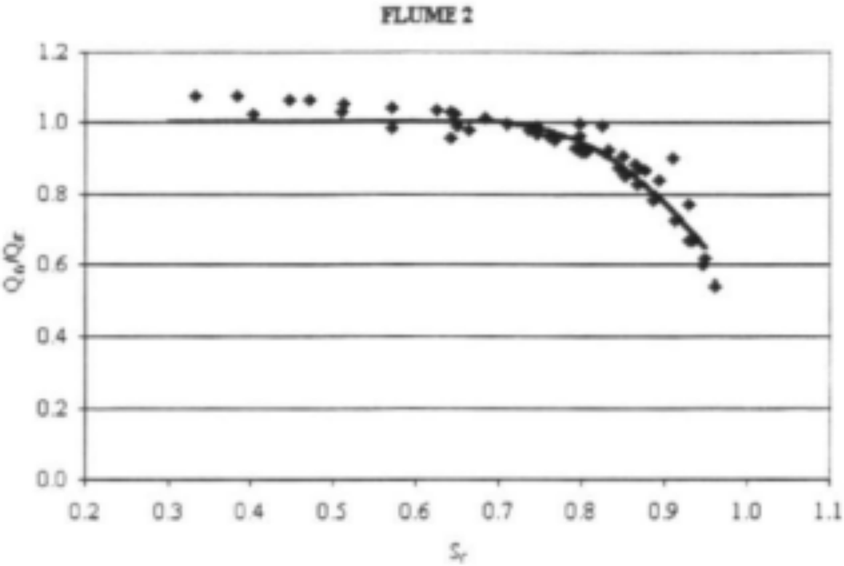


Figure 7.9: Submergence of flow over side weirs: flume 2 (b/d = 0.5) with full width sharp-crested weirs

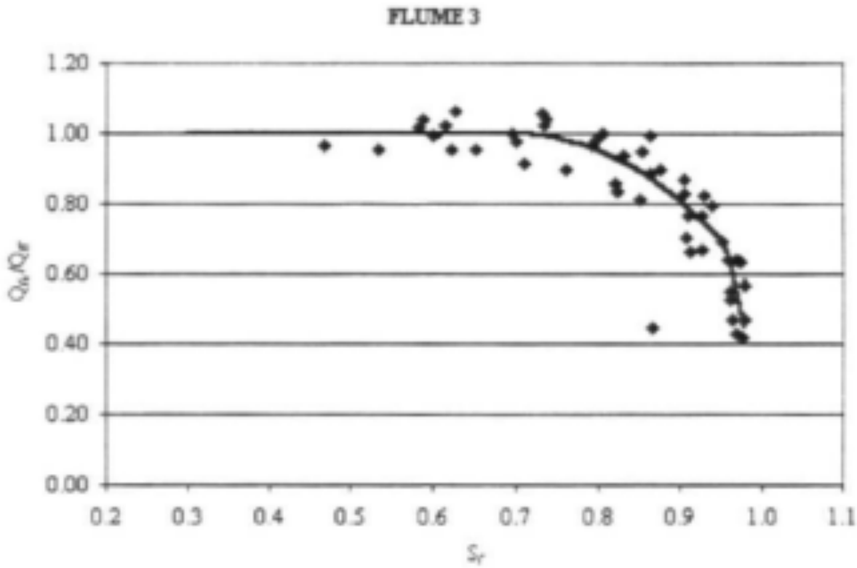


Figure 7.10: Submergence of flow over side weirs: flume 3 (d/b = 0.25) with full width sharp-crested weirs

Two restrictions have been placed on the fitted curves. The curves fitted in the region of degrees of submergence of between 0.70 and 0.95 have been fitted such that they approach the modular limit tangentially. The second curve (for degrees of submergence of greater than 0.95) has been fitted such that the transition between the two curves is smooth; namely the second curve joins the first at the same point, and at the same gradient at which the first terminates.

The correction for submergence of the sluicing flumes in combination with full width sharp-crested weirs uses the following fitted curves:

Flume 1 (d/b = 1.0):

$$Q_{fs}/Q_{ff} = -5.871.S_f^2 + 8.219.S_f - 1.877 \qquad \text{for } 0.70 < S_f \leq 0.95 \quad (7.8)$$

$$Q_{fs}/Q_{ff} = -251.047.S_f^2 + 474.053.S_f - 223.148 \qquad 0.95 < S_f \leq 0.99 \quad (7.9)$$

Flume 2 (d/b = 0.5):

$$Q_{fs}/Q_{ff} = -5.678.S_f^2 + 7.949.S_f - 1.782 \qquad \text{for } 0.70 < S_f \leq 0.95 \quad (7.10)$$

Flume 3 (d/b = 0.25):

$$Q_{fs}/Q_{ff} = -4.842.S_f^2 + 6.780.S_f - 1.373 \qquad \text{for } 0.70 < S_f \leq 0.95 \quad (7.11)$$

$$Q_{fs}/Q_{ff} = -195.561.S_f^2 + 369.146.S_f - 173.497 \qquad 0.95 < S_f \leq 0.98 \quad (7.12)$$

For all three flumes:

$$Q_{fs}/Q_{ff} = 1.0 \qquad \text{for } S_f \leq 0.70 \quad (7.13)$$

The above formulae are only applicable within the limits of S_f specified above and extrapolation of these formulae beyond these limits should be avoided.

7.3.1.2 End contracted sharp-crested weirs

Various configurations of end contractions were tested on sharp-crested weirs in combination with flume 2 (d/b = 0.5). This is the flume geometry most favoured in the prototype by DWAF. In prototype weirs, end contractions occur due to compounding of the sharp-crested weirs, and can also be introduced to provide aeration for the weir.

As done previously, the submerged discharge over the sharp-crested weirs, Q_{ws}, was calculated. Allowance was made for the end contractions in accordance with the methods laid out in section 5.2.1. (Correction for submergence of the crests was done according to the Villemonte equation in most cases, with correction by the Wessels' method in only a few instances.) This discharge was again subtracted from the discharge recorded in the laboratory, to give the submerged discharge through the flume, Q_{fs}, which was plotted against the degree of submergence of the flume, S_f, as was done previously.

It has been found that end contractions have a significant impact on flow over the compound weir. The Q_{fs}/Q_{ff} vs S_f relationship broadly follows a similar pattern to that followed previously, but deviation from unity starts much sooner than before. This is shown in Figure 7.11.

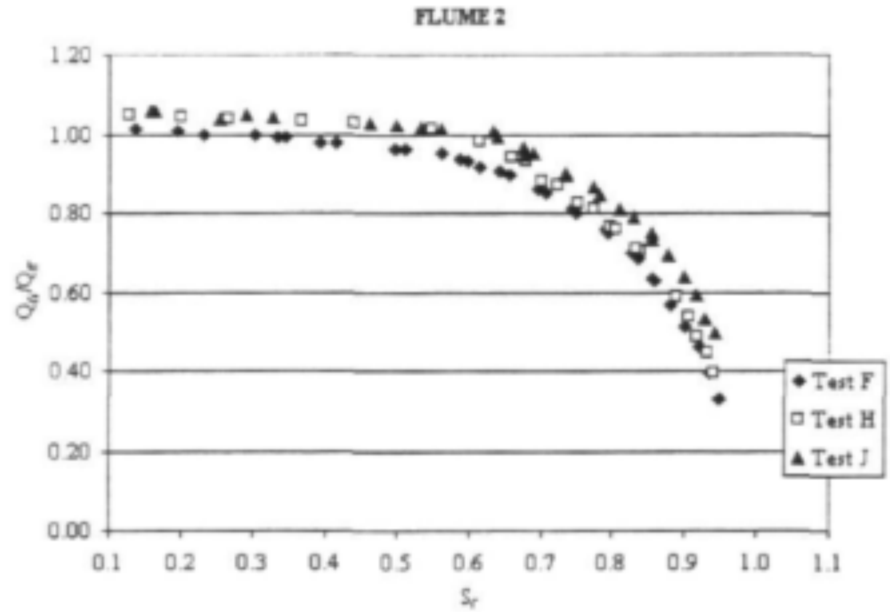


Figure 7.11: *Q_{fs}/Q_{ff} vs S_f for flume 2 (d/b = 0.5) with all end contracted sharp-crested weirs (data from tests B2S, D2S, F2S, H2S, and J2S; pages C4, C8 and C11 to C14)*

End contractions, by reducing the effective overflow width of the sharp-crests, cause an increase in the upstream water level. The upstream water level in the case of end contractions will be higher than for an equivalent flow with full width side weirs. Thus, in the case of end contractions, the degree of submergence of both the flume and sharp-crests is lower than would be the case without end contractions. This explains why the Q_{fs}/Q_{ff} vs S_f curve deviates from unity sooner than the curve representing full width side weirs. From the above curves, it can be seen that many of the data points (representing Q_{fs}/Q_{ff} values) are greater than unity, for degrees of submergence of less than the modular limit. The sharp-crested weirs become affected by submergence sooner than, and to a greater extent than the sluicing flume. Hence, before the flume experiences the effects of submergence, the discharge over the sharp-crested weirs is reduced due to submergence. To maintain a constant discharge over the compound weir, the effect is reflected in the analysis by allocating more discharge to the flume, which is not yet submerged. This is implicit in the process of calculating the submerged discharge over the sharp-crested weirs, and allocating the balance of the discharge to the flume. Since more discharge is allocated to the flume than actually flows through it, the Q_{fs}/Q_{ff} values in this region are greater than unity.

Due to the complex effects of the end contractions, it has been impossible to obtain the same Q_{fs}/Q_{ff} vs S_f curve for flumes with full width as well as end contracted side sharp-crested weirs. Since the varying end contractions have varying effects on the flow through the flume, it has also proved to be impossible to obtain a single curve for flumes featuring only end contracted side weirs. Since flow through the flume cannot be isolated from the effects of the end contractions, it has been decided that a range of curves of Q_{fs}/Q_{ff} vs S_f must be used, to cover the range of end contractions and their effects.

From Figure 7.11 it can be seen that the tests featuring the largest end contractions (test F) have the biggest effect on discharge through the flume, with this effect decreasing with the size of the end contractions (tests H to J to B and D). Clearly the overflow width of the sharp-crested weirs relative to the width of the flume is a key parameter in determining the pattern of flow over the compound weir. The ratio of $4d/(L_1 + L_2)$ is used to quantify this effect and to distinguish between the various cases of end contractions. This ratio is defined in Figure 7.12:

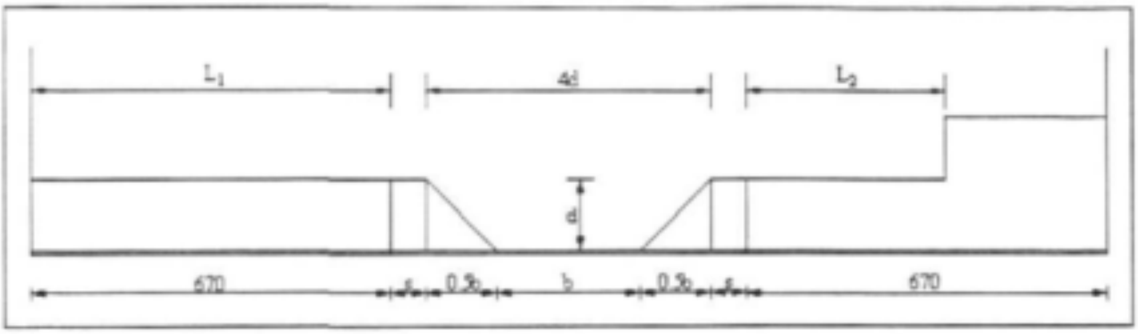


Figure 7.12: *Definition of terms for flume 2 (d/b = 0.5)*

Where L_1 and L_2 are the overflow lengths of the sharp-crested weirs.

For the various tests, this ratio has the values indicated in Table 7.1:

TEST	DESCRIPTION	$4d/(L_1 + L_2)$ ratio
B, D	Full width side weirs	0.394
F	300mm symmetrical end contractions	0.714
H	300mm end contraction on LHS crest	0.508
J	100mm symmetrical end contractions	0.463

Table 7.1: *Values of $4d/(L_1 + L_2)$ for various tests with flume 2, and sharp-crested weirs*

Curves have been fitted to the data in a manner similar to the previously used, with similar restrictions. In the case of test F, the modular limit has been set at 0.3. Two curves are fitted beyond this region; one for degrees of submergence between 0.3 and 0.6, and the other for degrees of submergence of greater than 0.6. This has been done because a single curve cannot adequately fit the data. In the case of tests H and J, the modular limits have been set at 0.55 and 0.6 respectively. These curves are illustrated in Figure 7.13:

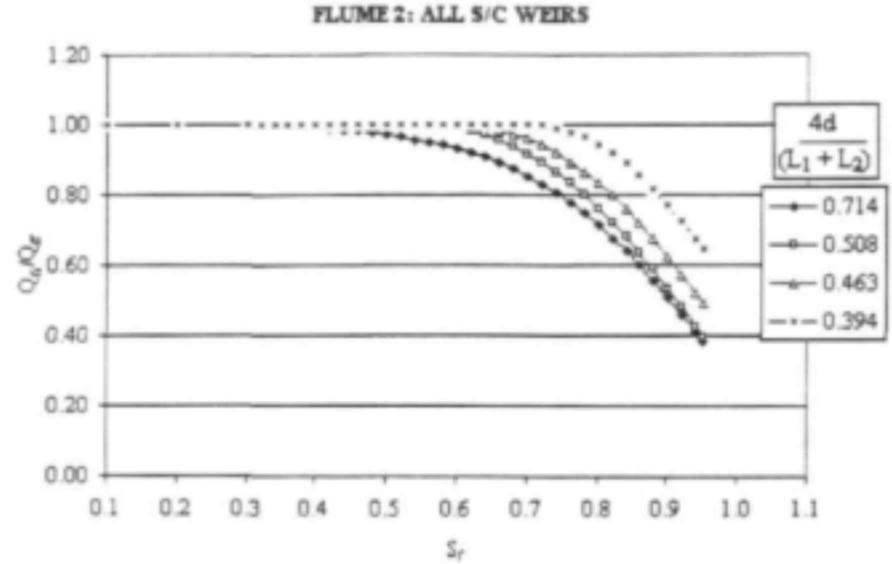


***Figure** 7.13: Fits for flume 2 (d/b = 0.5) with sharp-crested weirs*

The equations of the curves are as follows:

Flume 2 (d/b = 0.5) with sharp-crested weirs:

$4d/(L_1 + L_2) = 0.714$

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.30$	(7.14)
$Q_{fs}/Q_{ff} = -0.758.S_f^2 + 0.455.S_f + 0.932$	for $0.30 < S_f \leq 0.60$	(7.15)
$Q_{fs}/Q_{ff} = -3.183.S_f^2 + 3.365.S_f + 0.058$	for $0.60 < S_f \leq 0.95$	(7.16)

$4d/(L_1 + L_2) = 0.508$

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.55$	(7.17)
$Q_{fs}/Q_{ff} = -3.800.S_f^2 + 4.179.S_f - 0.149$	for $0.55 < S_f \leq 0.94$	(7.18)

$4d/(L_1 + L_2) = 0.463$

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.60$	(7.19)
$Q_{fs}/Q_{ff} = -4.162.S_f^2 + 4.994.S_f - 0.498$	for $0.60 < S_f \leq 0.94$	(7.20)

$4d/(L_1 + L_2) \leq 0.394$ (full width)

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.70$	(7.13)
$Q_{fs}/Q_{ff} = -5.678.S_f^2 + 7.949.S_f - 1.782$	for $0.70 < S_f \leq 0.95$	(7.10)

The above formulae are only applicable within the limits of S_f specified above and extrapolation of these formulae beyond these limits should be avoided.

7.3.2 Crump weirs

The correction for the submergence of Crump weirs is based on the ratio of the downstream to upstream energy levels (energy levels above the crest of the Crump), as in equations 5.27 and 5.28. In order that the downstream energy level above the crest of the Crump be calculated, the downstream structure height, Z, must be known. This value is not available for the WRC tests conducted previously. Hence, only data from the new range of submergence tests on the Crump weirs in combination with the sluicing flumes has been analysed.

The Q_{fs}/Q_{ff} vs S_f ratio for flume 2 with full width Crump weirs is shown in Figure 7.14:

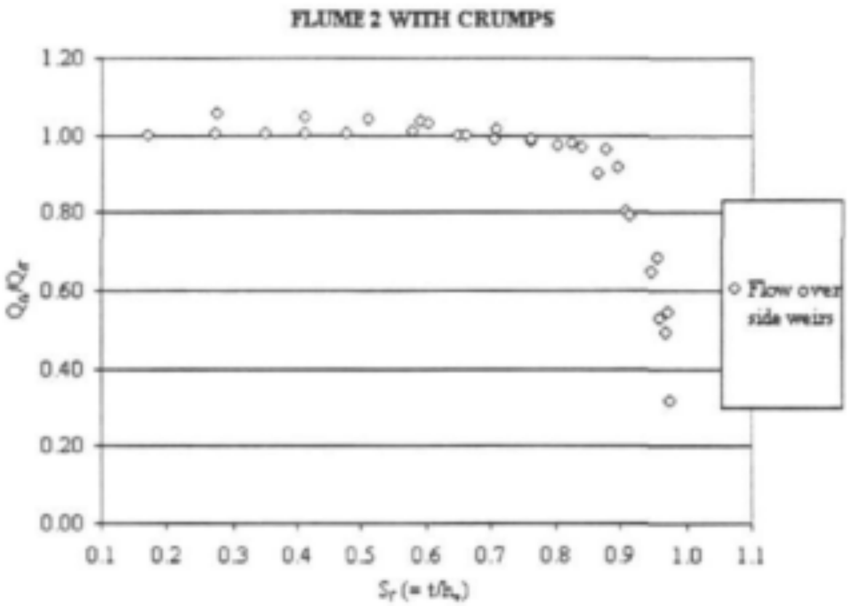


Figure 7.14: *Q_{fs}/Q_{ff} vs S_f for flume 2 (d/b = 0.5) with Crump weirs (data from test D2C, page C10)*

When the submergence of the flume in combination with Crump weirs is compared to that of the flume with sharp-crested weirs (Figure 7.3), it can be seen that the flume is slightly more robust with regard to submergence in the former case. This is due to the fact that Crump weirs are much less susceptible to submergence than are sharp-crested weirs. Crump weirs have a modular limit of 75%, whereas sharp-crested weirs become submerged as soon as the downstream water level rises above the crest level of the (sharp-crested) weir. In addition to the fact that Crump weirs have a higher modular limit, due to the more stable flow characteristics of this structure, the effect of submergence beyond the modular limit is much less pronounced than is the case with sharp-crested weirs.

This means that the discharge over the Crump weirs can be calculated more accurately over a much wider range as far as submergence is concerned, than is the case with sharp-crested weirs. For example, by the time the Crump weirs required correction for submergence, the sluicing flume was at least 95% submerged. By the time the flume was 95% submerged, the sharp-crested weirs were at least 90% submerged.

The fact that the Crump weirs only become submerged much later, and the discharge over these weirs can be calculated more accurately, means that the submerged discharge allocated to the flume by means of equation 7.1 is also more accurate. This in turn is reflected in the fact that the flume appears to be more robust with respect to submergence in the case where it is used in combination with Crump weirs. Hence, where the flume is used with Crump weirs, a modular limit of 0.8 can be applied.

Curves have been fitted to the data in a manner identical to that done previously, in two ranges: for degrees of submergence between 0.8 and 0.95, and for degrees of submergence of greater than 0.95. This is illustrated in Figure 7.15:

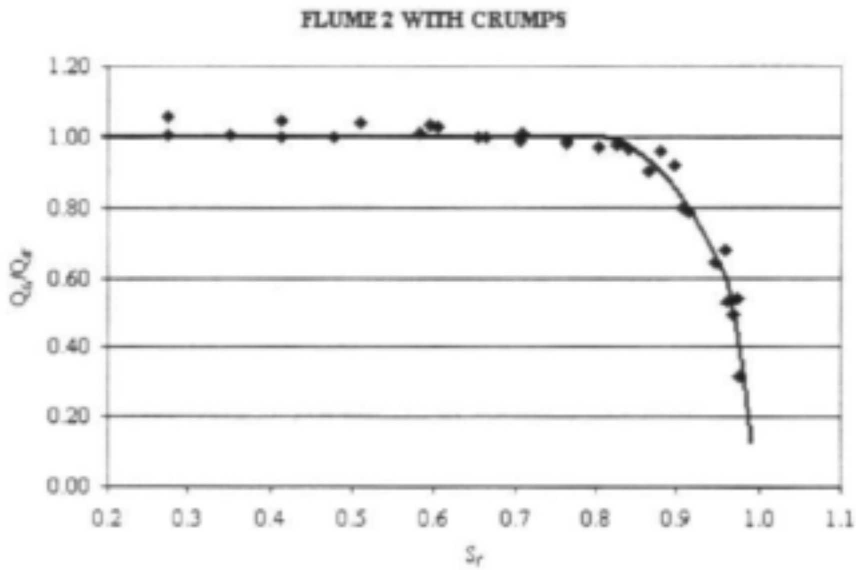


Figure 7.15: *Submergence of flow for flume 2 (d/b = 0.5) with Crump weirs*

The equations of these curves are as follows:

Flume 2 (d/b = 0.5) with Crump weirs:

$Q_{fs}/Q_{ff} = 1.0$ for $S_f \leq 0.80$ (7.21)

$Q_{fs}/Q_{ff} = -15.175.S_f^2 + 24.285.S_f - 8.716$ for $0.80 < S_f \leq 0.95$ (7.22)

$Q_{fs}/Q_{ff} = -220.855.S_f^2 + 415.077.S_f - 194.341$ $0.95 < S_f \leq 0.98$ (7.23)

It can be seen, from comparing Figures 7.15 and 7.9, as well as equations 7.10 and 7.22 and 7.23, that the same flume (flume 2) exhibits slightly different submergence characteristics when accompanied by different types of adjacent side weirs. This confirms what was alluded to earlier; that the flow lines or flow patterns across the compound weir differ slightly depending on whether sharp-crested or Crump weirs are used in combination with the sluicing flume. (This is due to the different positions of the side weirs, and the different cross flow patterns of flow into or out of the flume).

The effect of this is illustrated in Figure 7.16, where all the curves for the submergence effect of flume 2 (d/b = 0.5) are given:

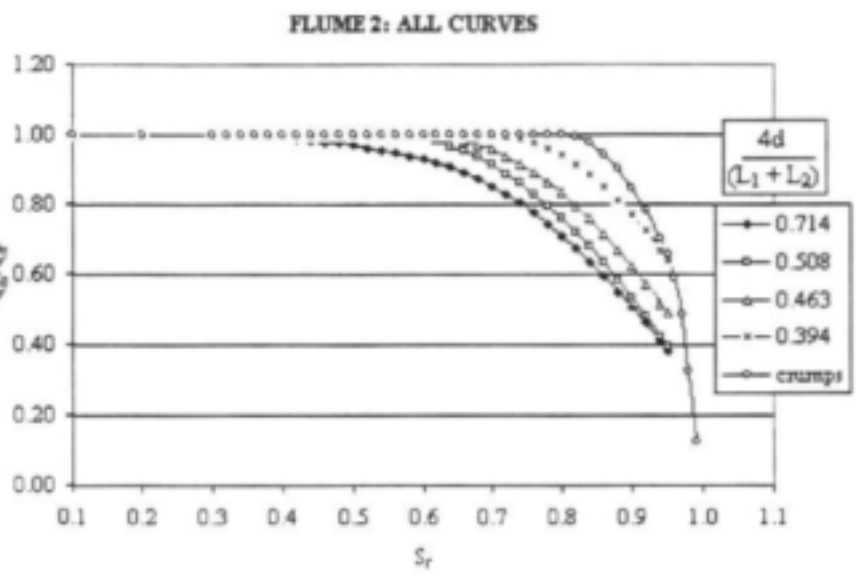


__Figure 7.16:__ Submergence of flow for flume 2 (d/b = 0.5) with all side weir combinations tested

It can be confirmed that the flume is more robust w.r.t. submergence when Crump weirs are used adjacent to the flume. The flume becomes submerged at a higher degree of submergence, but does so more rapidly in combination with Crump weirs.

7.4 RELATIONSHIP BETWEEN y_5 AND h_v

Under modular flow conditions, relationships between E_{s5} and h_o/d have been derived for each of the three flumes (Rossouw et. al., 1998). An example is equation 6.7 for flume 1. When flow overtops the flume walls and adjacent weirs, this allows conversion of the recorded water level, h_o, to the energy head in the upstream pool, E_{s5} which is needed to calculate the flow over the adjacent weirs. This process is necessary because the water level in the upstream pool is not recorded in the prototype.

Since this relationship holds only for modular flow conditions, a similar relationship must be derived for non-modular flow conditions. For sharp-crested weirs, the degree of submergence, $S_{s/c} = (t-d)/(y_5-d)$, is needed to calculate the discharge, and for Crump weirs, the upstream head, H_{ws}. In both instances, the water level y_5 must be known for this to be possible. It is easier to use the water level (y_5) to iterate to the energy level (H_{ws}) than it is to do the reverse. Hence, the relationship to be derived should preferably yield the water level, instead of the energy level, as was the case under modular conditions.

7.4.1 Relationship between y_5/h_v and h_v/d

In laboratory tests, y_5 is recorded, and can hence be used to derive a relationship for subsequent use in the prototype. Previously a relationship was derived between y_5 and h_v in the form of a plot of y_5/h_v vs h_v/d (Rossouw et al., 1998).

7.4.1.1 Sharp-crested weirs

7.4.1.1.1 Full width side weirs

This relationship is shown in Figures 7.17, 7.18 and 7.19 for the three flumes with full width side weirs:

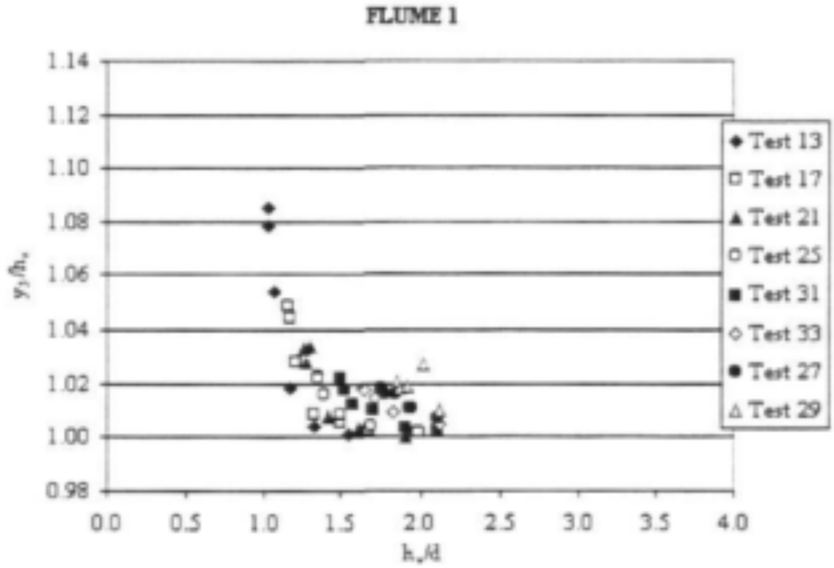


***Figure 7.17**: y_5/h_v vs h_v/d for flume 1 ($d/b = 1.0$) with full width sharp-crested weirs*

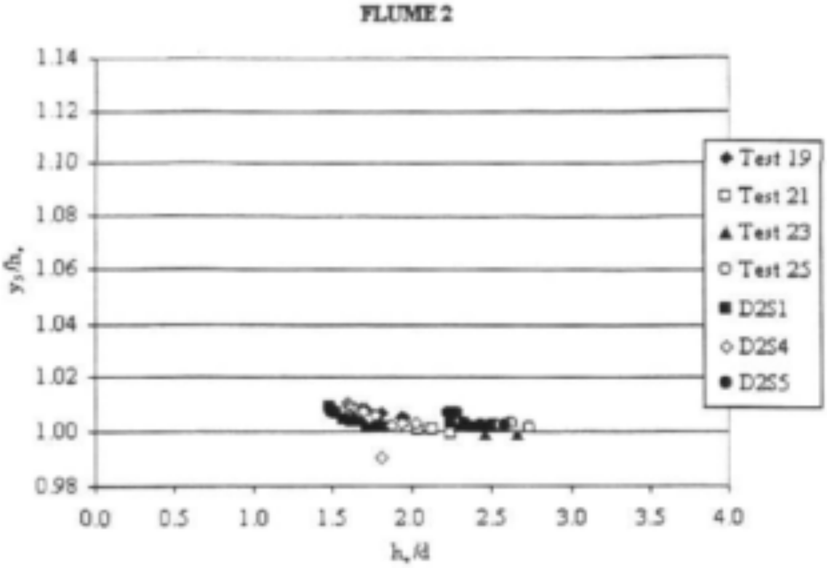


Figure 7.18: *y_5/h_v vs h_v/d for flume 2 ($d/b = 0.5$) with full width sharp-crested weirs*

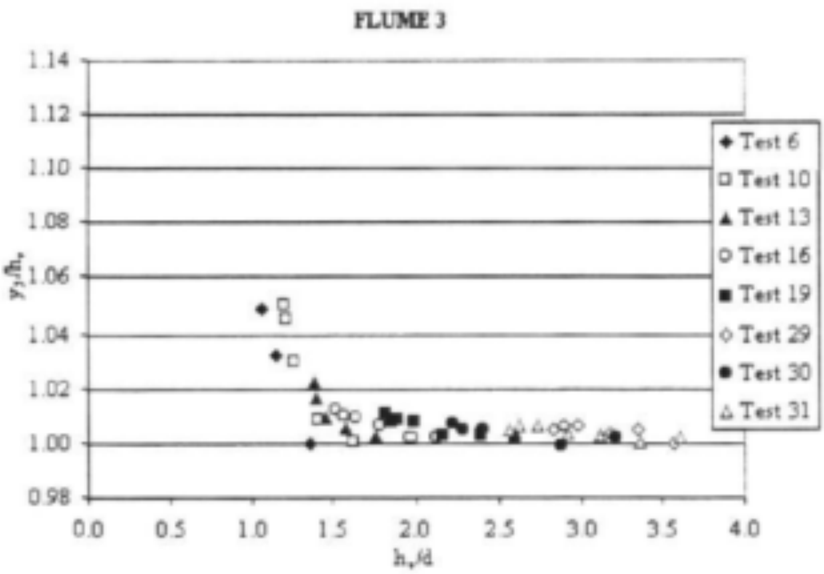


Figure 7.19: *y_5/h_v vs h_v/d for flume 3 ($d/b = 0.25$) with full width sharp-crested weirs*

It can be seen that there is a pattern to the scatter observed in these graphs, particularly for flumes 1 and 3. It can be seen that a similar progression is followed by the data points for each test. In the laboratory, for each run of tests, a unsubmerged flow is first established over the weir. This is then systematically submerged, the flow allowed to stabilise, and the recordings made. Hence, each test represents a different initial, unsubmerged flow. This initial flow is clearly a factor in the relationship between y_5 and h_v.

7.4.1.1.2 End contracted side weirs

The same relationship is again plotted for the tests conducted on flume 2 in combination with end-contracted sharp-crested weirs, as shown in Figures 7.20, 7.21 and 7.22:

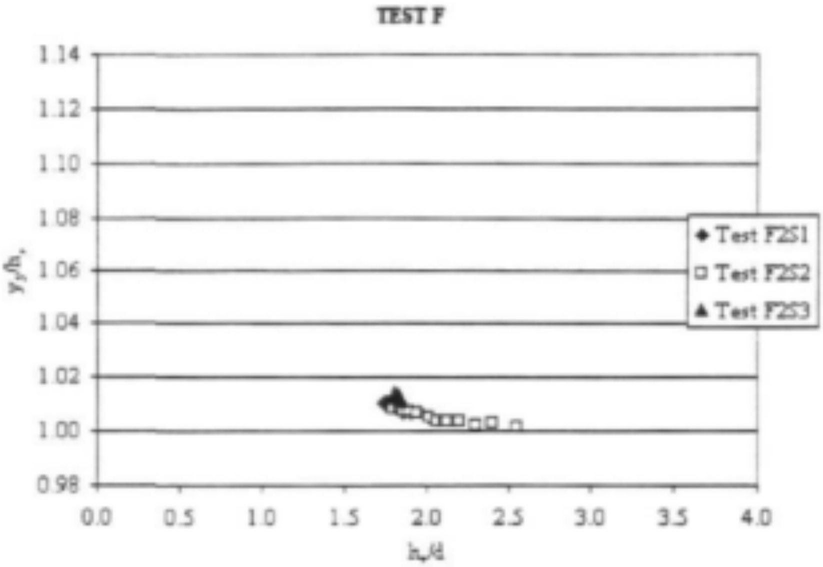


***Figure** 7.20:* y_5/h_v *vs* h_v/d *for flume 2 (d/b = 0.5), test F*

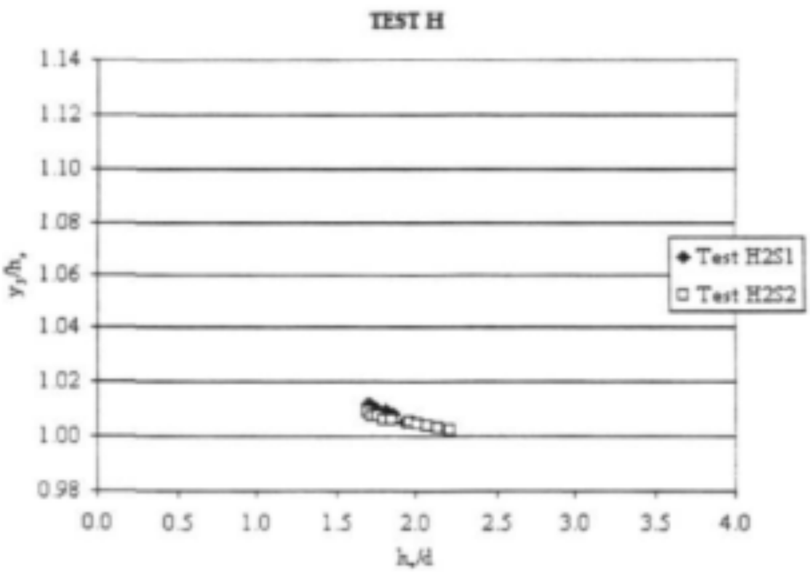


***Figure** 7.21:* y_5/h_v *vs* h_v/d *for flume 2 (d/b = 0.5), test H*

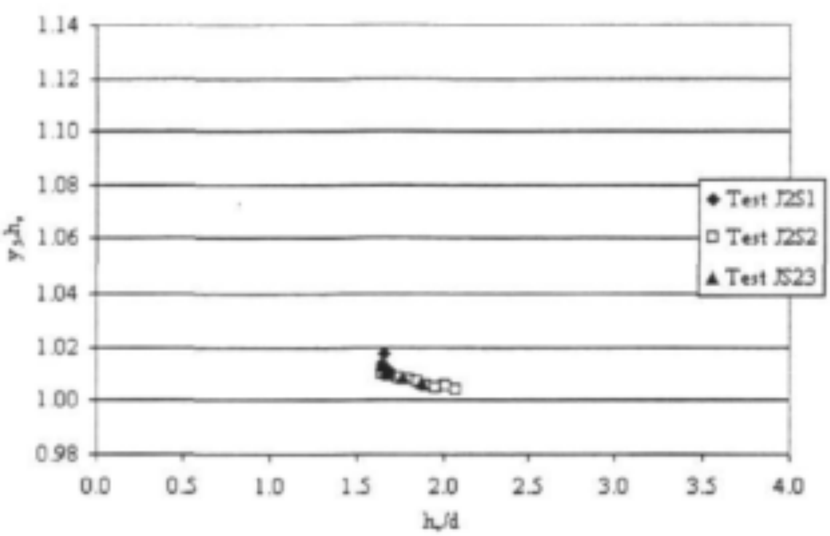


***Figure 7.22:** y_3/h_v vs h_v/d for flume 2 (d/b = 0.5), test J*

It can be seen from these graphs, that with end contractions on the side weirs, the effect of the initial flow is less pronounced, although this is most likely mitigated by the fact that the h_v/d values for each test configuration are of the same order of magnitude, unlike with the previous tests involving full width side weirs.

7.4.1.2 Crump weirs

As with sharp-crested weirs, the ratio of y_3/h_v is plotted against that of h_v/d. As can be seen in Figure 7.23, the effect of the initial flow is markedly greater than is the case with sharp-crested weirs.

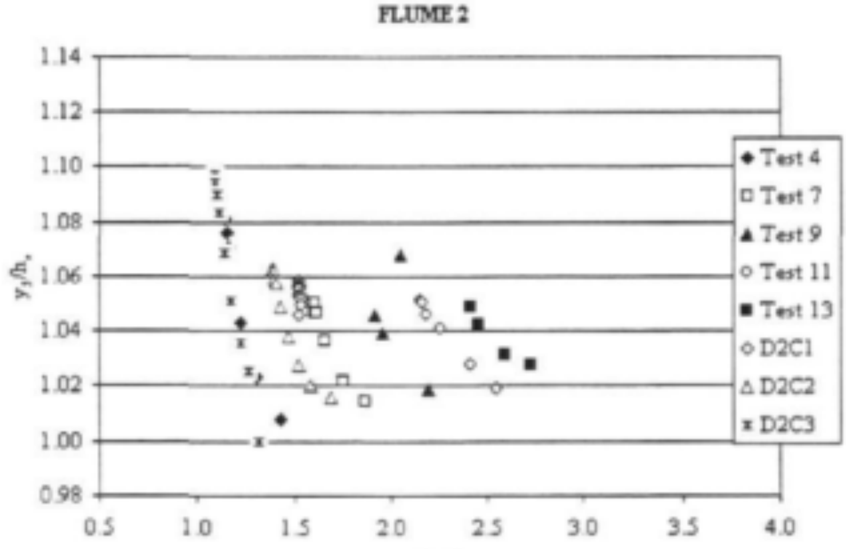


***Figure 7.23:** y_3/h_v vs h_v/d for flume 2 (d/b = 0.5) with full width Crump weirs*

7.4.2 Energy considerations

7.4.2.1 Sharp-crested weirs

7.4.2.1.1 Full width side weirs

As a possible alternative, and as a way to eliminate the influence of the initial unsubmerged flow, consideration was given to the energy levels. This is firstly analysed on flumes in combination with full width side weirs. It can be said that the energy level in the upstream pool (E_{s5}) is equal to the energy level at the gauge point in the flume (E_{s2}), plus any energy losses. Therefore:

$$E_{s5} = E_{s2}$$

$$y_5 + v_5^2/(2g) = h_v + v_2^2/(2g) + h_L \quad (h_L = \text{energy losses})$$

$$y_5 = h_v + (v_2^2 - v_5^2)/(2g) + h_L$$

$$\frac{y_5}{h_v} = 1 + \frac{\left(v_2^2 - v_5^2\right)}{2g.h_v} + \frac{h_L}{h_v} \qquad (7.24)$$

The divergent energy losses between points 5 and 2 must be a function of the difference in kinetic energy between these points, or: -

$$h_L = f\left[\frac{\left(v_2^2 - v_5^2\right)}{2g.h_v}\right]$$

A coefficient can be introduced to quantify the losses:

$$\Rightarrow h_L = \text{coefficient.}\left[\frac{\left(v_2^2 - v_5^2\right)}{2g.h_v}\right] \qquad (7.25)$$

Substituting equation 7.9 into 7.8 yields:

$$\frac{y_5}{h_v} = 1 + k\frac{\left(v_2^2 - v_5^2\right)}{2g.h_v} \qquad (7.26)$$

(with k = 1 + coefficient)

This expression can now be used to determine y_5 when the value of k is known. Using the values measured in the laboratory, when y_5 is known, k can be determined for each flume according to the equation 7.26 rearranged:

$$k = \frac{\left(y_5 / h_v - 1\right)2g.h_v}{\left(v_2^2 - v_5^2\right)} \qquad (7.27)$$

The value of k has been found to vary with the ratio h_v/d. It has also been found that this same pattern is followed by all three sluicing flumes. This is shown in Figure 7.24:

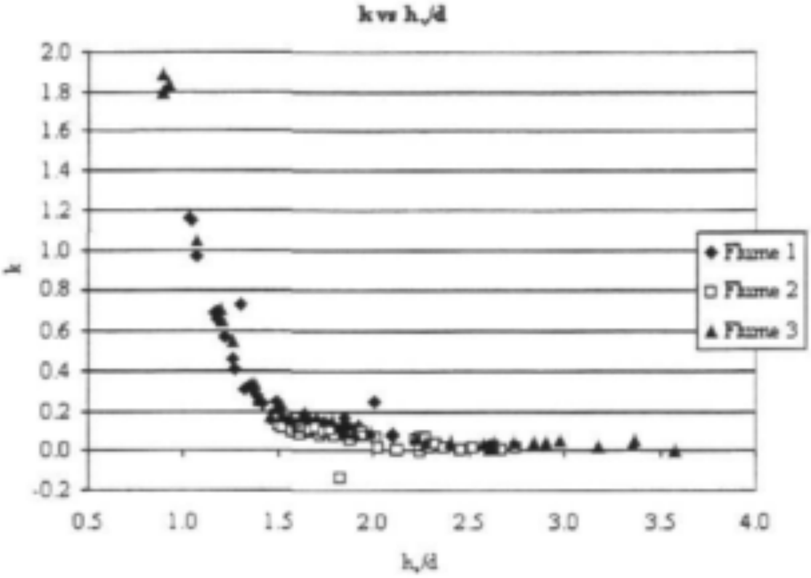


Figure 7.24: *k vs h_v/d for all three sluicing flumes in combination with full width sharp-crested weirs*

Coefficient k reflects the energy losses between the upstream pool and the gauging point in the flume. These energy losses must be a function of the degree of submergence, and hence k is found to vary with h_v/d. This ratio, whilst not the degree of submergence, does give some indication of the degree of submergence. For high degrees of submergence, and therefore h_v/d values, there is little difference between the water levels in the upstream pool and the gauge point. Flow between these points is smooth and even, and hence the energy losses are small. This is reflected in small values of k. Conversely, at smaller values of h_v/d and therefore at lower degrees of submergence, the energy losses will be higher. This is reflected in larger values of k.

It is interesting to note that for all three types of sluicing flumes in combination with sharp-crested weirs, k follows a very similar variation with the ratio h_v/d. This means that the energy losses between the upstream pool and the gauge point are similar in all three flume types.

In order to fit a smooth curve to the data, the data have been split into two ranges. A fit is made on the data where h_v/d is less than 2, and on the data where this ratio exceeds 2. This is illustrated in Figure 7.25:

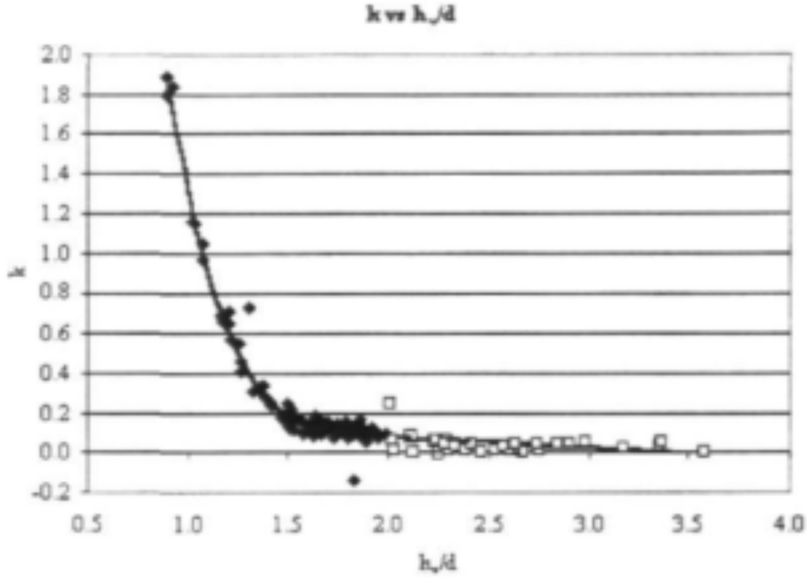


Figure 7.25: *Fitted curves to k vs h_v/d data: all flumes with full width sharp-crested weirs*

$$k = -2.294.(h_v/d)^3 + 12.394.(h_v/d)^2 - 22.372.(h_v/d) + 13.601$$

	for $h_v/d < 2.0$	(7.28)
$k = -0.058.(h_v/d) + 0.196$	for $2.0 \leq h_v/d \leq 3.4$	(7.29)
$k = 0$	for $h_v/d > 3.4$	(7.30)

These three expressions can be used to calculate the value of k, which means that equation 7.26 can then be used to calculate the value of y_5.

From Figure 7.23 it can be seen that the value of k (and therefore the energy losses) decreases rapidly, and that for values of h_v/d of greater than 2.0, k is close to zero. For simplicity of use, a straight line fit has been derived for the data in this region. The equation of this fit (equation 7.29) has a root at an h_v/d value of 3.4. For values of h_v/d of greater than this, it can be seen from Figure 7.25, that the "k" values are very close to zero. It can reasonably be assumed that k is equal zero in this region. This means that there are no transition energy losses between the upstream pool and the gauge point in the flume. For very high degrees of submergence this is to be expected. Equation 7.26 then yields y_5 equal to the value of h_v. Discharge calculation for non-modular flow conditions is covered in more detail in the next Chapter.

7.4.2.1.2 End contracted side weirs

For the three tests featuring end contractions, the same process in the calculation of k, as described above, was used. The k-values obtained are shown plotted in Figure 7.26 against the fits obtained previously:

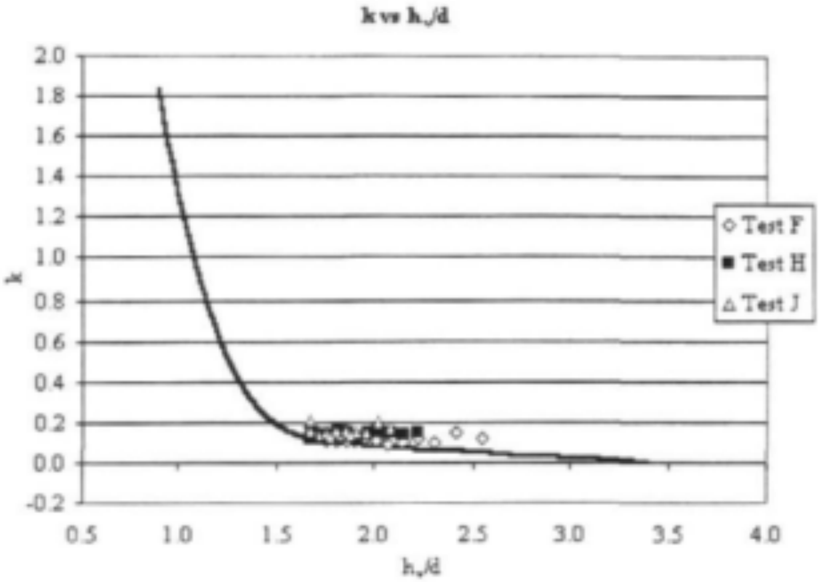


Figure 7.26: *k vs h_o/d data from flume 2 with end contracted sharp-crested weirs and fits from all flumes with full width sharp-crested weirs*

It can be seen that the k values obtained from weirs featuring end-contractions lie very close to those from weirs with full width side weirs. This is because the k-values represent the energy losses between the upstream pool and the gauge point, and the end contractions have little effect on the flow this far upstream of the sharp-crests. Initially, no adjustment is going to be made to the fits obtained for weirs featuring full width side weirs. These fits (equations 7.28 to 7.30) will be applied to all flumes featuring sharp-crested weirs, whether full width or end contracted. The accuracy of this assumption will be verified later.

7.4.2.2 Crump weirs

The coefficient k is calculated, and plotted against the h_v/d ratio for flume 2 with Crump weirs, as done previously. Data from both the new and old tests have been analysed here. It is possible to use the data from the WRC tests in this analysis, as it is only the discharges which cannot be calculated with that data.

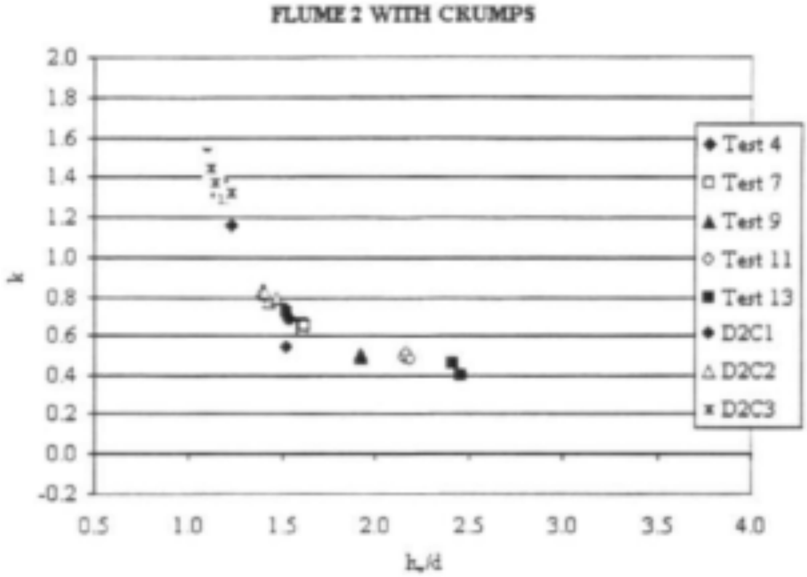


Figure 7.27: k vs h_v/d for flume 2 (d/b = 0.5) with Crump weirs

It can be seen that in broad terms the coefficient k follows a similar variation with the ratio h_v/d as it did for sharp-crested weirs: k still decreases with increasing values of h_v/d, up to a point where it remains more or less constant. It is interesting to note though, that k approaches a constant value of 0.4 with Crump weirs, in contrast to the value of zero approached by the k derived for sharp-crested weirs. The difference between the variation of k with h_v/d as illustrated in Figures 7.24 and 7.27 is due to the difference in flow patterns generated by the Crump and sharp-crested weirs. From Figure 7.27, it can be concluded that the energy losses between the upstream pool and gauge point in the flume are higher in the case of Crump weirs. This is to be expected, since the upstream edge of the Crump weir adjacent to the flume is upstream of the gauge point in the flume. (This is clearly visible in Figure 3.10) This means that the influence of the Crump extends some distance upstream of the gauge point, so that the flow lines are already significantly affected by the time they reach the gauge point. Where sharp-crested weirs are used, this is not the case, as the influence of the sharp-crest does not reach as far upstream as the gauge point. For this reason, a different fit must be used for the coefficient k in the case of Crump weirs. A curve has been fitted to the above data in the region where the h_v/d ratio is between 0.9 and 2.5. For values of h_v/d greater than 2.5, a constant value of 0.4 for k is advocated.

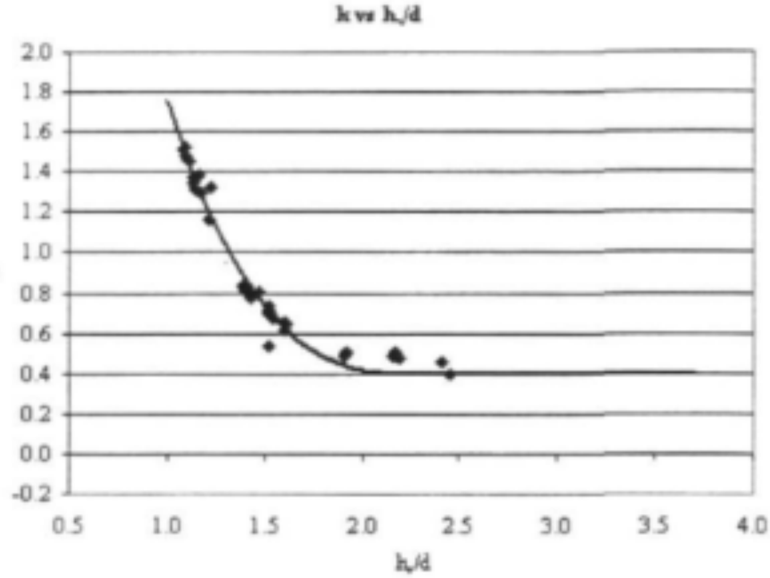


***Figure** 7.28: Fitted curves to k vs h_v/d data: flume 2 ($d/b = 0.5$) with Crump weirs*

$$k = -0.524.(h_v/d)^3 + 3.746.(h_v/d)^2 - 8.903.(h_v/d) + 7.434$$

for $h_v/d \leq 2.5$ (7.31)

$k = 0.4$ for $h_v/d > 2.5$ (7.32)

8 DISCHARGE CALCULATION OVER COMPOUND WEIRS FOR NON-MODULAR FLOW CONDITIONS

The method by which discharge through the compound weirs is calculated under non-modular flow conditions is discussed in this Chapter.

8.1 MODULAR LIMIT OF WEIR

Since each compound weir consists of two different types of gauging structures with very different submergence characteristics and modular limits, it is essential that a distinction be made between them as far as the onset of submergence is concerned.

8.1.1 Modular limit of sluicing flumes

As mentioned in Chapter 7.3, when flow is contained in the flume, (which is used in combination with sharp-crested weirs) the modular limit of the sluicing flumes has been determined at a degree of submergence in the flume of 0.8 (*i.e.* at $S_f = 0.8$)*. When the flume is used in combination with full width side weirs, and flow occurs over these side weirs, the modular limit of the flumes has been determined at a degree of submergence in the flume of 0.7 in the case of sharp-crested weirs, and 0.8 in the case of Crump weirs. End contractions on the sharp-crested side weirs reduce the modular limit of the flume, depending on the end-contraction ratio, as described in Chapter 7.3.1.2.

8.1.2 Modular limit of sharp-crested weirs

Submergence of a sharp-crested weir commences as soon as the downstream water level rises above the crest level of the weir. Hence correction for submergence starts when
$(t - d) > 0$.

8.1.3 Modular limit of Crump weirs

In accordance with equation 5.27, the modular limit of the Crump weir is determined at a degree of submergence of 0.75 (Ackers and White, 1978). The degree of submergence of the Crump weirs is expressed as a ratio of the energy levels up and downstream of the structure, and not as a ratio of the water levels as is the case with sharp-crested weirs.

*This holds for flumes 2 and 3. Flume 1 is treated slightly differently: see Chapter 7.3.1.1.1

8.2 FLOW THROUGH THE FLUME

Discharge calculations for flow through the flume proceed in a manner almost identical to that described previously in Chapter 6, the only difference being that h_v replaces the h_o used previously.

The value of h_v closely resembles that of h_o at low degrees of submergence, but is somewhat larger at higher degrees of submergence. The higher the degree of submergence, the greater the difference between these two values. The possible effects of this are discussed briefly below.

The ratio of h_o/d is used firstly to distinguish between cases of flow contained within the flume ($h_o/d<0.9^*$), and cases of flow over the side walls of the flume ($h_o/d>0.9^*$) under modular flow conditions. In order that the submerged discharge through the flume may be calculated, it is also important to know under submerged flow conditions, whether the initial, unsubmerged flow was contained in the flume or not. This is because separate equations are used in the two cases, as discussed in Chapter 7.3. Since the value of h_o is not known initially, the decision on which equation to use to describe the submergence of the flume, for example equation 7.5 or 7.10 for flume 2, must be based on the value of h_v/d. For values of h_v/d of less than 0.9, it can safely be assumed that flow is contained inside the flume walls. Conversely, for values of h_v/d greater than 0.9, it can be assumed that the side weirs are overtopped. However, since h_v is larger than the equivalent h_o, in some cases, the larger h_v/d ratio may incorrectly indicate flow over the side weirs. It is therefore important that once the discharge over the weir has been obtained, a back calculation be performed to obtain h_o, hence h_o/d, and then this assumption can be verified.

The ratio of h_o/d is used to calculate the values of C_{d2}, C_{d5} and E_{t5} according to the derived expressions for modular conditions. Examples of these expressions are equations 6.6 through 6.10 for flume 1. The expressions for the other two flumes are very similar. Since h_v is in most cases somewhat larger than h_o, so too the ratio of h_v/d will be larger than the equivalent h_o/d value. This means that the value of h_v/d will in some instances exceed the upper limits of validity of these expressions. This will not be a problem in equations 6.11 to 6.13 as the same limits imposed on the ratio of h_o/d can be applied to that of h_v/d. The h_v/d value which is larger than its equivalent h_o/d, will then fall into the next category. In equations 6.7 and 6.14, where the use of the larger h_v/d value cannot be placed in a next category, it can be seen from the derivation of these expressions (Rossouw et. al., 1998), that extrapolation of the curves, from which the equations are obtained through regression analysis, is possible. Thus the expressions will remain valid beyond their specified upper limits.

* 0.85 in the case of flume 3

The only other impact of the use of h_v/d in place of h_o/d is on flow over the side weirs. Under modular flow conditions, flow over the side weirs commences when h_o/d exceeds 0.9. As the equivalent h_v/d will be larger, it will prematurely indicate flow over the sharp crests. To overcome this, the submerged head over the weir crests is calculated. If this is greater than zero, flow over the weirs can be calculated. This is then the criterion used by which flow over the sharp-crests is calculated or not. The submerged head is calculated as below:

$$H_{ws} = (y_5^* + p) + \frac{Q_i^2}{(y_5 + p)^2 . b_5^2 . 2g} - d - p$$

$$\Rightarrow \qquad H_{ws} = y_5 + \frac{Q_i^2}{(y_5 + p)^2 . b_5^2 . 2g} - d \qquad (8.1)$$

The submerged head is used in line with the method of Villemonte, as discussed in Chapter 5.2.

Provided that a back calculation is conducted to obtain the h_o/d ratio, and confirmation obtained that flow is either contained in the flume, or overtops the flume walls and side weirs, it can therefore be seen that the use of h_v/d in the place of h_o/d does not have a marked effect on the accuracy of discharge estimation.

8.2.1 "Free" discharge through the flume

In accordance with the method developed by which submergence of the flume is corrected (Chapter 7), the so-called "free" discharge through the flume, Q_{ff}, is calculated with the submerged water level, h_v. This is corrected to give the actual submerged discharge later.

8.2.1.1 Discharge calculation for $h_v/d<0.9$

Discharge calculation proceeds in a manner identical to that described in Chapter 6.1.1 with the only difference being that h_v replaces the h_o used previously.

8.2.1.2 Discharge calculation for $h_v/d>0.9$

Again, the method used here resembles that of Chapter 6.1.2. The ratio h_v/d replaces that of h_o/d in all relevant expressions.

* The calculation of y_5 is covered in Chapter 8.3.1

8.2.2 Submerged discharge through the flume

The "free" discharge through the flume is now corrected to give the submerged discharge through the flume, Q_{fs}. This correction is done by means of the fits obtained in Chapter 7.3, with the equations used dependant on whether flow is contained within the flume walls or not.

8.2.2.1 Flow contained in flume

For values of h_v/d less than 0.9, flow is contained in the flume, and correction for the submergence of the flume takes place as follows:

For $S_f \leq 0.80$:	no correction: $Q_{fs} = Q_{ff}$ (flumes 2 and 3)	(7.7)
For $S_f > 0.80$:	correct Q_{ff} to Q_{fs} according to equations 7.5 or 7.6 depending on the flume type (2 or 3 respectively)	

Apply equations 7.2, 7.3, or 7.4 to flume 1

These equations have been derived for flumes in combination with sharp-crested weirs, and should only be used on these types of compound weirs. Even though flow does not overtop the side weirs, the type of structure adjacent to the flume still influences the flow patterns through the flume, and it is therefore important that the equations applicable to the type of weir analysed be used.

8.2.2.2 Flow over sharp-crested weirs

Flow is assumed to take place over the side weirs if the value of h_v/d exceeds 0.9. The end contraction ratio, $4d/(L_1 + L_2)$ must be calculated. For values of this ratio of less than or equal to 0.394, the side weirs can be considered full width.

For full width side weirs:

For $S_f \leq 0.70$:	no correction: $Q_{fs} = Q_{ff}$	(7.13)
For $0.70 < S_f \leq 0.95$:	correct Q_{ff} to Q_{fs} according to equations 7.8, 7.10 or 7.11 depending on the flume type	
For $S_f > 0.95$:	correct Q_{ff} to Q_{fs} according to equations 7.9 or 7.12 depending on the flume type	

For end contracted side weirs (flume 2):

Correction for the submergence of the flume is done according to the equations laid out in Chapter 7.3.1.2 (equations 7.14 to 7.20) depending on the value of the $4d/(L_1 + L_2)$ ratio. For values of this ratio not given in this report, interpolation between the curves in Figure 7.13, can be used for submergence correction.

8.2.2.3 Flow over Crump weirs (flume 2)

When flow overtops the Crump weirs, the following corrections are made to Q_{ff}:

For $S_f \leq 0.80$: no correction: $Q_{fs} = Q_{ff}$ (equation 7.21)

For $0.80 < S_f \leq 0.95$: correct Q_{ff} to Q_{fs} according to equation 7.22

For $S_f > 0.95$: correct Q_{ff} to Q_{fs} according to equation 7.23

8.2.3 Back calculation for h_o/d ratio

As mentioned previously, it is important that the h_o/d ratio be calculated in order that it be confirmed whether flow is contained in the flume, or whether it overtops the flume walls and side weirs. When calculated in reverse, the value of h_o cannot be calculated to exactly that value recorded in the laboratory. Hence the reverse-calculated value of h_o is not accurate enough for discharge estimation, but is accurate enough to verify the assumption of flow contained in the flume or not.

8.2.3.1 Flow contained in the flume

Flow will certainly be contained in the flume for values of h_v/d of less than 0.9. In this case, the reverse of the procedure described in Chapter 6.1.1 is used to calculate h_o.

For values of $S_f \leq 0.8$; the flume is unsubmerged, and $h_o = h_v$. Hence no back calculation for h_o is required.

For values of $S_f > 0.8$:

Calculate the "free" discharge through the flume; Q_{ff}
Correct this to give the submerged discharge through the flume; Q_{fs}. This is the actual discharge through the flume. This procedure is detailed above.

1. Use equation 6.16 to calculate y_c. In the place of Q_{ff} in this equation, use Q_{fs}.

   The equation then becomes:

   $$Q_{fs} = C_{d2}\sqrt{g.A_c^3 / B_c} \qquad (6.16 \text{ mod.})$$

   It can be assumed that $y_c < d$ (this can also be verified later). The relevant expressions for A_c, and B_c must then be used.

   In the first iteration, use h_v/d to calculate the value of C_{d2}

   $\Rightarrow$ solve for y_c (check that $y_c < d$)

2. In equation 6.9: $E_{sc} = E_{s2}$ (6.9)

   This can then be used to solve for h_o.

3. In the second and subsequent iterations, use h_o/d to calculate C_{d2}. Repeat 1 and 2 above until h_o converges.

4. Calculate h_o/d and verify that flow is contained in the flume ($h_o/d < 0.9$)

An example calculation is provided in Appendix D.

8.2.3.2 Flow over side weirs

The value of h_v/d may in some cases indicate flow over the side weirs, when this in fact does not occur. The value of h_o must therefore be calculated in order that it be verified that flow does in fact occur over the flume walls and side weirs.

To start with, for values of $h_v/d > 0.9$; flow over the side weirs is assumed.

Calculate the "free" discharge through the flume.
Correct this to the submerged discharge, Q_{fs}, as described in the previous section.

The calculation of h_o proceeds in reverse to that described in Chapter 6.1.2:

1. Using equation 6.17; solve for the value of y_c. In the place of Q_{ff}, Q_{fs} is used:

   $$Q_{fs} = C_{d5}\sqrt{g.A_c^3 / B_c} \qquad (6.17 \text{ mod.})$$

   It can be assumed that $y_c > d$, and the relevant expressions for A_c and B_c used (this must be verified later)

   In the first iteration; h_v/d can be used to calculate C_{d5}

   $\Rightarrow$ solve for y_c (check that $y_c > d$)

2. Using equation 6.10; $E_{sc} = E_{s5}$ (6.10)

$\Rightarrow$ solve for h_o

3. In the second and subsequent iterations, use h_o/d to calculate C_{d5}. Repeat 1 and 2 above until h_o converges.

4. Calculate h_o/d and verify that flow occurs over the flume walls and side weirs ($h_o/d > 0.9$)

An example calculation is provided in Appendix D.

8.3 FLOW OVER SIDE WEIRS

8.3.1 Calculation of y_5

Since the water depth in the upstream pool is not recorded in the prototype, it must be calculated with the aid of the derived relationships. The ratio h_v/d is used to calculate k, the specific equations used depending on whether sharp-crested or Crump weirs are adjacent to the flume. This value of k is then used in equation 7.26 to calculate y_5. The flow velocities needed in equation 7.26 are calculated as follows:

$$v_2 = \frac{Q_{ff}}{b_2 h_c} \tag{8.2}$$

$$v_5 = \frac{Q_t}{(y_5 + p)b_5} \tag{8.3}$$

The total discharge, Q_t, over the weir is needed to calculate v_5, which is needed to calculate y_5, which is in turn needed to calculate Q_t. Hence, and iterative process must be used to calculate y_5. This is covered in more detail later.

8.3.2 Sharp-crested weirs

8.3.2.1 "Free" discharge over sharp-crested weirs

Flow is calculated over the sharp-crested weirs as soon as there is head above the crests, as per equation 8.1. The total discharge over the weir, Q_t, is not yet known (it is calculated in 8.4), so an iterative process must be used to calculate H_{ws}. In the first step, (y_5 –d) can be used in the place of H_{ws}. This will allow "Q_{wf}" and therefore Q_{ws} to be calculated. In the second and subsequent steps Q_t can be used. Alternatively H_{ws} can be solved for directly with a solver solution. Since an iteration must now be done for H_{ws} and y_5, discharge calculation becomes fairly involved. This is covered step by step in Chapter 8.4.

8.3.2.2 Submerged discharge over sharp-crested weirs

The "free" discharge over the sharp-crested weirs is corrected to give the submerged discharge, Q_{ws}, in accordance with the methods discussed in Chapter 5.2.3.

An additional complication is the fact that the value of y_5 is required for the calculation of the effective length of end contracted sharp-crested weirs. Again, this is explained in greater detail in the next Chapter.

8.3.3 Crump weirs

8.3.3.1 "Free" discharge over Crump weirs

As previously, flow is calculated over the Crumps as soon as there is head over the crests. The head over the Crump weirs is calculated with equation 8.1. As with sharp-crested weirs, iteration must be used to obtain the values of H_{ws} and y_5.

8.3.3.2 Submerged discharge over Crump weirs

In accordance with equations 5.27 and 5.28, the "free" discharge over the Crump weirs, Q_{wf}, is corrected to give the submerged discharge, Q_{ws}. This correction is based on the degree of submergence of the Crump weir, H_t/H_{ws}. In order that the downstream energy level, H_t, be calculated, the total discharge through the compound weir must be known:

$$H_t = t - d + \frac{Q_t^2}{(t - d + Z)^2 \cdot b_5^2 \cdot 2g} \tag{8.4}$$

This is not known initially, and therefore H_t cannot be calculated directly. Hence, an additional iteration process must be carried out in order that H_t be calculated. In the first step of the iteration loop, H_t can be approximated with the value (t – d). This is also explained in greater detail in the next Chapter.

8.4 TOTAL SUBMERGED DISCHARGE OVER COMPOUND WEIR

8.4.1 Flow in flume only

When flow is contained in the flume only, the total discharge over the compound weirs is that through the flume:

$$Q_t = Q_{fs} \qquad (8.5)$$

8.4.2 Flow over sharp-crested weirs

When flow overtops the side weirs, the submerged discharge through the flume, Q_{fs}, is added to the submerged discharge over the side weirs, Q_{ws}, to give the total (submerged) discharge over the compound weir:

$$Q_t = Q_{fs} + Q_{ws} \qquad (8.6)$$

Discharge calculation under submerged conditions when flow occurs over the side weirs is more involved than the method used for free flow conditions. This is because two iterations must be made simultaneously; for the values of H_{ws} and y_5. For this reason, a recommended method is provided in detail in the following paragraphs.

Only two values are known: h_v and t. These are the only two recordings made in the prototype. In the method described below, it is assumed that flow occurs over the side (sharp-crested) weirs. This should otherwise be verified. (When submerged flow occurs only within the flume, discharge calculation is quite simple, and proceeds according to the method described in Chapter 8.2.1.1)

1. Calculate the "free" discharge through the flume, Q_{ff} (Chapter 8.2.1.2)
2. Correct this to give the submerged discharge, Q_{fs} (Chapter 8.2.2)
3. Calculate the value of the ratio h_v/d, and using the relevant equation (7.28, 7.29 or 7.30) calculate the value of k
4. Calculate the value of v_2^2 (equation 8.2)

First Iteration:

5. Calculate the value of v_5^2. This cannot be done directly in one step. In the first iteration, assume the following:

$v_5 = 0.35.v_2$	for flume 1 (d/b = 1.0)	(8.7)
$v_5 = 0.38.v_2$	for flume 2 (d/b = 0.5)	(8.8)
$v_5 = 0.46.v_2$	for flume 3 (d/b = 0.25)	(8.9)

(These values have been derived from the configurations tested in the laboratory which feature silted pools upstream of the flume. In the prototype these relationships may differ slightly, for example in deeper pools.)

6. Calculate y_5 (equation 7.26)
7. Calculate H_{ws}. This can also not be done directly. In the first step, assume:

$$H_{ws} = y_5 - d \qquad (8.10)$$

8. Calculate H_{ws}/P, and then C_w, using the relevant equation (equation 5.3 or 5.4)
9. Calculate $h = y_5 - d$ (6.20)
10. Calculate the value of H_{ws}/L, for each contracted sharp crest, and the value of n accordingly (equations 5.7 to 5.9)
11. Calculate the effective length of each of the contracted sharp crests (equations 5.6 or 5.10)
12. Calculate the "free" discharge over each of the sharp-crested weirs, Q_{wf} (equation 5.2)
13. Sum the discharge over each of the sharp-crested weirs, to obtain the total discharge over the side weirs, Q_{wf}
14. Correct this to the submerged discharge, Q_{ws}, with the relevant equation (Chapter 5.2.3)
15. Calculate the total submerged discharge over the compound weir, Q_t (equation 8.6)

Second iteration:

1. Since Q_t is now known, v_5 can be calculated by means of equation 8.3
2. Calculate y_5 with equation 7.26. Compare this to the previous value used (Iterations for y_5 should converge quickly)
3. Calculate H_{ws} with equation 8.1, since Q_t is now known
4. Calculate Q_{wf}, Q_{ws} and Q_t as above (steps 8 – 15)

Continue iteration until both y_5 and H_{ws} converge. An example calculation is provided in Appendix D.

Note:

- If the side weirs are full width; $L_e = L$, and steps 9 to 11 can be omitted.
- Verification must be made that the correct method for the calculation of the submerged discharge over the sharp crested weirs has been used (as laid out in Chapter 5.2.3)

8.4.3 Flow over Crump weirs

It should firstly be verified that flow does in fact overtop the Crump weirs.

1. Calculate the "free" discharge through the flume, Q_{ff} (Chapter 8.2.1.2)
2. Correct this to give the submerged discharge, Q_{fs} (Chapter 8.2.2)
3. Calculate the value of the ratio h_v/d, and using the relevant equations (7.31 or 7.32) calculate the value of k
4. Calculate the value of v_2^2 (equation 8.2)

First Iteration:

5. Calculate the value of v_5^2. This cannot be done directly in one step. In the first iteration, assume the following:

   $v_5 = 0.40.v_2$ for flume 2 ($d/b = 0.5$) (8.11)
6. Calculate y_5 (equation 7.26)
7. Calculate H_{ws}. This can also not be done directly. In the first step, assume:

   $H_{ws} = y_5 - d$ (8.10)
8. Calculate the "free" discharge over the Crump weirs, Q_{wf}, using equation 5.24
9. Calculate H_t. This cannot be done directly, and therefore the following approximation must be used:

   $H_t = t - d$ (8.12)

   (if $t < d$, then the Crump is unsubmerged, and step 10 can be omitted; $Q_{wf} = Q_{ws}$)
10. Calculate the ratio H_t/H_{ws}, and hence the correction factor f, using the relevant equations: 5.27 or 5.28 depending on the value of the H_t/H_{ws} ratio
11. Correct the "free" discharge to the submerged discharge over the Crump weirs, Q_{ws} (equation 5.25)
12. Calculate the total submerged discharge over the compound weir, Q_t (equation 8.6)

Second iteration:

1. Since Q_t is now known, v_5 can now be calculated by means of equation 8.3
2. Calculate y_5 with equation 7.26, and compare this to the previous value
3. Calculate H_{ws} with equation 8.1, since Q_t is now known
4. Calculate Q_{wf}
5. Calculate H_t with equation 8.4, as Q_t is known
6. H_{ws} and H_t are known, hence the correction factor f can be calculated
7. Correct Q_{wf} to Q_{ws}
8. Calculate the total discharge over the compound weir, Q_t

Continue iteration until Q_t converges. An example calculation is provided in Appendix D.

8.5 "ERRORS" ASSOCIATED WITH NON-MODULAR DISCHARGE CALCULATION

8.5.1 "Error" in the non-modular discharge

8.5.1.1 Calculation of the "error"

In all laboratory tests conducted, an unsubmerged flow is established and recorded. This is then systematically submerged. The submerged discharge for each degree of submergence is then compared to this unsubmerged discharge in order to obtain the error associated with the calculation process. The "error" is defined as:

$$\text{Error (\%)} = \left[\frac{Q_{t,sub} - Q_{t,free}}{Q_{t,free}}\right] 100\% \qquad (8.13)$$

8.5.1.2 Flow in the flume only

A summary of the "errors" made in discharge calculation under non-modular flow conditions, when flow occurs only in the flume is provided in Tables 8.1, 8.2 and 8.3:

Flume 1	$0 < S_f \leq 0.80$	$S_f > 0.80$	All points
Ave error (%)	-1.35	-1.16	-1.25
Std. Dev. (%)	1.78	10.06	7.41
Max. error (%)	1.49	15.27	15.27
Min. error (%)	-3.99	-20.10	-20.10
No. of points	8	10	18

Table 8.1: ***Summary of errors for flume 1 (d/b = 1.0): flow in flume only***

Flume 2	$0< S_f \leq 0.80$	$S_f>0.80$	All points
Ave error (%)	1.63	3.72	2.60
Std. Dev. (%)	0.98	5.55	3.86
Max. error (%)	3.34	13.74	13.74
Min. error (%)	0.37	-5.23	-5.23
No. of points	8	7	15

Table 8.2: *Summary of errors for flume 2 (d/b = 0.5): flow in flume only*

Flume 3	$0< S_f \leq 0.80$	$S_f>0.80$	All points
Ave error (%)	2.14	1.62	1.78
Std. Dev. (%)	1.07	4.43	3.66
Max. error (%)	3.37	7.94	7.94
Min. error (%)	1.42	-3.27	-3.27
No. of points	3	7	10

Table 8.3: *Summary of errors for flume 3 (d/b = 0.25): flow in flume only*

8.5.1.3 Flow over sharp-crested weirs

8.5.1.3.1 Full width sharp-crested weirs

Flume 1	$0<S_f\leq 0.70$	$0.70<S_f\leq0.95$	$S_f > 0.95$	All points	$S_f \leq 0.95$
Ave error (%)	1.91	1.00	0.66	1.16	1.32
Std. Dev. (%)	3.76	6.10	11.36	7.13	5.35
Max. error (%)	10.34	13.95	22.65	22.65	13.95
Min. error (%)	-2.69	-7.05	-8.65	-8.65	-7.05
No. of points	12	22	11	45	34

Table 8.4: *Summary of errors for flume 1 (d/b = 1.0) with full width sharp-crested weirs*

Flume 2	$0<S_f\leq 0.70$	$0.70<S_f\leq0.95$	$S_f > 0.95$	All points	$S_f \leq 0.95$
Ave error (%)	1.75	3.70	11.94	3.21	3.02
Std. Dev. (%)	1.87	4.45	---------	4.02	3.85
Max. error (%)	6.17	9.87	11.94	11.94	9.87
Min. error (%)	-1.43	-9.24	11.94	-9.24	-9.24
No. of points	16	30	1	47	46

Table 8.5: *Summary of errors for flume 2 (d/b = 0.5)with full width sharp-crested weirs*

Flume 3	$0<S_f\leq 0.70$	$0.70<S_f\leq0.95$	$S_f > 0.95$	All points	$S_f \leq 0.95$
Ave error (%)	0.43	0.41	5.99	1.72	0.42
Std. Dev. (%)	1.79	5.34	15.58	8.62	4.53
Max. error (%)	3.18	13.80	41.21	41.21	13.80
Min. error (%)	-3.47	-7.45	-12.98	-12.98	-7.45
No. of points	11	25	11	47	36

Table 8.6: *Summary of errors for flume 3 (d/b = 0.25)with full width sharp-crested weirs*

The distribution of all errors for flumes in combination with full width sharp-crested weirs is illustrated graphically in Figures 8.1, 8.2 and 8.3:

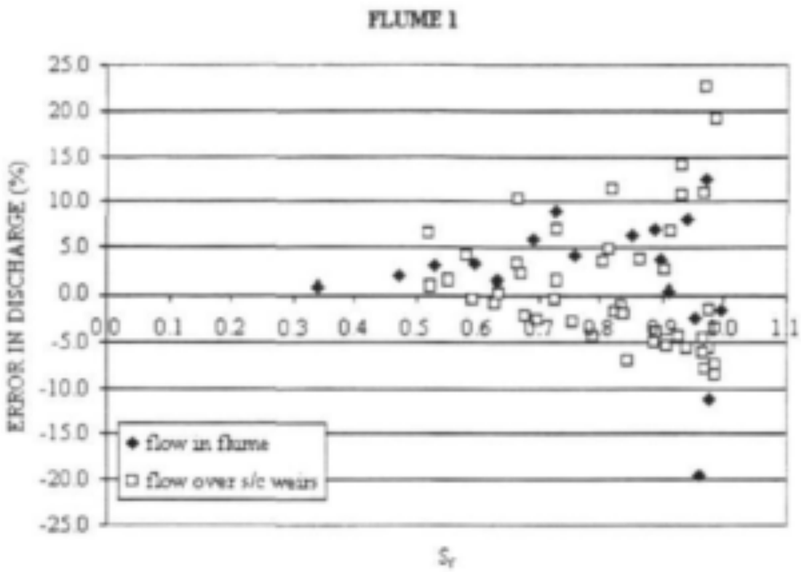


***Figure 8.1:** Errors in non-modular discharge for flume 1 (d/b = 1.0) with full width sharp-crested weirs*

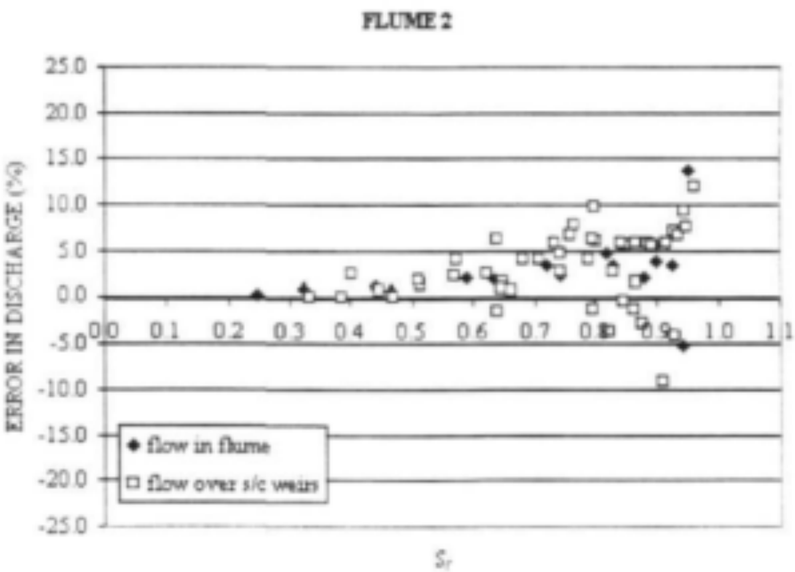


***Figure 8.2:** Errors in non-modular discharge for flume 2 (d/b = 0.5) with full width sharp-crested weirs*

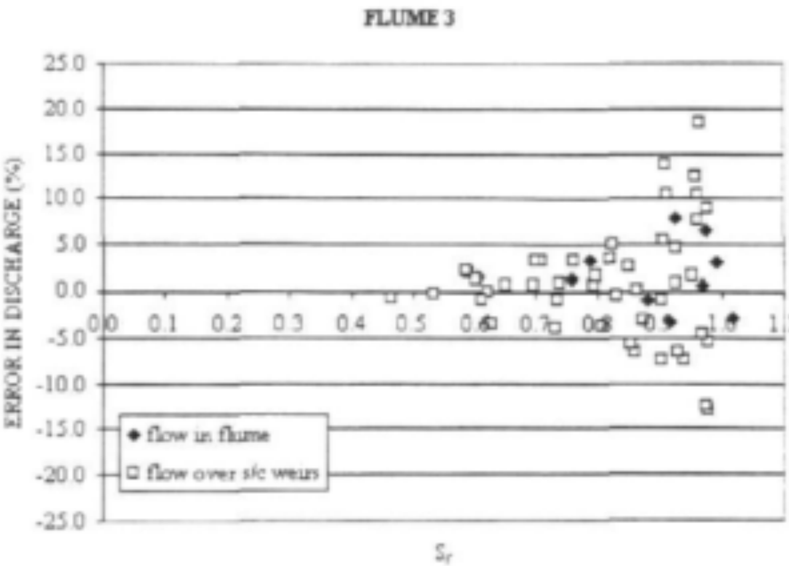


Figure 8.3: *Errors in non-modular discharge for flume 3 (d/b = 0.25) with full width sharp-crested weirs*

For flow over the side weirs, with degrees of submergence of less than 0.70 in the flume, no correction for submergence of the flume is made. Hence only flow over the side, sharp-crested weirs is corrected for submergence. The errors in this region are small, all within ±1.91%, with a maximum standard deviation of 3.76%. These errors can be attributed to the fact that the Q_{fs}/Q_{ff} ratio has some scatter about unity (Figures 7.8, 7.9 and 7.10), and to the corrections made with the use of the Villemonte equation which is used to correct for the submergence of the sharp-crested weirs.

For flume 1, as mentioned in the previous paragraph, many Q_{fs}/Q_{ff} values for degrees of submergence of less than 0.70, lie below unity (See Figure 7.5). This is the reason for the relatively high average error and standard deviation associated with discharge estimation in this region.(See Table 8.1)

For degrees of submergence of between 0.70 and 0.95, the errors are not significantly greater, although the standard deviations of the errors are. There is substantially more scatter in the errors. The errors in this range may have any one of three origins, and possibly a combination of all three. Errors may arise due to the fit used to correct the flume discharge for submergence, as well as the discharge over the sharp-crested weirs. Errors may also arise in the calculation of y_s. If the likelihood that these factors compound each other is considered, these errors are placed in perspective.

For degrees of submergence greater than 0.95, it can be seen that more significant errors are made in the calculation of the submerged discharge. Moreover, the scatter of these errors is too large to consider discharge calculation in this region worthwhile (standard deviations of 11.36% and 15.58% with flume 1 and 3 respectively). This was alluded to earlier, and is due to the very pronounced deviation of the Q_{fs}/Q_{ff} ratio of the flume with the degree of submergence. The effect of submergence on the flume is so significant that it cannot be adequately allowed for.

If no discharge calculation is to be attempted for degrees of submergence of greater than 0.95, and if it can be assumed that the weir will only start becoming submerged once flow overtops the side weirs, the errors indicated in Table 8.7 in the total discharge can be expected:

	Flume 1	**Flume 2**	**Flume 3**
Ave error (%)	1.32	3.02	0.42
Std. Dev. (%)	5.35	3.85	4.53
Max. error (%)	13.95	9.87	13.80
Min. error (%)	-7.05	-9.24	-7.45

Table 8.7: *Errors associated with discharges for flumes with full width sharp-crested weirs, for $S_f \leq 0.95$*

If these two restrictions are adhered to, it can be seen that the discharge can be calculated with greater accuracy, and less scatter.

8.5.1.3.2 End contracted sharp-crested weirs

With test F, the "errors" in Table 8.8 are made in the calculation of the total discharge:

Test F	$0<S_f\leq0.30$	$0.30<S_f\leq0.60$	$S_f > 0.60$	$S_f \leq 0.95$
Ave error (%)	0.48	1.16	-1.98	-0.72
Std. Dev. (%)	0.33	0.43	2.27	2.29
Max. error (%)	0.85	1.78	2.42	2.42
Min. error (%)	0.21	0.58	-4.62	-4.62
No. of points	3	10	18	31

Table 8.8: *Summary of errors for test F: flume 2 (d/b = 0.5) with 300mm symmetrically contracted sharp-crested weirs*

The "errors" in Table 8.9 are made in the calculation of the total discharge with test H:

Test H	$0<S_f\leq0.55$	$0.55<S_f\leq0.95$	$S_f \leq 0.95$
Ave error (%)	1.12	0.78	0.87
Std. Dev. (%)	0.76	2.42	2.08
Max. error (%)	2.44	4.39	4.39
Min. error (%)	0.29	-3.00	-3.00
No. of points	6	16	22

Table 8.9: *Summary of errors for test H: flume 2 (d/b = 0.5) with lhs sharp-crested weir 300mm end contracted*

The "errors" made in the estimation of the total non-modular discharge for test J are as indicated in Table 8.10:

Test J	$0<S_f\leq0.60$	$0.60<S_f\leq0.95$	$S_f \leq 0.95$
Ave error (%)	1.72	2.25	2.08
Std. Dev. (%)	1.00	2.07	1.78
Max. error (%)	3.37	5.00	5.00
Min. error (%)	0.38	-1.01	-1.01
No. of points	9	18	27

Table 8.10: *Summary of errors for test J; flume 2 (d/b = 0.5) with 100mm symmetrically contracted sharp-crested weirs*

The errors associated with non-modular discharge for flume 2 with end contracted sharp-crested weirs are shown in Figure 8.4:

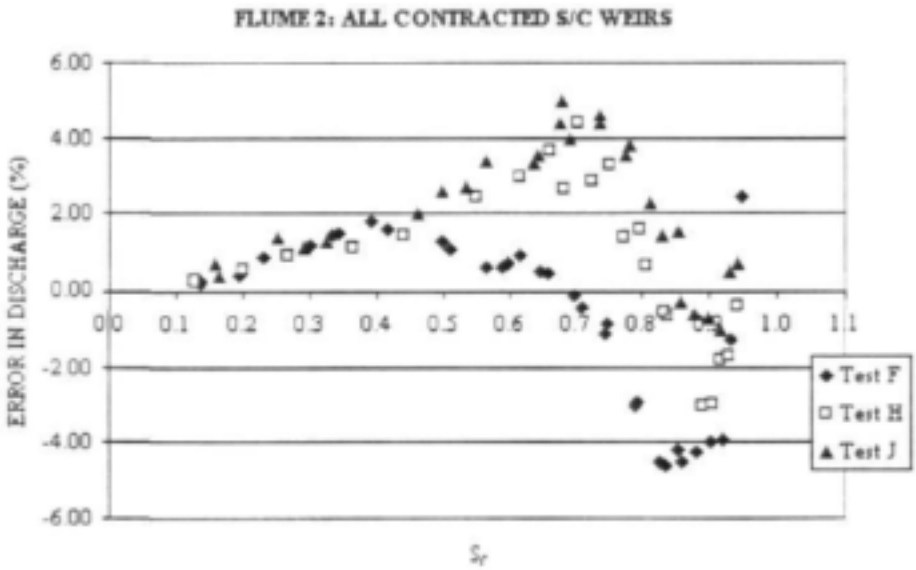


Figure 8.4: *Errors in non-modular discharge for flume 2 (d/b = 0.5) with end contracted sharp-crested weirs*

There appears to be a pattern in these errors, but the cyclical nature of the errors is due to the fact that the fitted curves cannot bend through the data sufficiently well, leaving some points above and others below the fitted curves.

8.5.1.4 Flow over Crump weirs

A summary of the "errors" made with non-modular discharge calculation for flume 2 with Crump weirs is indicated in Table 8.11:

Flume 2	$0<S_f\leq0.80$	$0.80<S_f\leq0.95$	$S_f > 0.95$	All points	$S_f \leq 0.95$
Ave error (%)	1.80	4.11	1.06	2.35	2.60
Std. Dev. (%)	2.21	5.33	8.95	4.72	3.67
Max. error (%)	6.96	11.29	9.34	11.29	11.29
Min. error (%)	-0.38	-3.98	-10.51	-10.51	-3.98
No. of points	17	9	5	31	26

Table 8.11: *Summary of errors for flume 2 (d/b = 0.5) with Crump weirs*

The distribution of these errors is illustrated graphically in Figure 8.5:

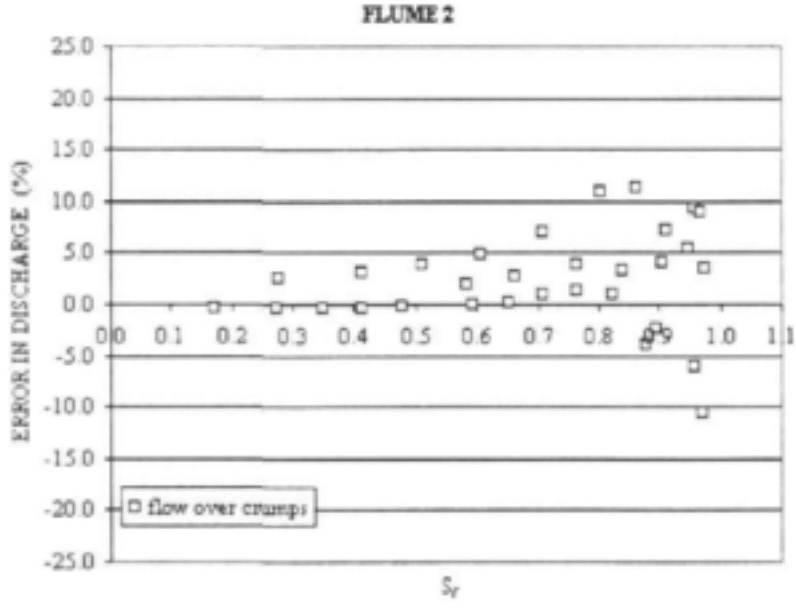


Figure 8.5: *Errors in non-modular discharge for flume 2 (d/b = 0.5) with Crump weirs*

The "errors" made in non-modular discharge estimation for flume 2 in combination with Crump weirs can be compared to those made by flume 2 as well as flumes 1 and 3 in combination with sharp-crested weirs.

In the range before the flume becomes submerged, the Crump weirs make flume 2 more accurate than flume 1 with sharp-crested weirs, but less accurate than flumes 3 and 2 with sharp-crests. In the range where the flume is corrected for submergence, up to a degree of submergence of 95% in the flume, flume 2 with Crump weirs has the largest average error, and the second largest standard deviation of the error.

For degrees of submergence of greater than 0.95 in the flume however, the combination of flume 2 with Crump weirs is on the whole markedly more accurate. The average error in the non-modular discharge is marginally smaller in the case of flume 1 with sharp-crested weirs, but flume 2 with Crumps has the only standard deviation of the error (8.95%) less than 10%; these values being 11.36% and 15.58% in flumes 1 and 3 with sharp-crested weirs respectively. Hence, flume 2 with Crump weirs is the most accurate combination of compound weir for discharge estimation at higher degrees of submergence.

With discharge estimation for degrees of submergence of less than 95% in the flume, flume 2 with Crumps has the second largest error, but the smallest deviation in the error. Flumes 1 and 3 with sharp-crested weirs have small average errors (less than 1.32%), but large standard deviations; greater than 4.5%. Flume 2 with sharp-crested weirs has the largest average error, 2.96%, but a standard deviation of 3.83%. Flume 2 with Crumps has an average error of 2.60%, and a standard deviation of 3.67%. Whilst the average error is not the best, a smaller standard deviation means that less scatter can be expected in the calculated discharges. In this regard, flume 2 with Crump weirs is the most accurate combination for discharge estimation in this range.

Overall, with discharge estimation for all degrees of submergence, flume 2 with Crump weirs has the second largest average error, and the second smallest standard deviation of the error, of the four combinations of flumes with full width side weirs. Flume 2 with sharp-crested weirs has the largest average error; 3.21%, but the smallest standard deviation; 4.02%. Flume 2 with Crump weirs has an average error of 2.35% and a standard deviation of the error of 4.72%. It must be said however, that no data has been analysed for flume 2 with sharp-crested weirs for degrees of submergence of greater than 0.95. Inclusion of data in this range will likely effect the Figures quoted above adversely. That would likely mean that flume 2 with Crump weirs will on the whole be the most accurate combination.

8.5.2 Errors associated with the calculation of y_5

8.5.2.1 Sharp-crested weirs

8.5.2.1 Full width sharp-crested weirs

The errors indicated in Table 8.12 are made in the calculation of y_5, when the method as developed in Chapter 7.4.2 is used:

	Flume 1	Flume 2	Flume 3
Ave. error (%)	-0.02	0.26	-0.03
Std. Dev. (%)	0.51	0.29	0.62
Max. error (%)	1.04	1.55	0.84
Min. error (%)	-1.70	-0.11	-3.80

Table 8.12: *Errors made in the calculation of y_5, for all three flumes with full width sharp-crested weirs*

These errors are small, as are the standard deviations of the errors. This means that the method using energy principles to calculate y_5 from h_v works well.

It is important to calculate the water depth in the upstream pool accurately as the prototype weirs used by the DWAF have long sharp-crested weirs on either side of the sluicing flumes, and y_5 has a significant impact on the accuracy of discharge calculation over the sharp-crested weirs.
In the prototypes, the compound weirs have sharp-crested weirs which are much longer relative to the total width of the weir than the three weir configurations analysed here. Due to the constraints of the 2m canal in the laboratory, the side weirs cannot be made longer. The largest portion of the error associated with non-modular discharge arises from the correction for submergence of the sluicing flumes. The values of y_5 can be calculated very accurately, and the Villemonte correction is on average more accurate than the total errors obtained here. This means that in the prototype weirs where the sharp-crested weirs are longer, flow through the flume will constitute a lower portion of the total flow over the compound weir. Since this is the source of most of the error, it is expected that the non-modular discharge can be calculated more accurately in the prototype weirs than is suggested here.

8.5.2.1.2 Contracted side weirs

As remarked in Chapter 7.4.2.2, the k values calculated for flume 2 with end contracted sharp-crested weirs lie very close to those obtained for full width weirs. The fits derived for full width weirs were used in the calculation of the y_5 values for end contracted sharp crests (see Table 8.13):

	Test F	**Test H**	**Test J**
Ave. error (%)	-0.16	-0.17	-0.23
Std. Dev. (%)	0.13	0.08	0.14
Max. error (%)	0.04	-0.03	-0.04
Min. error (%)	-0.43	-0.27	-0.77

Table 8.13: *Errors made in the calculation of y_5, for flume 2 ($d/b = 0.5$) with end contracted sharp-crested weirs*

It can be seen that the y_5 values can be calculated very accurately in the case of contracted side weirs, even with the use of the formulae derived for flumes with full width sharp-crested weirs. The standard deviations of these errors are even smaller than the specific cases for which the formulae were derived. It can therefore be assumed with sufficient accuracy that the same formulae for the calculation of k, and hence y_5, can be used for both full width and end contracted sharp-crested weirs.

8.5.2.2 Crump weirs

The method developed in Chapter 7.4.2.2 is used to calculate the values of y_5 when Crump weirs are used adjacent to flume 2. The errors made in the calculation of y_5 are indicated in Table 8.14:

	Flume 2
Ave. error (%)	0.11
Std. Dev. (%)	0.58
Max. error (%)	1.54
Min. error (%)	-1.24

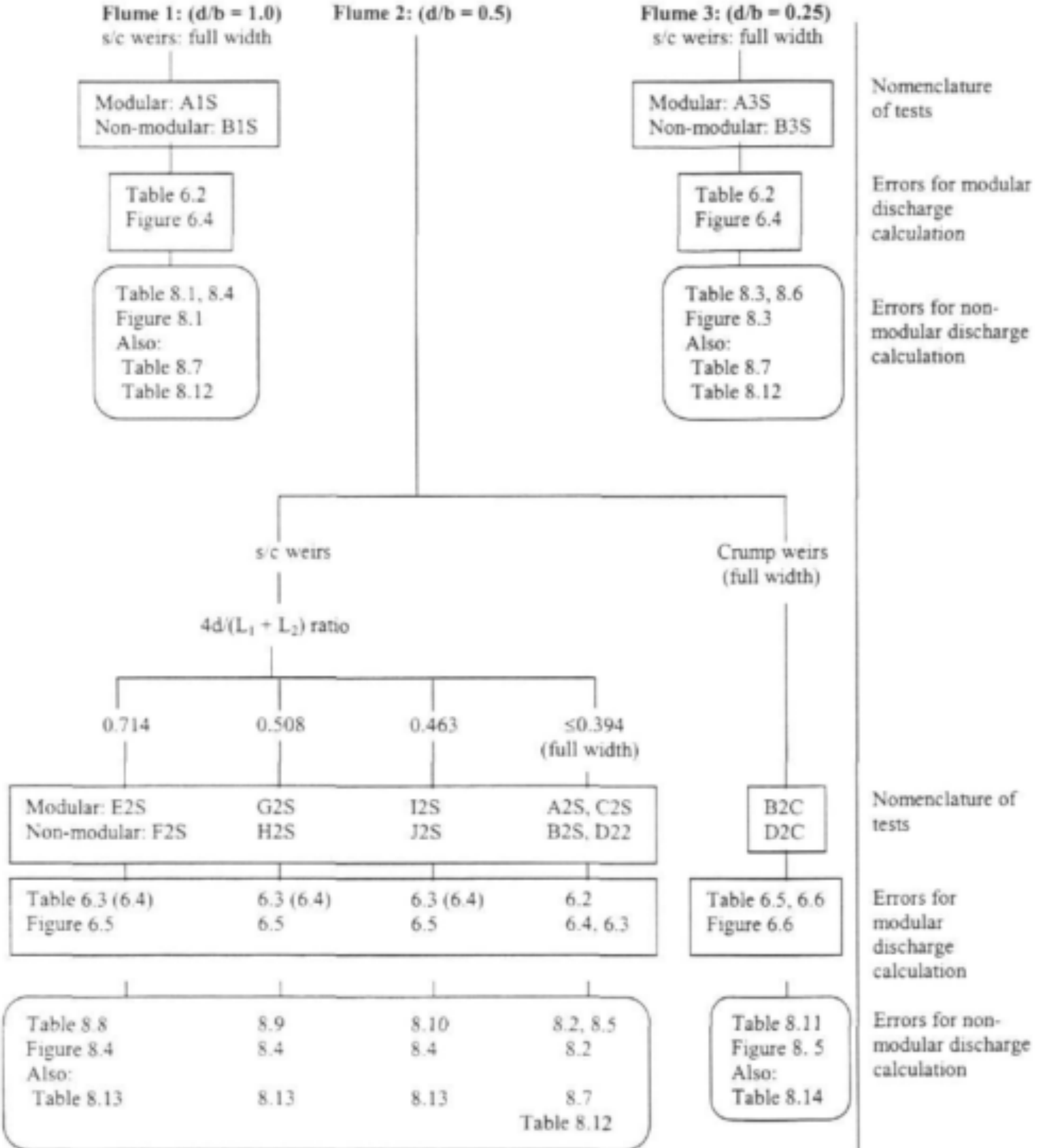
Table 8.14: *Errors made in the calculation of y_5, for flume 2 (d/b = 0.5) with Crump weirs*

The errors made in the calculation of y_5 using flume 2 in combination with Crump weirs compare favourably with those made for the flumes in combination with sharp-crested weirs. Slightly more scatter is evident in the case of flume 2 with Crumps, but this is not excessive. It can therefore be concluded that the method using energy principles to calculate the value of y_5 works well in both the cases of sharp-crested and Crump weirs.

9. SUMMARY AND RECOMMENDATIONS FOR IMPLEMENTATION

9.1 SUMMARY OF TESTS

A graphic summary of the tests analysed in this report is provided in the following schematic presentation:



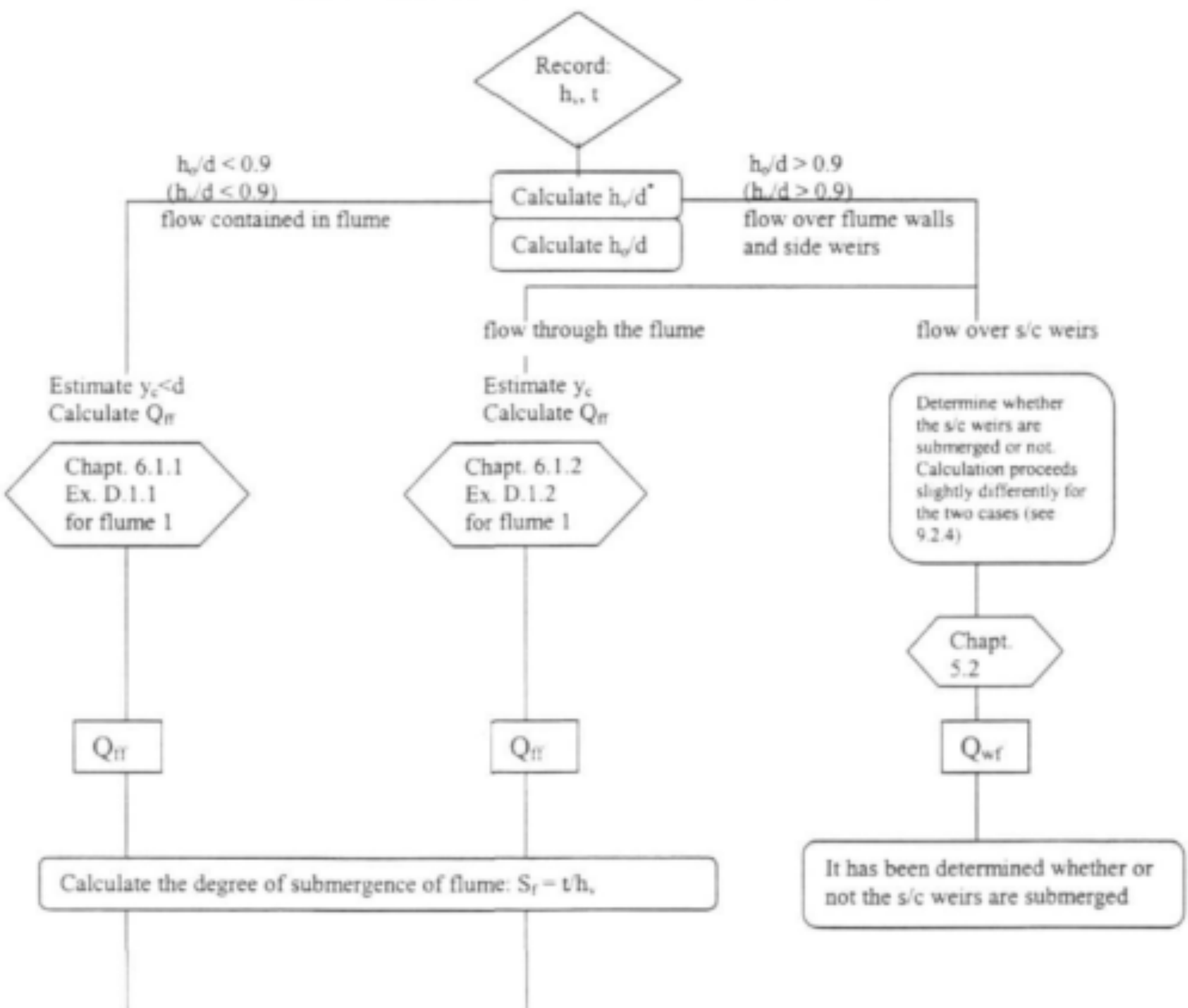
9.2 SUMMARY OF THE CALCULATION PROCESS

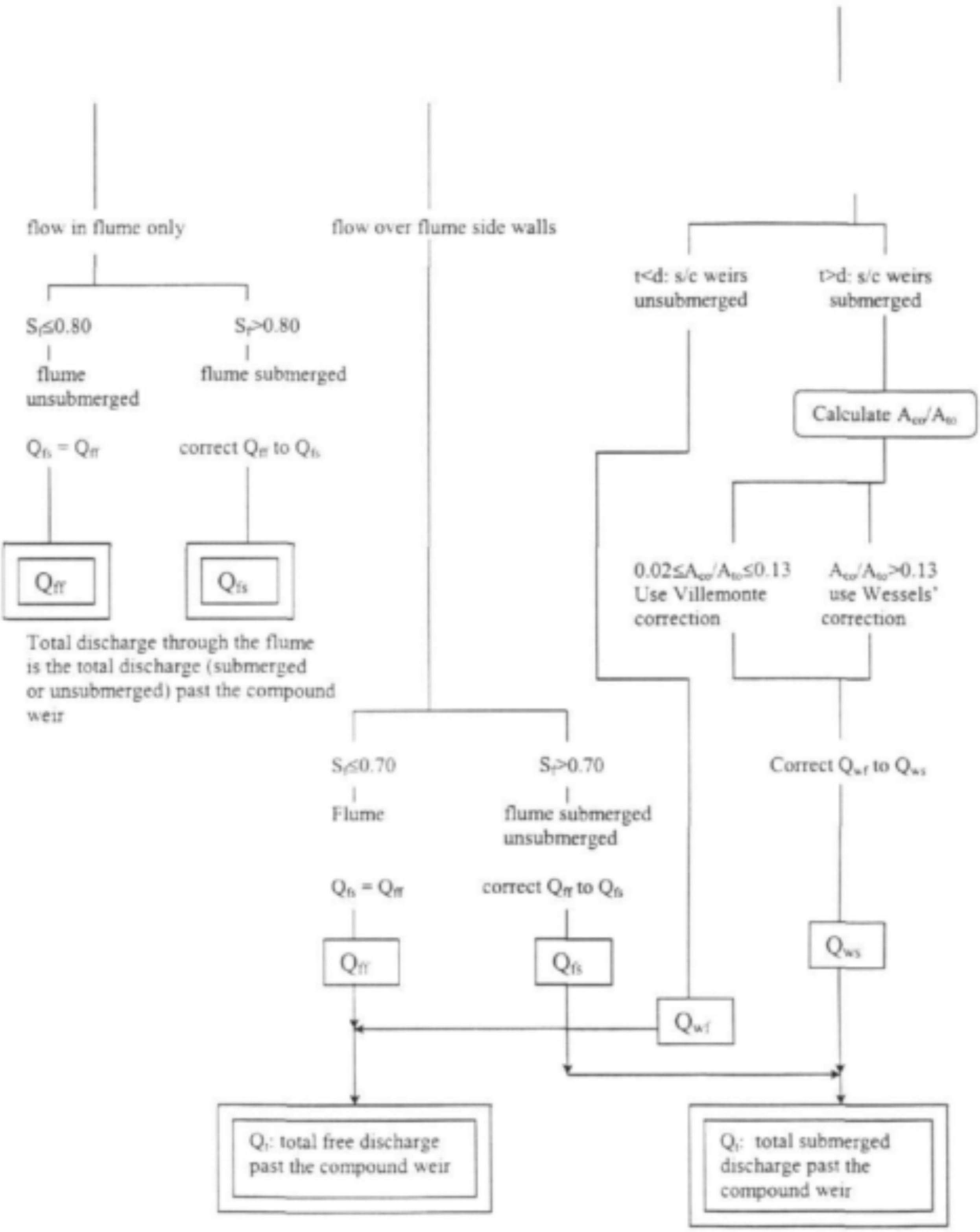
Since iteration is required in the calculation process, and often more than once, the calculation process can become quite involved. A graphic summary is provided below for the various calculation procedures described earlier in the report. It is recommended that these be used as a guideline when conducting the discharge calculations. A summary of all the formulae needed for discharge calculation is given in Appendix A.

9.2.1 Overview of calculation process

An overview of the calculation process is given below for flume 2 ($d/b = 0.5$). Procedures for flumes 1 and 3 will be very similar. More detailed procedures for the individual components of the compound weir follow.

FLUME 2:
$d/b = 0.5$
$4d/(L_1 + L_2) \leq 0.394$ (full width sharp-crested weirs)



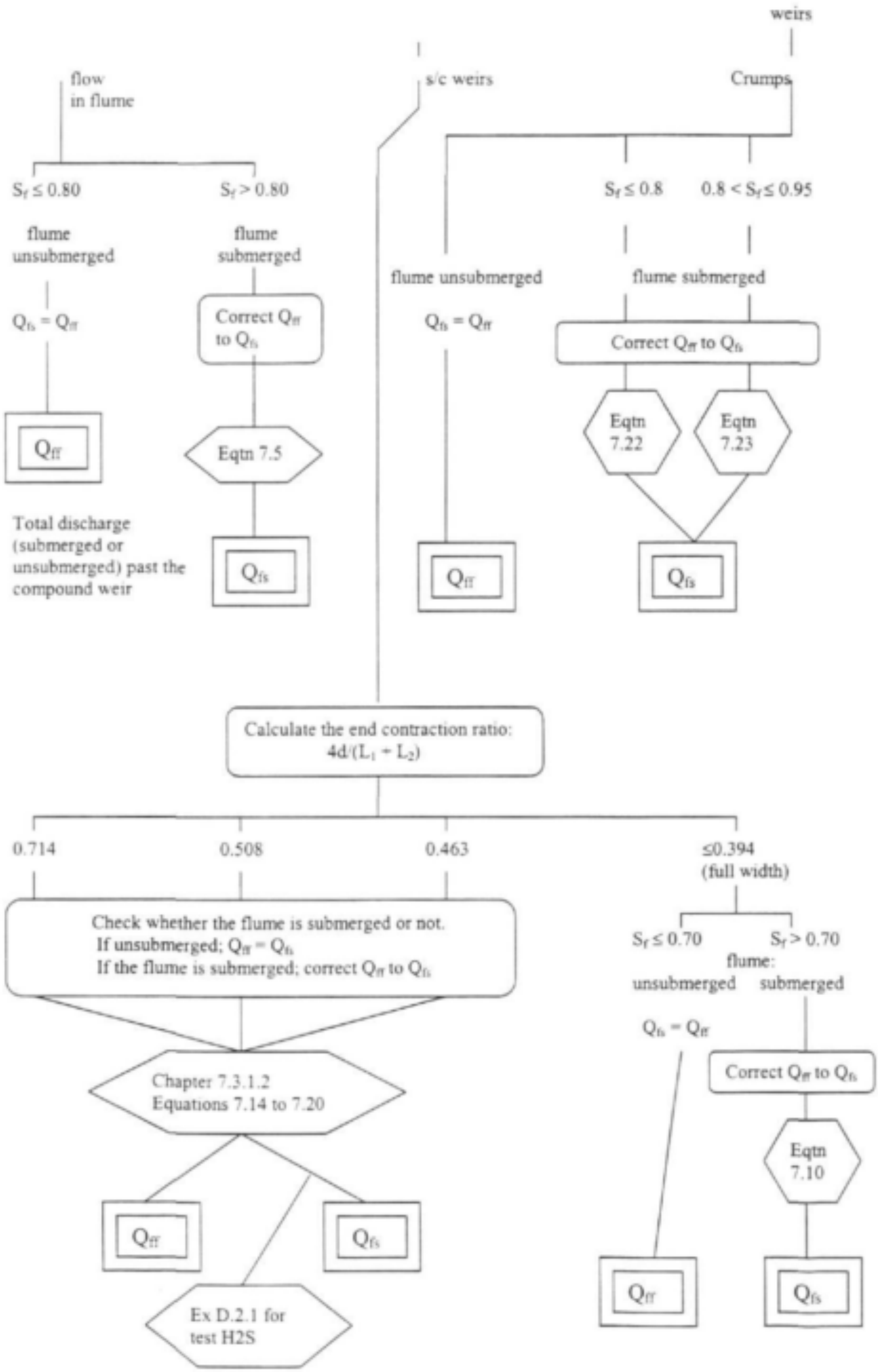


Note:
If the flume is unsubmerged; $h_o = h_v$
* Initially, h_o is unknown if the flume is submerged. The initial decision on whether flow occurs over the side weirs or not must therefore be based on the h_v/d ratio. Once the discharge has been calculated, a back calculation must be performed to calculate h_o, and

hence h_o/d. It must then be verified whether flow does in fact take place over the side weirs or not. (see Chapter 8.2.3)

9.2.2 Calculation of discharge through the flume

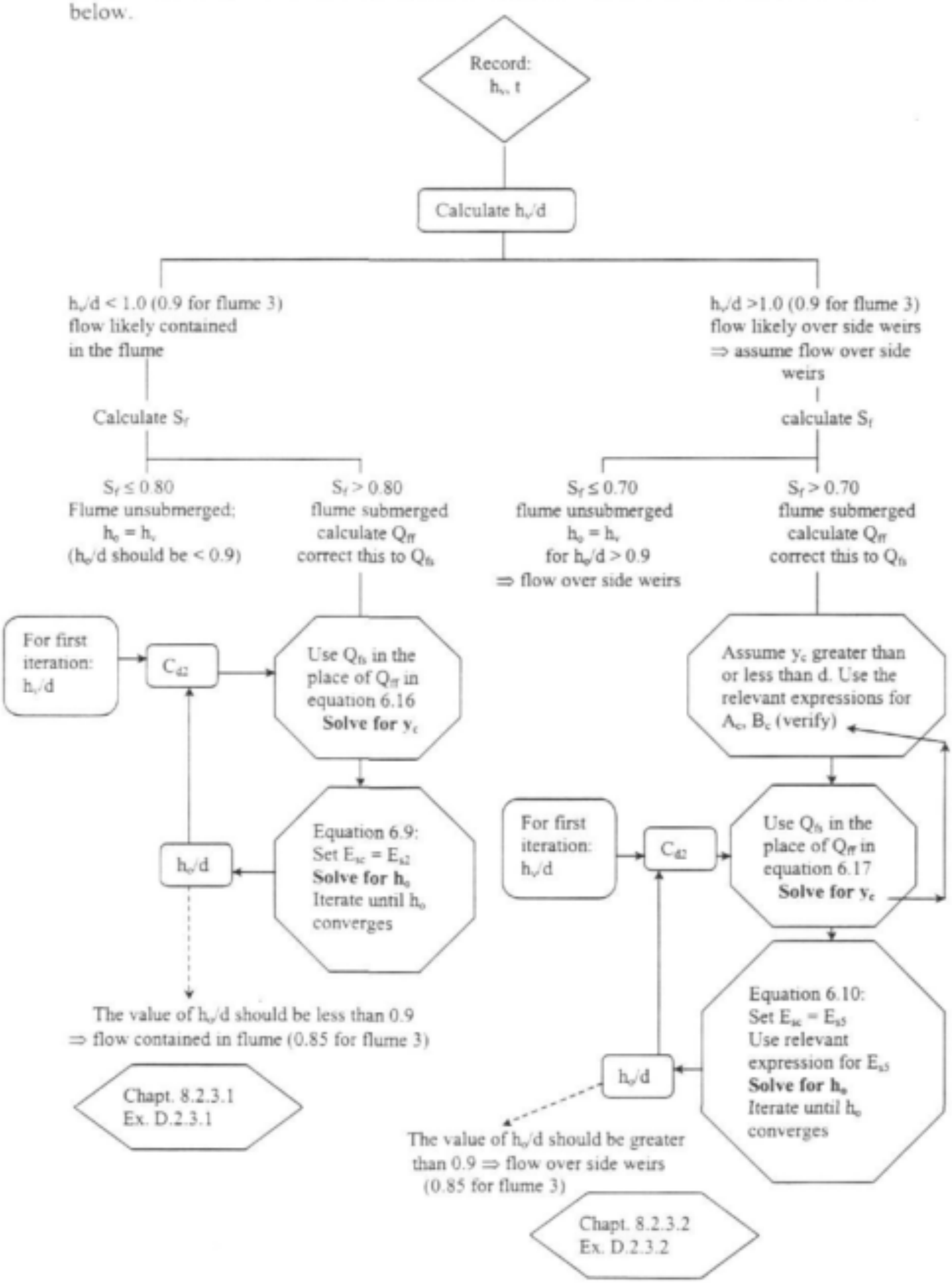
An overview of the calculation process for discharge estimation through flume 2 is provided below. Discharge calculation for flumes 1 and 3 will be less complicated, as only two cases must be considered there; namely flow contained in the flume, and flow over the flume side walls. There are more combinations with flume 2, since it has been tested with end contracted sharp-crested weirs as well as Crump weirs.



weirs
s/c weirs
Crumps
flow in flume
$S_f \leq 0.80$
$S_f > 0.80$
flume unsubmerged
flume submerged
$Q_{fs} = Q_{ff}$
Correct Q_{ff} to Q_{fs}
Q_{ff}
Eqtn 7.5
Total discharge (submerged or unsubmerged) past the compound weir
Q_{fs}
$S_f \leq 0.8$
$0.8 < S_f \leq 0.95$
flume unsubmerged
flume submerged
$Q_{fs} = Q_{ff}$
Correct Q_{ff} to Q_{fs}
Eqtn 7.22
Eqtn 7.23
Q_{ff}
Q_{fs}
Calculate the end contraction ratio: $4d/(L_1 + L_2)$
0.714
0.508
0.463
≤0.394 (full width)
Check whether the flume is submerged or not.
If unsubmerged; $Q_{ff} = Q_{fs}$
If the flume is submerged; correct Q_{ff} to Q_{fs}
Chapter 7.3.1.2 Equations 7.14 to 7.20
Q_{ff}
Q_{fs}
Ex D.2.1 for test H2S
$S_f \leq 0.70$
$S_f > 0.70$
flume:
unsubmerged
submerged
$Q_{fs} = Q_{ff}$
Correct Q_{ff} to Q_{fs}
Eqtn 7.10
Q_{ff}
Q_{fs}

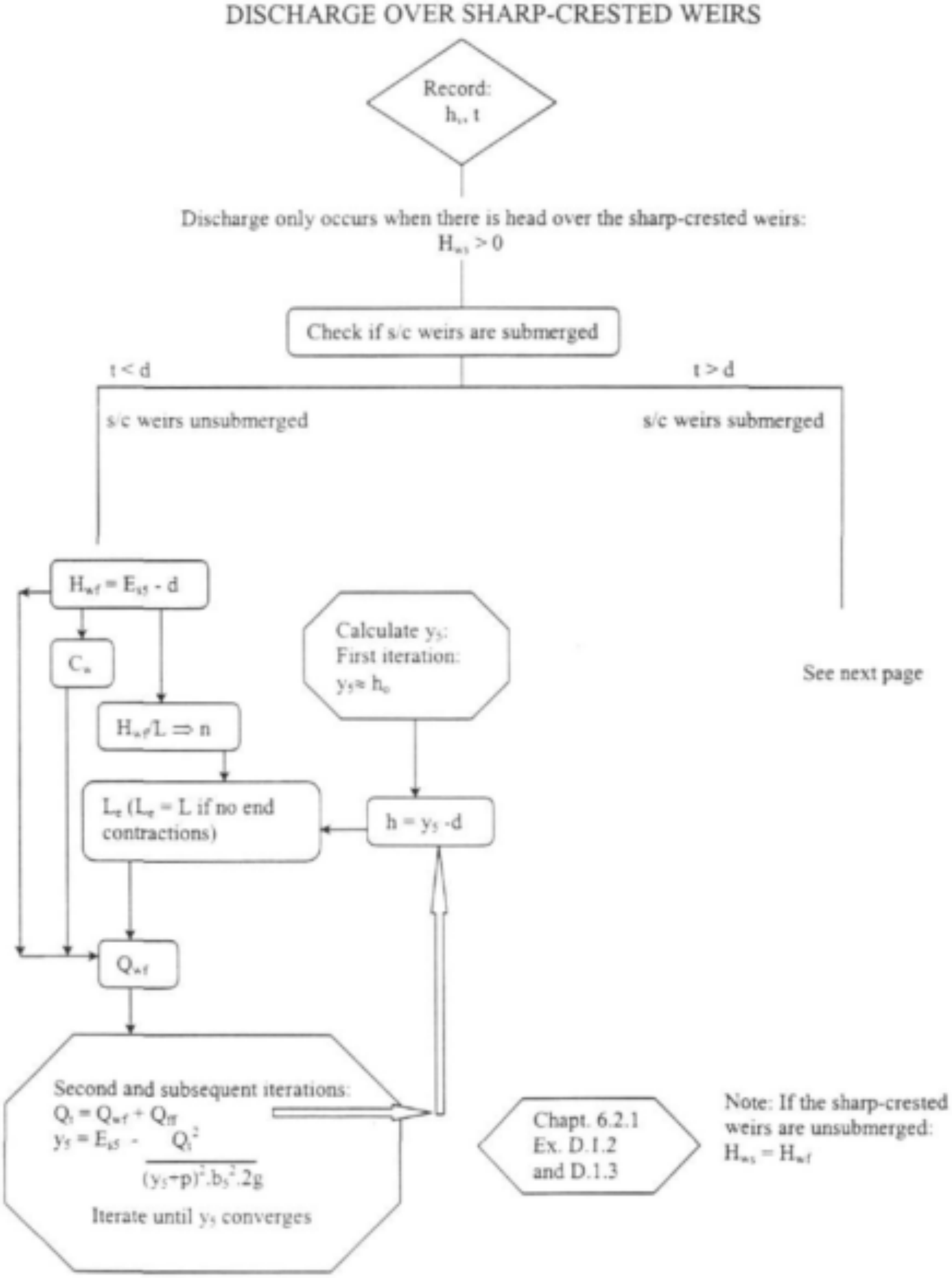
9.2.3 Back calculation of h_o

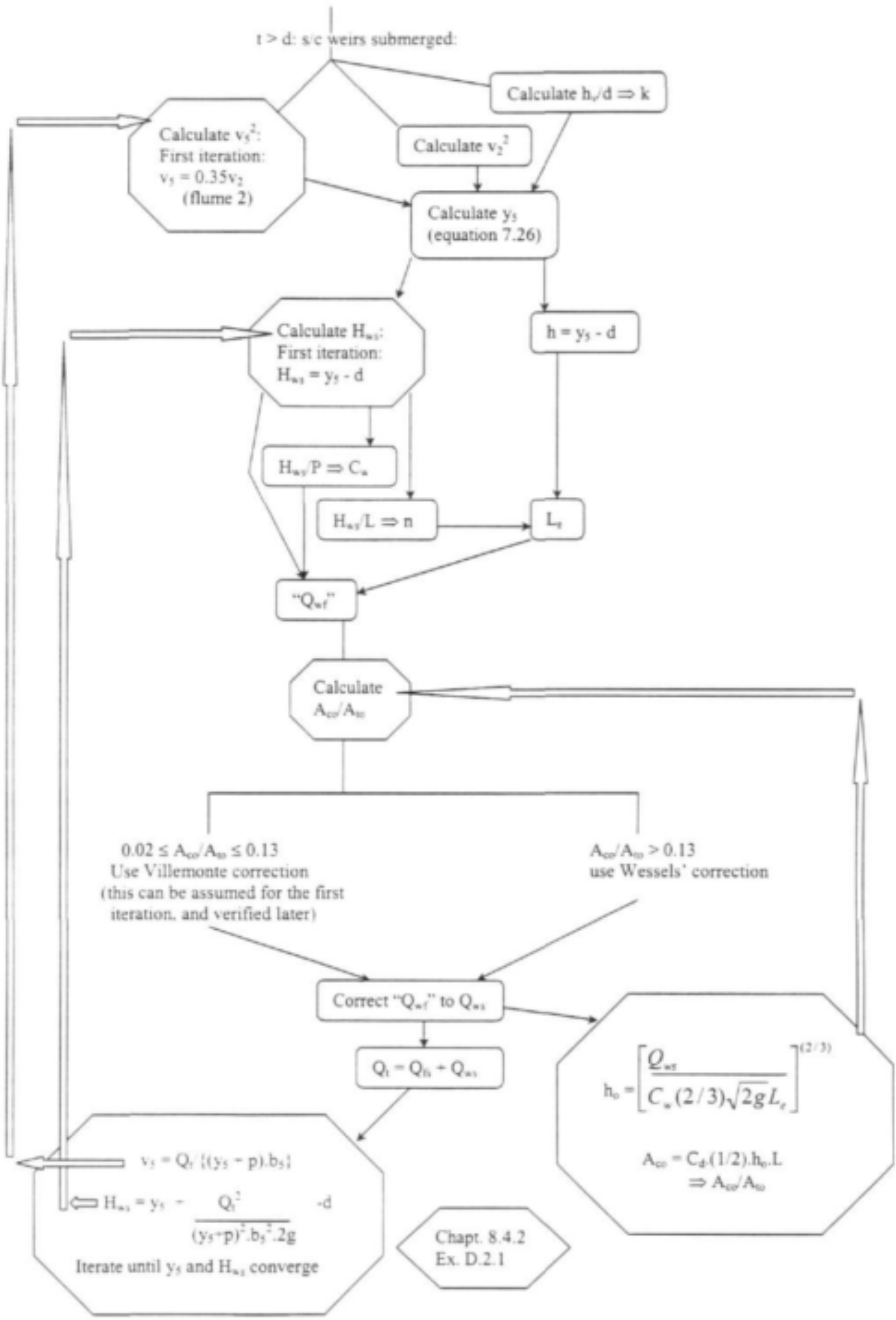
The procedure by which h_o is calculated to verify flow in the flume or not is detailed below.



9.2.4 Calculation of discharge over sharp-crested weirs

The modular discharge calculation for sharp-crested weirs is laid out in Chapter 6.2.1, and the non-modular discharge calculation in Chapter 8.4.3. Iteration is required under modular conditions when end contractions are present, and under non-modular flow conditions for all configurations of sharp-crested weirs. The iteration steps are laid out below:

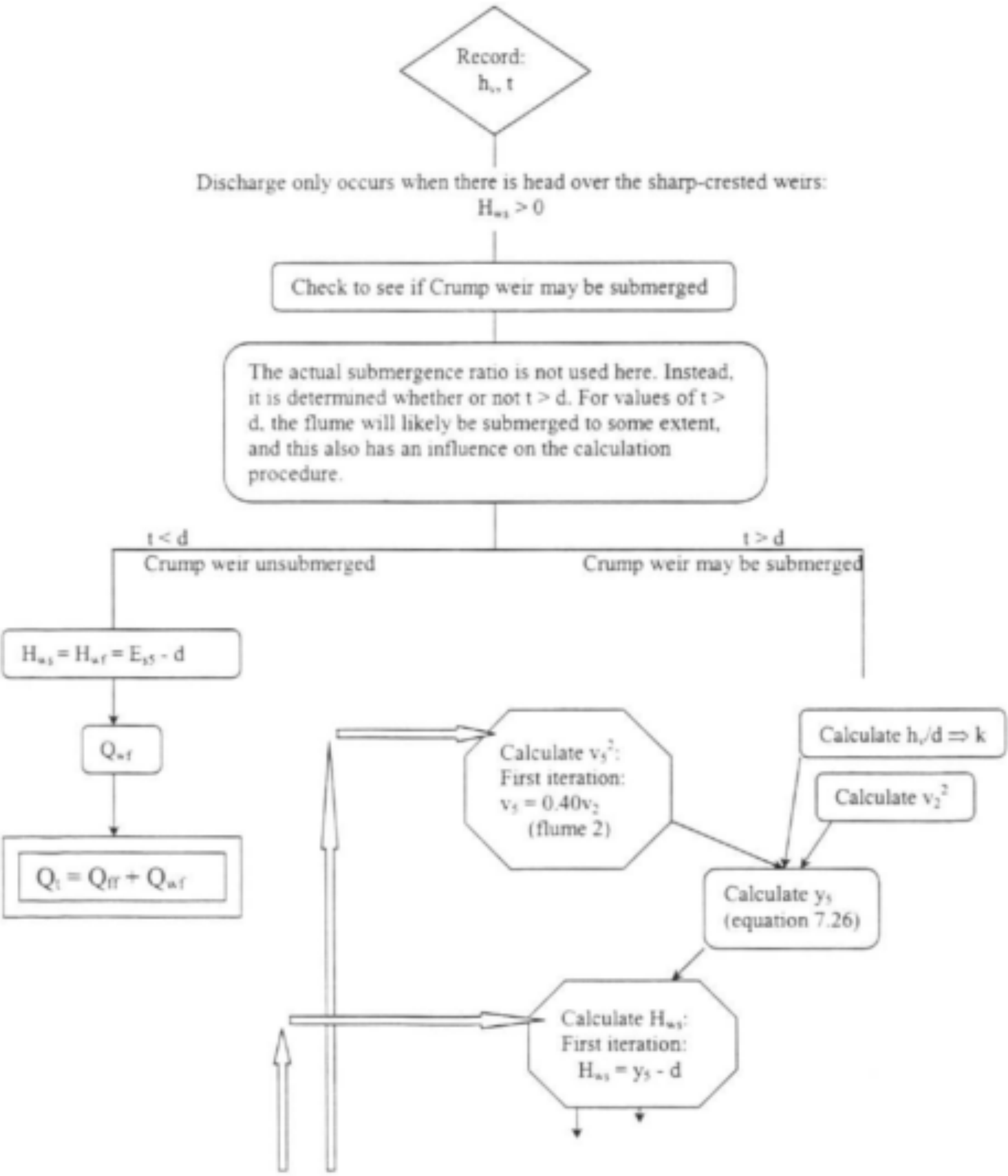


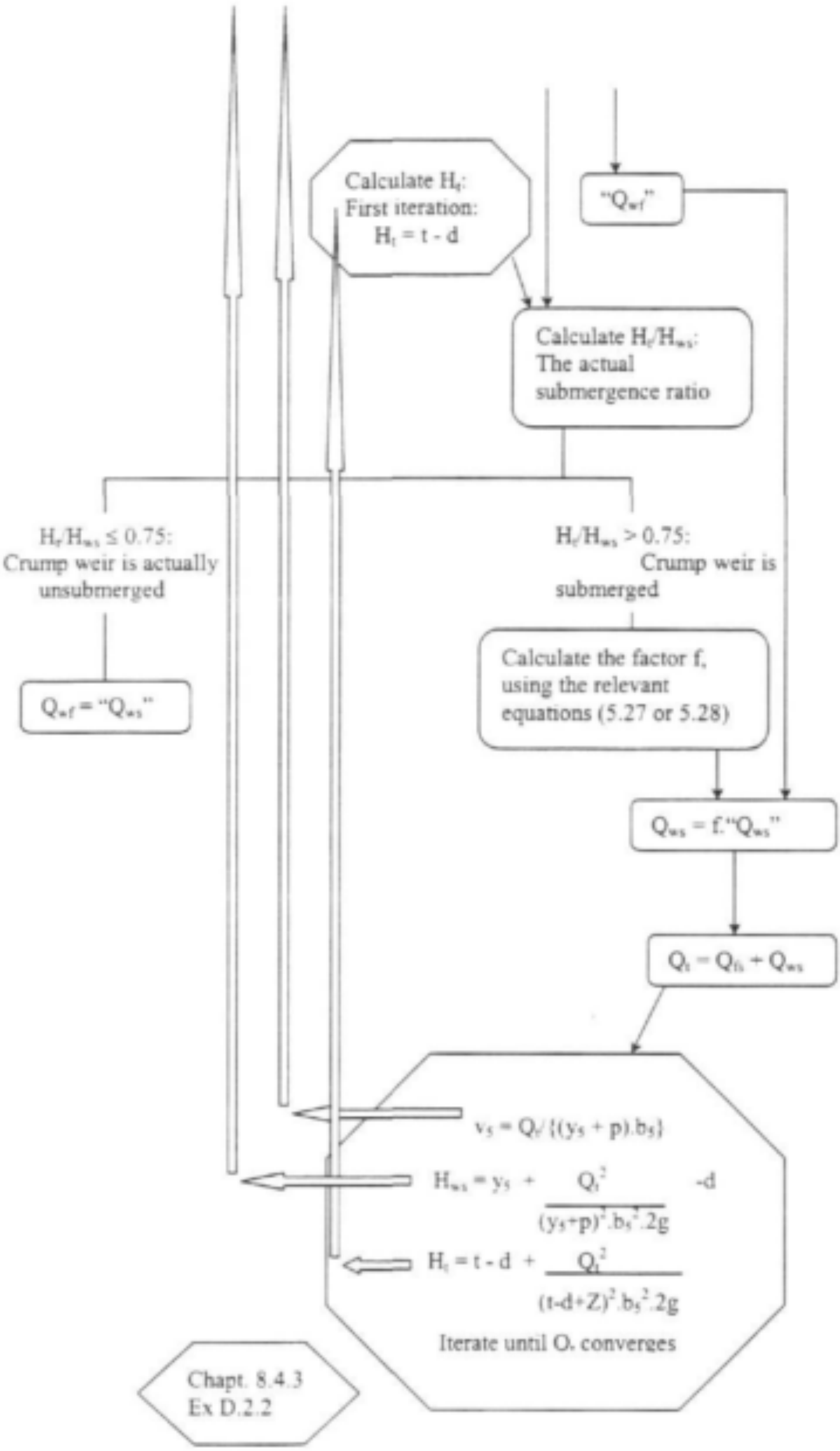

t > d: s/c weirs submerged:
Calculate $h_r/d \Rightarrow k$
Calculate v_5^2: First iteration: $v_5 = 0.35v_2$ (flume 2)
Calculate v_2^2
Calculate y_5 (equation 7.26)
Calculate H_{ws}: First iteration: $H_{ws} = y_5 - d$
$h = y_5 - d$
$H_{ws}/P \Rightarrow C_w$
$H_{ws}/L \Rightarrow n$
L_e
"Q_{wf}"
Calculate A_{co}/A_{to}
$0.02 \le A_{co}/A_{to} \le 0.13$ Use Villemonte correction (this can be assumed for the first iteration, and verified later)
$A_{co}/A_{to} > 0.13$ use Wessels' correction
Correct "Q_{wf}" to Q_{ws}
$Q_t = Q_{fs} + Q_{ws}$
$h_o = \left[\frac{Q_{ws}}{C_w(2/3)\sqrt{2g}L_e}\right]^{(2/3)}$
$A_{co} = C_d.(1/2).h_o.L \Rightarrow A_{co}/A_{to}$
$v_5 = Q_t/\{(y_5 + p).b_5\}$
$H_{ws} = y_5 + \frac{Q_t^2}{(y_5+p)^2.b_5^2.2g} - d$
Iterate until y_5 and H_{ws} converge
Chapt. 8.4.2 Ex. D.2.1

9.2.5 Calculation of discharge over Crump weirs

Under modular flow conditions, as described in Chapter 6.2.2, discharge calculation is less complicated with Crump weirs, than it is for sharp-crested weirs. This is because no iteration is required. Under non-modular flow conditions however, discharge calculation with Crump weirs is more involved. This is because the degree of submergence of the Crump weir is expressed in terms of the ratio of energy levels above the crest, and not the ratio of water levels, as is the case with sharp-crested weirs. As described in Chapter 8.4.4, this introduces a third iteration step into the calculation procedure. This is illustrated below:

DISCHARGE OVER CRUMP WEIRS




Calculate H_t:
First iteration:
$H_t = t - d$
"Q_{wf}"
Calculate H_t/H_{ws}:
The actual submergence ratio
$H_t/H_{ws} \leq 0.75$:
Crump weir is actually unsubmerged
$H_t/H_{ws} > 0.75$:
Crump weir is submerged
Q_{wf} = "Q_{ws}"
Calculate the factor f, using the relevant equations (5.27 or 5.28)
Q_{ws} = f."Q_{ws}"
$Q_t = Q_{fs} + Q_{ws}$
$v_5 = Q_t/\{(y_5 + p).b_5\}$
$H_{ws} = y_5 + \frac{Q_t^2}{(y_5+p)^2.b_5^2.2g} - d$
$H_t = t - d + \frac{Q_t^2}{(t-d+Z)^2.b_5^2.2g}$
Iterate until Q_t converges
Chapt. 8.4.3
Ex D.2.2

9.3 CALIBRATION CURVES

As it can be seen from the above flow charts, discharge calculation can become a very intricate process. Often, when recordings are taken in the field, a rough estimate of the discharge associated with these recordings is desired. It is obviously undesirable to have to undertake a major calculation process for such an estimate. In order that such a process be simplified, calibration curves are provided for all the combinations of compound weirs analysed in this report. These calibration curves not only provide useful estimates for use in the field, but also provide a graphic summary of the fits and laboratory data used to obtain these fits, and can also be used as a quick check on discharge calculations.

To use these calibration curves, the recorded values of h_v and t are all that are required. (These are the only values recorded in the prototype) The degree of submergence of the flume, S_f (= t/h_v), can be calculated, and the relevant curve chosen. With the recorded value of h_v, the total discharge (Q_t), whether submerged or unsubmerged, can then be read off.

For degrees of submergence between those for which curves are provided, interpolation must be used. For the recorded h_v and t values, Q_t can be read off from the S_f curve above and below the required S_f value. Interpolation between the Q_t values, based of the S_f values, can then be used to obtain the desired discharge.

Where end contraction ratios between those tested here are used, interpolation can again be used to obtain an estimate of the discharge. The end contraction ratio, $(4d/(L_1 + L_2)$, must be calculated for the weir. For the recorded h_v and t (and hence S_f) values, the discharge can be read off the graphs for the end contraction ratios either side of the one desired. The discharge over the compound weir configuration follows from interpolation between these discharge values read off, based on the end contraction ratios.

When using the calibration curves for weir configurations B1S, D2S, and B3S, which are the three flumes in combination with full width sharp-crested weirs, it must be borne in mind that the modular limit of the sluicing flumes (when flow occurs over the side weirs) is set at a degree of submergence in the flume of 0.7. Hence, for any degree of submergence of less than this, the free flow curve must be used. Similarly, when flow occurs only within the flumes, the modular limit of the flumes is 0.8. For degrees of submergence of less than this, the free flow curve must be used. The same holds true for the other weir combinations whose calibration curves are given here. When using each curve, the modular limit of the particular configuration should be borne in mind, and the free flow curve used for degrees of submergence of less than the modular limit.

For configurations B1S, B3S, and D2S, an additional curve is provided for when flow is contained in the flume. The main curves provided (Figures 9.1, 9.3 and 9.9 respectively) hold for all cases; flow contained in the flume, and flow over the side weirs. However, when flow is contained in the flume, the h_v and Q_t values are difficult to read off on the scale of the main figures. Hence, additional curves are provided for these cases (Figures 9.2, 9.4 and 9.10 respectively). These curves are therefore and enlargement of the scales of the main figures, and can be used so that the smaller h_v and Q_t values can be read off more easily.

9.3.1 Calibration curves for flume 1

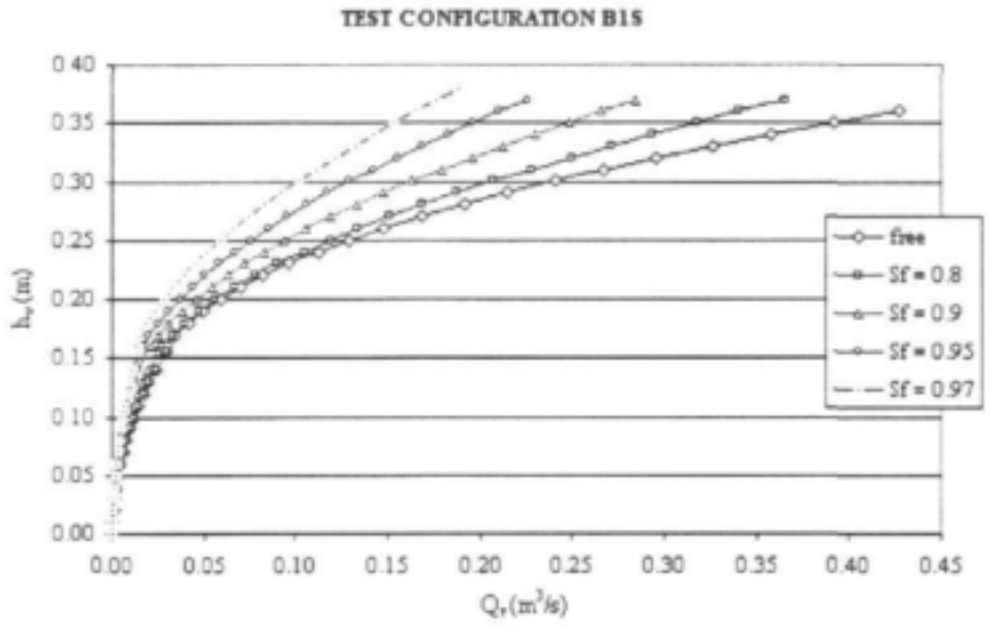


Figure 9.1: *Calibration curves for flume 1 with full width sharp-crested* ***weirs***

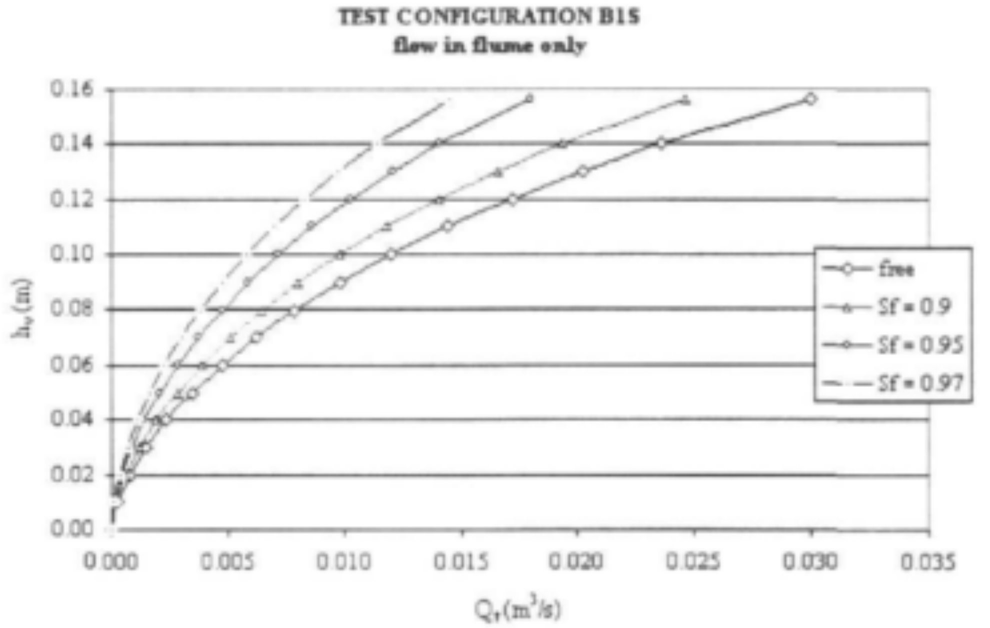


Figure 9.2: *Calibration curves for flume 1 with full width sharp-crested weirs: flow in flume only*

The three points above an h_v value of 0.16m are points where the initial, unsubmerged flow was contained in the flume. The submerged water level, h_v, however, is greater than the value of $0.9h_o$, and hence these points appear deviant. It is for such points, for example point B1S6.16 (the middle of the three points), that a back calculation for h_o must be conducted in order to ascertain whether flow is contained within the flume or not. (As is done in D.2.3.1)

9.3.2 Calibration curves for flume 2

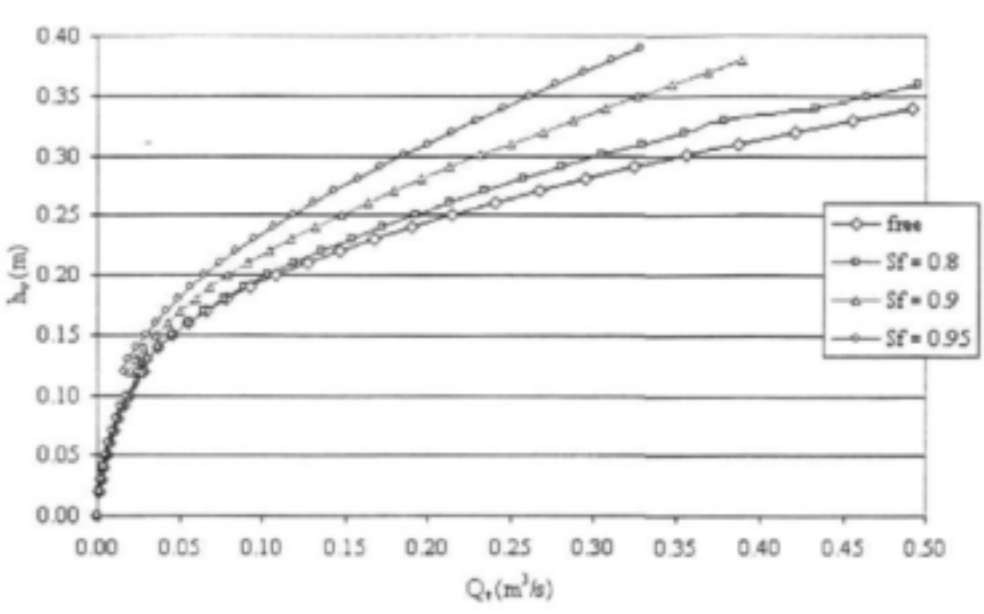


Figure 9.3: *Calibration curves for flume 2 with full width sharp-crested weirs* *($4d/(L_1 + L_2) \leq 0.394$)*

The slight flattening of the S_f = 0.8 curve around an h_v value of 0.35m is due to the transition between the Villemonte and Wessels' correction for the submerged discharge over the sharp-crested weirs.

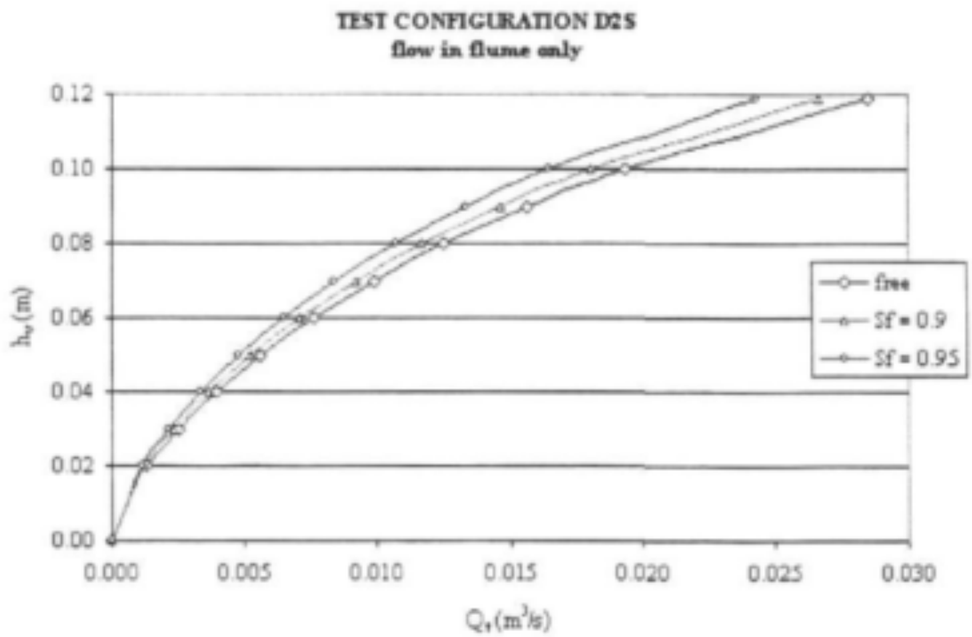


Figure 9.4: *Calibration curves for flume 2 with full width sharp-crested weirs: flow in flume only*

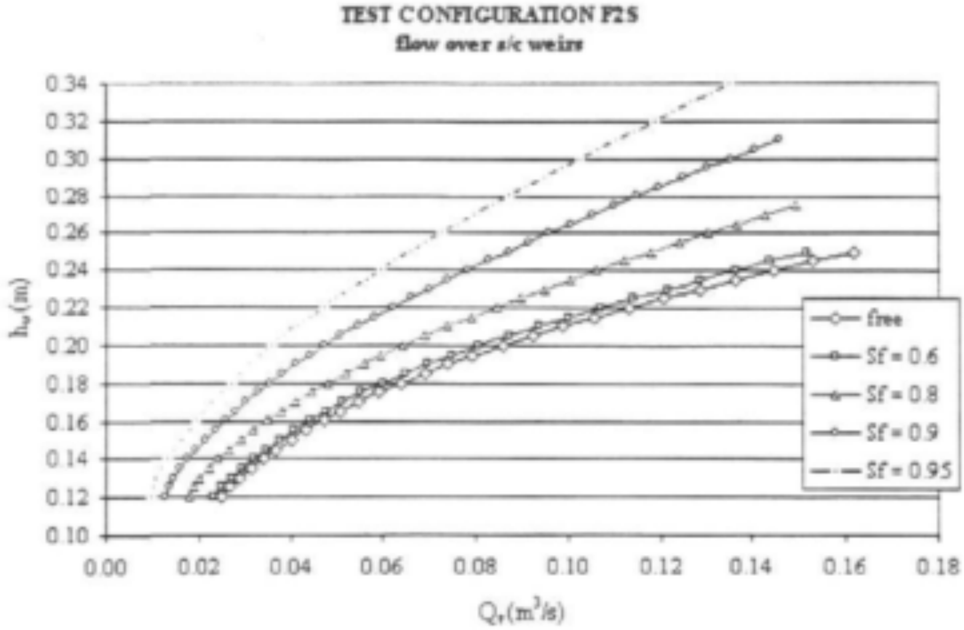


Figure 9.5: *Calibration curves for flume 2 with 300mm symmetrically end contracted sharp-crested weirs ($4d/(L_1 + L_2) = 0.714$)*

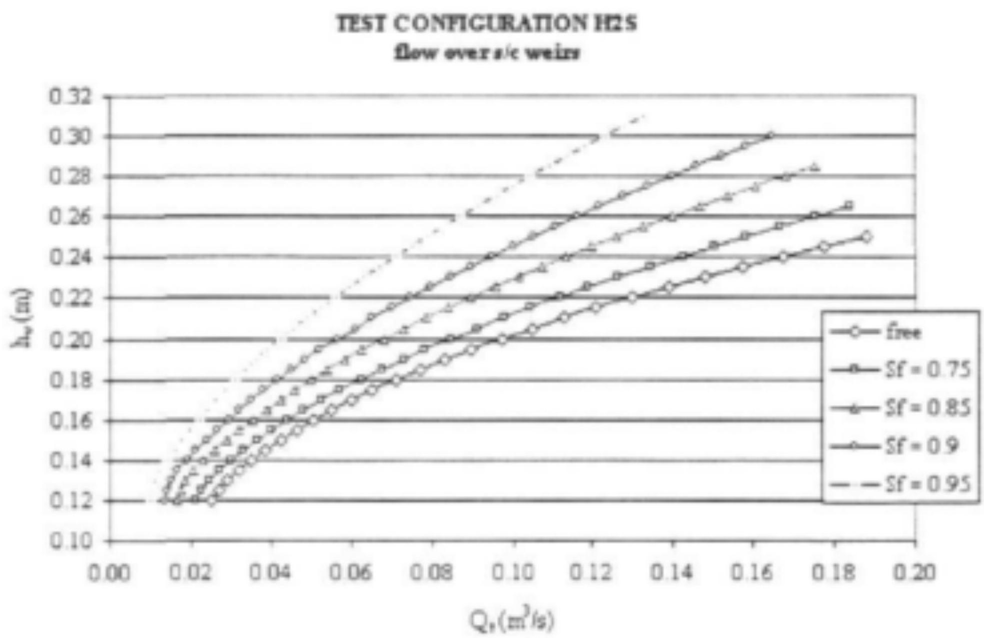


Figure 9.6: *Calibration curves for flume 2 with lhs sharp-crested weir 300mm end contracted ($4d/(L_1 + L_2) = 0.508$)*

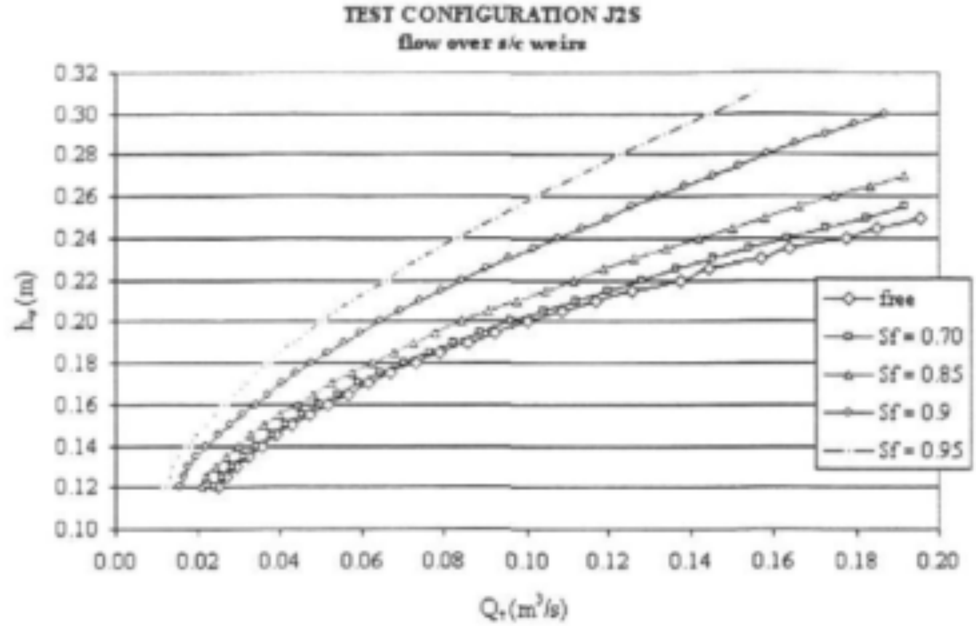


Figure 9.7: *Calibration curves for flume 2 with 100mm symmetrically end contracted sharp-crested weirs ($4d/(L_1 + L_2) = 0.463$)*

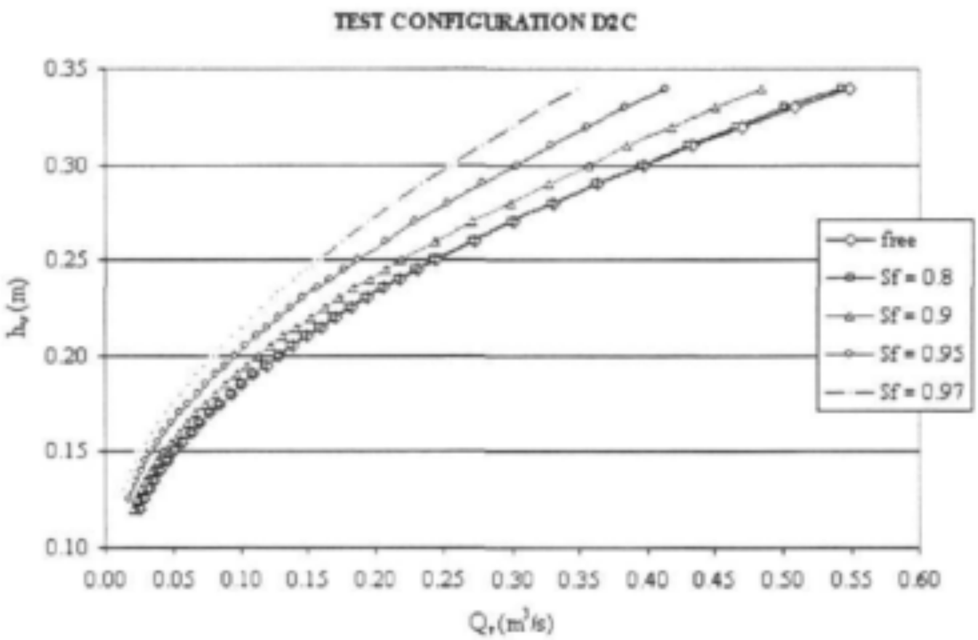


Figure 9.8: *Calibration curves for flume 2 with full width Crump weirs*

It can be seen that up to a degree of submergence (S_f) of 80%, that submergence has little effect on the compound weir featuring Crumps; the $S_f = 0.8$ line lies practically on top of the free flow line. Also, the various S_f lines lie much closer together than is the case with the weirs featuring sharp-crested weirs. This again demonstrates that the Crump weirs are much less susceptible to the effects of submergence than the sharp-crested weirs.

9.3.3 Calibration curves for flume 3

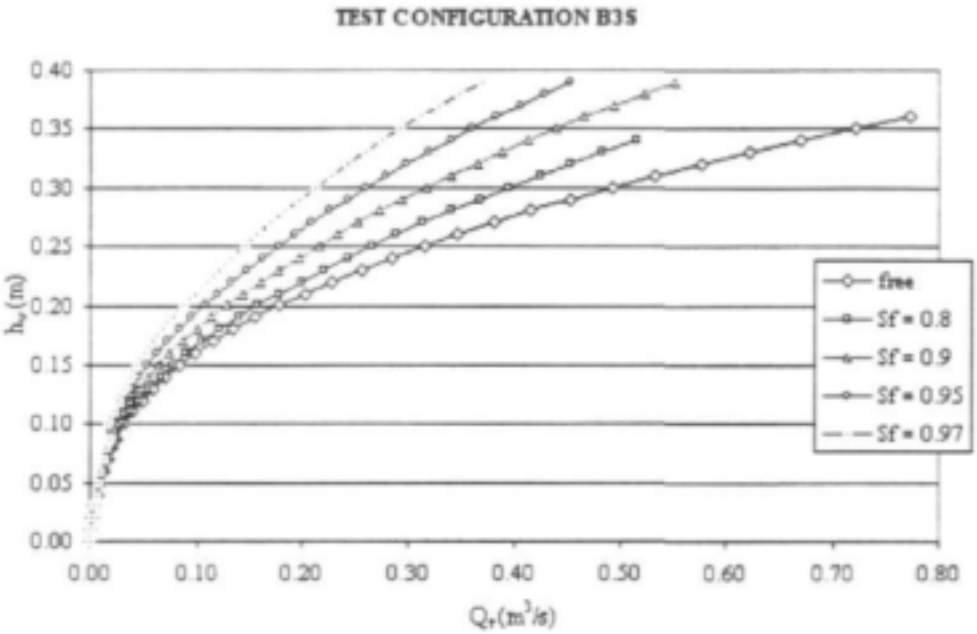


Figure 9.9: *Calibration curves for flume 3 with full width sharp-crested weirs*

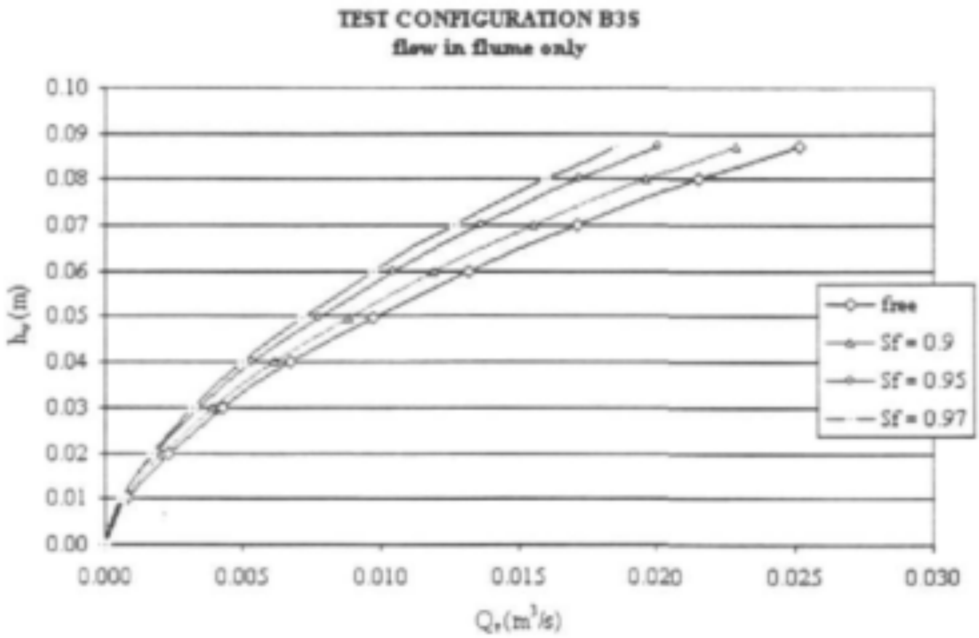


Figure 9.10: *Calibration curves for flume 3 with full width sharp-crested weirs: flow in flume only*

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The errors arising from discharge calculation under non-modular flow conditions for flumes used in combination with both full width and end contracted sharp-crested weirs as well as Crump weirs are considered acceptable. It can be concluded that the method developed here by which allowance can be made for the submergence of sluicing flumes provides satisfactory results. This method can therefore be recommended to the DWAF for use.

The principal goal of this project, namely that of finding a method to accurately calculate the discharge over compound weirs under non-modular flow conditions has therefore been achieved.

Where end contractions have been tested with flume 2, the most severe case has been where the end contractions constitute 45% of the total width of the sharp crests (test F). Even in the other configurations tested, the end contractions have constituted a significant percentage of the total length of the side weirs. It is predicted that the effect of end contractions in prototype weirs will be much less severe than in the configurations tested here. This is because the side weirs are much longer in relation to the total width of the weir in the prototype than is the case in the models tested. The deviation of the Q_{fs}/Q_{ff} vs S_f curves from those of full width weirs will therefore be much less marked. With less deviation of these curves, it is expected that the accuracy of non-modular discharge calculations will be greater for prototype weirs than has been the case here. For values of the $4d/(L_1 + L_2)$ ratio between those tested here, interpolation between the calibration curves in 9.3.2 can be used to obtain the desired discharge.

As mentioned previously, it is expected that non-modular discharge estimation in the prototype weirs will be more accurate than is suggested in this report. The largest portion of the error arises from the correction for submergence of the sluicing flume. In prototype weirs, the side weirs are much longer relative to the total width of the compound weir than is the case for the configurations tested in the laboratory. (This is due to the restrictions of width in the laboratory canal in which the tests were conducted) This means that the discharge through the flume will constitute a much lower portion of flow past the compound weir in the prototype, and hence discharge estimation should be possible with a greater degree of accuracy.

The water level in the pool upstream of the flume, y_5, can be calculated very accurately under both modular and non-modular flow conditions. This water level is used to calculate the discharge over the side weirs. Where the side weirs are much longer relative to the total width of the compound weir in the prototype, this flow constitutes a greater portion of the total flow past the compound weir, and hence it is expected that discharge estimations will be more accurate in the prototype weirs than is suggested here.

10.2 RECOMMENDATIONS

It is recommended that wherever possible, the prototype weirs be so designed that submergence of the weir only occurs after flow has overtopped the flume walls and side weirs. This will avoid very high degrees of submergence of the flumes, and the errors associated with them. This will also simplify the calculation process significantly, as if it is known that submergence occurred only once the side weirs were over topped, no back calculation for h_o need be performed.

It is recommended that no discharge estimation be attempted for degrees of submergence of greater than 0.95 for flumes in combination with sharp-crested weirs. The errors associated with discharge calculation in this region are too large and erratic to be considered acceptable.

It is recommended that Crump weirs be used adjacent to the sluicing flumes as far as possible. This combination is more accurate for both modular and non-modular discharge estimation. For non-modular discharge estimation, the flume with Crump weirs is more accurate over the whole range of flows, but particularly so at the higher degrees of submergence. Crump weirs also do not have the disadvantage that sharp-crested weirs do of requiring aeration underneath the nappe. This means that Crump weirs do not require end contractions, or pillars built into their crests, allowing for cheaper and easier construction. Furthermore, Crump weirs have better sedimentation characteristics than do sharp-crested weirs.

It is recommended that wherever possible flume 2 ($d/b = 0.5$) be used, preferable with Crump weirs. Flume 2 represents a compromise between the capacities of flume 1 and 3, and is more accurate under non-modular discharge conditions than is flume 1, particularly as far as the standard deviation of the errors is concerned.

It is recommended that the data contained in this report be incorporated into a user-friendly software package that also allows for the calculation of the discharge over any configuration of compound weir, given the relevant water levels, and parameters of the weir. Such a package can be used to generate flow records from the recorded water levels electronically, as manual repetition of the calculation procedure will be both tedious and time consuming. It is also recommended that calibration curves be drawn up for each weir configuration used in the prototype. These curves can be used both as a check on manual or automated calculations, and as an estimate of discharge when in the field.

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APPENDIX A

FLUME DIMENSIONS AND EXPRESSIONS FOR C_{d2}, C_{d5} and E_{s5}/d
(Rossouw et al., 1998)

FORMULAE FOR DISCHARGE CALCULATION

The derived expressions for C_{d2}, C_{d5} and E_{s5} for the three sluicing flumes are provided (Rossouw et al., 1998).

A.1 FLUME 1 (d/b = 1.0) IN COMBINATION WITH SHARP-CRESTED WEIRS:

b (m)	0.174
d (m)	0.174
b_2 (m)	0.348
b_5 (m)	1.520
L (m)	2.000
p (m)	0.027
s (m)	0.066

$C_{d2} = 0.811 + 0.275(h_o/d)$ for $0<h_o/d<0.9$
$C_{d5} = 0.845 + 0.081(h_o/d)$ for $0.9<h_o/d<1.5$
$C_{d5} = 0.094 + 0.887(h_o/d) - 0.203(h_o/d)^2$ for $1.5<h_o/d<2.0$
$C_{d5} = 1.06$ for $2.0<h_o/d<3.0$

$E_{s5}/d = 0.525 + 0.335(h_o/d) + 0.232(h_o/d)^2$ for $0.9<h_o/d<2.0$

<u>If $y_c<d$:</u>
$A_c = by_c + 0.5y_c^2$ (6.2)
$B_c = b + y_c$ (6.3)

<u>If $y_c>d$:</u>
$A_c = 1.5bd + B_c(y_c - d)$ (6.4)
$B_c = 2(b + s)$ (6.5)

A.2 FLUME 2 (d/b = 0.5) IN COMBINATION WITH SHARP-CRESTED WEIRS:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
b_5 (m)	1.340
L (m)	2.000
p (m)	0.025
s (m)	0.066

$C_{d2} = 0.92$ for $0<h_o/d<0.5$
$C_{d2} = 1.031 - 0.479(h_o/d) + 0.517(h_o/d)^2$ for $0.5<h_o/d<0.9$
$C_{d5} = 0.899 - 0.0267(h_o/d)$ for $0.9<h_o/d<1.5$
$C_{d5} = 0.104 + 0.718(h_o/d) - 0.140(h_o/d)^2$ for $1.5<h_o/d<2.5$
$C_{d5} = 1.02$ for $2.5<h_o/d<3.0$

$E_{s5}/d = 0.315 + 0.630(h_o/d) + 0.125(h_o/d)^2$ for $0.9<h_o/d<2.5$

<u>If $y_c<d$:</u>
$A_c = by_c + y_c^2$
$B_c = b + 2y_c$

<u>If $y_c>d$:</u>
$A_c = 1.5bd + B_c(y_c - d)$
$B_c = 2(b + s)$

A.3 FLUME 2 (d/b = 0.5) IN COMBINATION WITH CRUMP WEIRS:

B (m)	0.264
D (m)	0.132
B_2 (m)	0.528
B_5 (m)	1.340
L (m)	2.000
P (m)	0.025
s (m)	0.066

$C_{d2} = 0.92$ for $0<h_o/d<0.5$
$C_{d2} = 1.031 - 0.479(h_o/d) + 0.517(h_o/d)^2$ for $0.5<h_o/d<0.9$
$C_{d5} = 0.766 + 0.078(h_o/d)$ for $0.9<h_o/d<3.0$

$E_{s5}/d = 0.275 + 0.703(h_o/d) + 0.126(h_o/d)^2$ for $0.9<h_o/d<2.5$

A.4 FLUME 3 (d/b = 0.25) IN COMBINATION WITH SHARP-CRESTED WEIRS:

b (m)	0.412
d (m)	0.103
b_2 (m)	0.721
b_5 (m)	1.147
L (m)	2.000
p (m)	0.025
s (m)	0.066

$C_{d2} = 0.98$ for $0<h_o/d<0.85$
$C_{d5} = 0.884 + 0.025(h_o/d$ for $0.85<h_o/d<1.55$
$C_{d5} = 0.327 + 0.544(h_o/d) - 0.140(h_o/d)^2$ for $1.55<h_o/d<2.5$
$C_{d5} = 1.03$ for $2.5<h_o/d<3.0$

$E_{s5}/d = 0.438 + 0.528(h_o/d) + 0.149(h_o/d)^2$ for $0.85<h_o/d<3.0$

If $y_c<d$:
$A_c = by_c + 1.5y_c^2$
$B_c = b + 3y_c$

If $y_c>d$:
$A_c = 1.375bd + B_c(y_c - d)$
$B_c = 2s + 1.75b$

A.5 SUMMARY OF FORMULAE FOR DISCHARGE CALCULATION

A.5.1 Sharp-crested weirs

A.5.1.1 Modular flow conditions

$$Q_{wf} = C_w.2/3.\sqrt{2g}\, L_e H_{wf}^{\,3/2} \qquad (5.2)$$

$$C_w = 0.627 + 0.018\, H_{wf}/P \qquad \text{for } H_{wf}/P \leq 1.867 \qquad (5.3)$$

$$C_w = 0.689\left[\frac{P}{P+H_{wf}}\right]^{0.04} \qquad \text{for } 1.867 < H_{wf}/P \leq 15 \qquad (5.4)$$

$$H_{wf} = h + v^2/(2g) \qquad (5.5)$$

For a full-width weir, $L_e = L$. For end contractions on both sides, L_e is calculated as follows:

$$L_e = L - nh \qquad (5.6)$$

$$n = 0.2 \qquad \text{for } H_{wf}/L < 0.35 \qquad (5.7)$$

$$n = 0.174(L/H_{wf})^{0.517} - 0.1 \qquad \text{for } 0.35 \leq H_{wf}/L \leq 2.00 \qquad (5.8)$$

$$n = 0.0216 \qquad \text{for } H_{wf}/L > 2.00 \qquad (5.9)$$

(L is the overflow length of the sharp-crest.)

If only one side of the notch is contracted, then half of the above correction is applied:

$$L_e = L - ½.nh \qquad (5.10)$$

Also:

$$P = p + d \qquad (6.18)$$

$$H_{wf} = E_{s5} - d \qquad (6.19)$$

$$y_5 = E_{s5} - \frac{Q_i^2}{(y_5 + p)^2\, b_5^2 .2g} \qquad (6.21)$$

For the first iteration only:

$$h = y_5 - d \qquad (6.20)$$

A.5.1.2 Non-modular flow conditions

$$A_o = h_o.L \qquad (5.11)$$

$$A_c = C_d.½.(h_v + t).L \qquad (5.12)$$

(where the value of C_d can be taken as 0.6 for single notch weirs: Canto, 2000)

$$A_{co} = Cd.½.h_o.L \qquad (5.13)$$

$$A_{to} = B.Z \qquad (5.14)$$

Villemonte Method:

The Villemonte method is advocated in the following region (Canto, 2000):

$$0.02 \le A_{co}/A_{to} \le 0.130 \qquad (5.15)$$

$$Q_{ws} = Q_{wf}\left[1-\left[\frac{t-d}{y_5-d}\right]^{1.5}\right]^{0.385} \qquad (5.16)$$

Wessels' Method:

$$h_o = \frac{h_v\sqrt{1-(t/h_v)^2}}{\alpha} \qquad (5.18)$$

$$\alpha = \frac{-b+\sqrt{b^2+4c}}{2} \qquad (5.19)$$

$$b = -0.34074 - 0.30623(t/h_v) \qquad (5.20)$$

$$c = 0.62879(t/h_v)^2 + 0.10159(t/h_v) - 01.6096 \qquad (5.21)$$

also

$$H_{ws} = y_5 + \frac{Q_t^2}{(y_5+p)^2.b_5^2.2g} - d \qquad (8.1)$$

For the first iteration only:

$$H_{ws} = y_5 - d \qquad (8.10)$$

$$h = y_5 - d \qquad (6.20)$$

A.5.2 Crump weirs

A.5.2.1 Modular flow conditions

$$Q_{wf} = 1.982.L.H_{wf}^{1.5} \quad (5.24)$$

A.5.2.2 Non-modular flow conditions

$$Q_{ws} = f.Q_{wf} \quad (5.25)$$

$$f = 1.035[0.817 - (H_t/H_{ws})^4]^{0.0647} \quad \text{for } 0.75 < H_t/H_{ws} \leq 0.93 \quad (5.27)$$

$$f = 8.686 - 8.403(H_t/H_{ws}) \quad \text{for } 0.93 < H_t/H_{ws} \leq 0.985 \quad (5.28)$$

$$H_{ws} = y_5 + \frac{Q_t^2}{(y_5 + p)^2 . b_5^2 .2g} - d \quad (8.1)$$

$$H_t = t - d + \frac{Q_t^2}{(t - d + Z)^2 . b_5^2 .2g} \quad (8.4)$$

For the first iteration only:

$$H_{ws} = y_5 - d \quad (8.10)$$

$$H_t = t - d \quad (8.12)$$

A.5.3 Sluicing flumes

A.5.3.1 Modular flow conditions

$$Q_{ff} = C_{d2}\sqrt{g.A_c^3 / B_c} \tag{6.16}$$

$$Q_{ff} = C_{d5}\sqrt{g.A_c^3 / B_c} \tag{6.17}$$

A.5.3.2 Non-modular flow conditions

Flow in flume only (flumes with sharp-crested weirs):

Flume 1 (d/b = 1.0):

$Q_{fs}/Q_{ff} = 1$ for $S_f < 0.30$ (7.2)

$Q_{fs}/Q_{ff} = -0.154.S_f + 1.043$ for $0.30 \leq S_f \leq 0.80$ (7.3)

$Q_{fs}/Q_{ff} = -13.852.S_f^2 + 22.009.S_f - 7.822$ for $0.80 < S_f \leq 0.99$ (7.4)

Flume 2 (d/b = 0.5):

$Q_{fs}/Q_{ff} = -6.539.S_f^2 + 10.462.S_f - 3.185$ for $0.80 < S_f \leq 0.95$ (7.5)

Flume 3 (d/b = 0.25):

$185Q_{fs}/Q_{ff} = -9.011.S_f^2 + 14.417.S_f - 4.767$ for $0.80 < S_f \leq 1.02$ (7.6)

For flumes 1 and 2:

$Q_{fs}/Q_{ff} = 1.0$ for $S_f \leq 0.80$ (7.7)

Flumes with full width sharp-crested weirs (flow over flume walls):

Flume 1 (d/b = 1.0):

$Q_{fs}/Q_{ff} = -5.871.S_f^2 + 8.219.S_f - 1.877$ for $0.70 < S_f \leq 0.95$ (7.8)

$Q_{fs}/Q_{ff} = -251.047.S_f^2 + 474.053.S_f - 223.148$ $0.95 < S_f \leq 0.99$ (7.9)

Flume 2 (d/b = 0.5):

$Q_{fs}/Q_{ff} = -5.678.S_f^2 + 7.949.S_f - 1.782$ for $0.70 < S_f \leq 0.95$ (7.10)

Flume 3 (d/b = 0.25):

$Q_{fs}/Q_{ff} = -4.842.S_f^2 + 6.780.S_f - 1.373$ for $0.70 < S_f \leq 0.95$ (7.11)

$Q_{fs}/Q_{ff} = -195.561.S_f^2 + 369.146.S_f - 173.497$ $0.95 < S_f \leq 0.98$ (7.12)

For all three flumes:

$Q_{fs}/Q_{ff} = 1.0$ for $S_f \leq 0.70$ (7.13)

Flume 2 ($d/b = 0.5$) with end contracted side sharp-crested weirs (flow over flume walls):

4d/(L₁ + L₂) = 0.714

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.30$	(7.14)
$Q_{fs}/Q_{ff} = -0.758.S_f^2 + 0.455.S_f + 0.932$	for $0.30 < S_f \leq 0.60$	(7.15)
$Q_{fs}/Q_{ff} = -3.183.S_f^2 + 3.365.S_f + 0.058$	for $0.60 < S_f \leq 0.95$	(7.16)

4d/(L₁ + L₂) = 0.508

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.55$	(7.17)
$Q_{fs}/Q_{ff} = -3.800.S_f^2 + 4.179.S_f - 0.149$	for $0.55 < S_f \leq 0.94$	(7.18)

4d/(L₁ + L₂) = 0.463

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.60$	(7.19)
$Q_{fs}/Q_{ff} = -4.162.S_f^2 + 4.994.S_f - 0.498$	for $0.60 < S_f \leq 0.94$	(7.20)

4d/(L₁ + L₂) ≤ 0.394 (full width)

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.70$	(7.13)
$Q_{fs}/Q_{ff} = -5.678.S_f^2 + 7.949.S_f - 1.782$	for $0.70 < S_f \leq 0.95$	(7.10)

Flume 2 with crump weirs:

$Q_{fs}/Q_{ff} = 1.0$	for $S_f \leq 0.80$	(7.21)
$Q_{fs}/Q_{ff} = -15.175.S_f^2 + 24.285.S_f - 8.716$	for $0.80 < S_f \leq 0.95$	(7.22)
$Q_{fs}/Q_{ff} = -220.855.S_f^2 + 415.077.S_f - 194.341$	$0.95 < S_f \leq 0.98$	(7.23)

also:

$$v_2 = \frac{Q_{ff}}{b_2.h_v} \quad (8.2)$$

$$v_5 = \frac{Q_t}{(y_5 + p)b_5} \quad (8.3)$$

For the first iteration only:

$v_5 = 0.35.v_2$	for flume 1 ($d/b = 1.0$)	(8.7)
$v_5 = 0.38.v_2$	for flume 2 ($d/b = 0.5$)	(8.8)
$v_5 = 0.46.v_2$	for flume 3 ($d/b = 0.25$)	(8.9)

Flume 2 with crump weirs:

$v_5 = 0.40.v_2$	for flume 2 ($d/b = 0.5$)	(8.11)

A.5.3.3 Calculation of y_5 (non-modular flow conditions)

A.5.3.3.1 Sharp-crested weirs: full width and end-contracted

$$\frac{y_5}{h_v} = 1 + k\frac{\left(v_3^2 - v_5^2\right)}{2g.h_v} \qquad (7.26)$$

$$k = -2.294.(h_v/d)^3 + 12.394.(h_v/d)^2 - 22.372.(h_v/d) + 13.601$$

$$\text{for } h_v/d < 2.0 \qquad (7.28)$$

$$k = -0.058.(h_v/d) + 0.196 \qquad \text{for } 2.0 \le h_v/d \le 3.4 \qquad (7.29)$$

$$k = 0 \qquad \text{for } h_v/d > 3.4 \qquad (7.30)$$

A.5.3.3.2 Crump weirs

$$k = -0.524.(h_v/d)^3 + 3.746.(h_v/d)^2 - 8.903.(h_v/d) + 7.434$$

$$\text{for } h_v/d \le 2.5 \qquad (7.31)$$

$$k = 0.4 \qquad \text{for } h_v/d > 2.5 \qquad (7.32)$$

A.5.4 Total discharge over compound weir

A.5.4.1 Modular flow conditions

Flow only in flume:

$$Q_t = Q_{ff} \qquad (6.22)$$

Flow over side weirs:

$$Q_t = Q_{ff} + Q_{wf} \qquad (6.23)$$

A.5.4.2 Non-modular flow conditions

Flow only in flume:

$$Q_t = Q_{fs} \qquad (8.4)$$

Flow over side weirs:

$$Q_t = Q_{fs} + Q_{ws} \qquad (8.5)$$

APPENDIX B

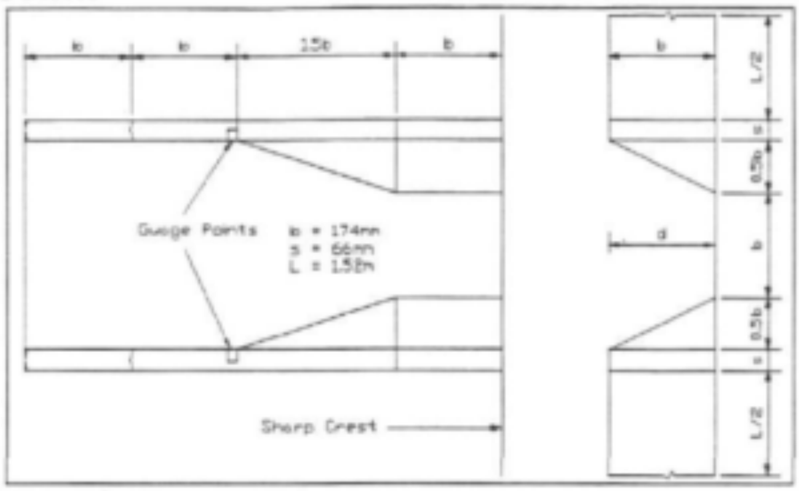
DATA FROM MODULAR FLOW TESTS

MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test A1S

Flume 1, (d/b = 1.0) with sharp-crested weirs.



Flume dimensions:

b (m)	0.174
d (m)	0.174
b_2 (m)	0.348
L (m)	1.520
b_5 (m)	2.000
p (m)	0.027
s (m)	0.066

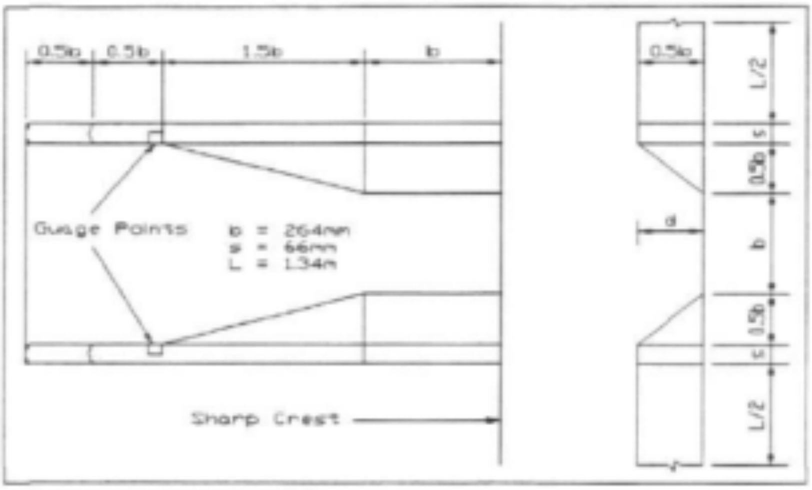
		Water levels relative to flume invert (m)					
Test Nr.	Q_{lab} (m^3/s)	2.1	2.2	2.3	4	5	6
A1S1	0.0013	0.0280	0.0280	0.0280	0.0290	0.0295	0.0290
A1S2	0.0030	0.0460	0.0455	0.0455	0.0480	0.0485	0.0480
A1S3	0.0069	0.0740	0.0725	0.0735	0.0790	0.0795	0.0790
A1S4	0.0102	0.0930	0.0910	0.0920	0.0995	0.1000	0.0995
A1S5	0.0120	0.1000	0.0980	0.0995	0.1085	0.1085	0.1085
A1S6	0.0151	0.1120	0.1110	0.1120	0.1235	0.1235	0.1235
A1S7	0.0174	0.1210	0.1185	0.1205	0.1335	0.1340	0.1335
A1S8	0.0200	0.1300	0.1280	0.1300	0.1450	0.1455	0.1450
A1S9	0.0225	0.1375	0.1360	0.1375	0.1550	0.1555	0.1550
A1S10	0.0245	0.1425	0.1410	0.1430	0.1625	0.1630	0.1625
A1S11	0.0277	0.1500	0.1490	0.1505	0.1730	0.1730	0.1730
A1S13	0.0402	0.1770	0.1755	0.1760	0.1930	0.1935	0.1930
A1S14	0.0448	0.1830	0.1830	0.1840	0.1980	0.1980	0.1980
A1S15	0.0503	0.1905	0.1900	0.1905	0.2030	0.2035	0.2030
A1S16	0.0556	0.1965	0.1955	0.1960	0.2075	0.2075	0.2075
A1S17	0.0603	0.2005	0.2005	0.2000	0.2115	0.2120	0.2115
A1S18	0.0650	0.2050	0.2050	0.2045	0.2150	0.2155	0.2150
A1S19	0.0699	0.2100	0.2095	0.2095	0.2190	0.2190	0.2190
A1S20	0.0757	0.2150	0.2145	0.2150	0.2230	0.2235	0.2230
A1S21	0.0796	0.2190	0.2185	0.2190	0.2265	0.2265	0.2265
A1S22	0.0854	0.2240	0.2225	0.2235	0.2300	0.2305	0.2300
A1S23	0.0899	0.2275	0.2260	0.2270	0.2335	0.2340	0.2335
A1S24	0.0948	0.2310	0.2295	0.2305	0.2365	0.2370	0.2365
A1S25	0.1014	0.2345	0.2330	0.2345	0.2400	0.2405	0.2405
A1S26	0.1252	0.2465	0.2465	0.2470	0.2525	0.2530	0.2525
A1S27	0.1487	0.2605	0.2590	0.2605	0.2660	0.2660	0.2660
A1S28	0.1742	0.2710	0.2710	0.2715	0.2765	0.2770	0.2765
A1S29	0.2009	0.2840	0.2815	0.2835	0.2895	0.2895	0.2895
A1S30	0.2251	0.2930	0.2915	0.2930	0.2995	0.2995	0.2995
A1S31	0.2484	0.3030	0.3000	0.3030	0.3090	0.3095	0.3090
A1S32	0.2764	0.3125	0.3110	0.3120	0.3180	0.3180	0.3180
A1S33	0.3030	0.3210	0.3185	0.3220	0.3290	0.3295	0.3290
A1S34	0.3247	0.3290	0.3260	0.3290	0.3360	0.3360	0.3360
A1S35	0.3488	0.3370	0.3330	0.3370	0.3445	0.3445	0.3445
A1S36	0.3751	0.3465	0.3410	0.3465	0.3530	0.3540	0.3535
A1S37	0.3977	0.3530	0.3480	0.3530	0.3610	0.3610	0.3610

MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test A2S

Flume 2, (d/b = 0.5) with sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.340
b_5 (m)	2.000
p (m)	0.025
s (m)	0.066

		Water levels relative to flume invert (m)					
Test Nr.	Q_{lab} (m^3/s)	2.1	2.2	2.3	4	5	6
A2S1	0.0123	0.0795	0.0787	0.0795	0.0865	0.0865	0.0865
A2S2	0.0198	0.1010	0.1005	0.1000	0.1120	0.1130	0.1130
A2S3	0.0058	0.0510	0.0495	0.0505	0.0540	0.0540	0.0540
A2S4	0.0093	0.0680	0.0665	0.0675	0.0730	0.0730	0.0730
A2S5	0.0131	0.0820	0.0810	0.0815	0.0890	0.0890	0.0895
A2S6	0.0159	0.0905	0.0900	0.0905	0.1000	0.1000	0.1005
A2S7	0.0211	0.1040	0.1040	0.1035	0.1165	0.1165	0.1170
A2S8	0.0247	0.1120	0.1130	0.1120	0.1275	0.1275	0.1275
A2S9	0.0344	0.1335	0.1330	0.1335	0.1450	0.1450	0.1455
A2S10	0.0389	0.1425	0.1410	0.1425	0.1505	0.1505	0.1510
A2S11	0.0429	0.1485	0.1465	0.1480	0.1550	0.1550	0.1555
A2S12	0.0481	0.1550	0.1535	0.1550	0.1605	0.1605	0.1610
A2S13	0.0511	0.1580	0.1565	0.1580	0.1625	0.1630	0.1630
A2S14	0.0932	0.1915	0.1895	0.1905	0.1935	0.1935	0.1945
A2S15	0.0683	0.1735	0.1710	0.1735	0.1765	0.1765	0.1770
A2S16	0.0573	0.1635	0.1615	0.1635	0.1670	0.1675	0.1680
A2S17	0.0784	0.1815	0.1790	0.1815	0.1835	0.1835	0.1845
A2S18	0.0855	0.1860	0.1840	0.1860	0.1880	0.1885	0.1885
A2S19	0.1538	0.2215	0.2180	0.2215	0.2235	0.2235	0.2240
A2S20	0.2009	0.2420	0.2400	0.2420	0.2440	0.2445	0.2445
A2S21	0.2510	0.2640	0.2600	0.2640	0.2645	0.2650	0.2650
A2S22	0.3013	0.2810	0.2765	0.2810	0.2815	0.2815	0.2820
A2S23	0.3513	0.2985	0.2935	0.2990	0.3000	0.3000	0.3005
A2S24	0.3961	0.3125	0.3065	0.3125	0.3135	0.3140	0.3135
A2S25	0.4507	0.3280	0.3215	0.3290	0.3285	0.3290	0.3290
A2S26	0.4810	0.3370	0.3295	0.3375	0.3385	0.3390	0.3390
A2S27	0.0544	0.1615	0.1620	0.1620	0.1655	0.1655	0.1660
A2S28	0.0735	0.1800	0.1795	0.1800	0.1810	0.1815	0.1815
A2S29	0.1052	0.1995	0.1995	0.2000	0.2005	0.2005	0.2015
A2S30	0.1273	0.2120	0.2100	0.2120	0.2125	0.2125	0.2130
A2S31	0.1504	0.2235	0.2210	0.2230	0.2235	0.2235	0.2240
A2S32	0.1735	0.2330	0.2305	0.2325	0.2335	0.2335	0.2335
A2S33	0.0852	0.1875	0.1870	0.1880	0.1885	0.1885	0.1895
A2S34	0.0904	0.1915	0.1905	0.1910	0.1920	0.1925	0.1925
A2S35	0.0961	0.1950	0.1940	0.1950	0.1955	0.1955	0.1960

MODULAR FLOW CONDITIONS - EXISTING DATA

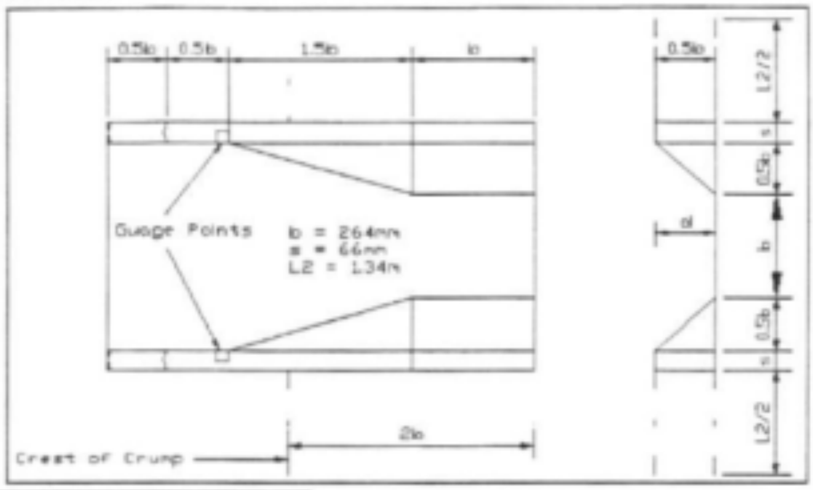
Data contained in WRC Report 442/3/98

Test A2C

Flume 2, (d/b = 0.5) with sharp-crested weirs.

Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.340
b_5 (m)	2.000
p (m)	0.025
s (m)	0.066



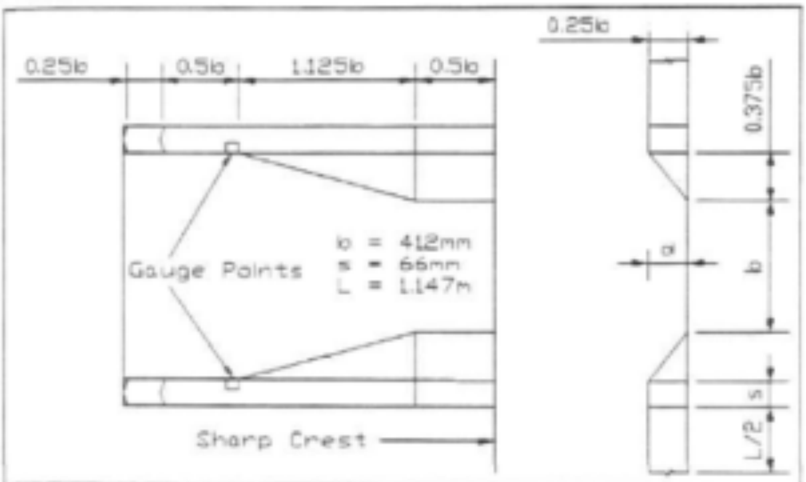
		Water levels relative to flume invert (m)					
Test Nr.	Q_{lab} (m^3/s)	2.1	2.2	2.3	4	5	6
A2C1	0.0063	0.0535	0.0540	0.0540	0.0580	0.0580	0.0580
A2C2	0.0154	0.0890	0.0890	0.0890	0.0995	0.0995	0.0995
A2C3	0.0243	0.1105	0.1135	0.1105	0.1280	0.1280	0.1280
A2C4	0.0503	0.1490	0.1485	0.1500	0.1620	0.1620	0.1615
A2C5	0.0753	0.1675	0.1665	0.1685	0.1800	0.1800	0.1800
A2C6	0.0960	0.1820	0.1795	0.1825	0.1935	0.1935	0.1935
A2C7	0.1496	0.2115	0.2055	0.2115	0.2215	0.2220	0.2220
A2C8	0.1977	0.2315	0.2240	0.2325	0.2435	0.2435	0.2430
A2C9	0.2510	0.2520	0.2435	0.2525	0.2645	0.2645	0.2645
A2C10	0.3013	0.2695	0.2700	0.2700	0.2835	0.2840	0.2840
A2C11	0.3469	0.2840	0.2735	0.2845	0.2995	0.2995	0.2995
A2C12	0.4025	0.3015	0.2885	0.3025	0.3175	0.3175	0.3175
A2C13	0.4536	0.3150	0.3015	0.3160	0.3320	0.3325	0.3325
A2C14	0.4877	0.3245	0.3100	0.3255	0.3425	0.3425	0.3420

MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test A3S

Flume 3, (d/b = 0.25) with sharp-crested weirs.



Flume dimensions:

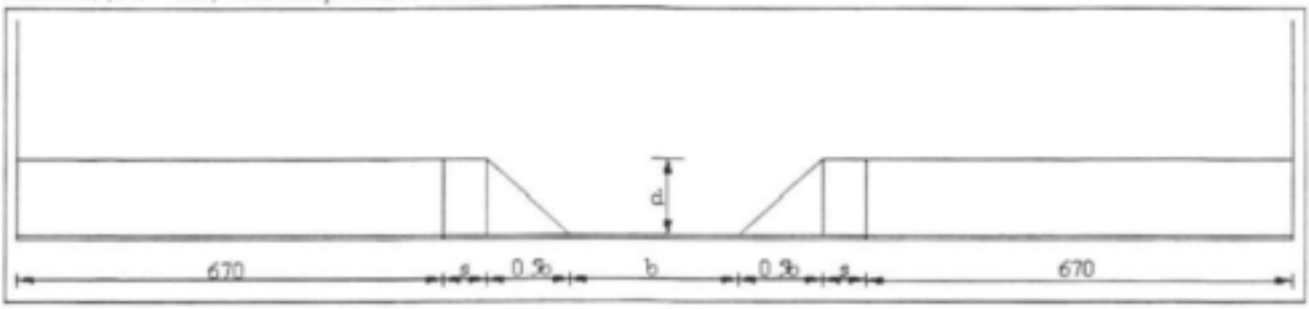
b (m)	0.412
d (m)	0.103
b_2 (m)	0.721
L (m)	1.147
b_5 (m)	2.000
p (m)	0.025
s (m)	0.066

		Water levels relative to flume invert (m)					
Test Nr.	Q_{lab} (m^3/s)	2.1	2.2	2.3	4	5	6
A3S1	0.0059	0.0355	0.0355	0.0355	0.0385	0.0385	0.0385
A3S1.1	0.0076	0.0450	0.0455	0.0455	0.0495	0.0495	0.0495
A3S2	0.0107	0.0525	0.0540	0.0530	0.0590	0.0590	0.0585
A3S2.1	0.0126	0.0590	0.0595	0.0590	0.0665	0.0665	0.0665
A3S3	0.0147	0.0640	0.0650	0.0640	0.0725	0.0725	0.0725
A3S3.1	0.0176	0.0705	0.0715	0.0705	0.0800	0.0800	0.0800
A3S4	0.0200	0.0750	0.0780	0.0755	0.0860	0.0865	0.0860
A3S5	0.0270	0.0890	0.0905	0.0885	0.1045	0.1045	0.1045
A3S6	0.0302	0.0910	0.0930	0.0905	0.1080	0.1080	0.1080
A3S7.1	0.0403	0.1060	0.1105	0.1055	0.1200	0.1200	0.1200
A3S8	0.0455	0.1170	0.1165	0.1170	0.1250	0.1250	0.1250
A3S10	0.0502	0.1235	0.1225	0.1230	0.1295	0.1295	0.1295
A3S11	0.0555	0.1280	0.1275	0.1275	0.1340	0.1340	0.1335
A3S11.1	0.0606	0.1325	0.1320	0.1325	0.1375	0.1375	0.1370
A3S12	0.0648	0.1370	0.1355	0.1365	0.1410	0.1410	0.1405
A3S13	0.0698	0.1415	0.1400	0.1415	0.1450	0.1450	0.1450
A3S14	0.0750	0.1450	0.1430	0.1445	0.1480	0.1480	0.1475
A3S14.1	0.0794	0.1485	0.1475	0.1480	0.1510	0.1510	0.1510
A3S15	0.0859	0.1525	0.1505	0.1525	0.1550	0.1550	0.1550
A3S16	0.0904	0.1565	0.1540	0.1560	0.1585	0.1585	0.1585
A3S17	0.0946	0.1580	0.1560	0.1580	0.1605	0.1610	0.1605
A3S18	0.1252	0.1750	0.1720	0.1750	0.1770	0.1770	0.1770
A3S19	0.1530	0.1875	0.1840	0.1875	0.1895	0.1900	0.1885
A3S20	0.1757	0.1970	0.1935	0.1970	0.1990	0.1990	0.1985
A3S21	0.2028	0.2070	0.2030	0.2075	0.2090	0.2090	0.2090
A3S22	0.2754	0.2355	0.2295	0.2350	0.2365	0.2370	0.2365
A3S23	0.3000	0.2445	0.2380	0.2450	0.2460	0.2460	0.2460
A3S24	0.2296	0.2195	0.2140	0.2195	0.2210	0.2210	0.2210
A3S25	0.3259	0.2525	0.2460	0.2530	0.2545	0.2545	0.2545
A3S26	0.3778	0.2695	0.2615	0.2695	0.2710	0.2710	0.2705
A3S27	0.4025	0.2765	0.2700	0.2780	0.2790	0.2790	0.2785
A3S28	0.4288	0.2835	0.2760	0.2845	0.2860	0.2860	0.2860
A3S29	0.4522	0.2910	0.2820	0.2905	0.2930	0.2930	0.2935
A3S30	0.2510	0.2275	0.2215	0.2275	0.2295	0.2295	0.2290
A3S31	0.3550	0.2620	0.2545	0.2625	0.2640	0.2640	0.2645

MODULAR FLOW CONDITIONS - NEW DATA

Test C2S

Flume 2, (d/b = 0.5) with sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_s (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

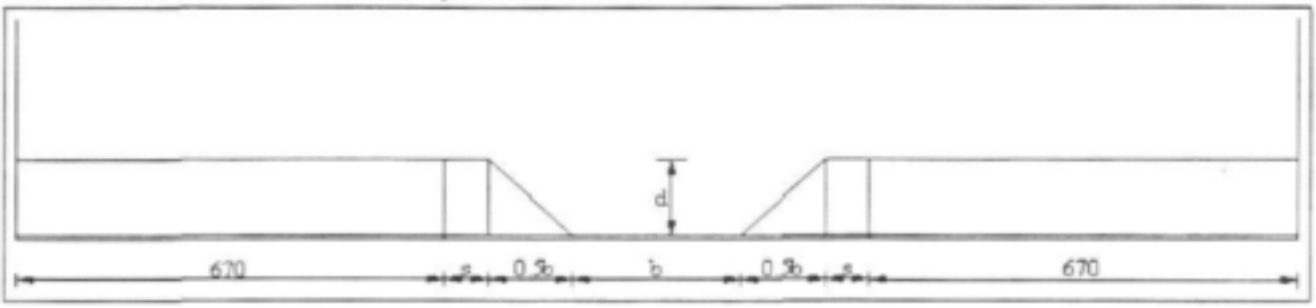
d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

		Water levels relative to flume invert (m)							
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6
C2S1	0.0108	0.0752	0.0777	0.0738	0.0729	0.0742	0.0785	0.0800	0.0813
C2S2	0.0224	0.1154	0.1179	0.1053	0.1063	0.1057	0.1186	0.1200	0.1213
C2S3	0.0352	0.1412	0.1437	0.1347	0.1336	0.1339	0.1443	0.1757	0.1471
C2S4	0.0459	0.1528	0.1551	0.1507	0.1488	0.1506	0.1559	0.1572	0.1586
C2S5	0.0579	0.1630	0.1656	0.1630	0.1611	0.1628	0.1661	0.1677	0.1689
C2S6	0.0685	0.1710	0.1734	0.1722	0.1699	0.1721	0.1742	0.1757	0.1771
C2S7	0.0820	0.1800	0.1826	0.1820	0.1797	0.1820	0.1833	0.1850	0.1861
C2S8	0.0986	0.1901	0.1928	0.1923	0.1899	0.1924	0.1935	0.1952	0.1963
C2S9	0.1123	0.1973	0.1998	0.1997	0.1970	0.1997	0.2011	0.2024	0.2037
C2S10	0.1255	0.2037	0.2060	0.2063	0.2035	0.2064	0.2065	0.2090	0.2103
C2S11	0.1342	0.2073	0.2102	0.2101	0.2071	0.2102	0.2111	0.2127	0.2136
C2S12	0.1441	0.2118	0.2143	0.2145	0.2115	0.2146	0.2157	0.2170	0.2180
C2S13	0.0154	0.0923	0.0947	0.0878	0.0875	0.0879	0.0956	0.0972	0.0983
C2S14	0.0202	0.1087	0.1112	0.1003	0.1010	0.1007	0.1120	0.1134	0.1147

MODULAR FLOW CONDITIONS - NEW DATA

Test C2C

Flume 2, (d/b = 0.5) with full width crump weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_s (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

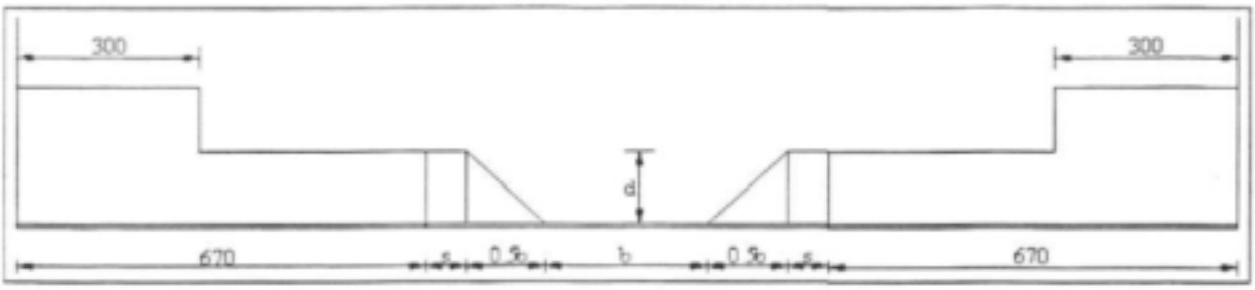
d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

		Water levels relative to flume invert (m)					
Test Nr.	Q_{lab} (m^3/s)	2.1	2.2	2.3	4	5	6
C2C1	0.0105	0.0715	0.0712	0.0719	0.0778	0.0790	0.0803
C2C2	0.0228	0.1072	0.1091	0.1077	0.1228	0.1241	0.1257
C2C3	0.0359	0.1270	0.1302	0.1284	0.1467	0.1479	0.1494
C2C4	0.0508	0.1483	0.1472	0.1491	0.1614	0.1626	0.1642
C2C5	0.0647	0.1595	0.1576	0.1605	0.1719	0.1730	0.1746
C2C6	0.0773	0.1675	0.1655	0.1683	0.1800	0.1814	0.1831
C2C7	0.0373	0.1291	0.1321	0.1323	0.1484	0.1493	0.1512
C2C8	0.0505	0.1476	0.1467	0.1488	0.1613	0.1620	0.1639
C2C9	0.0686	0.1620	0.1601	0.1627	0.1747	0.1755	0.1772
C2C10	0.0801	0.1691	0.1672	0.1702	0.1821	0.1827	0.1845
C2C11	0.0920	0.1768	0.1740	0.1779	0.1892	0.1903	0.1919
C2C12	0.1015	0.1834	0.1797	0.1845	0.1951	0.1964	0.1977
C2C13	0.1087	0.1877	0.1835	0.1889	0.1990	0.1996	0.2013
C2C14	0.1159	0.1918	0.1873	0.1929	0.2029	0.2040	0.2060
C2C15	0.1212	0.1950	0.1901	0.1959	0.2064	0.2070	0.2089
C2C16	0.1267	0.2000	0.1928	0.1987	0.2092	0.2100	0.2118
C2C17	0.1321	0.2002	0.1957	0.2020	0.2120	0.2133	0.2150
C2C18	0.1372	0.2033	0.1981	0.2044	0.2145	0.2158	0.2174

MODULAR FLOW CONDITIONS - NEW DATA

Test E2S

Flume 2, (d/b = 0.5) with 300 mm symmetrically end-contracted s/c weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_s (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

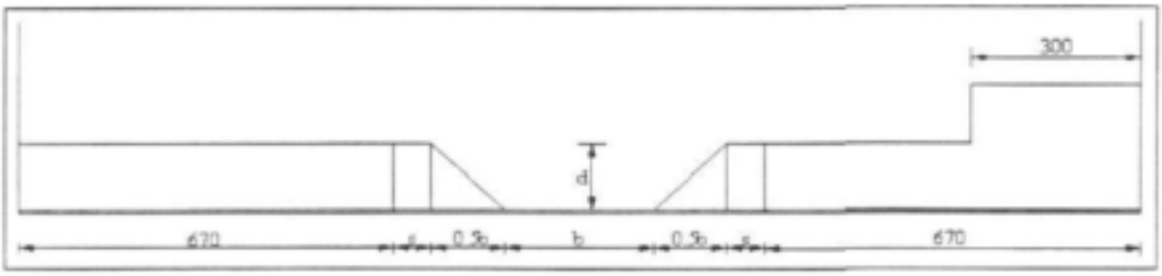
d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

		Water levels relative to flume invert (m)							
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6
E2S1	0.0483	0.1616	0.1639	0.1589	0.1593	0.1609	0.1645	0.1660	0.1675
E2S2	0.0595	0.1723	0.1757	0.1736	0.1723	0.1747	0.1755	0.1780	0.1793
E2S3	0.0713	0.1856	0.1880	0.1869	0.1854	0.1879	0.1888	0.1903	0.1917
E2S4	0.0826	0.1949	0.1975	0.1966	0.1950	0.1976	0.1981	0.1997	0.2013
E2S5	0.0961	0.2040	0.2069	0.2061	0.2043	0.2070	0.2075	0.2091	0.2104
E2S6	0.1066	0.2123	0.2146	0.2140	0.2121	0.2150	0.2157	0.2171	0.2187
E2S7	0.1190	0.2206	0.2229	0.2223	0.2203	0.2233	0.2239	0.2255	0.2267
E2S8	0.1273	0.2263	0.2285	0.2277	0.2256	0.2288	0.2296	0.2308	0.2324
E2S9	0.1363	0.2320	0.2345	0.2334	0.2311	0.2346	0.2355	0.2369	0.2382
E2S10	0.1423	0.2358	0.2382	0.2375	0.2351	0.2385	0.2394	0.2411	0.2422
E2S11	0.0414	0.1529	0.1553	0.1498	0.1487	0.1509	0.1559	0.1573	0.1589
E2S12	0.0539	0.1676	0.1697	0.1669	0.1658	0.1679	0.1705	0.1720	0.1734
E2S13	0.0650	0.1794	0.1817	0.1803	0.1790	0.1814	0.1824	0.1839	0.1855
E2S14	0.0765	0.1899	0.1922	0.1914	0.1901	0.1926	0.1933	0.1950	0.1962
E2S15	0.0887	0.1986	0.2009	0.2002	0.1987	0.2012	0.2017	0.2032	0.2048
E2S16	0.0981	0.2057	0.2081	0.2074	0.2057	0.2084	0.2091	0.2105	0.2117
E2S17	0.1056	0.2111	0.2134	0.2129	0.2110	0.2138	0.2145	0.2159	0.2175
E2S18	0.1118	0.2154	0.2177	0.2172	0.2153	0.2181	0.2187	0.2201	0.2219
E2S19	0.1164	0.2188	0.2215	0.2206	0.2186	0.2217	0.2224	0.2238	0.2257
E2S20	0.1235	0.2233	0.2259	0.2252	0.2231	0.2262	0.2268	0.2280	0.2298
E2S21	0.1265	0.2257	0.2281	0.2273	0.2250	0.2282	0.2289	0.2304	0.2319
E2S22	0.1301	0.2279	0.2308	0.2297	0.2275	0.2307	0.2315	0.2330	0.2348
E2S23	0.1345	0.2306	0.2330	0.2322	0.2299	0.2332	0.2339	0.2354	0.2369
E2S24	0.1374	0.2325	0.2347	0.2341	0.2318	0.2351	0.2361	0.2373	0.2387

MODULAR FLOW CONDITIONS - NEW DATA

Test G2S

Flume 2, (d/b = 0.5) with sharp-crested weirs. (LHS 300mm end-contracted)



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_s (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

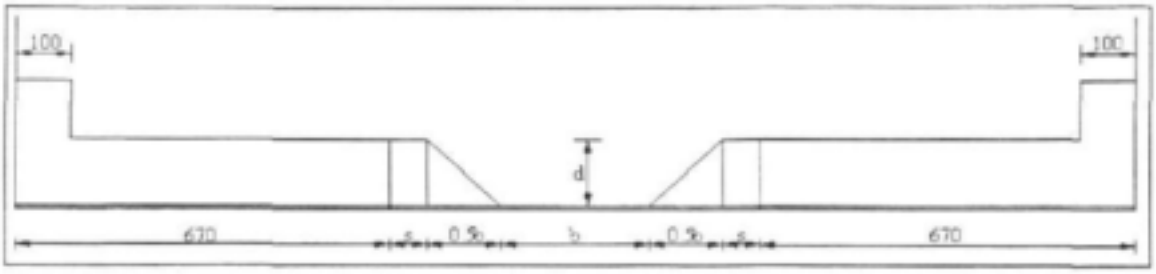
d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

		Water levels relative to flume invert (m)							
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6
G2S1	0.0459	0.1553	0.1577	0.1526	0.1519	0.1536	0.1583	0.1597	0.1611
G2S2	0.0608	0.1693	0.1717	0.1684	0.1680	0.1704	0.1725	0.1740	0.1754
G2S3	0.0726	0.1796	0.1818	0.1802	0.1790	0.1814	0.1826	0.1843	0.1856
G2S4	0.0853	0.1881	0.1902	0.1893	0.1881	0.1904	0.1913	0.1929	0.1940
G2S5	0.0975	0.1965	0.1982	0.1978	0.1964	0.1987	0.1998	0.2014	0.2025
G2S6	0.1079	0.2029	0.2045	0.2042	0.2027	0.2051	0.2064	0.2078	0.2089
G2S7	0.1139	0.2069	0.2083	0.2078	0.2062	0.2087	0.2101	0.2113	0.2126
G2S8	0.1217	0.2115	0.2124	0.2123	0.2106	0.2132	0.2141	0.2160	0.2168
G2S9	0.1268	0.2142	0.2155	0.2154	0.2136	0.2162	0.2172	0.2186	0.2202
G2S10	0.1308	0.2167	0.217	0.2170	0.2152	0.2179	0.2196	0.2205	0.2219

MODULAR FLOW CONDITIONS - NEW DATA

Test I2S

Flume 2, (d/b = 0.5) with 100 mm symmetrically end-contracted sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_t (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

		Water levels relative to flume invert (m)							
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6
I2S1	0.0402	0.1486	0.151	0.1429	0.1429	0.1447	0.1516	0.1529	0.1545
I2S2	0.0553	0.1633	0.1659	0.1621	0.1612	0.1631	0.1663	0.1678	0.1694
I2S3	0.0688	0.1744	0.1771	0.1751	0.1736	0.1759	0.1777	0.1791	0.1805
I2S4	0.0811	0.1832	0.1858	0.1846	0.1831	0.1853	0.1867	0.1880	0.1893
I2S5	0.0943	0.1921	0.1947	0.1936	0.1920	0.1944	0.1954	0.1968	0.1982
I2S6	0.1047	0.1983	0.2012	0.2002	0.1985	0.2008	0.2017	0.2033	0.2045
I2S7	0.1134	0.2032	0.2060	0.2050	0.2032	0.2056	0.2069	0.2081	0.2097
I2S8	0.1214	0.2079	0.2102	0.2094	0.2074	0.2100	0.2113	0.2125	0.2139
I2S9	0.1246	0.2096	0.2123	0.2114	0.2094	0.2120	0.2129	0.2145	0.2156
I2S10	0.1294	0.2121	0.2147	0.2137	0.2117	0.2143	0.2156	0.2169	0.2187
I2S11	0.1327	0.2139	0.2164	0.2155	0.2134	0.2161	0.2174	0.2184	0.2202
I2S12	0.1432	0.2189	0.2217	0.2211	0.2189	0.2216	0.2229	0.2243	0.2258

APPENDIX C

DATA FROM NON-MODULAR FLOW TESTS

NON-MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test B1S

Flume 1, (d/b = 1.0) with sharp-crested weirs.

Flume dimensions:

b (m)	0.174
d (m)	0.174
b_2 (m)	0.348
L (m)	1.520
b_5 (m)	2.000
p (m)	0.027
s (m)	0.066

		Water levels relative to flume invert (m)									
Test Nr.	Q_{lab} (m^3/s)	h_o	2.1	2.2	2.3	4	5	6	7	8	9
B1S4.11	0.010	0.0925	0.0935	0.0920	0.0930	0.1005	0.1005	0.1005	0.0505	0.0670	0.0595
B1S4.12	0.010	0.0925	0.0950	0.0935	0.0940	0.1015	0.1015	0.1015	0.0675	0.0725	0.0750
B1S4.13	0.010	0.0925	0.1035	0.1025	0.1030	0.1090	0.1095	0.1095	0.0870	0.0925	0.0950
B1S4.14	0.010	0.0925	0.1205	0.1200	0.1205	0.1255	0.1255	0.1255	0.1095	0.1145	0.1160
B1S4.15	*0.010*	*0.0925*	*0.1420*	*0.1420*	*0.1420*	*0.1455*	*0.1460*	*0.1455*	*0.1340*	*0.1390*	*0.1405*
B1S4.16	0.010	0.0925	0.1730	0.1735	0.1730	0.1760	0.1760	0.1760	0.1715	0.1720	0.1725
B1S6.11	0.015	0.1120	0.1140	0.1115	0.1135	0.1245	0.1250	0.1245	0.0570	0.0595	0.0640
B1S6.12	0.015	0.1120	0.1155	0.1130	0.1150	0.1255	0.1255	0.1255	0.0770	0.0795	0.0820
B1S6.13	0.015	0.1120	0.1185	0.1170	0.1185	0.1290	0.1290	0.1290	0.0985	0.1010	0.1035
B1S6.14	0.015	0.1120	0.1275	0.1260	0.1270	0.1365	0.1365	0.1365	0.1135	0.1160	0.1185
B1S6.15	0.015	0.1120	0.1445	0.1430	0.1440	0.1515	0.1515	0.1515	0.1350	0.1375	0.1400
B1S6.16	0.015	0.1120	0.1680	0.1680	0.1680	0.1740	0.1740	0.1740	0.1615	0.1640	0.1665
B1S8.11	0.020	0.1300	0.1310	0.1280	0.1300	0.1455	0.1460	0.1455	0.0420	0.0445	0.0470
B1S8.12	0.020	0.1300	0.1315	0.1290	0.1310	0.1465	0.1465	0.1465	0.0600	0.0625	0.0650
B1S8.13	0.020	0.1300	0.1320	0.1300	0.1320	0.1470	0.1475	0.1470	0.0760	0.0785	0.0810
B1S8.14	0.020	0.1300	0.1360	0.1335	0.1350	0.1495	0.1500	0.1495	0.0960	0.0985	0.1010
B1S8.15	0.020	0.1300	0.1450	0.1430	0.1445	0.1575	0.1575	0.1575	0.1275	0.1300	0.1325
B1S8.16	0.020	0.1300	0.1650	0.1655	0.1660	0.1770	0.1770	0.1770	0.1560	0.1585	0.1610
B1S13.11	0.040	0.1765	0.1785	0.1775	0.1785	0.1935	0.1940	0.1935	0.0845	0.0925	0.1020
B1S13.12	0.040	0.1765	0.1805	0.1800	0.1805	0.1945	0.1950	0.1945	0.1130	0.1200	0.1270
B1S13.13	0.040	0.1765	0.1870	0.1860	0.1865	0.1965	0.1970	0.1970	0.1490	0.1535	0.1560
B1S13.14	0.040	0.1765	0.2045	0.2040	0.2040	0.2080	0.2080	0.2080	0.1860	0.1915	0.1920
B1S13.15	0.040	0.1765	0.2310	0.2305	0.2310	0.2320	0.2320	0.2320	0.2225	0.2245	0.2240
B1S13.16	0.040	0.1765	0.2705	0.2700	0.2700	0.2705	0.2705	0.2705	0.2630	0.2675	0.2680
B1S17.11	0.060	0.2003	0.2025	0.2025	0.2020	0.2120	0.2125	0.2120	0.1120	0.1200	0.1220
B1S17.12	0.060	0.2003	0.2045	0.2045	0.2040	0.2130	0.2135	0.2135	0.1445	0.1510	0.1520
B1S17.13	0.060	0.2003	0.2120	0.2115	0.2115	0.2175	0.2180	0.2175	0.1790	0.1840	0.1860
B1S17.14	0.060	0.2003	0.2315	0.2305	0.2305	0.2330	0.2330	0.2330	0.2115	0.2155	0.2170
B1S17.15	0.060	0.2003	0.2610	0.2610	0.2610	0.2625	0.2625	0.2625	0.2510	0.2550	0.2590
B1S17.16	0.060	0.2003	0.2920	0.2920	0.2920	0.2925	0.2930	0.2925	0.2855	0.2885	0.2900
B1S21.11	0.080	0.2190	0.2195	0.2195	0.2200	0.2270	0.2270	0.2270	0.1105	0.1170	0.1185
B1S21.12	0.080	0.2190	0.2215	0.2205	0.2210	0.2275	0.2275	0.2275	0.1420	0.1490	0.1500
B1S21.13	0.080	0.2190	0.2270	0.2255	0.2265	0.2310	0.2315	0.2410	0.1800	0.1870	0.1880
B1S21.14	0.080	0.2190	0.2470	0.2465	0.2470	0.2490	0.2490	0.2490	0.2215	0.2285	0.2275
B1S21.15	0.080	0.2190	0.2820	0.2815	0.2815	0.2825	0.2830	0.2825	0.2690	0.2745	0.2735
B1S21.16	0.080	0.2190	0.3330	0.3325	0.3330	0.3330	0.3335	0.3330	0.3265	0.3295	0.3295
B1S25.11	0.101	0.2345	0.2360	0.2350	0.2355	0.2410	0.2415	0.2410	0.1260	0.1340	0.1315
B1S25.12	0.101	0.2345	0.2365	0.2355	0.2360	0.2415	0.2415	0.2415	0.1520	0.1610	0.1625

NON-MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test B1S - continued

Flume 1, (d/b = 1.0) with sharp-crested weirs.

		Water levels relative to flume invert (m)									
Test Nr.	Q_{lab} (m^3/s)	h_o	2.1	2.2	2.3	4	5	6	7	8	9
B1S25.13	0.101	0.2345	0.2425	0.2410	0.2420	0.2460	0.2465	0.2460	0.1910	0.1970	0.1965
B1S25.14	0.101	0.2345	0.2615	0.2605	0.2610	0.2635	0.2635	0.2635	0.2310	0.2395	0.2385
B1S25.15	0.101	0.2345	0.2950	0.2945	0.2950	0.2960	0.2965	0.2960	0.2850	0.2860	0.2880
B1S25.16	0.101	0.2345	0.3455	0.3450	0.3450	0.3460	0.3460	0.3455	0.3375	0.3410	0.3410
B1S27.11	0.149	0.2605	0.2605	0.2590	0.2605	0.2660	0.2665	0.2660	0.1620	0.1635	0.1650
B1S27.12	0.149	0.2605	0.2640	0.2625	0.2640	0.2685	0.2690	0.2685	0.1920	0.1945	0.1910
B1S27.13	0.149	0.2605	0.2735	0.2720	0.2735	0.2761	0.2775	0.2770	0.2330	0.2285	0.2240
B1S27.14	0.149	0.2605	0.2965	0.2960	0.2965	0.2995	0.2995	0.2995	0.2780	0.2745	0.2710
B1S27.15	0.149	0.2605	0.3320	0.3310	0.3320	0.3330	0.3335	0.3330	0.3235	0.3210	0.3185
B1S27.16	0.149	0.2605	0.3655	0.3660	0.3660	0.3660	0.3670	0.3670	0.3585	0.3570	0.3560
B1S29.11	0.201	0.2838	0.2850	0.2820	0.2850	0.2900	0.2905	0.2900	0.1750	0.1800	0.1870
B1S29.12	0.201	0.2838	0.2880	0.2855	0.2880	0.2930	0.2930	0.2930	0.2075	0.2100	0.2095
B1S29.13	0.201	0.2838	0.2990	0.2970	0.2995	0.3035	0.3035	0.3035	0.2505	0.2470	0.2440
B1S29.14	0.201	0.2838	0.3185	0.3170	0.3190	0.3215	0.3220	0.3215	0.2945	0.2890	0.2835
B1S29.15	0.201	0.2838	0.3690	0.3680	0.3690	0.3705	0.3710	0.3705	0.3580	0.3565	0.3550
B1S31.11	0.248	0.3030	0.3045	0.3020	0.3050	0.3105	0.3105	0.3100	0.2025	0.2120	0.2055
B1S31.12	0.248	0.3030	0.3100	0.3070	0.3100	0.3150	0.3150	0.3150	0.2320	0.2380	0.2325
B1S31.13	0.248	0.3030	0.3210	0.3190	0.3205	0.3260	0.3260	0.3260	0.2750	0.2675	0.2695
B1S31.14	0.248	0.3030	0.3375	0.3355	0.3375	0.3410	0.3415	0.3410	0.3020	0.2995	0.2970
B1S31.15	0.248	0.3030	0.3670	0.3660	0.3670	0.3695	0.3695	0.3695	0.3450	0.3450	0.3450
B1S33.11	0.303	0.3215	0.3230	0.3185	0.3235	0.3300	0.3300	0.3300	0.1865	0.1985	0.1890
B1S33.12	0.303	0.3215	0.3260	0.3190	0.3260	0.3320	0.3320	0.3320	0.2270	0.2320	0.2240
B1S33.13	0.303	0.3215	0.3350	0.3220	0.3345	0.3410	0.3415	0.3410	0.2590	0.2685	0.2640
B1S33.14	0.303	0.3215	0.3505	0.3490	0.3500	0.3565	0.3565	0.3665	0.2885	0.2970	0.2965
B1S33.15	0.303	0.3215	0.3675	0.3660	0.3670	0.3710	0.3710	0.3710	0.3270	0.3285	0.3260

NON-MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test B2S

Flume 2, (d/b = 0.5) with sharp-crested weirs.

Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.340
b_5 (m)	2.000
p (m)	0.025
s (m)	0.066

		Water levels relative to flume invert (m)									
Test Nr.	Q_{lab} (m^3/s)	h_o	2.1	2.2	2.3	4	5	6	7	8	9
B2S19.1	0.151	0.2215	0.2230	0.2200	0.2230	0.2245	0.2250	0.2250	0.1445	0.1450	0.1435
B2S19.2	0.151	0.2215	0.2270	0.2240	0.2270	0.2285	0.2290	0.2290	0.1690	0.1685	0.1695
B2S19.3	0.151	0.2215	0.2400	0.2375	0.2400	0.2415	0.2415	0.2420	0.2075	0.2065	0.2070
B2S19.4	0.151	0.2215	0.2580	0.2575	0.2575	0.2590	0.2590	0.2595	0.2395	0.2395	0.2385
B2S21.1	0.247	0.2640	0.2680	0.2645	0.2685	0.2685	0.2685	0.2685	0.1815	0.1770	0.1750
B2S21.2	0.247	0.2640	0.2800	0.2790	0.2810	0.2805	0.2805	0.2810	0.2300	0.2190	0.2170
B2S21.3	0.247	0.2640	0.2960	0.2945	0.2965	0.2955	0.2960	0.2970	0.2645	0.2585	0.2545
B2S23.1	0.350	0.2988	0.3030	0.2980	0.3030	0.3035	0.3035	0.3040	0.1955	0.1975	0.1885
B2S23.2	0.350	0.2988	0.3240	0.3195	0.3245	0.3240	0.3240	0.3245	0.2720	0.2645	0.2650
B2S23.3	0.350	0.2988	0.3515	0.3485	0.3520	0.3515	0.3515	0.3520	0.3235	0.3150	0.3215
B2S25.1	0.451	0.3285	0.3330	0.3255	0.3335	0.3335	0.3340	0.3345	0.2100	0.2080	0.2270
B2S25.2	0.451	0.3285	0.3465	0.3415	0.3470	0.3475	0.3475	0.3485	0.2755	0.2675	0.2865
B2S25.3	0.451	0.3285	0.3625	0.3575	0.3620	0.3625	0.3630	0.3630	0.3075	0.3025	0.3110

NON-MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test B2C

Flume 2, (d/b = 0.5) with sharp-crested weirs.

Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.340
b_5 (m)	2.000
p (m)	0.025
s (m)	0.066

		Water levels relative to flume invert (m)									
Test Nr.	Q_{lab} (m^3/s)	h_o	2.1	2.2	2.3	4	5	6	7	8	9
B2C4.11	0.050	0.1495	0.1500	0.1495	0.1505	0.1625	0.1625	0.1625	0.0880	0.0885	0.0885
B2C4.12	0.050	0.1495	0.1510	0.1510	0.1520	0.1630	0.1630	0.1630	0.1085	0.1090	0.1105
B2C4.13	0.050	0.1495	0.1535	0.1530	0.1540	0.1650	0.1650	0.1640	0.1295	0.1295	0.1310
B2C4.14	0.050	0.1495	0.1605	0.1610	0.1615	0.1680	0.1680	0.1680	0.1515	0.1515	0.1515
B2C4.15	0.050	0.1495	0.1730	0.1730	0.1735	0.1770	0.1775	0.1775	0.1700	0.1700	0.1700
B2C4.16	0.050	0.1495	0.1890	0.1885	0.1890	0.1905	0.1905	0.1906	0.1865	0.1865	0.1865
B2C7.11	0.150	0.2115	0.2115	0.2060	0.2120	0.2225	0.2225	0.2225	0.1490	0.1520	0.1500
B2C7.12	0.150	0.2115	0.2125	0.2070	0.2125	0.2225	0.2225	0.2225	0.1665	0.1685	0.1675
B2C7.13	0.150	0.2115	0.2135	0.2085	0.2135	0.2235	0.2235	0.2235	0.1885	0.1920	0.1895
B2C7.14	0.150	0.2115	0.2195	0.2155	0.2200	0.2275	0.2280	0.2280	0.2095	0.2105	0.2085
B2C7.15	0.150	0.2115	0.2305	0.2275	0.2315	0.2360	0.2360	0.2360	0.2295	0.2295	0.2295
B2C7.16	0.150	0.2115	0.2465	0.2445	0.2470	0.2505	0.2505	0.2500	0.2455	0.2455	0.2455
B2C9.11	0.251	0.2523	0.2525	0.2440	0.2535	0.2645	0.2650	0.2645	0.1980	0.2030	0.2000
B2C9.12	0.251	0.2523	0.2535	0.2455	0.2540	0.2655	0.2655	0.2655	0.2200	0.2250	0.2220
B2C9.13	0.251	0.2523	0.2590	0.2515	0.2585	0.2690	0.2690	0.2690	0.2485	0.2495	0.2485
B2C9.14	0.251	0.2523	0.2705	0.2645	0.2705	0.2890	0.2890	0.2890	0.2695	0.2710	0.2695
B2C9.15	0.251	0.2523	0.2900	0.2855	0.2900	0.2955	0.2955	0.2955	0.2885	0.2885	0.2885
B2C11.11	0.347	0.2843	0.2845	0.2736	0.2855	0.2995	0.2995	0.2995	0.2175	0.2240	0.2180
B2C11.12	0.347	0.2843	0.2850	0.2745	0.2870	0.3005	0.3005	0.3005	0.2395	0.2455	0.2430
B2C11.13	0.347	0.2843	0.2890	0.2785	0.2895	0.3025	0.3030	0.3025	0.2680	0.2725	0.2690
B2C11.14	0.347	0.2843	0.2985	0.2900	0.2990	0.3110	0.3110	0.3110	0.2960	0.2975	0.2950
B2C11.15	0.347	0.2843	0.3185	0.3125	0.3190	0.3275	0.3275	0.3275	0.3205	0.3195	0.3185
B2C11.16	0.347	0.2843	0.3355	0.3295	0.3370	0.3425	0.3430	0.3425	0.3385	0.3375	0.3385
B2C13.11	0.454	0.3155	0.3180	0.3050	0.3200	0.3345	0.3350	0.3345	0.2775	0.2795	0.2825
B2C13.12	0.454	0.3155	0.3240	0.3115	0.3245	0.3380	0.3380	0.3380	0.3065	0.3085	0.3095
B2C13.13	0.454	0.3155	0.3425	0.3335	0.3430	0.3535	0.3535	0.3535	0.3455	0.3455	0.3455
B2C13.14	0.454	0.3155	0.3590	0.3515	0.3595	0.3690	0.3695	0.3690	0.3645	0.3675	0.3730

NON-MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test B3S

Flume 3, (d/b = 0.25) with sharp-crested weirs.

Flume dimensions:

b (m)	0.412
d (m)	0.103
b_2 (m)	0.721
L (m)	1.147
b_5 (m)	2.000
p (m)	0.025
s (m)	0.066

		Water levels relative to flume invert (m)									
Test Nr.	Q_{lab} (m^3/s)	h_o	2.1	2.2	2.3	4	5	6	7	8	9
B3S2.11	0.011	0.053	0.0530	0.0540	0.0535	0.0595	0.0595	0.0590	0.0380	0.0400	0.0430
B3S2.12	0.011	0.053	0.0545	0.0560	0.0545	0.0610	0.0610	0.0610	0.0495	0.0460	0.0485
B3S2.13	0.011	0.053	0.0605	0.0610	0.0610	0.0650	0.0650	0.0650	0.0570	0.0555	0.0565
B3S2.14	0.011	0.053	0.0660	0.0675	0.0665	0.0705	0.0705	0.0705	0.0655	0.0635	0.0645
B3S2.15	0.011	0.053	0.0725	0.0740	0.0730	0.0765	0.0765	0.0765	0.0755	0.0750	0.0720
B3S4.11	0.020	0.075	0.0755	0.0770	0.0765	0.0870	0.0870	0.0865	0.0465	0.0455	0.0455
B3S4.12	0.020	0.075	0.0765	0.0775	0.0770	0.0875	0.0875	0.0875	0.0605	0.0615	0.0595
B3S4.13	0.020	0.075	0.0795	0.0815	0.0800	0.0900	0.0900	0.0900	0.0730	0.0745	0.0720
B3S4.14	0.020	0.075	0.0875	0.0900	0.0885	0.0965	0.0965	0.0965	0.0855	0.0865	0.0840
B3S4.15	0.020	0.075	0.0975	0.1000	0.0985	0.1050	0.1055	0.1050	0.0975	0.0985	0.0960
B3S6.11	0.030	0.091	0.0925	0.0950	0.0920	0.1085	0.1085	0.1085	0.0520	0.0560	0.0550
B3S6.12	0.030	0.091	0.0925	0.0960	0.0915	0.1090	0.1090	0.1090	0.0650	0.0695	0.0690
B3S6.13	0.030	0.091	0.0945	0.0985	0.0950	0.1100	0.1100	0.1100	0.0800	0.0835	0.0815
B3S6.14	0.030	0.091	0.1100	0.1110	0.1105	0.1155	0.1160	0.1155	0.0995	0.1005	0.1005
B3S6.15	0.030	0.091	0.1205	0.1210	0.1175	0.1230	0.1230	0.1225	0.1140	0.1140	0.1140
B3S6.16	0.030	0.091	0.1405	0.1405	0.1405	0.1405	0.1405	0.1405	0.1355	0.1365	0.1365
B3S10.11	0.050	0.123	0.1240	0.1235	0.1235	0.1300	0.1300	0.1300	0.0565	0.0590	0.0575
B3S10.12	0.050	0.123	0.1250	0.1245	0.1240	0.1300	0.1305	0.1300	0.0795	0.0825	0.0805
B3S10.13	0.050	0.123	0.1300	0.1305	0.1295	0.1335	0.1340	0.1335	0.1055	0.1075	0.1065
B3S10.14	0.050	0.123	0.1450	0.1445	0.1445	0.1460	0.1460	0.1460	0.1300	0.1330	0.1330
B3S10.15	0.050	0.123	0.1675	0.1670	0.1675	0.1675	0.1680	0.1675	0.1615	0.1615	0.1620
B3S13.11	0.070	0.142	0.1425	0.1410	0.1420	0.1455	0.1455	0.1455	0.0765	0.0755	0.0755
B3S13.12	0.070	0.142	0.1445	0.1430	0.1440	0.1465	0.1470	0.1465	0.1015	0.1040	0.1020
B3S13.13	0.070	0.142	0.1510	0.1495	0.1505	0.1520	0.1525	0.1520	0.1220	0.1255	0.1250
B3S13.14	0.070	0.142	0.1630	0.1625	0.1630	0.1640	0.1640	0.1640	0.1470	0.1485	0.1480
B3S13.15	0.070	0.142	0.1815	0.1810	0.1815	0.1820	0.1820	0.1820	0.1730	0.1750	0.1755
B3S13.16	0.070	0.142	0.2030	0.2030	0.2030	0.2025	0.2030	0.2025	0.1975	0.1985	0.1990
B3S16.11	0.090	0.156	0.1570	0.1550	0.1570	0.1590	0.1590	0.1590	0.0940	0.0995	0.0985
B3S16.12	0.090	0.156	0.1615	0.1600	0.1615	0.1630	0.1635	0.1630	0.1215	0.1240	0.1235
B3S16.13	0.090	0.156	0.1685	0.1675	0.1690	0.1700	0.1705	0.1705	0.1415	0.1450	0.1440
B3S16.14	0.090	0.156	0.1845	0.1835	0.1845	0.1855	0.1860	0.1855	0.1690	0.1720	0.1720
B3S16.15	0.090	0.156	0.2040	0.2035	0.2040	0.2045	0.2045	0.2045	0.1945	0.1970	0.1970
B3S16.16	0.090	0.156	0.2185	0.2180	0.2185	0.2190	0.2190	0.2190	0.2140	0.2140	0.2140
B3S19.11	0.153	0.188	0.1885	0.1860	0.1885	0.1905	0.1905	0.1905	0.1100	0.1155	0.1140
B3S19.12	0.153	0.188	0.1920	0.1890	0.1920	0.1935	0.1935	0.1935	0.1310	0.1370	0.1350
B3S19.13	0.153	0.188	0.1960	0.1935	0.1960	0.1975	0.1980	0.1975	0.1540	0.1575	0.1555
B3S19.14	0.153	0.188	0.2050	0.2030	0.2055	0.2070	0.2070	0.2065	0.1770	0.1770	0.1770
B3S19.15	0.153	0.188	0.2225	0.2210	0.2225	0.2230	0.2235	0.2230	0.2060	0.2060	0.2060

NON-MODULAR FLOW CONDITIONS - EXISTING DATA

Data contained in WRC Report 442/3/98

Test B3S - continued

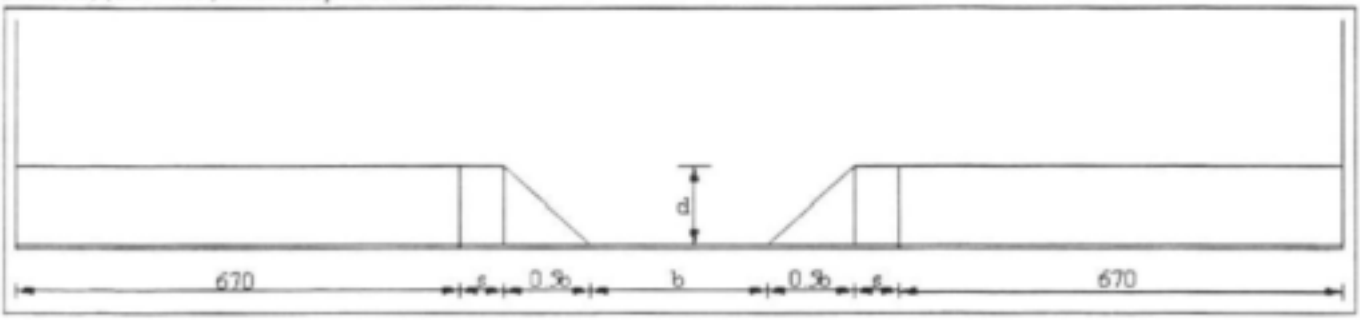
Flume 3, (d/b = 0.25) with sharp-crested weirs.

		Water levels relative to flume invert (m)									
Test Nr.	Q_{lab} (m^3/s)	h_c	2.1	2.2	2.3	4	5	6	7	8	9
B3S19.16	0.153	0.188	0.2460	0.2455	0.2465	0.2470	0.2470	0.2470	0.2385	0.2385	0.2385
B3S29.11	0.452	0.291	0.2925	0.2840	0.2925	0.2940	0.2940	0.2940	0.1635	0.1840	0.1640
B3S29.12	0.452	0.291	0.2985	0.2890	0.2980	0.3000	0.3005	0.3000	0.2010	0.2135	0.2070
B3S29.13	0.452	0.291	0.3060	0.2995	0.3075	0.3085	0.3090	0.3090	0.2425	0.2485	0.2440
B3S29.14	0.452	0.291	0.3265	0.3200	0.3270	0.3285	0.3280	0.3275	0.2695	0.2880	0.2795
B3S29.15	0.452	0.291	0.3450	0.3395	0.3455	0.3470	0.3470	0.3470	0.3060	0.3190	0.3110
B3S29.16	0.452	0.291	0.3675	0.3635	0.3685	0.3680	0.3680	0.3680	0.3460	0.3485	0.3425
B3S30.11	0.251	0.228	0.2290	0.2240	0.2290	0.2305	0.2310	0.2305	0.1380	0.1425	0.1400
B3S30.12	0.251	0.228	0.2345	0.2295	0.2345	0.2355	0.2360	0.2355	0.1710	0.1755	0.1705
B3S30.13	0.251	0.228	0.2475	0.2440	0.2475	0.2485	0.2490	0.2485	0.1990	0.2115	0.2065
B3S30.14	0.251	0.228	0.2680	0.2650	0.2680	0.2680	0.2685	0.2685	0.2365	0.2460	0.2440
B3S30.15	0.251	0.228	0.2965	0.2945	0.2975	0.2970	0.2970	0.2965	0.2800	0.2860	0.2820
B3S30.16	0.251	0.228	0.3305	0.3295	0.3305	0.3310	0.3315	0.3310	0.3210	0.3255	0.3240
B3S31.11	0.355	0.262	0.2645	0.2575	0.2650	0.2650	0.2665	0.2665	0.1610	0.1725	0.1640
B3S31.12	0.355	0.262	0.2700	0.2635	0.2710	0.2720	0.2725	0.2725	0.1945	0.2020	0.1970
B3S31.13	0.355	0.262	0.2815	0.2755	0.2820	0.2835	0.2840	0.2835	0.2185	0.2355	0.2280
B3S31.14	0.355	0.262	0.3005	0.2955	0.3015	0.3020	0.3025	0.3015	0.2570	0.2695	0.2635
B3S31.15	0.355	0.262	0.3205	0.3165	0.3205	0.3215	0.3215	0.3215	0.2970	0.2975	0.2980
B3S31.16	0.355	0.262	0.3465	0.3435	0.3470	0.3470	0.3470	0.3470	0.3270	0.3330	0.3290
B3S31.17	0.355	0.262	0.3710	0.3695	0.3715	0.3720	0.3720	0.3720	0.3610	0.3615	0.3620

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test D2S

Flume 2, (d/b = 0.5) with sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_3 (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

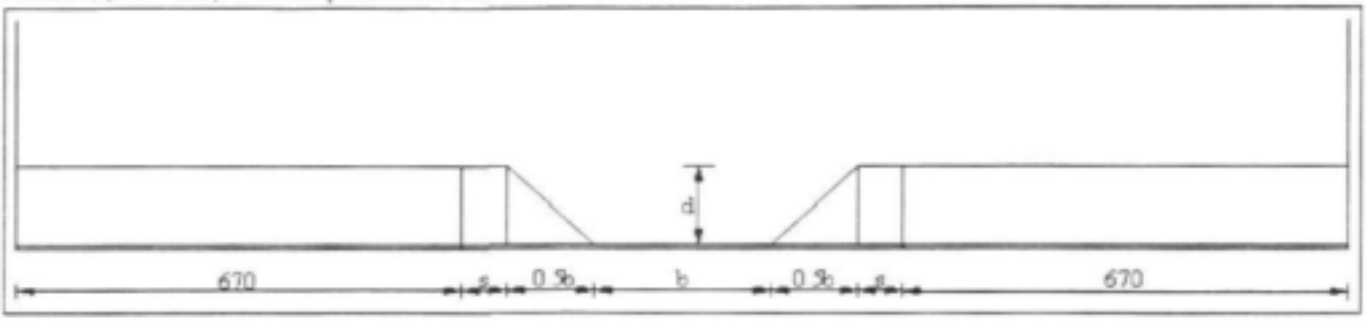
Z (m)	0.371

		Water levels relative to flume invert (m)										
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6	7	8	9
D2S1	0.0995	0.1901	0.1927	0.1927	0.1900	0.1928	0.1935	0.1949	0.1963	---------	---------	---------
D2S1.1	0.0995	0.1925	0.1954	0.1959	0.1936	0.1961	0.1962	0.1981	0.1993	0.1378	---------	0.1398
D2S1.2	0.0995	0.1953	0.1978	0.1986	0.1963	0.1987	0.1987	0.2002	0.2015	0.1518	---------	0.1503
D2S1.3	0.0995	0.1983	0.2012	0.2020	0.1998	0.2020	0.2020	0.2034	0.2046	0.1620	---------	0.1612
D2S1.4	0.0995	0.2040	0.2066	0.2080	0.2061	0.2081	0.2076	0.2092	0.2104	0.1774	---------	0.1763
D2S1.5	0.0995	0.2100	0.2132	0.2145	0.2126	0.2145	0.2139	0.2153	0.2166	0.1899	---------	0.1896
D2S1.6	0.0995	0.2167	0.2193	0.2208	0.2191	0.2209	0.2203	0.2218	0.2229	0.2017	---------	0.2008
D2S1.7	0.0995	0.2237	0.2262	0.2281	0.2264	0.2281	0.2272	0.2288	0.2301	0.2124	---------	0.2116
D2S1.8	0.0995	0.2328	0.2354	0.2373	0.2358	0.2373	0.2365	0.2380	0.2391	0.2249	---------	0.2245
D2S1.9	0.0995	0.2423	0.2448	0.2469	0.2456	0.2470	0.2459	0.2476	0.2488	0.2375	---------	0.2368
D2S2	0.0233	0.1174	0.1201	0.1072	0.1084	0.1076	0.1208	0.1222	0.1235	---------	---------	---------
D2S2.1	0.0233	0.1178	0.1203	0.1076	0.1079	0.1081	0.1211	0.1224	0.1237	0.0344	---------	0.0352
D2S2.2	0.0233	0.1179	0.1205	0.1077	0.1091	0.1083	0.1212	0.1226	0.1240	0.0480	---------	0.0473
D2S2.3	0.0233	0.1181	0.1206	0.1081	0.1095	0.1087	0.1214	0.1228	0.1242	0.0646	---------	0.0630
D2S2.4	0.0233	0.1185	0.1211	0.1087	0.1100	0.1093	0.1218	0.1232	0.1246	0.0794	---------	0.0780
D2S2.5	0.0233	0.1191	0.1217	0.1097	0.1109	0.1100	0.1224	0.1239	0.1251	0.0906	---------	0.0897
D2S2.6	0.0233	0.1211	0.1236	0.1130	0.1133	0.1123	0.1245	0.1259	0.1271	0.1021	---------	0.1009
D2S2.7	0.0233	0.1266	0.1291	0.1188	0.1200	0.1193	0.1299	0.1313	0.1326	0.1127	---------	0.1118
D2S3	0.0195	0.1057	0.1083	0.0981	0.0988	0.0986	0.1090	0.1105	0.1118	---------	---------	---------
D2S3.1	0.0195	0.1059	0.1085	0.0984	0.0990	0.0986	0.1091	0.1106	0.1120	0.0253	---------	0.0232
D2S3.2	0.0195	0.1061	0.1085	0.0985	0.0992	0.0989	0.1094	0.1107	0.1121	0.0473	---------	0.0449
D2S3.3	0.0195	0.1063	0.1087	0.0990	0.0997	0.0994	0.1095	0.1109	0.1123	0.0635	---------	0.0628
D2S3.4	0.0195	0.1065	0.1092	0.0993	0.1000	0.0996	0.1098	0.1113	0.1126	0.0745	---------	0.0735
D2S3.5	0.0195	0.1072	0.1097	0.1001	0.1008	0.1004	0.1105	0.1118	0.1133	0.0839	---------	0.0827
D2S3.6	0.0195	0.1080	0.1106	0.1011	0.1019	0.1015	0.1113	0.1128	0.1141	0.0896	---------	0.0886
D2S3.7	0.0195	0.1112	0.1138	0.1050	0.1058	0.1054	0.1146	0.1159	0.1173	0.0967	---------	0.0983
D2S3.8	0.0195	0.1170	0.1198	0.1123	0.1130	0.1123	0.1204	0.1218	0.1233	0.1069	---------	0.1066

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test D2S

Flume 2, (d/b = 0.5) with sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_c (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

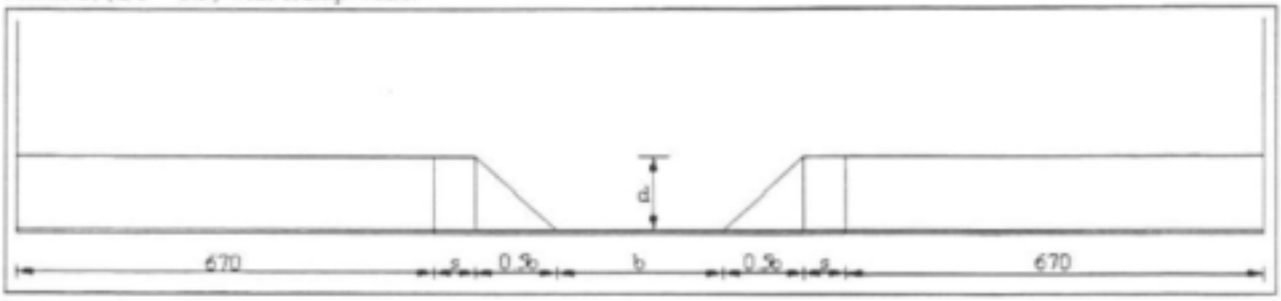
Z (m)	0.371

		Water levels relative to flume invert (m)										
Test Nr.	Q_{lab} (m^3/s)	1	3	2.1	2.2	2.3	4	5	6	7	8	9
D2S4	0.1370	0.2096	0.2121	0.2121	0.2089	0.2122	0.2132	0.2148	0.2159	--------	--------	--------
D2S4.1	0.1370	0.2091	0.2124	0.2123	0.2092	0.2123	0.2131	0.2147	0.2158	0.0683	--------	0.0725
D2S4.2	0.1370	0.2094	0.2123	0.2123	0.2092	0.2123	0.2131	0.2148	0.2158	0.0807	--------	0.0824
D2S4.3	0.1370	0.2097	0.2124	0.2127	0.2096	0.2127	0.2134	0.2150	0.2165	0.0975	--------	0.0925
D2S4.4	0.1370	0.2099	0.2129	0.2132	0.2101	0.2131	0.2137	0.2153	0.2165	0.1097	--------	0.1095
D2S4.5	0.1370	0.2105	0.2132	0.2136	0.2106	0.2137	0.2143	0.2157	0.2171	0.1222	--------	0.1220
D2S4.6	0.1370	0.2108	0.2136	0.2139	0.2109	0.2139	0.2145	0.2156	0.2171	0.1344	--------	0.1325
D2S4.7	0.1370	0.2127	0.2155	0.2158	0.2131	0.2159	0.2165	0.2178	0.2190	0.1474	--------	0.1469
D2S4.8	0.1370	0.2155	0.2186	0.2187	0.2160	0.2188	0.2192	0.2208	0.2219	0.1609	--------	0.1609
D2S4.9	0.1370	0.2180	0.2208	0.2215	0.2189	0.2215	0.2217	0.2233	0.2244	0.1707	--------	0.1693
D2S4.10	0.1370	0.2216	0.2247	0.2252	0.2226	0.2253	0.2255	0.2270	0.2283	0.1818	--------	0.1806
D2S4.11	0.1370	0.2266	0.2295	0.2306	0.2282	0.2306	0.2305	0.2321	0.2332	0.1948	--------	0.1940
D2S4.12	0.1370	0.2310	0.2341	0.2351	0.2327	0.2351	0.2352	0.2365	0.2378	0.2039	--------	0.2034
D2S4.13	0.1370	0.2272	0.2298	0.2412	0.2390	0.2412	0.2309	0.2422	0.2438	0.2153	--------	0.2147
D2S4.14	0.1370	0.2450	0.2477	0.2491	0.2471	0.2491	0.2485	0.2499	0.2509	0.2286	--------	0.2275
D2S4.15	0.1370	0.2536	0.2560	0.2578	0.2561	0.2580	0.2575	0.2588	0.2600	0.2415	--------	0.2402
D2S4.16	0.1370	0.2627	0.2678	0.2672	0.2656	0.2673	0.2665	0.2680	0.2695	0.2542	--------	0.2531
D2S5	0.3473	0.2885	0.2945	0.2943	0.2870	0.2935	0.2946	0.2958	0.2978	--------	--------	--------
D2S5.1	0.3473	0.2893	0.2947	0.2975	0.2883	0.2947	0.2943	0.2981	0.2988	0.1196	--------	0.1191
D2S5.2	0.3473	0.2881	0.2937	0.2940	0.2866	0.2930	0.2947	0.2958	0.2963	0.1380	--------	0.1383
D2S5.3	0.3473	0.2911	0.2965	0.2968	0.2896	0.2959	0.2974	0.2985	0.2996	0.1513	--------	0.1517
D2S5.4	0.3473	0.2963	0.3022	0.3015	0.2947	0.3007	0.3029	0.3025	0.3041	0.1752	--------	0.1696
D2S5.5	0.3473	0.3010	0.3070	0.3075	0.3009	0.3067	0.3066	0.3084	0.3093	0.1975	--------	0.1952
D2S5.6	0.3473	0.3071	0.3137	0.3138	0.3075	0.3130	0.3127	0.3139	0.3155	0.2324	--------	0.2343
D2S5.7	0.3473	0.3144	0.3200	0.3213	0.3155	0.3206	0.3210	0.3211	0.3231	0.2551	--------	0.2559
D2S5.8	0.3473	0.3242	0.3289	0.3298	0.3244	0.3291	0.3283	0.3304	0.3319	0.2743	--------	0.2727
D2S5.9	0.3473	0.3256	0.3405	0.3415	0.3366	0.3409	0.3404	0.3427	0.3431	0.2964	--------	0.2954

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test D2C

Flume 2, (d/b = 0.5) with crump weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_s (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

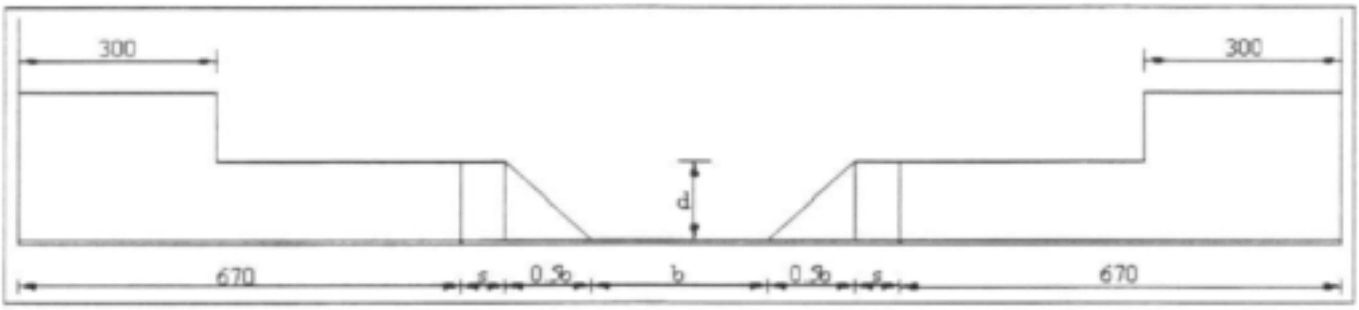
Z (m)	0.374

		Water levels relative to flume invert (m)								
Test Nr.	Q_{lab} (m^3/s)	2.1	2.2	2.3	4	5	6	7	8	9
D2C1	0.1304	0.2009	0.2074	0.2012	0.2059	0.2121	0.2136	---------	---------	---------
D2C1.1	0.1304	0.2002	0.1951	0.2015	0.2112	0.2123	0.2141	0.0311	---------	0.0378
D2C1.2	0.1304	0.2002	0.1951	0.2015	0.2110	0.2122	0.2134	0.0531	---------	0.0570
D2C1.3	0.1304	0.2002	0.1951	0.2015	0.2108	0.2122	0.2135	0.0693	---------	0.0714
D2C1.4	0.1304	0.2003	0.1952	0.2015	0.2112	0.2122	0.2136	0.0823	---------	0.0836
D2C1.5	0.1304	0.2004	0.1952	0.2015	0.2108	0.2122	0.2137	0.0895	---------	0.1028
D2C1.6	0.1304	0.2005	0.1953	0.2016	0.2108	0.2063	0.2140	0.1188	---------	0.1198
D2C1.7	0.1304	0.2006	0.1956	0.2019	0.2109	0.2124	0.2138	0.1305	---------	0.1322
D2C1.8	0.1304	0.2012	0.1961	0.2024	0.2113	0.2125	0.2138	0.1419	---------	0.1435
D2C1.9	0.1304	0.2015	0.1964	0.2026	0.2115	0.2127	0.2141	0.1536	---------	0.1552
D2C1.10	0.1304	0.2016	0.1961	0.2030	0.2116	0.2126	0.2142	0.1663	---------	0.1674
D2C1.11	0.1304	0.2027	0.1965	0.2038	0.2120	0.2132	0.2149	0.1778	---------	0.1794
D2C2	0.0998	0.1824	0.1788	0.1837	0.1939	0.1952	0.1966	---------	---------	---------
D2C2.1	0.0998	0.1832	0.1796	0.1845	0.1940	0.1956	0.1968	0.1071	---------	0.1067
D2C2.2	0.0998	0.1836	0.1801	0.1850	0.1943	0.1957	0.1973	0.1222	---------	0.1221
D2C2.3	0.0998	0.1844	0.1807	0.1856	0.1945	0.1959	0.1974	0.1403	---------	0.1420
D2C2.4	0.0998	0.1852	0.1818	0.1865	0.1951	0.1965	0.1980	0.1552	---------	0.1570
D2C2.5	0.0998	0.1879	0.1844	0.1891	0.1962	0.1977	0.1992	0.1680	---------	0.1702
D2C2.6	0.0998	0.1935	0.1908	0.1945	0.2000	0.2014	0.2028	0.1702	---------	0.1818
D2C2.7	0.0998	0.2005	0.1982	0.2013	0.2051	0.2063	0.2079	0.1918	---------	0.1935
D2C2.8	0.0998	0.2089	0.2072	0.2096	0.2121	0.2135	0.2149	0.2028	---------	0.2045
D2C2.9	0.0998	0.2228	0.2215	0.2238	0.2255	0.2270	0.2280	0.2172	---------	0.2188
D2C3	0.0453	0.1428	0.1420	0.1438	0.1563	0.1577	0.1590	---------	---------	---------
D2C3.1	0.0453	0.1428	0.1422	0.1441	0.1565	0.1577	0.1591	0.0392	---------	0.0398
D2C3.2	0.0453	0.1432	0.1424	0.1443	0.1566	0.1580	0.1593	0.0589	---------	0.0597
D2C3.3	0.0453	0.1435	0.1427	0.1446	0.1567	0.1581	0.1596	0.0725	---------	0.0747
D2C3.4	0.0453	0.1440	0.1433	0.1450	0.1567	0.1581	0.1596	0.0866	---------	0.0884
D2C3.5	0.0453	0.1449	0.1441	0.1458	0.1572	0.1583	0.1598	0.1023	---------	0.1039
D2C3.6	0.0453	0.1465	0.1456	0.1475	0.1579	0.1592	0.1606	0.1169	---------	0.1190
D2C3.7	0.0453	0.1498	0.1486	0.1508	0.1592	0.1607	0.1621	0.1289	---------	0.1308
D2C3.8	0.0453	0.1550	0.1539	0.1559	0.1621	0.1634	0.1647	0.1411	---------	0.1428
D2C3.9	0.0453	0.1614	0.1607	0.1624	0.1663	0.1679	0.1689	0.1527	---------	0.1541
D2C3.10	0.0453	0.1672	0.1664	0.1680	0.1706	0.1720	0.1730	0.1601	---------	0.1617
D2C3.11	0.0453	0.1730	0.1723	0.1738	0.1753	0.1768	0.1681	0.1673	---------	0.1690

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test F2S

Flume 2, (d/b = 0.5) with 300 mm symmetrically end-contracted sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_5 (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

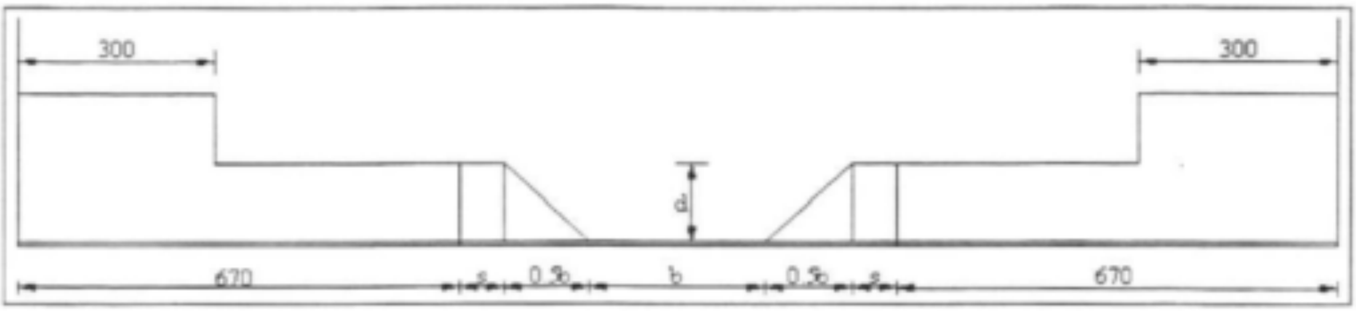
Z (m)	0.371

		Water levels relative to flume invert (m)										
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6	7	8	9
F2S1	0.1268	0.2260	0.2284	0.2273	0.2253	0.2284	0.2294	0.2307	0.2320	--------	--------	--------
F2S1.1	0.1268	0.2266	0.2293	0.2286	0.2265	0.2295	0.2298	0.2316	0.2329	0.0513	--------	0.0549
F2S1.2	0.1268	0.2273	0.2296	0.2291	0.2271	0.2300	0.2305	0.2321	0.2335	0.0778	--------	0.0751
F2S1.3	0.1268	0.2279	0.2304	0.2297	0.2277	0.2306	0.2314	0.2327	0.2341	0.0902	--------	0.0910
F2S1.4	0.1268	0.2284	0.2309	0.2306	0.2286	0.2315	0.2320	0.2330	0.2346	0.1149	--------	0.1150
F2S1.5	0.1268	0.2301	0.2327	0.2320	0.2301	0.2330	0.2334	0.2345	0.2360	0.1344	--------	0.1383
F2S1.6	0.1268	0.2328	0.2352	0.2348	0.2330	0.2357	0.2363	0.2374	0.2387	0.1498	--------	0.1527
F2S1.7	0.1268	0.2365	0.2386	0.2387	0.2370	0.2397	0.2398	0.2413	0.2426	0.1658	--------	0.1669
F2S1.8	0.1268	0.2413	0.2436	0.2438	0.2423	0.2447	0.2442	0.2459	0.2478	0.1805	--------	0.1828
F2S1.9	0.1268	0.2469	0.2496	0.2500	0.2485	0.2508	0.2507	0.2522	0.2533	0.1967	--------	0.1988
F2S1.10	0.1268	0.2546	0.2570	0.2573	0.2559	0.2581	0.2584	0.2596	0.2611	0.2128	--------	0.2138
F2S1.11	0.1268	0.2626	0.2653	0.2658	0.2647	0.2668	0.2664	0.2679	0.2689	0.2267	--------	0.2288
F2S2	0.1335	0.2299	0.2327	0.2316	0.2293	0.2325	0.2333	0.2347	0.2360	--------	--------	--------
F2S2.1	0.1335	0.2349	0.2369	0.2369	0.2350	0.2379	0.2380	0.2396	0.2407	0.1397	--------	0.1435
F2S2.2	0.1335	0.2380	0.2402	0.2402	0.2384	0.2412	0.2414	0.2431	0.2442	0.1564	--------	0.1592
F2S2.3	0.1335	0.2420	0.2446	0.2444	0.2426	0.2454	0.2454	0.2469	0.2482	0.1710	--------	0.1752
F2S2.4	0.1335	0.2473	0.2502	0.2497	0.2481	0.2507	0.2505	0.2524	0.2535	0.1858	--------	0.1887
F2S2.5	0.1335	0.2533	0.2561	0.2560	0.2546	0.2569	0.2568	0.2582	0.2598	0.2029	--------	0.2041
F2S2.6	0.1335	0.2620	0.2643	0.2648	0.2635	0.2658	0.2655	0.2668	0.2680	0.2203	--------	0.2232
F2S2.7	0.1335	0.2692	0.2716	0.2723	0.2712	0.2732	0.2724	0.2737	0.2755	0.2330	--------	0.2354
F2S2.8	0.1335	0.2783	0.2806	0.2817	0.2807	0.2827	0.2819	0.2834	0.2845	0.2483	--------	0.2494
F2S2.9	0.1335	0.2883	0.2904	0.2915	0.2905	0.2924	0.2917	0.2932	0.2944	0.2631	--------	0.2631
F2S2.10	0.1335	0.2995	0.3024	0.3030	0.3022	0.3040	0.3028	0.3042	0.3059	0.2789	--------	0.2797
F2S2.11	0.1335	0.3137	0.3161	0.3172	0.3166	0.3182	0.3172	0.3189	0.3201	0.2958	--------	0.2976
F2S2.12	0.1335	0.3325	0.3347	0.3359	0.3355	0.3369	0.3354	0.3373	0.3383	0.3184	--------	0.3190

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test F2S3

Flume 2, (d/b = 0.5) with 300 mm symmetrically end-contracted sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_5 (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

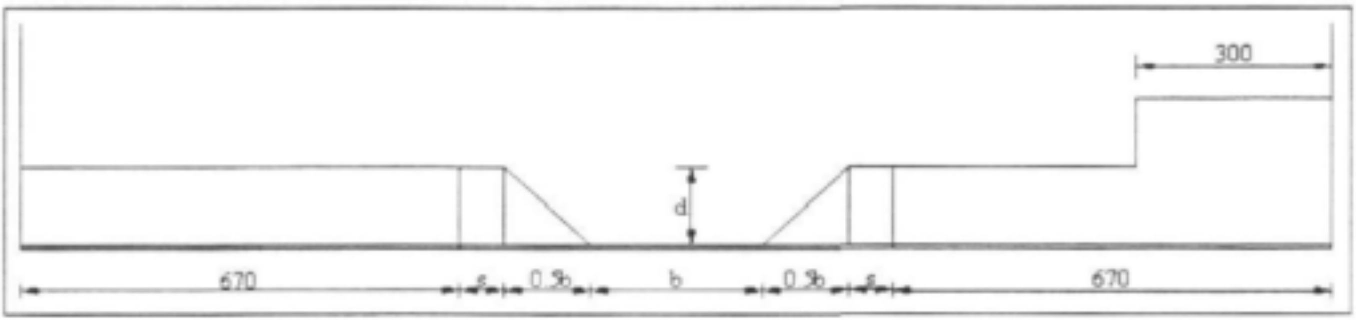
Z (m)	0.371

		Water levels relative to flume invert (m)										
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6	7	8	9
F2S3	0.1418	0.2359	0.2383	0.2368	0.2347	0.2373	0.2392	0.2406	0.2419	--------	--------	--------
F2S3.1	0.1418	0.2363	0.2392	0.2375	0.2356	0.2380	0.2399	0.2411	0.2427	0.0339	--------	0.0317
F2S3.2	0.1418	0.2362	0.2391	0.2376	0.2358	0.2382	0.2397	0.2413	0.2430	0.0458	--------	0.0473
F2S3.3	0.1418	0.2369	0.2395	0.2382	0.2364	0.2389	0.2403	0.2418	0.2432	0.0730	--------	0.0710
F2S3.4	0.1418	0.2370	0.2399	0.2385	0.2369	0.2393	0.2405	0.2424	0.2437	0.0819	--------	0.0828
F2S3.5	0.1418	0.2373	0.2401	0.2391	0.2374	0.2399	0.2409	0.2428	0.2437	0.0994	--------	0.0998
F2S3.6	0.1418	0.2381	0.2412	0.2400	0.2384	0.2409	0.2422	0.2436	0.2446	0.1228	--------	0.1222
F2S3.7	0.1418	0.2392	0.2416	0.2410	0.2392	0.2415	0.2429	0.2445	0.2459	0.1347	--------	0.1364
F2S3.8	0.1418	0.2415	0.2443	0.2434	0.2417	0.2441	0.2452	0.2462	0.2479	0.1474	--------	0.1515

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test H2S

Flume 2, (d/b = 0.5) with sharp-crested weirs. (LHS 300mm end-contracted)



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_5 (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604

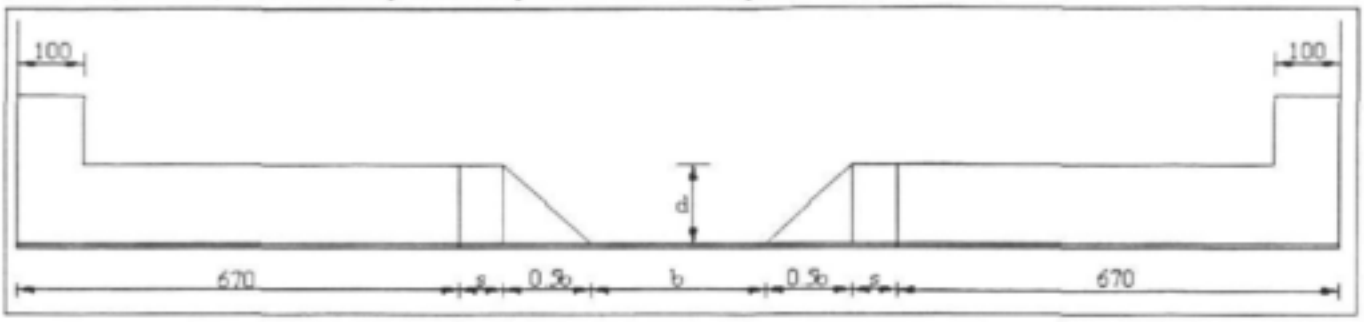
Z (m)	0.371

		Water levels relative to flume invert (m)										
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6	7	8	9
H2S1	0.1411	0.2223	0.2236	0.2232	0.2212	0.2242	0.2257	0.2269	0.2281	--------	--------	--------
H2S1.1	0.1411	0.2227	0.2236	0.2237	0.2216	0.2246	0.2257	0.2271	0.2278	0.0194	--------	0.0382
H2S1.2	0.1411	0.2227	0.2236	0.2239	0.2218	0.2248	0.2257	0.2274	0.2282	0.0367	--------	0.0533
H2S1.3	0.1411	0.2228	0.2237	0.2241	0.2219	0.2251	0.2262	0.2274	0.2284	0.0499	--------	0.0698
H2S1.4	0.1411	0.2231	0.2239	0.2242	0.2222	0.2253	0.2264	0.2275	0.2285	0.0741	--------	0.0903
H2S1.5	0.1411	0.2229	0.2243	0.2246	0.2225	0.2254	0.2264	0.2278	0.2289	0.0942	--------	0.1044
H2S1.6	0.1411	0.2241	0.2245	0.2258	0.2234	0.2257	0.2269	0.2285	0.2293	0.1164	--------	0.1310
H2S1.7	0.1411	0.2255	0.2259	0.2267	0.2249	0.2277	0.2283	0.2298	0.2307	0.1406	--------	0.1387
H2S1.8	0.1411	0.2286	0.2291	0.2297	0.2280	0.2306	0.2312	0.2327	0.2339	0.1498	--------	0.1540
H2S1.9	0.1411	0.2321	0.2329	0.2338	0.2322	0.2347	0.2351	0.2365	0.2371	0.1708	--------	0.1581
H2S1.10	0.1411	0.2374	0.2383	0.2389	0.2374	0.2398	0.2405	0.2417	0.2427	0.1872	--------	0.1725
H2S1.11	0.1411	0.2328	0.2445	0.2453	0.2439	0.2460	0.2463	0.2478	0.2488	0.2011	--------	0.1904
H2S1.12	0.1411	0.2503	0.2515	0.2529	0.2517	0.2536	0.2533	0.2550	0.2557	0.2172	--------	0.2073
H2S2	0.1283	0.2153	0.2164	0.2164	0.2143	0.2174	0.2180	0.2196	0.2208	--------	--------	--------
H2S2.1	0.1283	0.2201	0.2225	0.2230	0.2212	0.2238	0.2239	0.2256	0.2269	0.1500	--------	0.1536
H2S2.2	0.1283	0.2251	0.2261	0.2271	0.2255	0.2281	0.2276	0.2296	0.2309	0.1704	--------	0.1588
H2S2.3	0.1283	0.2300	0.2315	0.2326	0.2311	0.2335	0.2335	0.2349	0.2361	0.1861	--------	0.1744
H2S2.4	0.1283	0.2349	0.2364	0.2375	0.2361	0.2384	0.2381	0.2395	0.2406	0.1969	--------	0.1859
H2S2.5	0.1283	0.2407	0.2421	0.2430	0.2418	0.2439	0.2438	0.2448	0.2464	0.2079	--------	0.1980
H2S2.6	0.1283	0.2561	0.2571	0.2587	0.2576	0.2595	0.2589	0.2606	0.2617	0.2329	--------	0.2281
H2S2.7	0.1283	0.2634	0.2648	0.2661	0.2652	0.2669	0.2666	0.2677	0.2690	0.2443	--------	0.2384
H2S2.8	0.1283	0.2709	0.2726	0.2740	0.2732	0.2749	0.2739	0.2755	0.2769	0.2540	--------	0.2499
H2S2.9	0.1283	0.2790	0.2804	0.2820	0.2812	0.2828	0.2817	0.2834	0.2846	0.2646	--------	0.2608
H2S2.10	0.1283	0.2882	0.2901	0.2918	0.2910	0.2925	0.2915	0.2931	0.2941	0.2762	--------	0.2736

NON-MODULAR FLOW CONDITIONS - NEW DATA

Test J2S

Flume 2, (d/b = 0.5) with 100 mm symmetrically end-contracted sharp-crested weirs.



Flume dimensions:

b (m)	0.264
d (m)	0.132
b_2 (m)	0.528
L (m)	1.339
b_5 (m)	2.000
p (m)	0.032
s (m)	0.066

Orifice plate:

d_1 (m)	0.300
d_2 (m)	0.213
C_d	0.604
Z (m)	0.371

		Water levels relative to flume invert (m)										
Test Nr.	Qlab (m^3/s)	1	3	2.1	2.2	2.3	4	5	6	7	8	9
J2S1	0.1376	0.2166	0.2191	0.2184	0.2158	0.2191	0.2202	0.2214	0.2230	---------	---------	---------
J2S1.1	0.1376	0.2170	0.2193	0.2189	0.2166	0.2196	0.2207	0.2222	0.2237	0.0375	---------	0.0346
J2S1.2	0.1376	0.2189	0.2210	0.2196	0.2171	0.2203	0.2224	0.2238	0.2251	0.0574	---------	0.0542
J2S1.3	0.1376	0.2176	0.2195	0.2196	0.2171	0.2202	0.2210	0.2226	0.2234	0.0713	---------	0.0723
J2S1.4	0.1376	0.2180	0.2207	0.2201	0.2177	0.2207	0.2214	0.2228	0.2245	0.0995	---------	0.1042
J2S1.5	0.1376	0.2182	0.2208	0.2206	0.2183	0.2212	0.2223	0.2236	0.2247	0.1148	---------	0.1202
J2S1.6	0.1376	0.2193	0.2222	0.2220	0.2197	0.2226	0.2234	0.2250	0.2261	0.1392	---------	0.1453
J2S1.7	0.1376	0.2221	0.2251	0.2247	0.2226	0.2254	0.2261	0.2275	0.2286	0.1511	---------	0.1536
J2S1.8	0.1376	0.2260	0.2287	0.2289	0.2268	0.2295	0.2298	0.2313	0.2323	0.1670	---------	0.1701
J2S1.9	0.1376	0.2311	0.2336	0.2340	0.2320	0.2347	0.2347	0.2365	0.2378	0.1807	---------	0.1855
J2S1.10	0.1376	0.2372	0.2400	0.2405	0.2387	0.2411	0.2415	0.2426	0.2439	0.1979	---------	0.2015
J2S2	0.1266	0.2109	0.2131	0.2125	0.2102	0.2131	0.2140	0.2155	0.2168	---------	---------	---------
J2S2.1	0.1266	0.2158	0.2181	0.2183	0.2161	0.2189	0.2195	0.2207	0.2223	0.1507	---------	0.1510
J2S2.2	0.1266	0.2196	0.2220	0.2222	0.2202	0.2229	0.2233	0.2246	0.2262	0.1617	---------	0.1652
J2S2.3	0.1266	0.2275	0.2303	0.2304	0.2288	0.2310	0.2313	0.2327	0.2339	0.1851	---------	0.1891
J2S2.4	0.1266	0.2345	0.2370	0.2375	0.2360	0.2382	0.2384	0.2398	0.2411	0.2023	---------	0.2048
J2S2.5	0.1266	0.2405	0.2432	0.2437	0.2423	0.2443	0.2442	0.2459	0.2471	0.2130	---------	0.2160
J2S2.6	0.1266	0.2473	0.2504	0.2508	0.2495	0.2514	0.2509	0.2526	0.2541	0.2250	---------	0.2270
J2S2.7	0.1266	0.2548	0.2574	0.2582	0.2570	0.2588	0.2585	0.2598	0.2612	0.2357	---------	0.2389
J2S2.8	0.1266	0.2626	0.2650	0.2659	0.2648	0.2665	0.2663	0.2677	0.2692	0.2460	---------	0.2489
J2S2.9	0.1266	0.2704	0.2731	0.2739	0.2729	0.2745	0.2738	0.2754	0.2770	0.2570	---------	0.2597
J2S3	0.1394	0.2172	0.2196	0.2192	0.2165	0.2197	0.2208	0.2221	0.2238	---------	---------	---------
J2S3.1	0.1394	0.2194	0.2214	0.2212	0.2187	0.2218	0.2226	0.2241	0.2254	0.1084	---------	0.1130
J2S3.2	0.1394	0.2193	0.2220	0.2217	0.2183	0.2224	0.2233	0.2246	0.2256	0.1219	---------	0.1278
J2S3.3	0.1394	0.2201	0.2226	0.2224	0.2199	0.2229	0.2238	0.2253	0.2260	0.1387	---------	0.1437
J2S3.4	0.1394	0.2222	0.2252	0.2250	0.2226	0.2255	0.2265	0.2274	0.2291	0.1518	---------	0.1525
J2S3.5	0.1394	0.2305	0.2331	0.2336	0.2315	0.2342	0.2345	0.2359	0.2373	0.1794	---------	0.1827
J2S3.6	0.1394	0.2442	0.2468	0.2474	0.2457	0.2479	0.2479	0.2495	0.2508	0.2106	---------	0.2125
J2S3.7	0.1394	0.2177	0.2206	0.2198	0.2173	0.2205	0.2216	0.2231	0.2244	0.0370	---------	0.0332
J2S3.8	0.1394	0.2183	0.2208	0.2202	0.2176	0.2207	0.2220	0.2235	0.2248	0.0648	---------	0.0641

APPENDIX D

EXAMPLE CALCULATIONS

D.1 MODULAR FLOW CONDITIONS:

D.1.1 Example calculation for $h_o/d<0.9$ (flume 1, d/b = 1.0):

Test A1S6

h_o recorded = 0.1120m

First Iteration:

1. Estimate $y_c = 0.090$m ($y_c<d$)
2. Calculate:

$A_c = by_c + 0.5y_c^2 = 0.174(0.090) + 0.5(0.090)^2 = 0.0197m^2$ (equation 6.2)

$B_c = b + y_c = 0.174 + 0.090 = 0.264m$ (equation 6.3)

$E_{sc} = y_c + A_c/(2.B_c) = 0.090 + 0.0197/(2*0.264) = 0.1273m$ (equation 6.9b)

3. Calculate $Q = \sqrt{g.A_c^3 / B_c} = \sqrt{9.81*0.0197^3 / 0.264} = 0.0169m^3/s$ (equation 6.16)

$h_o/d = 0.644 \Rightarrow C_{D2} = 0.988$ (equation 6.11)

$$h_o + \frac{C_{d2}.Q_{ff}^2}{b_2^2.h_o^2.2g} = 0.112 + \frac{0.988*0.0169^2}{0.348^2(0.112)^2 19.62} = 0.1215m$$ (equation 6.9a)

4. $E_{s2} = 0.1215$m

$E_{sc} = 0.1273$m

Since $E_{s2}<E_{sc}$; estimate y_c lower.

For the second iteration, estimate $y_c = 0.0843$m

2. $A_c = 0.0182$m

$B_c = 0.2583$m

$E_{sc} = 0.1195$m

3. $Q_{ff} = 0.0151m^3/s$

$E_{s2} = 0.1196$m

4. Since E_{sc} (= 0.1195m) $\Rightarrow$ E_{s2} (= 0.1196m), accept last estimate of y_c.

Free discharge through the flume, Q_{ff} follows from equation 6.16:

$$Q_{ff} = C_{d2}\sqrt{g.A_c^3 / B_c}$$

$$\mathbf{Q_{ff}} = 0.988\sqrt{9.81*0.0182^3 / 0.2583} = \mathbf{0.0149m^3/s}$$

D.1.2 Example calculation for $h_o/d>0.9$ (flume 1 with full width sharp-crested weirs):

Test A1S29

h_o recorded = 0.2838m

Flow through the flume:

First Iteration:

1. Estimate $y_c = 0.250$m $(y_c > d)$
2. Calculate:

$B_c = 2(b + s) = 2(0.174 + 0.066) = 0.480$m (equation 6.5)

$A_c = 1.5bd + B_c(y_c - d) = 1.5*0.174^2 + 0.48(0.250 - 0.147) = 0.0819m^2$

(equation 6.4)

$E_{sc} = y_c + A_c/(2.B_c) = 0.250 + 0.0819/(2*0.480) = 0.3353$m (equation 6.9b)

3. Calculate:

$E_{s5} = [0.525 + 0.335(0.2838/0.174) + 0.232(0.2838/0.174)^2]*0.174 = 0.2938$m

(equation 6.7)

4. Compare:

E_{s5} (=0.2938m) and E_{sc} (=0.3353m)

Since $E_{sc} > E_{s5}$, estimate a second value of y_c lower than 0.250m

For the second iteration estimate $y_c = 0.2223$m

2. $B_c = 0.480$m

$A_c = 0.0686$m

$E_{sc} = 0.2938$m

3. $E_{s5} = 0.2938$m

4, 5. Since $E_{s5} = E_{sc} = 0.2938$, accept last estimate of y_c

6. Calculate $C_{d5} = 0.094 + 0.887(0.2828/0.174) - 0.203(0.2838/0.174)^2 = 1.001$

The free discharge through the flume , Q_{ff}, follows from equation 6.17:

$$Q_{ff} = C_{d5}\sqrt{g.A_c^3 / B_c}$$

$$\mathbf{Q_{ff}} = 0.1001\sqrt{9.81*0.0686^3 / 0.480} = \mathbf{0.0813m^3/s}$$

Flow over the side (sharp-crested) weirs:

$P = p + d = 0.027 + 0.174 = 0.201m$ (equation 6.18)

$H_{wf} = E_{s5} - d = 0.2938 - 0.174 = 0.1198m$ (equation 6.19)

$H_{wf}/P = 0.1198/0.201 = 0.596 < 1.867 \Rightarrow$ equation 5.3 holds for C_w

$C_w = 0.627 + 0.018(H/P) = 0.627 + 0.018(0.596) = 0.638$ (equation 5.3)

The free discharge over the sharp-crested weirs follows from equation 5.2:

$\mathbf{Q_{wf}} = C_w.2/3.\sqrt{2g}\, LH_{wf}^{3/2} = 0.638.2/3.\sqrt{19.62}\,.1.52.(0.1198)^{1.5} = \mathbf{0.1187m^3/s}$

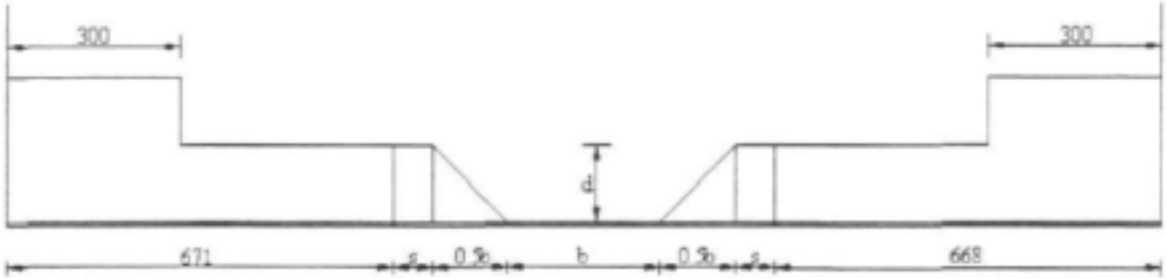
The total discharge over the compound weir follows from equation 6.23:

$Q_t = Q_{ff} + Q_{wf}$

$\mathbf{Q_t} = 0.0813 + 0.1187 = \mathbf{0.2000m^3/s}$

D.1.3 Example calculation for $h_o/d>0.9$ (flume 2 with end contracted sharp-crested weirs):

Test E2S10:



h_o recorded = 0.2380m

The calculation of the discharge is done in accordance with the method laid out in section 6.2.1.1:

1. In accordance with section 6.1.2, calculate the free discharge through the flume;

$$\mathbf{Q_{ff} = 0.0896\ m^3/s}$$

$$(E_{s5} = 0.2452m)$$

2. Calculate $H_{wf} = E_{s5} - d = 0.2452 - 0.132 = 0.1132m$ (equation 6.19)

3. Calculate $H_{wf}/P = 0.1132/0.164 = 0.690 < 1.867$

$$\Rightarrow C_w = 0.627 + 0.018(0.690) \quad \text{(equation 5.3)}$$

$$C_w = 0.639$$

First Iteration:

4. Estimate $y_5 \approx h_o = 0.238m$

5. Calculate $h = y_5 - d = 0.238 - 0.132 = 0.106m$ (equation 6.20)

LHS crest

6. $H_{wf}/L = 0.1132/0.368 = 0.3076 < 0.35$

$$\Rightarrow n = 0.2 \quad \text{(equation 5.7)}$$

7. Calculate the effective length of the sharp crest, which is only half-contracted:

$$L_e = L - ½.n.h = 0.368 - 0.5(0.2)0.106 = 0.3574m \quad \text{(equation 5.10)}$$

8. Calculate the discharge over this crest:

$$Q_{wf} = C_w.(2/3).\sqrt{2g}.L_e.H_{wf}^{1.5} \quad \text{(equation 5.2)}$$

$$Q_{wf} = 0.639.(2/3).\sqrt{19.62}\,(0.3574).0.1132^{1.5} = 0.0257\ m^3/s$$

RHS crest:

6. $H_{wf}/L = 0.1132/0.371 = 0.3051 < 0.35$

$\Rightarrow n = 0.2$ (equation 5.7)

7. Calculate the effective length of the sharp crest, which is only half-contracted:

$L_e = L - ½.n.h = 0.371 - 0.5(0.2)0.106 = 0.3604m$ (equation 5.10)

8. Calculate the discharge over this crest:

$Q_{wf} = C_w.(2/3).\sqrt{2g}.L_e.H_{wf}^{1.5}$ (equation 5.2)

$Q_{wf} = 0.639.(2/3).\sqrt{19.62}(0.3604).0.1132^{1.5} = 0.0259\ m^3/s$

9. Calculate the total discharge over the side weirs:

$\mathbf{Q_{wf}} = 0.0257 + 0.0259 = \mathbf{0.0516\ m^3/s}$

10. Calculate the total modular discharge over the compound weir:

$Q_t = Q_{ff} + Q_{wf}$ (equation 6.23)

$\Rightarrow \mathbf{Qt} = 0.0896 + 0.0516 = \mathbf{0.1412\ m^3/s}$

Second Iteration:

4. Calculate new value of $y_5 = E_{s5} - \dfrac{Q_t^2}{(y_5 + p)^2.b_5^2.2g}$ (equation 6.21)

$$= 0.2452 - \frac{0.1412^2}{(0.238 + 0.032)^2.2^2.(19.62)}$$

$\Rightarrow y_5 = 0.2417m$

5. $h = y_5 - d = 0.2417 - 0.132 = 0.1097m$ (equation 6.20)

LHS crest:

6. Establish that $n = 0.2$

7. Calculate $L_e = 0.3570m$

8. Calculate $Q_{wf} = 0.0257\ m_3/s$

RHS crest:

6. Establish that $n = 0.2$

7. Calculate $L_e = 0.360m$

8. Calculate $Q_{wf} = 0.0259\ m^3/s$

9. Calculate the total modular discharge over the side weirs:

$$Q_{wf} = 0.0257 + 0.0259 = \mathbf{0.0516\ m^3/s}$$

10. Calculate the total modular discharge over the compound weir:

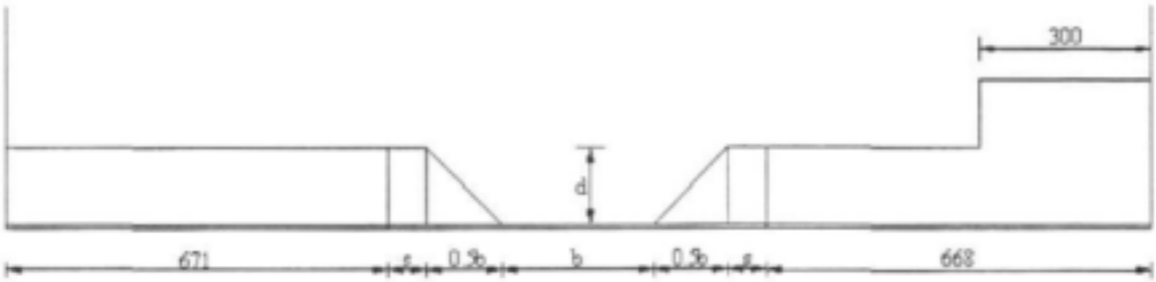
$$Q_t = 0.0896 + 0.0516 = \mathbf{0.1412\ m^3/s}$$

With equation 6.22, calculate the value of y_5 for the third iteration; y_5 = 0.2418m. This is not much different from the previous iteration, and it can be shown that the value of the total discharge will remain unchanged. The total modular discharge over the compound weir is therefore as calculated above.

D.2 NON-MODULAR FLOW CONDITIONS

D.2.1 Example calculation for $h_v/d>0.9$; flume 2 ($d/b = 0.5$) with end contracted sharp-crested weirs

Test H2S1.11:



Values recorded: $h_v = 0.246$m
$t = 0.196$m

1. Calculate the "free" discharge through the flume, $\mathbf{Q_{ff} = 0.0967m^3/s}$

2. Calculate $S_f = t/h_v = 0.196/0.246 = 0.797$m.

   calculate $4d/(L_1 + L_2) = 4(0.132)/(0.671 + 0.368) = 0.508$

   $\Rightarrow S_f > 0.55 \Rightarrow$ equation 7.18

   $Q_{fs} = \{-3.800(0.797)^2 + 4.179(0.797) - 0.149\}0.0967$

   $\mathbf{Q_{fs} = 0.0743m^3/s}$

3. Calculate $h_v/d = 0.246/0.132 = 1.864 < 2.0 \Rightarrow$ equation 7.28 for k:

   $k = -2.294(1.864)^3 + 12.394(1.864)^2 - 22.372(1.864) + 13.601$

   $\underline{k = 0.106}$

4. Calculate v_2^2 with equation 8.2

   $v_2 = Q_{fs}/(b_2.h_v) = 0.0743/(0.528*0.246) = 0.572$m/s

   $\underline{v_2^2 = 0.327}$

First iteration:

5. In the first iteration assume $v_5 = 0.38*v_2$ for flume 2:

   $\Rightarrow v_5 = 0.38*0.572 = 0.2174$m/s (equation 8.8)

   $\Rightarrow \underline{v_5^2 = 0.0472}$

6. Calculate $y_5 = h_v\{1 + k.(v_2^2 - v_5^2)/(2g.h_v)\}$ (equation 7.26)

$= 0.246\{1 + 0.106(0.327 - 0.0472)/(19.62*0.246)\}$

$\Rightarrow$ $\mathbf{y_5 = 0.2475m}$

7. Estimate $H_{ws} \Rightarrow y_5 - d = 0.2475 - 0.132 = 0.1155m$ (equation 8.10)

8. Calculate $H_{ws}/P = 0.1155/0.164 = 0.704 < 1.867$

$\Rightarrow \underline{C_w} = 0.627 + 0.018(0.704) = \underline{0.640}$ (equation 5.3)

9. Calculate $h = y_5 - d = 0.2475 - 0.132 = 0.1155m$ (equation 6.20)

LHS crest:

10. Calculate $H_{ws}/L = 0.1155/0.368 < 0.35 \Rightarrow n = 0.2$ (equation 5.7)

11. Calculate the effective length of the sharp crest, which is only half-contracted:

$L_e = L - \frac{1}{2}.n.h = 0.368 - 0.5(0.2)0.1155 = 0.3565m$ (equation 5.10)

12. Calculate the "free" discharge over this crest:

$Q_{wf} = C_w.(2/3).\sqrt{2g}.L_e.H_{ws}^{1.5}$ (equation 5.2)

$Q_{wf} = 0.640.(2/3).\sqrt{19.62}(0.3565).0.1155^{1.5} = 0.0264\ m^3/s$

RHS crest:

This is a full width crest; $\Rightarrow L_e = L$

12. Calculate the "free" discharge over this crest:

$Q_{wf} = C_w.(2/3).\sqrt{2g}.L.H_{ws}^{1.5}$ (equation 5.2)

$Q_{wf} = 0.6640.(2/3).\sqrt{19.62}(0.671).0.1155^{1.5} = 0.0498\ m^3/s$

13. Calculate the total "free" discharge over the side, sharp-crested weirs:

$Q_{wf} = 0.0264 + 0.0498 = 0.0762\ m^3/s$

14. Correct for submergence with the Villemonte equation:

$$\mathbf{Q_{ws}} = 0.0762\left[1-\left[\frac{0.196-0.132}{0.2475-0.132}\right]^{1.5}\right]^{0.385} = \mathbf{0.0621m^3/s}$$ (equation 5.16)

15. Calculate the total submerged discharge over the compound weir, Q_t:

$\mathbf{Q_t} = Q_{fs} + Q_{ws} = 0.0743 + 0.0621 = \mathbf{0.1364m^3/s}$ (equation 8.6)

Check that the Villemonte correction was correctly applied:

LHS crest:

$Q_{ws} = 0.0264\ m^3/s = 2/3.C_d.\sqrt{19.62}\ Le.h_o^{1.5}$ (equation 5.17)

$\Rightarrow h_o = 0.1204m\ \ (C_d = 0.6)$

$A_o = h_o.L = 0.1204*0.368 = 0.0443$ (equation 5.11)

$A_{co} = ½.(0.6).A_o = 0.3*0.0443 = 0.0133$ (equation 5.13)

$A_{to} = B.Z = 0.668*0.371 = 0.2478\ \ (Z = 0.371m)$ (equation 5.14)

$A_{co}/A_{to} = 0.0133/\ 0.2478 = 0.0537 < 0.13 \Rightarrow$ Villemonte correction valid

RHS crest:

$Q_{ws} = 0.0264\ m^3/s = 2/3.C_d.\sqrt{19.62}\ Le.h_o^{1.5}$ (equation 5.17)

$\Rightarrow h_o = 0.1206m\ \ (C_d = 0.6)$

$A_o = h_o.L = 0.1206*0.671 = 0.0809$ (equation 5.11)

$A_{co} = ½.(0.6).A_o = 0.3*0.0809 = 0.0243$ (equation 5.13)

$A_{to} = B.Z = 0.671*0.371 = 0.2489\ \ (Z = 0.371m)$ (equation 5.14)

$A_{co}/A_{to} = 0.0243/\ 0.2489 = 0.0976 < 0.13 \Rightarrow$ Villemonte correction valid

Second iteration:

6. Calculate v_5^2, using equation 8.3:

$v_5 = Q_t/\{(y_5+p).b_5\} = 0.1364/\{(0.2475+0.032)*2\} = 0.2440m/s$

$\Rightarrow \underline{v_5^2 = 0.0595}$

Calculate y_5, using equation 7.26:

$y_5 = h_v\{1 + k.(v_2^2 - v_5^2)/(2g.h_v)\}$

$= 0.246\{1 + 0.106(0.327 - 0.0595)/(19.62*0.246)\}$

$\Rightarrow$ **$y_5 = 0.2474m$**

7. Calculate H_{ws} with equation 8.1:

$$H_{ws} = y_5 + \frac{Q_t^2}{(y_5 + p)^2\, b_5^2.2g} - d$$

$= 0.246 + 0.1364^2/\{(0.246+0.032)^2*2^2*19.62\} - 0.132$

$\Rightarrow H_{ws} = 0.1184m$

8. $H_{ws}/P = 0.1184/0.164 \Rightarrow C_w = 0.640$ (equation 5.3)

9. $h = y_5 - d = 0.2474 - 0.132 = 0.1154m$

LHS crest: RHS crest:

10. $H_{ws}/L = 0.322 < 0.35 \Rightarrow n = 0.2$

11. $L_e = 0.3565$m $L_e = L = 0.671$m

12. $Q_{wf} = 0.0274$ m^3/s $Q_{wf} = 0.0517$ m^3/s

13. Total modular discharge over side weirs; $Q_{wf} = 0.0274 + 0.0517 = 0.0791$ m^3/s

14. Correct this with Villemonte; $Q_{ws} = 0.0644$ m^3/s

15. Total non-modular discharge over weir; $Q_t = 0.0743 + 0.0644 = 0.1387$ m^3/s

Third Iteration

6. Calculate $y_5 = 0.2474$m. This is unchanged from previously, so y_5 has converged.

7. Calculate $H_{ws} = 0.1185$m

8. $C_w = 0.640$

9. $h = 0.1154$m

LHS crest: RHS crest:

10. $n = 0.2$

11. $L_e = 0.3565$ $L_e = L = 0.671$m

12. $Q_{wf} = 0.0275$ m^3/s $Q_{wf} = 0.0517$ m^3/s

13. Total "free" discharge over side weirs: $Q_{wf} = 0.0792$ m^3/s

14. Non-modular discharge over sharp-crest weirs: Qws = 0.0645 m^3/s

15. Total non-modular discharge over compound weir: $\mathbf{Q_t = 0.1388}$ **m^3/s**

A fourth iteration shows that the values of y_5 and H_{ws} remain unchanged. Further iteration is therefore not required, and the total non-modular discharge over the compound weir is that given above.

D.2.2 Example calculation for $h_v/d > 0.9$; flume 2 ($d/b = 0.5$) with crump weirs

Test D2C2.9

Values recorded: $h_v = 0.2233m$
$t = 0.2180m$

1. Calculate the "free" discharge through the flume, $\mathbf{Q_{ff} = 0.0824m^3/s}$
2. Calculate $S_f = t/h_v = 0.218/0.2233 = 0.976m > 0.95 \Rightarrow$ equation 7.23

   $Q_{fs} = 0.0824\{-220.855(0.976)^2 + 415.077(0.976) - 194.341\}$

   $\mathbf{Q_{fs} = 0.0320\ m^3/s}$
3. Calculate $h_v/d = 0.233/0.132 = 1.692 < 2.5 \Rightarrow$ equation 7.31

   $k = -0.524(1.692)^3 + 3.746(1.692)^2 - 8.903(1.692) + 7.434$

   $\underline{k = 0.866}$
4. Calculate v_2^2 (equation 8.2)

   $v_2 = Q_{fs}/(b_2.h_v) = 0.0320/(0.2233*0.528) = 0.271$ m/s

   $\underline{v_2^2 = 0.0737}$

First iteration:

5. In the first iteration assume $v_5 = 0.40*v_2$ for flume 2:

   $\Rightarrow v_5 = 0.40*0.271 = 0.1084$ m/s (equation 8.10)

   $\Rightarrow \underline{v_5^2 = 0.0188}$
6. Calculate $y_5 = h_v\{1 + k(v_2^2 - v_5^2)/(2g.h_v)\}$ (equation 7.26)

   $= 0.2233\{1 + 0.866(0.0737 - 0.0118)/(19.62*0.2233)\}$

   $\mathbf{\Rightarrow y_5 = 0.2260m}$
7. Estimate $H_{ws} \approx y_5 - d = 0.2260 - 0.132 = 0.0940m$ (equation 8.10)
8. Calculate "free" discharge over crump weirs

   $Q_{wf} = 1.982.L.H_{ws}^{1.5} = 1.982(1.34)(0.0940)^{1.5}$

   $Q_{wf} = 0.0765m^3/s$ (equation 5.24)
9. Estimate $H_t = t - d = 0.218 - 0.132 = 0.0860m$ (equation 8.12)
10. Calculate $H_t/H_{ws} = 0.086/0.0940 = 0.915 < 0.93$

    $\Rightarrow f = 1.035\{0.817 - 0.915^4\}^{0.0647} = 0.900$ (equation 5.27)
11. Calculate the submerged discharge over the crump weirs:

    $\mathbf{Q_{ws}} = f.Q_{wf} = 0.900.0.0765 = \mathbf{0.0689\ m^3/s}$ (equation 5.25)

12. Calculate the total submerged discharge over the compound weir:

$$\mathbf{Q_t} = Q_{fs} + Q_{ws} = 0.0320 + 0.0689 = \mathbf{0.1009\ m^3/s} \qquad \text{(equation 8.6)}$$

Second iteration:

1. Calculate $v_5 = Q_t/(b5(y_5 + p)) = 0.1009/(2(0.2260 + 0.032)) = 0.1955 m/s$

(equation 8.3)

$\Rightarrow v_5^2 = 0.0382$

2. Calculate $y_5 = 0.2233\{1 + 0.866(0.0737 - 0.0382)/(19.62*0.2233)\}$

$\Rightarrow \mathbf{y_5 = 0.2249m}$ (equation 7.26)

3. Calculate H_{ws} with equation 8.1:

$$H_{ws} = y_5 + \frac{Q_t^2}{(y_5 + p)^2 b_5^2.2g} - d$$

$$= 0.2249 + 0.1009^2/\{(0.2249+0.032)^2*2^2*19.62\} - 0.132$$

$\Rightarrow H_{ws} = 0.0949m$

4. Calculate $Q_{wf} = 0.0776\ m^3/s$

5. Calculate H_t with equation 8.4:

$$H_t = t - d + \frac{Q_t^2}{(t - d + Z)^2 b_5^2.2g}$$

$\Rightarrow H_t = 0.218 - 0.132 + 0.1009^2/((0.218 - 0.132 + 0.374)^2.(2^2)19.62)$

$\Rightarrow H_t = 0.0866m$

6. Calculate $H_t/H_{ws} = 0.9125 \Rightarrow f = 0.904$ (equation 5.27)

7. Calculate $Q_{ws} = 0.904*0.0776 = 0.0702$ m3/s

8. Calculate $\mathbf{Q_t} = Q_{fs} + Q_{ws} = 0.032 + 0.0702 = \mathbf{0.1022\ m^3/s}$

Third iteration:

1. $v_5 = 0.1989 \Rightarrow v_5^2 = 0.0396$
2. $y_5 = 0.2248m$
3. $H_{ws} = 0.0948m$
4. $Q_{wf} = 0.0775$ m3/s
5. $H_t = 0.0866m$
6. $f = 0.902$
7. $Q_{ws} = 0.0699$ m3/s
8. $\mathbf{Q_t = 0.1019\ m^3/s}$

A fourth iteration shows that the value of Q_t remains unchanged. Further iteration is therefore not required, and the total non-modular discharge over the compound weir is that given above.

D.2.3 Examples of back calculation for h_o

D.2.3.1 Flow contained in flume

Test B1S6.16: Flume 1 with full width sharp-crested weirs
Recorded values: $h_v = 0.168$m
$t = 0.164$m

The ratio $h_v/d = 0.168/0.174 = 0.966 > 0.9 \Rightarrow$ it would appear that flow occurs over the side weirs. However, $h_v/d < 1.0; \Rightarrow$ flow may be contained in the flume only. This will be investigated.

Calculate the "free" discharge through the flume; $Q_{ff} = 0.0299\ m^3/s$

Calculate $S_f = 0.164/0.168 = 0.976 > 0.8 \Rightarrow$ flume is submerged

Correct Q_{ff} to give the actual, submerged discharge; $Q_{fs} = 0.0138\ m^3/s$

1. Calculate $C_{d2} = 0.845 + 0.081(0.966) = 0.923$ (equation 6.12)

assume $y_c < d$

$\Rightarrow Q_{fs} = 0.0138 = C_{d2}\sqrt{g.A_c^3 / B_c}$ (equation 6.16 mod.)

$\Rightarrow Q_{fs} = 0.0138 = 0.923\sqrt{g.(0.174.y_c + 0.5.y_c^2)^3 / (0.174 + y_c}$

$\Rightarrow$ solve for $y_c = 0.0836$m (<d = 0.174 $\Rightarrow$ assumption valid)

2. Set $E_{sc} = E_{s2}$ (equation 6.9)

$$E_{s2} = y_c + A_c/(2.B_c) = h_o + \frac{C_{d2}.Q_{fs}^2}{b_2^2.h_o^2.2g}$$

$$\Rightarrow 0.0836 + 0.0180/(2*0.2576) = h_o + \frac{0.923.(0.0138^2)}{0.348^2.(h_o^2).19.62}$$

$\Rightarrow$ **h_o = 0.1128m**

2nd iteration:	3rd iteration:	4th iteration:
$h_o/d = 0.648$	$h_o/d = 0.614$	$h_o/d = 0.619$
$C_{d2} = 0.989$	$C_{d2} = 0.980$	$C_{d2} = 0.981$
$y_c = 0.0801$m	$y_c = 0.0806$m	$y_c = 0.0805$m
$h_o = 0.1069$m	$h_o = 0.1077$m	$\Rightarrow$ **h_o = 0.1076m**

Further iteration is not required. The value of $h_o = 0.1076m$.

The ratio $h_o/d = 0.618 < 0.9 \Rightarrow$ flow is contained in the flume, contrary to what the h_v/d value suggested.

(h_o recorded in laboratory = 0.1120m)

D.2.3.2 Flow over flume walls and side weirs

Test H2S1.11: Flume 2 with sharp-crested weirs (lhs crest end contracted)
Recorded values: $h_v = 0.246m$
$t = 0.196m$

The ratio $h_v/d = 0.246/0.132 = 1.86 >> 0.9 \Rightarrow$ it would appear that flow occurs over the side weirs.

Calculate the "free" discharge through the flume; $Q_{ff} = 0.0967\ m^3/s$

Calculate $S_f = 0.246.196 = 0.797 > 0.55 \Rightarrow$ flume is submerged

Correct this to give the actual, submerged discharge; $Q_{fs} = 0.0743\ m^3/s$

1. Calculate $C_{d5} = -0.14(1.86)^2 + 0.7184(1.86) + 0.104 = 0.956$

assume $y_c > d$

$\Rightarrow Q_{fs} = 0.0743 = C_{d5}\sqrt{g.A_c^3 / B_c}$ (equation 6.17 mod.)

$\Rightarrow Q_{fs} = 0.0743 = 0.956\sqrt{g.(1.5*0.264*0.132 + 0.66(y_c - d))^3 / 0.66}$

$\Rightarrow$ solve for $y_c = 0.165m$ (>d = 0.132 Assumption valid)

2. Set $E_{sc} = E_{s5}$ (equation 6.10)

$E_{s2} = y_c + A_c/(2.B_c) = \{0.315 + 0.63(h_o/d) + 0.125(h_o/d)^2\}d$

$\Rightarrow 0.165 + 0.0741/(2*0.66) = \{0.315 + 0.63(h_o/d) + 0.125(h_o/d)^2\}0.132$

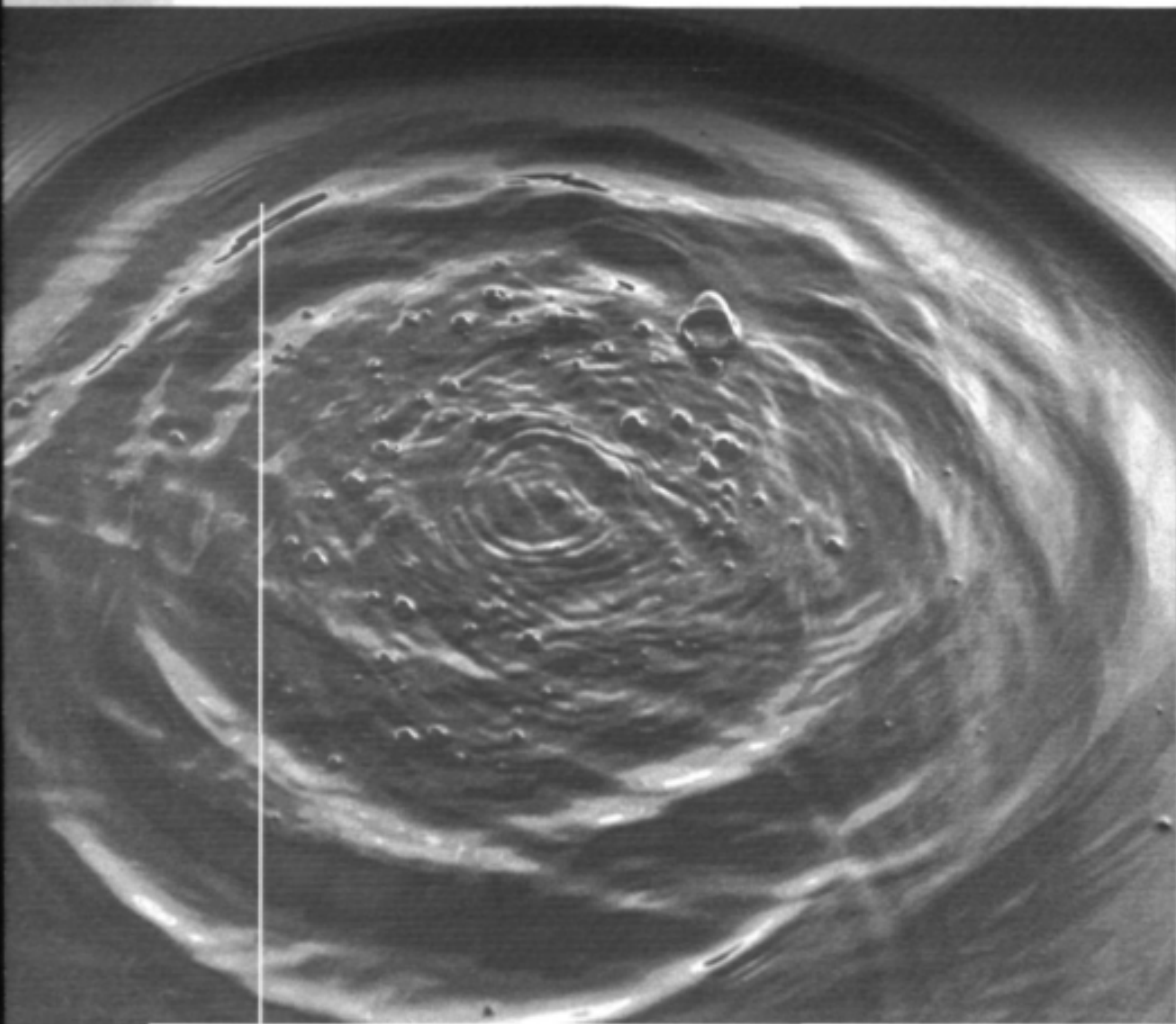
$\Rightarrow$ **h_o = 0.2216m**

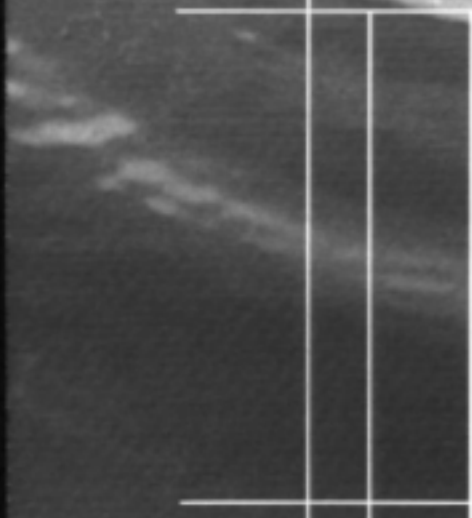
2nd iteration:	3rd iteration:	4th iteration:
$h_o/d = 1.679$	$h_o/d = 0.1.67$	$h_o/d = 1.67$
$C_{d5} = 0.916$	$C_{d2} = 0.913$	$C_{d2} = 0.913$
$y_c = 0.1683m$	$y_c = 0.1685m$	$y_c = 0.1685m$
$h_o = 0.2200m$	$h_o = 0.2204m$	$\Rightarrow$ **h_o = 0.2203m**

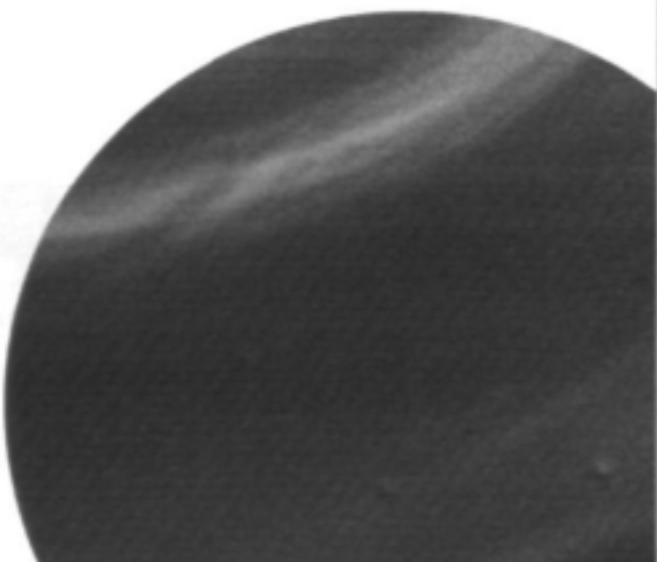
Further iteration is not required. The value of $h_o = 0.2203m$.

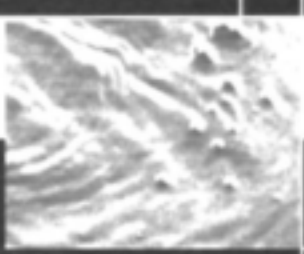
The ratio $h_o/d = 1.67 > 0.9 \Rightarrow$ flow does occur over the side weirs, as assumed.

(h_o recorded in laboratory = 0.2237m)









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