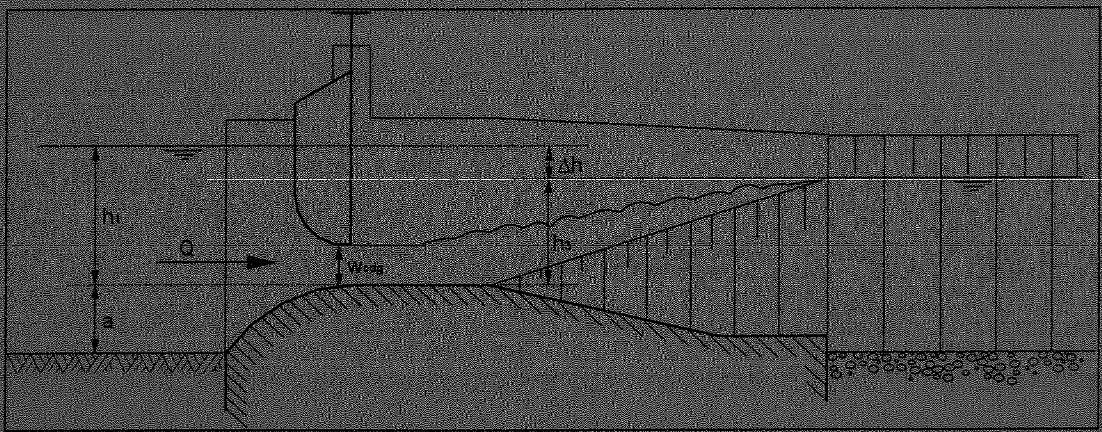
Report of measurements

Crump-De Gruyter orifice



B.J.A de Graaff
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Delft University of Technology
Faculty of Civil Engineering and Geosciences
Subfaculty of Civil Engineering
Department of Water Management, Environmental and Sanitary Engineering
Section Land- and Water Management

Contents

Chapter 1 Introduction

1.1 Basics of the Crump-de Gruyter structure

The Crump-De Gruyter adjustable orifice is a weir in combination with a vertically movable gate (see figure 1.1). The basic structure was introduced in 1922 by E.S. Crump and consisted of a fixed gate (roof block) above a weir. P. Gruyter replaced the fixed gate by a sliding gate and presented a hydraulic study of the structure in 1926 [Gruyter, 1926]. Since both E.S. Crump and P. Gruyter contributed to the design of the structure it is called: Crump-De Gruyter.

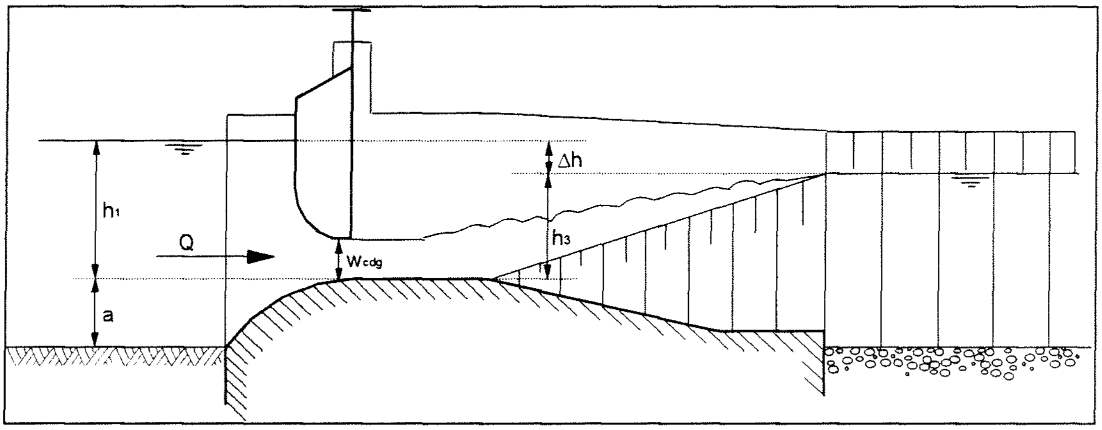

Figure 1.1 Crump-de Gruyter adjustable orifice

The structure is of the orifice type, which implies that the discharge through the structure is proportional to the root of the upstream water level above the weir crest (h_1), thus: $Q \sim h_1^{0.5}$. This feature of the structure makes it an excellent discharge regulator. Water level fluctuations upstream of the Crump-De Gruyter have a relatively small influence on the flow through the structure. The discharge (Q) through the non-submerged structure can be expressed by [Bos, 1990]:

$$Q = C_{d,cdg} C_v b_w \mu w_{cdg} \sqrt{2g(h_1 - \mu w_{cdg})} \quad (1.1)$$

in which	$C_{d,cdg}$	=	discharge coefficient	[-]
	C_v	=	correction term for use of water level h_1 instead of energy head H_1	[-]
	b_w	=	width of the sliding gate	[m]
	μ	=	contraction coefficient	[-]
	h_1	=	upstream water level above the weir crest	[m]
	w_{cdg}	=	orifice opening	[m]

The bottom of the sliding gate is rounded, which should result in parallel streamlines under the gate. The contraction of the jet downstream of the gate above the weir can then be neglected resulting in a contraction coefficient of $\mu = 1.0$. To obtain modular flow, a minimum head over the structure is required. This fall Δh, is a function of both h_1 and w_{cdg} and can be found in [Bos, 1990: Crump-De Gruyter adjustable orifice]. For proper orifice flow the gate opening (w_{cdg}) should be less than $2/3H_1$. If the demands for modular- and proper orifice flow are satisfied, the discharge through the Crump-De Gruyter depends on the upstream water level (h_1) and the gate opening (w_{cdg}) only.

The flow through the Crump-De Gruyter can be determined by measuring the upstream water level h_1 and the orifice opening w_{cdg}. With these values and the coefficients $C_{d,cdg}$ and C_v, the discharge can be calculated from formula 1.1. By shifting the sliding gate up or down, the orifice opening w_{cdg} is varied. This variation of orifice opening can be used to control the flow through the Crump-De Gruyter.

1.2 Problem description

Spaan [Spaan,1994] developed a mathematical model of the Crump-De Gruyter for use in a one dimensional flow package: Modis. For this mathematical model, experimental data on the operation of the Crump-De Gruyter was needed. Previous experiments on the structure were executed to gain data for the design and were therefore restricted to free orifice flow and the determination of the modular limit.

New experiments were executed by Spaan to obtain the characteristics of the structure for all possible flow conditions. The possible flow conditions are: free and submerged weir flow, free and submerged orifice flow and the transitions between weir and orifice flow. From the experimental results of the study by Spaan, only one complete data set (for one discharge) is available for all possible flow conditions through the structure.

1.3 Objective of laboratory study

The purpose of this study is to complete the experimental data from the research by Spaan. The interest is especially focused on the transition between free flow and submerged flow of the structure both as weir and orifice and the transition between weir flow and orifice flow. All measurements are to be taken under steady flow conditions.

Chapter 2 Set up of experiments

2.1 Identification of experiments

The main objective of this research is an investigation of the Crump-De Gruyter structure for all possible flow conditions. The possible flow conditions are: free- and submerged weir flow, free and submerged orifice flow and the transitions between weir and orifice flow (see figure 2.1). Six experiments are proposed to cover all flow conditions of the structure systematically:

- *Experiment I:* *Free - and submerged weir flow*
  When the gate of the Crump-De Gruyter is lifted from the water surface, the flow through the structure is determined by weir flow. Experiment I investigates the weir from free flow to submerged flow conditions by raising the water level downstream of the structure in steps for a constant flow rate. For each step important variables (section 2.4) will be measured.
- *Experiment II:* *Free weir- and free orifice flow plus transitional area*
  This experiment investigates the Crump-De Gruyter from free weir flow to free orifice flow. The water level downstream of the structure is kept well below the crest level of the weir used in the Crump-De Gruyter structure to obtain free flow trough the structure. To obtain the characteristics from free weir- to free orifice flow, the gate of the Crump-De Gruyter structure is lowered in steps from above the water surface into the water for a constant flow rate. For each step important variables (section 2.4) will be measured.
- *Experiment III* *Free- and submerged orifice flow*
  At first the water level downstream of the Crump-De Gruyter is kept well below the crest level of the weir used in the structure to obtain a free flow condition. The gate of the Crump-De Gruyter is lowered into the water. To obtain the characteristics of the Crump-De Gruyter structure from free to submerged orifice flow, the water level downstream of the structure is raised in steps for a constant flow rate and a constant gate opening. For each step important variables (section 2.4) will be measured.

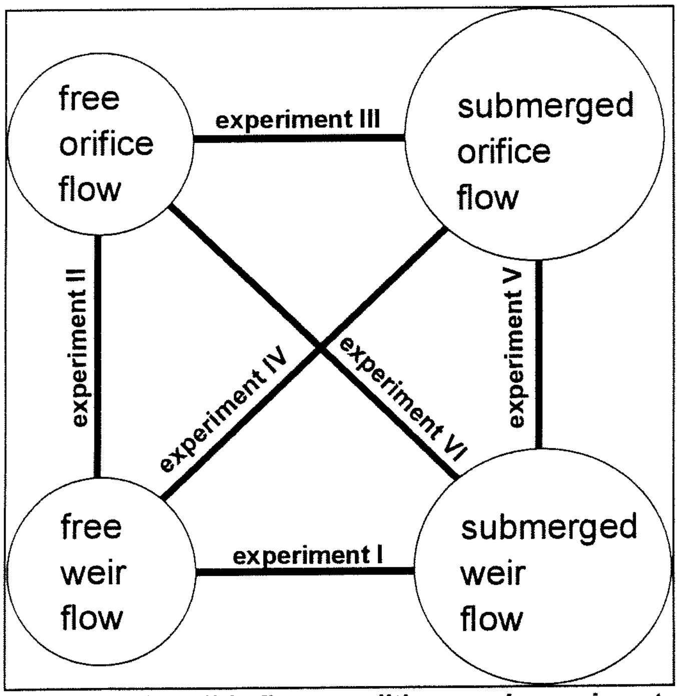

Figure 2.1 Possible flow conditions and experiments covering all conditions

- *Experiment IV:* *Free weir- and submerged orifice flow plus transitional area*
  At first the water level downstream of the Crump-De Gruyter structure is kept well below the crest level of the weir used in the structure to obtain a free flow condition. The gate of the Crump-De Gruyter structure is placed just upon the water surface. The flow through

the structure is then still determined by free weir flow. To obtain the characteristics of the Crump-De Gruyter from free weir to submerged orifice flow, the water level downstream of the Crump-De Gruyter is raised in steps for a constant flow rate and a constant gate opening. For each step important variables (section 2.4) will be measured.

- *Experiment V:* *Submerged weir- and submerged orifice flow plus transitional area*
  For a submerged weir flow condition, the gate of the Crump-De Gruyter structure will be lowered just upon the water surface. To obtain the characteristics of the Crump-De Gruyter structure from submerged weir flow to submerged orifice flow, the water level downstream of the structure is raised in steps for a constant flow rate and a constant gate opening. For each step important variables (section 2.4) will be measured.
- *Experiment VI:* *Submerged weir- and free orifice flow plus transitional area*
  For a submerged weir flow condition, the gate of the Crump-De Gruyter will be lowered just upon the water surface. To obtain the characteristics of the Crump-De Gruyter structure from submerged weir to free orifice flow, the gate will be lowered stepwise into the water for a constant flow rate. For each step important variables (section 2.4) will be measured.

In the experiments described above (experiment I up to VI), the characteristics of the Crump-De Gruyter are determined for a constant flow rate and a decreasing gate opening or an increasing downstream water level. To check for possible hysteresis phenomenon, the characteristics of the structure have to be determined for an increasing gate opening and a decreasing downstream water level as well. This check will be executed for every experiment and for one flow rate. If hysteresis phenomenon are encountered, the check will be executed for all flow rates under investigation.

2.2 Laboratory arrangement

The laboratory equipment (see figure 2.2) consists of a pump, a reservoir, an inlet structure, the Crump-De Gruyter structure, an outlet structure and measurement equipment. The pump is used to keep the water level in the reservoir constant. The discharge flowing out of the reservoir and into the laboratory canal can be regulated by tuning a butterfly valve in the supplying pipe. The orifice opening of the Crump-De Gruyter structure can be varied by shifting the sliding gate in the structure up- or down. The water level downstream of the Crump-De Gruyter can be varied by shifting the weir of the outlet structure up- or down.

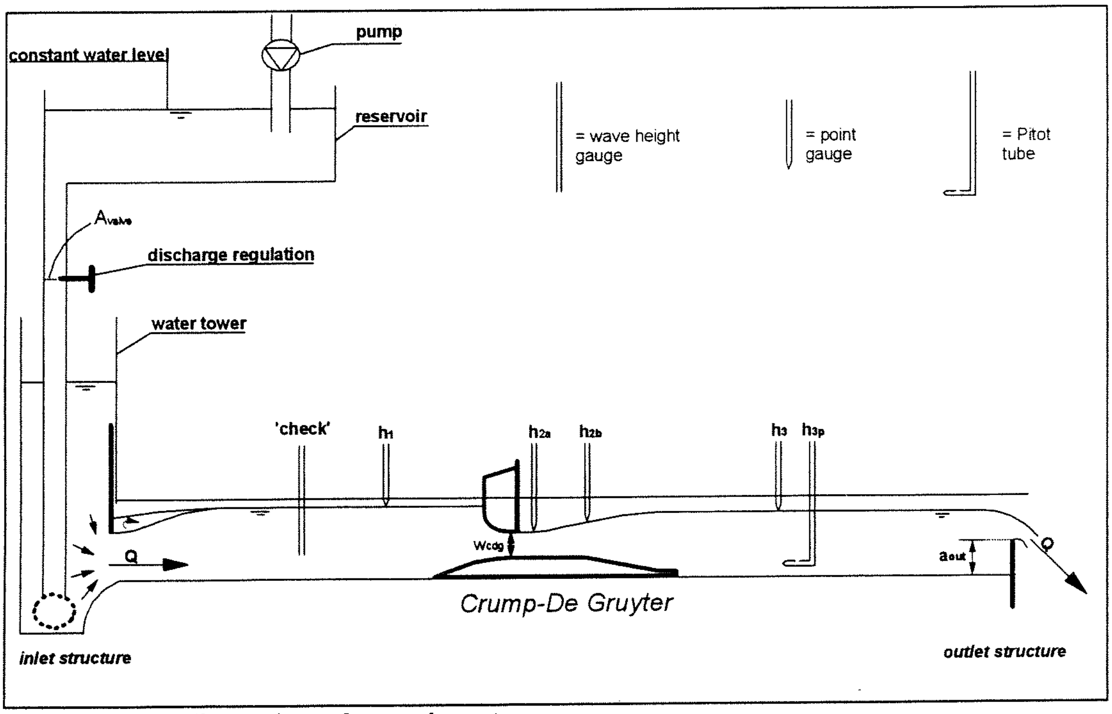

Figure 2.2 Configuration of experiment

To ensure that the experimental results of this study are comparable to the results of the research by Spaan [Spaan, 1994], the experiments will be executed in the same laboratory canal and it is tried to create the same Crump-De Gruyter structure (appendix F). The sliding gate of the Crump-De Gruyter model used by Spaan could be recovered, but a new weir had to be constructed and is slightly different than the one Spaan used. The width of the weir in this study is 37.9 cm and the width in Spaan's study is 38.0 cm. The horizontal length of the sloping downstream side of the weir in this study is 31.5 cm compared to 32 cm in Spaan's study. The extension of the weir downstream of the sloping surface is 8.5 cm in this study and 8.0 cm in Spaan's study. The dimensions of the Crump- De Gruyter structure can be viewed in figure 2.3. The characteristics of the laboratory canal can be viewed in Table 2.1.

width [m]	depth [m]	length [m]	capacity [m^3/s]
0.40	0.40	14.47	0.01-0.10 l/s

Table 2.1 Characteristics of laboratory canal

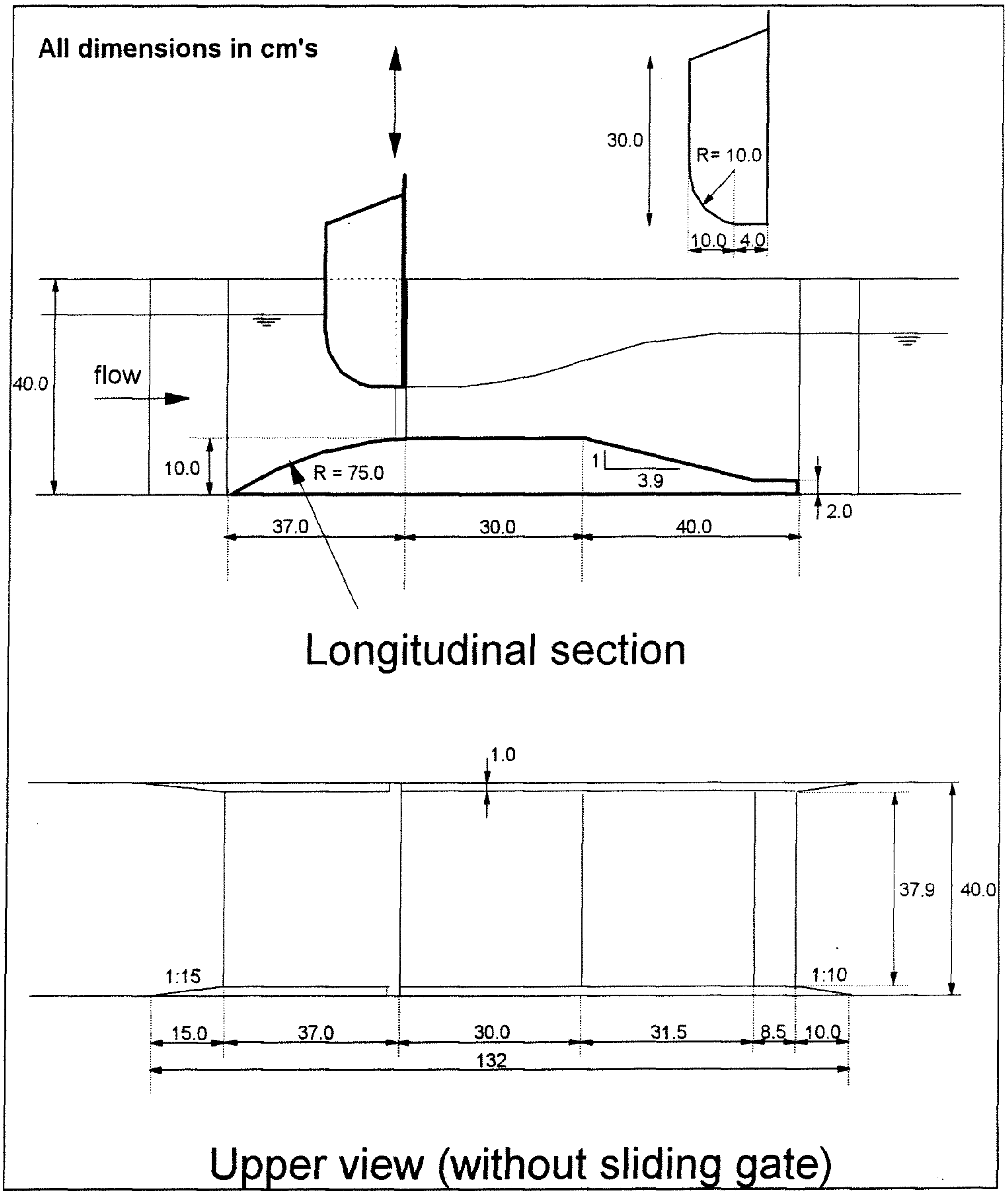

Figure 2.3 Crump- De Gruyter structure for the experiments

2.3 Independent variables

In section 2.2 it was identified that the setting of the butterfly valve in the supplying pipe, the orifice opening of the Crump-De Gruyter structure and the weir height of the outlet structure can be varied. The valve, orifice and weir settings are expressed in variables:

1. valve opening in supplying pipe: A_{valve}
2. orifice opening Crump-De Gruyter: w_{cdg}
3. weir height outlet structure: a_{out}

These variables will be varied during the experiments. An important aspect of A_{valve}, w_{cdg} and a_{out} is that they are independent of other variables of the experiment such as water levels or flow rates. They will be used to regulate the discharge flowing into the laboratory canal (A_{valve}), to regulate the water level downstream of the Crump-De Gruyter structure (a_{out}) and to adjust the orifice opening of the Crump-De Gruyter (w_{cdg}).

2.4 Variables that have to be measured

The water levels and the flow rate in the laboratory canal are dependent on the settings of the independent variables: A_{valve}, w_{cdg} and a_{out}. The variables that have to be measured are listed below:

1. upstream water level, h_1, and downstream water level h_3
   The location of the h_1 measurement should be located sufficiently upstream of the Crump-De Gruyter structure to avoid the influence of draw down of the water surface upon this water level. The h_3 measurement has to be taken downstream of the hydraulic jump. The h_1 level will be measured with a point gauge. The h_3 water level will be measured with a point gauge if the water fluctuations are small. But due to a possible hydraulic jump upstream of the h_3 measurement, water level fluctuations may become too large. In these situations, the h_3 water level will be measured using a Pitot tube. The water level fluctuations will damp out, since the hole in the Pitot tube is small compared to the water surface in the static pressure tube.
2. 'check'-water level in the upstream channel pool
   A water level at a fixed location in the upstream channel pool will be measured real-time with a wave height gauge to check if a steady state is reached and to determine the transition between free- and submerged flow through the Crump-De-Gruyter structure. With this wave height gauge it can be clearly seen when a rising downstream water level starts to influence the water level upstream of the Crump-De Gruyter structure.
3. water levels downstream of the Crump -De Gruyter orifice and above its weir: h_{2a} and h_{2b}
   These water levels are important for estimating the water level just downstream of the orifice and will be measured at fixed locations using point gauges.
4. orifice opening: w_{cdg}
5. the discharge: Q
   The discharge flowing out of the laboratory canal can be determined by means of a Rehbock-weir downstream of the outlet structure. Since the measurements are taken under steady flow conditions, the discharge through the Crump-De Gruyter structure will be equal to the discharge over the Rehbock-weir.

2.5 Needed measurement equipment

The following measurement equipment will be used for the experiments:

- one wave height gauge for automatic water level registration in the upstream channel pool.
- a PC and a data acquisition program for the automatic water level registration
- four point gauges for manual water level measurement.
- Pitot tube + static pressure tube
- a reading on the Crump- De Gruyter orifice for determining of the orifice opening

2.6 Program of measurements

2.6.1 Limitations of independent variables

valve opening in the supplying pipe (A_{valve}) and thus the discharge, Q:
The discharge capacity of the laboratory canal is approximately 0.1 m^3/s. This flow rate will not be reached during the experiments. The Crump-De Gruyter structure will restrict the discharge capacity. A suitable discharge range for the experiments is determined by examining the orifice operation under free flow conditions. The energy head upstream of the Crump-de Gruyter orifice above the laboratory canal bottom for several combinations of discharges and orifice openings is named $H_{1,bottom}$ and can be viewed in table 2.2.

w [m] =	0.01	0.02	0.04	0.06	0.08	0.1	0.12	0.13	0.14	0.16	0.18
Q[m³/s											
0.01	flood	0.202	0.165	weir	weir	weir	weir	weir	weir	weir	weir
0.02	flood	flood	0.240	0.204	weir	weir	weir	weir	weir	weir	weir
0.03	flood	flood	0.365	0.260	0.236	weir	weir	weir	weir	weir	weir
0.04	flood	flood	flood	0.338	0.280	0.264	weir	weir	weir	weir	weir
0.05	flood	flood	flood	flood	0.336	0.300	0.289	weir	weir	weir	weir
0.06	flood	flood	flood	flood	flood	0.344	0.320	0.315	0.313	weir	weir
0.07	flood	flood	flood	flood	flood	0.396	0.356	0.346	0.340	weir	weir
0.08	flood	flood	flood	flood	flood	flood	0.398	381	0.370	0.360	weir
0.09	flood	flood	flood	flood	flood	flood	flood	flood	flood	0.368	0.38 0

Table 2.2 $H_{1,bottom}$ value for different combinations of orifice openings and discharges

This energy head is determined using a discharge formula based upon formula 1.1, where the water level h_1 is replaced by energy head H_1 above the weir crest. The C_v value in this case is equal to 1.0. The flow through the Crump-De Gruyter under free flow conditions can then be described by:

$$Q = C_{d,cdg} b_w \mu w_{cdg} \sqrt{2g(H_1 - \mu w_{cdg})} \qquad (2.1)$$

The contraction coefficient of the Crump-de Gruyter orifice can be estimated at 1.0 and the discharge coefficient $C_{d,cdg}$ can be estimated at 0.94 [Bos, 1990]. The energy head above the laboratory canal bottom can be calculated from:

$$H_{1,bottom} = a + w_{cdg} + \frac{1}{2g}\left(\frac{Q}{C_{d,cdg} b_w w_{cdg}}\right)^2 \qquad (2.2)$$

in which $H_{1,bottom}$ = energy head above laboratory canal bottom [m]
a = weir height above bottom laboratory canal [m]

Some calculations resulted in upstream energy heads above the canal bottom larger than the height of the canal walls. These values are replaced by 'flood' in table 2.2. When the critical depth above the weir crest is smaller than the orifice opening (w_{cdg}>2/3H_1) , the flow through the Crump-De Gruyter is determined by weir flow. These situations are listed in table 2.2 as 'weir'.

The orifice openings needed for proper orifice flow at 0.01m^3/s are small. To allow for accurate measurements it seems advisable to start measuring at 0.02m^3/s. To allow comparison with the work of Spaan it is decided to start measuring at 0.019m^3/s.

The maximum discharge for which the measurements are to be executed is determined by the energy head above the canal bottom. This value should be limited to approximately 0.35m to allow a 0.05m margin from the top of the laboratory canal walls. From table 2.2 it can be seen that the discharge should then be limited to approximately 0.06m^3/s.

The measurements will be executed for five discharges:
Q= 0.019; 0.027; 0.035; 0.043 and 0.051 m^3/s
(measurements by Spaan are executed for 0.010≤ Q ≤ 0.056 m^3/s)

orifice opening, w_{cdg} and weir crest height downstream of Crump-De Gruyter, a_{out}:
The values of the variables, w_{cdg} and a_{out} will be determined in the preparation for each measurement (see section 2.6.2).

2.6.2 Measurement protocol

This section gives a detailed description of the steps to be taken for each experiment. The experiments were identified in section 2.1 and the discharge range to investigate was determined in section 2.6.1.

2.6.2.1 Experiment I: Free- and submerged weir flow

Preparation for each discharge (0.019/0.027/0.035/0.043/0.051 m^3/s)

- Lower the weir at the end of the channel to its lowest position.
- Raise the gate of the Crump-De-Gruyter to its highest position.
- Set the discharge to 0.019/0.027/0.035/0.043/0.051 m^3/s, depending upon the discharge that is being measured.
- Wait for a stationary situation.
- Measure water level h_3 and call this water level $h_{3,min}$.
- Slowly raise the weir at the end of the channel until the water level h_1 starts to increase. Call the h_3 level at this point $h_{3,trans}$.
- Slowly raise the weir at the end of the channel until the water level h_1 is located 5cm under the top of the channel walls. Call the h_3 level at this point $h_{3,max}$.

The measurements will be executed for the following eleven h_3 (downstream) water levels:

- $h_{3,min}$
- Choose two measurement points in the interval $h_{3,min}$ to $h_{3,trans}$-0.005 m
- $h_{3,trans}$ -0.005 m
- Choose three measurement points in the interval $h_{3,trans}$-0.005 to $h_{3,trans}$+0.005 m
- $h_{3,trans}$+0.005 m
- Choose two measurement points in the interval $h_{3,trans}$+0.005 to $h_{3,max}$
- $h_{3,max}$

Measurements

1. Measure for the eleven downstream water levels described above from the lowest to the highest and a discharge of 0.019 m^3/s the h_1, h_{2a}, h_{2b} and h_3 levels.
2. Repeat the measurements under point 1 for the highest to the lowest downstream water level for one flow rate (for example for 0.019 m^3/s) to check for hysteresis phenomenon.
3. Execute the measurements also for discharges of 0.027, 0.035, 0.043 and 0.051 m^3/s.

2.6.2.2 Experiment II: Free weir- and free orifice flow

Preparation for each discharge (0.019/0.027/0.035/0.043/0.051 m^3/s)

- Lower the weir at the end of the channel to its lowest position
- Raise the Crump-De Gruyter to its highest position
- Set the discharge to 0.019/0.027/0.035/0.043/0.051 m^3/s, depending upon the discharge that is being be measured.
- Wait for a stationary situation
- Lower the Crump-De Gruyter gate until it just touches the water surface
- Measure the orifice opening and call it $w_{cdg,max}$
- Slowly lower the gate until the h_1 water level above the weir crest amounts to twice the gate opening. Call the gate opening at this point $w_{cgd,2}$.
- Slowly lower the gate until the h_1 water level above the weir crest amounts to four times the gate opening. Call the gate opening at this point $w_{cdg,4}$.
- Slowly lower the gate until the h_1 water level is located 5cm under the top of the channel wall. Call the gate opening at this point $w_{cdg,min}$.

The measurements will be executed for the following ten gate settings:

- $w_{cdg,max}$
- Choose two measurement points in the interval $w_{cdg,max}$ to $w_{cdg,2}$.
- $w_{cdg,2}$
- Choose two measurement points in the interval $w_{cdg,2}$ to $w_{cdg,4}$.
- $w_{cdg,4}$
- Choose two measurement points in the interval $w_{cdg,4}$ to $w_{cdg,min}$
- $w_{cdg,min}$

measurements

1. Measure for the ten gate settings described above from the highest to the lowest and a discharge of 0.019m^3/s the h_1, h_{2a} and h_{2b} levels.
2. Repeat the measurements under point 1 for the highest to the lowest downstream water level for one flow rate (for example for 0.019 m^3/s) to check for hysteresis phenomenon
3. Execute the measurements also for discharges of 0.027, 0.035, 0.043 and 0.051m^3/s.

2.6.2.3 Experiment III: Free- and submerged orifice flow

Preparation for each discharge (0.019/0.027/0.035/0.043/0.051 m^3/s)

- Lower the weir at the end of the channel to its lowest position.
- Raise the Crump-De Gruyter gate to its highest position.
- Set the discharge to 0.019/0.027/0.035/0.043/0.051 m^3/s, depending upon the discharge that is being be measured.
- Wait for a stationary situation
- Measure the h_3 level and call this level $h_{3,min}$.
- Slowly lower the gate until the h_1 level above the weir crest is approximately equal to three times the gate opening. Call this gate opening $w_{cdg,3}$.
- Slowly raise the weir at the end of the channel until the h_1 level starts to increase systematically. Call the h_3 level at this point $h_{3,trans}$.
- Raise the weir at the end of the channel until the h_1 level is located 5cm under the top of the channel wall. Call the h_3 level at this point $h_{3,max}$.

The measurements will be executed for the following h_3 levels:

- $h_{3,min}$
- Choose two measurement points in the interval $h_{3,min}$ to $h_{3,trans}$ - 0.005 m.
- $h_{3,trans}$ - 0.005 m
- Choose three measurement points in the interval $h_{3,trans}$ - 0.005 m to $h_{3,trans}$ + 0.005 m.
- $h_{3,trans}$ + 0.005 m
- Choose two measurement points in the interval $h_{3,trans}$ + 0.005 m to $h_{3,max}$.
- $h_{3,max}$

Measurements:

1. Set gate to $w_{cdg,3}$.
2. Measure for the eleven downstream water levels described above from the lowest to the highest and a discharge of 0.019m^3/s the h_1, h_{2a}, h_{2b} and h_3 levels.
3. Repeat the measurements under point 1 for the highest to the lowest downstream water level for one flow rate (for example for 0.019 m^3/s) to check for hysteresis phenomenon
4. Execute the measurements also for discharges of 0.027,0.035,0.043 and 0.051 m^3/s.

2.6.2.4 Experiment IV: Free weir- and submerged orifice flow

Preparation for each discharge (0.019/0.027/0.035/0.043/0.051 m^3/s)

- Lower the weir at the end of the channel to its lowest position
- Raise the Crump-De Gruyter to its highest position
- Set the discharge to 0.019/0.027/0.035/0.043/0.051 m^3/s, depending upon the discharge that is being be measured.
- Wait for a stationary situation
- Measure the h_3 level and call it $h_{3,min}$.

- Slowly lower the gate until the gate just touches the water surface. Call the gate opening at this point $w_{cdg,t}$.
- Raise the weir at the end of the channel until the h_1 level above the weir crest is approximately equal to two times the opening $w_{cdg,t}$. Call the h_3 level at this point $h_{3,w2}$.
- Raise the weir at the end of the channel until the h_1 level above the weir crest is approximately equal to four times the opening $w_{cdg,t}$. Call the h_3 level at this point $h_{3,w4}$.
- Raise the weir at the end of the channel until the h_1 water level is located 5cm under the top of the channel walls. Call the h_3 level at this point $h_{3,max}$.

The measurements will be executed for the following eleven downstream water levels:

- $h_{3,min}$
- Choose three measurement points in the interval $h_{3,min}$ to $h_{3,w2}$.
- $h_{3,w2}$
- Choose two measurement points in the interval $h_{3,w2}$ to $h_{3,w4}$.
- $h_{3,w4}$
- Choose two measurements points in the interval $h_{3,w4}$ to $h_{3,max}$.
- $h_{3,max}$

Measurements

1. set the gate to $w_{cdg,t}$.
2. Measure for the eleven downstream water levels described above from the lowest to the highest and a discharge of 0.019m^3/s the h_1, h_{2a}, h_{2b} and h_3 levels.
3. Repeat the measurements under point 1 for the highest to the lowest downstream water level for one flow rate (for example for 0.019 m^3/s) to check for hysteresis phenomenon
4. Execute the measurements also for discharges of 0.027, 0.035, 0.043 and 0.051 m^3/s.

2.6.2.5 Experiment V: Submerged weir- and submerged orifice flow

Preparation for each discharge (0.019/0.027/0.035/0.043/0.051 m^3/s)

- Lower the weir at the end of the channel to its lowest position.
- Raise the Crump-De Gruyter gate to its highest position
- Set the discharge to 0.019/0.027/0.035/0.043/0.051 m^3/s, depending upon the discharge that is being be measured.
- Wait for a stationary situation
- Measure the h_1 level above the weir crest and call it h_{1ref}
- Raise the weir of the outlet structure until the h_1 level above the weir crest is approximately 1.25 times h_{1ref}.
- Wait for a stationary situation.
- Measure the h_3 level and call it $h_{3,min}$.
- Slowly lower the gate until the gate touches the water surface. Call the gate opening $w_{cdg,ref}$.
- Raise the weir of the outlet structure until the h_1 level above the weir crest amounts to 2 times $w_{cdg,ref}$. Call the h_3 level at this point $h_{3,w2}$.
- Raise the weir of the outlet structure until the h_1 level above the weir crest amounts to 4 times $w_{cdg,ref}$. Call the h_3 level at this point $h_{3,w4}$.
- Raise the weir of the outlet structure until the h_1 level is located 5 cm under the top of the channel walls. Call the h_3 level at this point $h_{3,max}$.

The measurements will be executed for the following eleven downstream water levels:

- $h_{3,min}$
- Choose three measurement points in the interval $h_{3,min}$ to $h_{3,w2}$
- $h_{3,w2}$
- Choose two measurement points in the interval $h_{3,w2}$ to $h_{3,w4}$
- $h_{3,w4}$
- Choose two measurement points in the interval $h_{3,w4}$ to $h_{3,max}$
- $h_{3,max}$

Measurements

1. Set the discharge to 0.019 m^3/s.

2. Set the gate to $w_{cdg,ref}$
3. Measure for the eleven downstream water levels described above from the lowest to the highest and a discharge of 0.019 m^3/s the h_1, h_{2a}, h_{2b}, and h_3 levels.
4. Repeat the measurements under point 1 for the highest to the lowest downstream water level for one flow rate (for example for 0.019 m^3/s) to check for hysteresis phenomenon
5. Execute the measurements also for discharges of 0.027, 0.035, 0.043 and 0.051 m^3/s.

2.6.2.6 Experiment VI: Submerged weir- and free orifice flow

Preparation for each discharge (0.019/0.027/0.035/0.043/0.051 m^3/s)

- Lower the weir of the outlet structure to its lowest position
- Raise the Crump-De Gruyter gate to its highest position
- Set the discharge to 0.019/0.027/0.035/0.043/0.051 m^3/s, depending upon the discharge that is being be measured.
- Wait for a stationary situation
- Measure the h_1 level above the weir crest and call it $h_{1,ref}$
- Raise the weir of the outlet structure until the h_1 level above the weir crest amounts to 1.25 times $h_{1,ref}$. Call the h_3 level at this point $h_{3,ref}$.
- Wait for a stationary situation
- Lower the Crump-De Gruyter gate until it touches the water surface. Call this gate setting $w_{cdg,max}$.
- Lower the Crump-De Gruyter gate until the h_1 water level is located 5 cm under the top of the channel walls. Call the gate setting $w_{cdg,min}$.

The measurements will be executed for the following 5 gate settings:

- $w_{cdg,max}$
- Choose three measurements points in the interval $w_{cdg,max}$ to $w_{cdg,min}$.
- $w_{cdg,min}$

measurements:

1. Set the discharge to 0.019 m^3/s
2. Set the downstream water level to $h_{3,ref}$
3. Measure for the 5 gate settings described above from the highest to the lowest the h_1, h_{2a}, h_{2b} and h_3 levels.
4. Repeat the measurements under point 3 for the highest to the lowest gate setting for one flow rate (for example for 0.019 m^3/s) to check for hysteresis phenomenon
5. Execute the measurements also for discharges of 0.027, 0.035, 0.043 and 0.051 m^3/s.

Chapter 3 Experiments

3.1 Location of point gauges, Pitot tube and Crump-De Gruyter structure

The location of important objects in the laboratory canal are determined relative to the downstream side of the gate in the Crump-De Gruyter structure (see figure 3.1) and can be viewed in Table 3.1.

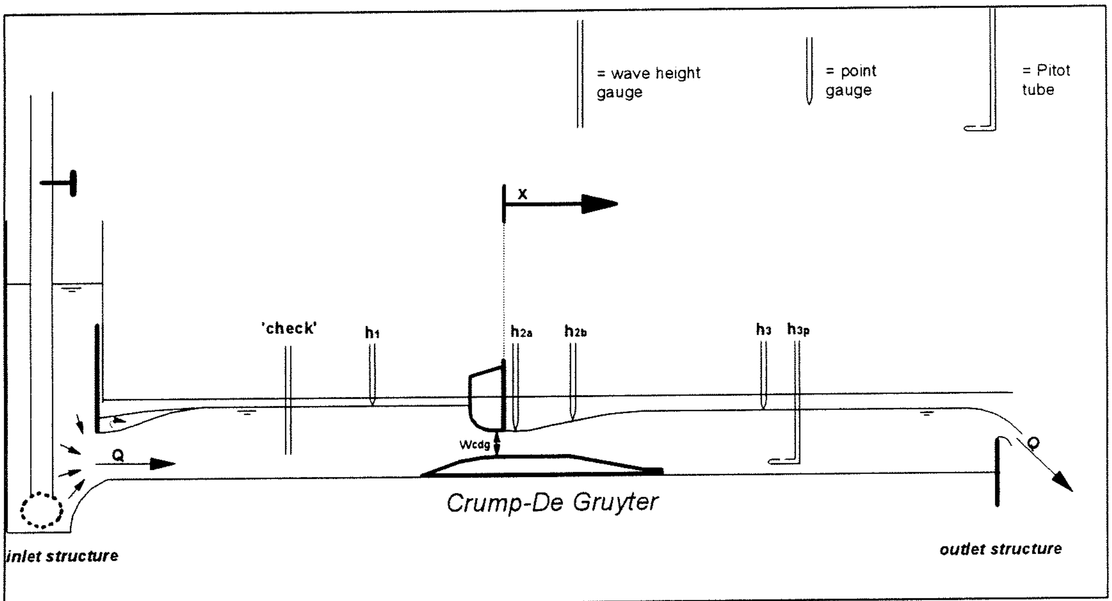

Figure 3.1 Location of point gauges, Pitot tube and Crump-De Gruyter structure

Object	x [m]	max. error = Δx [m]
point gauge: h_1 level	- 1.50	0.001
point gauge: h_{2a} level	+ 0.05	0.001
point gauge: h_{2b} level	+ 0.28	0.001
point gauge: h_3 level	+ 5.00	0.005
Pitot tube: h_3 level	+ 5.16	0.005
inlet sluice	- 6.98	0.005
weir at the outlet	+ 7.49	0.005

Table 3.1 Location of point gauges, Pitot tube and inlet- and outlet structure

3.2 Reference levels of point gauges and Pitot tube

The reference levels of the point gauges and Pitot tube respectively to the crest level of the weir in the Crump-De Gruyter structure or to the bottom level under the point gauge can be viewed in table 3.2.

Gauge	Reference crest level [m]		Reference bottom level [m]	
	crest level	max. error	bottom level	max. error
point gauge h_1 level	0.1358	$3\ 10^{-4}$	0.0339	$1\ 10^{-4}$
point gauge: h_{2a} level	0.0360	$1\ 10^{-4}$	*****	****
point gauge: h_{2b} level	0.0163	$1\ 10^{-4}$	*****	****
point gauge: h_3 level	0.1659	$3\ 10^{-4}$	0.0651	$1\ 10^{-4}$
Pitot tube: h_3 level	-0.042	$7\ 10^{-4}$	-0.143	$7\ 10^{-4}$

Table 3.2 Reference crest- and bottom levels

3.3 Discharge measurement

A steel flume is placed under the laboratory canal. This flume has to discharge all water flowing out of the laboratory canal. The discharge flowing out of the flume is measured using a standard Rehbock-weir, which is located at the downstream end. The discharge over the weir is calculated as follows (ISO 1438-1975 (E)):

$$Q = C_e \frac{2}{3}\sqrt{2g}bh_e^{1.5} \qquad (3.1)$$

where	Q	= discharge over the weir	[m^3/s]
	C_e	= 0.602 + 0.083 h/p	[-]
	h	= upstream water level above weir crest	[m]
	p	= height of weir crest above channel bottom	[m]
	b	= weir width	[m]
	h_e	= $h + k_h$	[m]
	k_h	= 0.0012	[m]

Some of the parameters described above can be viewed in figure 3.2.

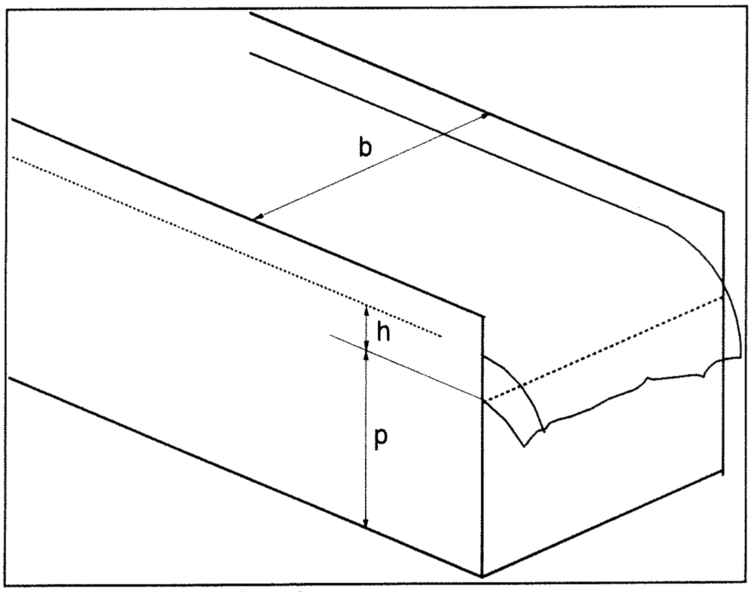

Figure 3.2 Rehbock-weir

The Rehbock-weir used for discharge measurements has the following characteristics:

b	= 44.4 cm	(max. error = 0.1 cm)
p	= 25.0 cm	(max. error = 0.1 cm)

The upstream water level, h, is measured with a point gauge in a basin which is connected to the steel flume just upstream of the Rehbock-weir by means of a small opening between the basin and the channel. Due to this small opening and a relatively large basin surface, water level fluctuations in the basin can be neglected. The crest level of the Rehbock weir is determined by reducing the discharge flowing into the laboratory canal to zero. When the flow over the Rehbock-weir is also reduced to zero, the water level in the basin is equal to the weir crest level. The weir crest level amounts to 0.1263 m (max. error = 5 10^{-5} m).

The desired water level upstream of the Rehbock-weir is calculated for the discharges for which the measurements are to be executed. The results of these calculations can be viewed in table 3.3.

Q [m^3/s]	h [m]	h level [m] = h + 0.1263
0.019	0.0798	0.2061
0.027	0.1005	0.2268
0.035	0.1189	0.2452
0.043	0.1358	0.2621
0.051	0.1514	0.2777

Table 3.3 Water levels in basin to reach desired discharge

3.4 Results of measurements and data processing

The results of the measurements can be viewed in Appendix H. This appendix presents the basic data such as readings on point gauges. To make this data more accessible it is processed in Appendix I.

3.5 Comparison experimental results with previous studies

The discharge coefficient of the weir and the orifice of the Crump-De Gruyter are determined. The results of these calculations are compared to the discharge coefficients found from the study by Spaan [Spaan, 1994]. The discharge coefficient for free orifice flow could also be compared to the coefficient that resulted from measurements by Gruyter in 1926. The coefficients are important for the discharge characteristics of the weir- and orifice and are used to find out if the results of this study are comparable to the results of the study by Spaan.

3.5.1 Discharge coefficient for free weir flow

The head-discharge relationship of the weir in the Crump-De Gruyter structure under free flow conditions can be described by a general applicable head-discharge relationship for broad-crested weirs [Bos, 1990]:

$$Q = C_{d,w}\frac{2}{3}\sqrt{\frac{2}{3}g}\,b_w H_{1weir}^{\ 1.5} \qquad (3.2)$$

in which:

Q	= discharge over weir	$[m^3/s]$
$C_{d,w}$	= discharge coefficient for free weir flow	[-]
b_w	= weir width	[m]
$H_{1\,weir}$	= upstream energy head above weir crest	[m]

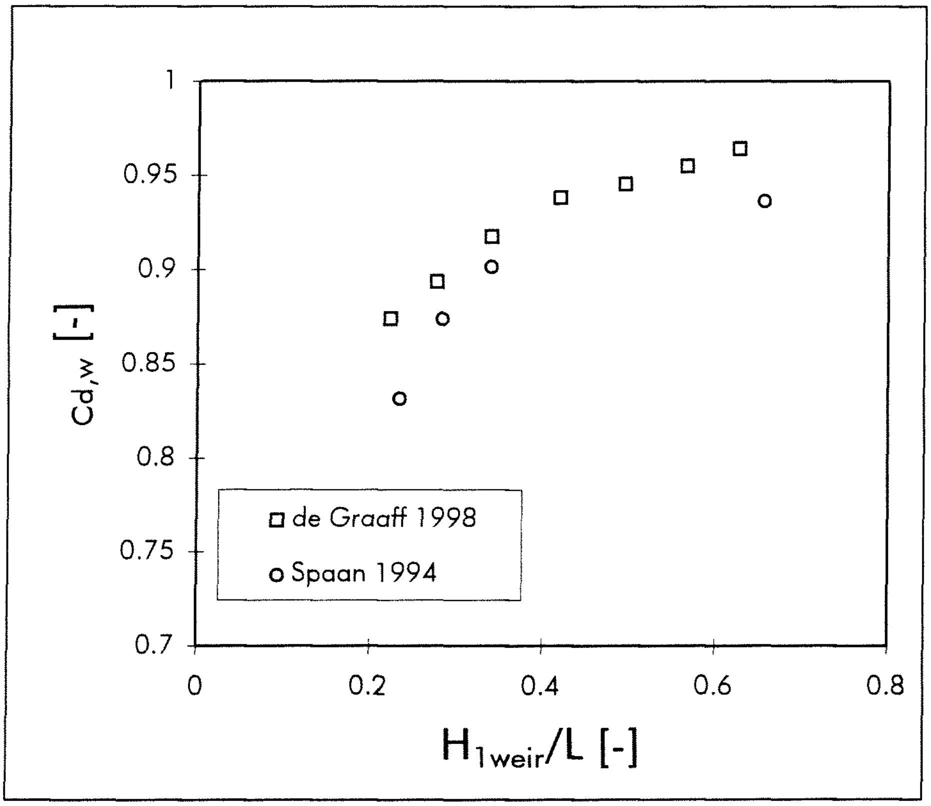

Figure 3.3 Discharge coefficient for free weir flow

The upstream energy head $H_{1\,weir}$ in this formula can be calculated from the measurements by adding the velocity head to the upstream water level above the weir crest ($h_{1\,weir}$):

$$H_{1weir} = h_{1weir} + \frac{v_1^2}{2g} \qquad (3.3)$$

in which: v_1 = average velocity in section 1 [m/s]

The discharge coefficient $C_{d,w}$ is dependent on the shape of the weir and can be calculated from:

$$C_{d,w} = \frac{Q}{\frac{2}{3}\sqrt{\frac{2}{3}g}\, b_w H_{1weir}^{1.5}} \qquad (3.4)$$

The discharge coefficient is determined for the measurements during this study (de Graaff 1998) and for measurements during the previous study by Spaan (Spaan 1994). The results of the calculations can be viewed in figure 3.3 where the $C_{d,w}$ values are plotted against H_{1weir}/L values (L = length of the weir crest of Crump-De Gruyter = 0.30m). The $C_{d,w}$ values from this study may be expected to have an error less than 4% (Appendix B). As can be seen from figure 3.3 the discharge coefficient from this study is slightly higher than the coefficient found from Spaan's study.

3.5.2 Discharge coefficient for free orifice flow

The head discharge relationship for the Crump-De Gruyter orifice under free flow conditions can be described by formula 2.1. The discharge coefficient for free orifice flow can be calculated from this formula:

$$C_{d,cdg} = \frac{Q}{b_w \mu w_{cdg}\sqrt{2g\left(H_{1weir} - \mu w_{cdg}\right)}} \qquad (3.5)$$

The contraction coefficient μ can be estimated 1.0 for the Crump-De Gruyter [Bos, 1990]. The upstream energy head above the weir crest can be calculated from formula 3.3.

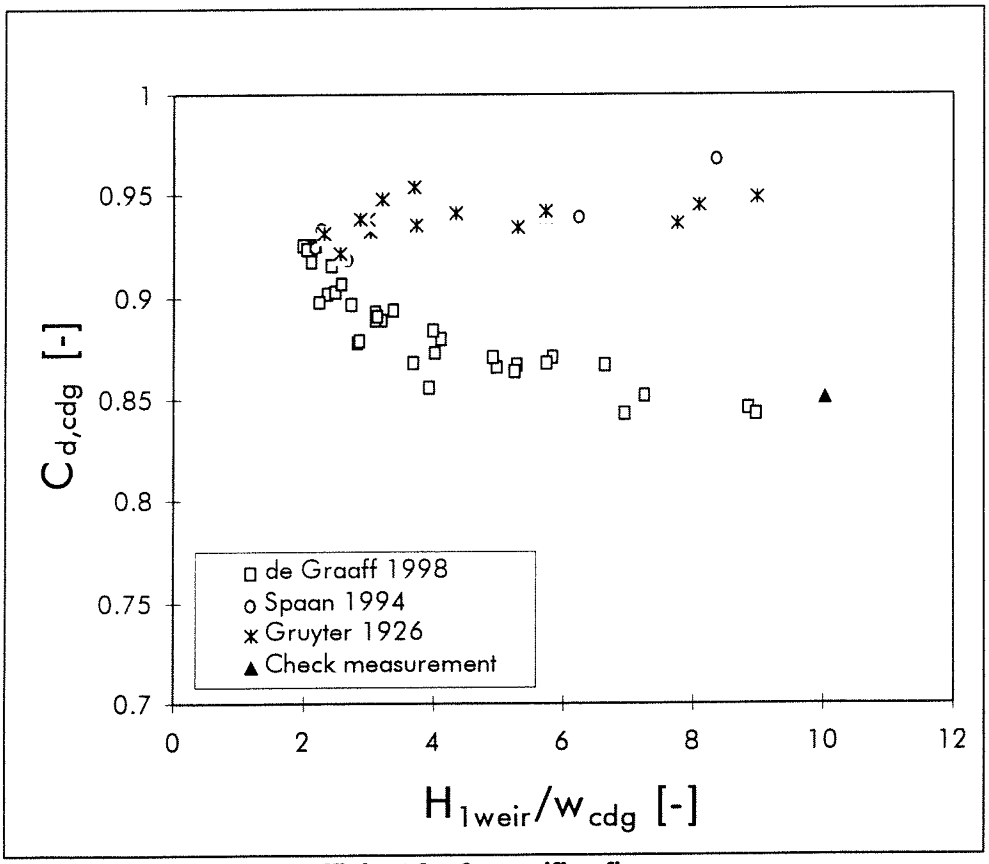

Figure 3.4 Discharge coefficient for free orifice flow

The discharge coefficient $C_{d,cdg}$ is determined for the measurements during this study (de Graaff 1998), for measurements during the previous study by Spaan (Spaan 1994) and for measurements by Gruyter (Gruyter, 1926). The drawing of the Crump-De Gruyter model used in Gruyter's study can be found in appendix G. The results of the calculations can be viewed in figure 3.4. The $C_{d,cdg}$ values from this study may be expected to have an error of less than 5% (appendix B).

For a H_{1weir}/w_{cdg} value of 2.0, the discharge coefficient of the Crump-De Gruyter in this study is practically equal to the discharge coefficients found from the previous measurements (by Spaan and Gruyter). For increasing H_{1weir}/w_{cdg} values the deviation between the discharge coefficient found from this study and the discharge coefficients found from the measurements by Spaan or Gruyter grows. The discharge coefficient of the Crump-De Gruyter in this study is smaller than or equal to the coefficients found from previous experiments.

Some differences between the experiments from this study and the experiments by Gruyter in 1926 could be expected since different Crump-De Gruyter structures are used, but a systematic deviation up to approximately 10% from the results of Spaan's study is unexpected. The systematic deviation cannot be appointed to the maximum error (5%) induced by errors in the measurements.

3.5.3 Possible sources for deviations from previous studies

This section treats possible sources for the differences between the experimental results of Spaan and this study. The deviations were found in section 3.5.2 for the Crump-De Gruyter operating under free orifice flow.

Causes for the smaller discharge coefficient of the Crump-De Gruyter operating under free orifice flow in this study compared to the coefficient found from the results of Spaan's study can be found in:

1. Systematic errors during the measurements
   To rule out errors in the measurements, a measurement is executed by a second person. The reference levels and other important data such as the Rehbock weir width, the Crump-De Gruyter weir width and the laboratory canal width are also measured. This experiment can be viewed in Appendix C. The discharge coefficient is calculated and can be viewed in figure 3.4 (check measurement). The result of this 'check measurement' is comparable to previous results of this study. Therefore errors in the measurements during this study are not probable.
2. Differences in measurement methods
   Spaan used wave height gauges to measure the water level upstream of the Crump-De Gruyter. An experiment is executed to find out if systematic differences between water level measurement using point gauges and water level measurement using wave height gauges exist. This experiment is presented in Appendix D. It turned out that the measurement using wave height gauges led to larger water levels for increasing discharges. This is caused by the placement of the wave height gauges in the flow. The water level just upstream of the gauges is slightly larger than the water level a little further upstream, because a part of the energy head at the wave height gauges is converted in an increase of water level. This effect is larger for increasing velocity heads (and discharges in this case). But the deviation is restricted to a few millimeters and can therefore not account for the difference in discharge coefficient.
   The h_1 measurement is located 1.50 - (0.37 + 0.15) = 0.98m upstream of the Crump-De Gruyter structure. Therefore the effect of backwater upon the h_1 measurement can be neglected. The exact location of the h_1 measurement by Spaan could not be found from the information available, but it can be expected that Spaan's h_1 measurement was situated at a location where the influences of backwater could be neglected.
3. Differences in the Crump-De Gruyter structure design
   The sliding gate of the Crump-De Gruyter structure in this study is identical to the sliding gate used by Spaan. The weir in the structure is copied from drawings provided by Spaan, but the part of the weir downstream of the horizontal weir crest is slightly different than this part in Spaan's model (see section 2.2 and appendix F). But since critical flow occurs just downstream of the sliding gate of the Crump-De Gruyter, this will have no influence upon the measurements for free orifice flow. Therefore the deviation in discharge coefficient found between this study and Spaan's study cannot be appointed to differences in the shape of the sliding gate or the weir.

Next the location of the sliding gate above the weir is investigated. In Spaan's drawing of the Crump-De Gruyter (appendix F) and in Bos [Bos, 1994] the rear of the sliding gate is located above the start of the horizontal weir crest. The sliding gate in Gruyter's structure (appendix G) is almost completely located above the horizontal weir crest. The measurements in this study are executed for a gate location conform Spaan and Bos, but an extra measurement is presented in appendix E which investigates the shift of the sliding gate in downstream direction. The gate is shifted over 1/3 of the length of the horizontal weir crest (1/3*0.30=0.10m). It appeared that the influence of the horizontal shift upon the discharge coefficient for free orifice flow could be neglected and that this coefficient is not very sensitive to the location of the sliding gate above the horizontal weir crest.

3.6 Conclusions from comparison

The discharge coefficient for free weir flow of the Crump-De Gruyter model in this study is comparable to the coefficient found from the measurements by Spaan. The discharge coefficient for free orifice flow deviates from results of previous studies. Possible sources for this deviation were investigated (section 3.5.3) such as: systematic errors during the measurements, differences in measurement methods and Crump-De Gruyter structure design.

Systematic errors during the measurements could be ruled out by an experiment executed by a second person (appendix C).

The difference in measurement method between the two studies is the use wave height gauges by Spaan and the use of point gauges in this study. In an experiment (appendix D) a systematic deviation between measurements using point gauges and wave height gauges was found, but this deviation was too small to account for the difference in discharge coefficient.

The design of the Crump-De Gruyter in this study is compared to the design of the structure in Spaan's study. No differences were found that could account for the deviation in discharge coefficient.

Chapter 4 Conclusions

The experiments are executed according to the measurement program. All possible flow conditions through the Crump-De Gruyter structure were investigated. Steady flow conditions could be reached for all measurements and hysteresis phenomenon (section 2.1) were not found.

The purpose of this study was to complete the experimental data from the research by Spaan. Therefore it was tried to copy the Crump-De Gruyter model used by Spaan. In spite of this, the characteristics of the Crump-De Gruyter operating under free orifice flow conditions deviate from the characteristics of the structure used by Spaan. Possible sources for the differences were identified (section 3.5.3), but none of these sources were found to be the origin of the deviations between the two studies.

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De Waterstaats-Ingenieur, Orgaan der Vereeniging van Waterstaats-Ingenieurs in Nederlandsch-Oost-Indië
No. 12, December 1926

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Msc. thesis of Delft University of Technology
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Section Land and Water management
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Appendix A Accuracy of measurement equipment

Point gauges:
The maximum error in measuring a fixed level with the point gauges can be expected to be less than 1 10^{-4} m. This can be reached when a point gauge is lowered on the bottom of the laboratory canal or on the weir crest of the Crump-De Gruyter. Under still water conditions this accuracy can be reached in measuring water levels in the laboratory canal. Under flow conditions the error in measuring water levels in the laboratory canal can be expected to be less than 5 10^{-4}m.

Pitot tube:
The maximum error in reading the water level on a static pressure tube connected to the Pitot tube can be expected to be less than 0.5 mm. Where water level fluctuations in the static pressure tube occurred during the experiments, the range of water level variation is given.

Measurement of orifice opening:
The maximum error in measuring the orifice opening can be expected to be less than 1 mm.

Appendix B Accuracy of calculated parameters

The accuracy of measurement equipment is given in appendix A. This appendix treats the accuracy of the calculated parameters.

water levels h_{1weir}, $h_{1bottom}$, h_{2aweir}, h_{2bweir}, h_{3weir} and $h_{3bottom}$ above reference levels:
The maximum error in the reference levels can be found in table 3.2. The maximum error in measuring the water levels under flow conditions can be expected to be less than 5 10^{-4} (appendix A). The resulting maximum errors in calculating the water levels relative to the reference levels can be found in table B.1.

	max. error in reference level [m]	max. error in level measurement [m]	total max. error [m]
h_{1weir}	3 10^{-4}	5 10^{-4}	8 10^{-4}
$h_{1bottom}$	1 10^{-4}	5 10^{-4}	6 10^{-4}
h_{2aweir}	1 10^{-4}	5 10^{-4}	6 10^{-4}
h_{2bweir}	1 10^{-4}	5 10^{-4}	6 10^{-4}
$h_{3point\ gauge\ weir}$	3 10^{-4}	5 10^{-4}	8 10^{-4}
$h_{3\ point\ gauge\ bottom}$	1 10^{-4}	5 10^{-4}	6 10^{-4}
$h_{3pitot\ weir}$	7 10^{-4}	5 10^{-4}	1.2 10^{-3}
$h_{3pitot\ bottom}$	7 10^{-4}	5 10^{-4}	1.2 10^{-3}

Table B.1 Error in the calculation of water levels above the reference levels

discharge Q:

The discharge over the Rehbock-weir is calculated with formula 3.1. An error in the calculated flow rate can be initiated by an error in the discharge coefficient, ΔC_e, an error in the Rehbock weir width measurement: Δb and an error in the h level measurement: Δh.

The relative error in the coefficient of discharge can be expected to be of the order of 1% [ISO 1438-1975 (E)], thus:
ΔC_e = 0.01 C_e

The maximum error in the Rehbock weir width measurement, b, and the water level measurement h_e:
Δb = 1 10^{-3} m
Δh_e = Δh = 1 10^{-4} m

The maximum error in the calculated discharge can then be estimated by:

$$\Delta Q = \left|\frac{\partial Q}{\partial C_e}\right|\Delta C_e + \left|\frac{\partial Q}{\partial b}\right|\Delta b + \left|\frac{\partial Q}{\partial h_e}\right|\Delta h_e \qquad \text{(B.1)}$$

in which ΔQ = absolute error in calculated discharge [m^3/s]
and in which:

$$\frac{\partial Q}{\partial C_e} = \frac{2}{3}\sqrt{2g}\, b h_e^{1.5} \quad ; \quad \frac{\partial Q}{\partial b} = C_e \frac{2}{3}\sqrt{2g}\, h_e^{1.5} \quad ; \quad \frac{\partial Q}{\partial h_e} = C_e\sqrt{2g}\, b h_e^{0.5}$$

ΔQ is determined with formula B.1 for a discharge range of 0.010 m^3/s up to 0.051 m^3/s. The maximum relative error in the calculation of the discharge flowing over the Rehbock-weir calculated with formula 3.1 and valid for this discharge range amounts to 1.5%.

energy head H_1:

The energy head in the rectangular channel cross-section, upstream of the Crump-De Gruyter and relative to the weir crest level can be calculated from:

$$H_{1weir} = h_{1weir} + \frac{v_1^2}{2g} = h_{1weir} + \frac{\left[Q / \left(b_c h_{1bottom}\right)\right]^2}{2g} \qquad \text{(B.2)}$$

in which:

$H_{1\,weir}$	= upstream energy head relative to the weir crest level	[m]
$h_{1\,weir}$	= upstream water level above the weir crest	[m]
v_1	= average velocity in channel cross-section	[m/s]
Q	= discharge	[m^3/s]
b_c	= width of channel cross-section	[m]
$h_{1\,bottom}$	= upstream water level above the channel bottom	[m]

The maximum error in calculating this energy head can be estimated by:

$$\Delta H_{1weir} = \left|\frac{\partial H1_{weir}}{\partial h_{1weir}}\right|\Delta h_{1weir} + \left|\frac{\partial H_{1weir}}{\partial Q}\right|\Delta Q + \left|\frac{\partial H_{1weir}}{\partial b_c}\right|\Delta b_c + \left|\frac{\partial H_{1weir}}{\partial h_{1bottom}}\right|\Delta h_{1bottom} \qquad \text{(B.3)}$$

in which ΔH_{weir} = maximum error in the calculated energy head
and in which:

$$\frac{\partial H_{1weir}}{\partial h_{1weir}} = 1 \quad ; \quad \frac{\partial H_{1weir}}{\partial Q} = \frac{Q}{g b_c^2 h^2_{1bottom}} \quad ; \quad \frac{\partial H_{1weir}}{\partial b_c} = -\frac{Q^2}{g b_c^3 h^2_{1bottom}} \quad ; \quad \frac{\partial H_{1weir}}{\partial h_{1bottom}} = -\frac{Q^2}{g b_c^2 h^3_{1bottom}}$$

discharge coefficient of weir for free flow:
The discharge coefficient for free weir flow is calculated using formula 3.4. An error in the calculated discharge coefficient can be initiated by an error in the discharge measurement ΔQ, an error in the weir width measurement Δb_w and an error in the upstream energy head ΔH_{1weir}.

The relative error in the discharge measurement has been derived above and amounts to approximately 1.5%. Thus
ΔQ = 0.015Q

The maximum error in the measurement of the Crump-De Gruyter weir width:
Δb_w = 1 10^{-3} m

The maximum error in the upstream energy head (ΔH_{1weir}) calculation is estimated with formula B.3. The error is determined for the measurements which were used for the calculation of the discharge coefficient. The maximum error amounts to 1 10^{-3} m.

The maximum error in calculating the discharge coefficient can be estimated by:

$$\Delta C_{d,w} = \left|\frac{\partial C_{d,w}}{\partial Q}\right|\Delta Q + \left|\frac{\partial C_{d,w}}{\partial b_w}\right|\Delta b_w + \left|\frac{\partial C_{d,w}}{\partial H_{1weir}}\right|\Delta H_{1weir} \qquad \text{(B.4)}$$

in which $\Delta C_{d,w}$ = maximum error in discharge coefficient for free weir flow [-]
and in which:

$$\frac{\partial C_{d,w}}{\partial Q} = \frac{1}{\frac{2}{3}\sqrt{\frac{2}{3}g}\, b_w H_{1weir}^{1.5}} \quad ; \quad \frac{\partial C_{d,w}}{\partial b_w} = -\frac{Q}{\frac{2}{3}\sqrt{\frac{2}{3}g}\, b_w^2 H_{1weir}^{1.5}} \quad ; \quad \frac{\partial C_{d,w}}{\partial H_1} = -\frac{3}{2}\frac{Q}{\frac{2}{3}\sqrt{\frac{2}{3}g}\, b_w H_{1weir}^{2.5}}$$

$\Delta C_{d,w}$ is determined with formula B.4 for the measurements which were used to calculate $C_{d,w}$. The maximum relative error in the calculated discharge coefficient for this discharge range amounts to 4%.

discharge coefficient for free orifice flow:
The discharge coefficient for free orifice flow is calculated using formula 3.5. The contraction coefficient μ is estimated 1.0. An error in the calculated discharge coefficient can be initiated by an error in the discharge measurement ΔQ, an error in the weir width measurement Δb_w, an error in the upstream energy head ΔH_1 and an error in the orifice opening measurement Δw_{cdg}.

The maximum relative error in the discharge measurement has been derived above and amounts to:

$\Delta Q \quad = 0.015Q$

The maximum error in the measurement of the Crump-De Gruyter weir width:

$\Delta b_w \quad = 1\ 10^{-3}$

The maximum error in the upstream energy head (ΔH_{1weir}) calculation is estimated with formula B_3. The error is determined for the measurements which were used for the calculation of the discharge coefficient. The maximum error amounts to $1\ 10^{-3}$ m.

The error in measuring the orifice opening can amount to $1\ 10^{-3}$ m, thus:

$\Delta w_{cdg} \quad = 1\ 10^{-3}$m

The error in calculating the discharge coefficient can be estimated by:

$$\Delta C_{d,cdg} = \left|\frac{\partial C_{d,cdg}}{\partial Q}\right|\Delta Q + \left|\frac{\partial C_{d,cdg}}{\partial b_w}\right|\Delta b_w + \left|\frac{\partial C_{d,cdg}}{\partial w_{cdg}}\right|\Delta w_{cdg} + \left|\frac{\partial C_{d,cdg}}{\partial H_{1weir}}\right|\Delta H_{1weir} \qquad \text{(B.5)}$$

in which $\Delta C_{d,cdg}$ = maximum error in the discharge coefficient for free orifice flow [-]

and in which:

$$\frac{\partial C_{d,cdg}}{\partial Q} = \frac{1}{b_w w_{cdg}\sqrt{2g\left(H_{1weir} - w_{cdg}\right)}} \quad ; \quad \frac{\partial C_{d,cdg}}{\partial b_w} = -\frac{Q}{b_w^2 w_{cdg}\sqrt{2g\left(H_{1weir} - w_{cdg}\right)}}$$

and in which:

$$\frac{\partial C_{d,cdg}}{\partial w_{cdg}} = \frac{Q}{b_w w_{cdg}\sqrt{2g\left(H_{1weir} - w_{cdg}\right)}}\left[\frac{1}{2\left(H_{1weir} - w_{cdg}\right)} - \frac{1}{w_{cdg}}\right] \quad ; \quad \frac{\partial C_{d,cdg}}{\partial H_{1weir}} = -\frac{Q}{2b_w w_{cdg}\sqrt{2g}\left(H_{1weir} - w_{cdg}\right)^{1.5}}$$

$\Delta C_{d,cdg}$ is determined with formula B.5 for the measurements which were used to calculate $C_{d,cdg}$. The maximum relative error in the calculated discharge coefficient for this discharge range amounts to 5%.

Appendix C Check measurement

An extra measurement was carried out by a second person to verify the measurements for free orifice flow. It is tried to reproduce measurement 105 of Spaan [Spaan, 1994: Bijlage 6]:

Q = 0.023 m^3/s

h_{1weir} = 0.250 m

w_{cdg} = 0.030 m

<u>measurements:</u>

Laboratory canal width	=	b_c	=	40.0	cm
Rehbock weir width	=	b	=	44.4	cm
height Rehbock weir crest	=	p	=	25.0	cm
Crump-De Gruyter weir width	=	b_w	=	37.8	cm
$h_{rehbock}$ level	=			21.48	cm
$h_{rehbock}$ weir crest level	=			12.63	cm
h_{1weir} level	=			43.62	cm
reference h_{1weir} crest level	=			13.64	cm

(This crest level is determined by reducing the discharge flowing into the laboratory canal to zero. When the flow over the Crump-De Gruyter weir is also reduced to zero, the h_{1weir} level is practically equal to the weir crest level. The difference between this reference level and the previously determined crest level (13.58) is caused by a thin layer of water that is still located on the weir crest when the discharge over this weir is reduced to zero.)

reference h_{1weir} bottom level	=	3.40	cm
w_{cdg}	=	3.00	cm

<u>Calculations:</u>

$h_{rehbock}$ = 0.2148 - 0.1263 = 0.0885 m

C_e = 0.602 + 0.083 h/p = 0.602+0.083*8.85/25.0 = 0.631 [-] (formula 3.1)

h_e = $h_{rehbock}$ + k_h = 0.0885 + 0.0012 = 0.0897 m (formula 3.1)

$$Q = 0.631 * \frac{2}{3}\sqrt{2*9.81} * 0.444 * 0.0897^{1.5} = 0.0222 \text{ m}^3/\text{s (formula 3.1)}$$

h_{1weir} = 0.4362 - 0.1364 = 0.2998 m

(This water depth above the weir crest is considerably larger than the level measured by Spaan (0.250 m) for a comparable gate opening and discharge)

$h_{1bottom}$ = 0.4362 - 0.0340 = 0.4022 m

$$H_{1weir} = 0.2998 + \frac{[0.0222/(0.40*0.4022)]^2}{2*9.81} = 0.3008 \text{ m (formula 3.3)}$$

The discharge coefficient for this measurement can now be calculated from formula 3.5:

$$C_{d,cdg} = \frac{0.0222}{0.378*1.0*0.030*\sqrt{2*9.81(0.3008-1.0*0.030)}} = 0.851 \text{ [-]}$$

and

$$\frac{H_{1weir}}{w_{cdg}} = \frac{0.3008}{0.030} = 10.03 \text{ [-]}$$

The result of this extra measurement can be viewed in figure 3.4. The check measurement is located on the trend of the previous measurements, therefore an error in the measurements can be ruled out.

Appendix D Measurement: Comparison wave height gauge and point gauge

An extra measurement is executed to check for systematic differences between water level measurement using point gauges and wave height gauges. The gate of the Crump-De Gruyter is lifted from the water surface and the water level upstream of the Crump-De Gruyter is measured for several discharges. The results of these measurements can be viewed in Table D.1.

Q [m^3/s]	$h_{1point\ gauge}$ [m]	$h_{1wave\ height\ gauge}$ [m]
0.0066	0.0522	0.0525
0.0252	0.1163	0.1172
0.0346	0.1410	0.1423
0.0454	0.1657	0.1678
0.0575	0.1909	0.1935

Table D.1 Measurement for comparison point gauge and wave height gauge

In figure D.1 the difference between wave height gauge and point gauge measurement ($\delta h = h_{1wave\ height\ gauge} - h_{1point\ gauge}$) can be viewed with respect to the velocity head at the h_1 level measurement location. The velocity head ($v_1^2/2g$) is calculated from the average velocity in the channel section. The deviation δh grows for increasing velocity heads.

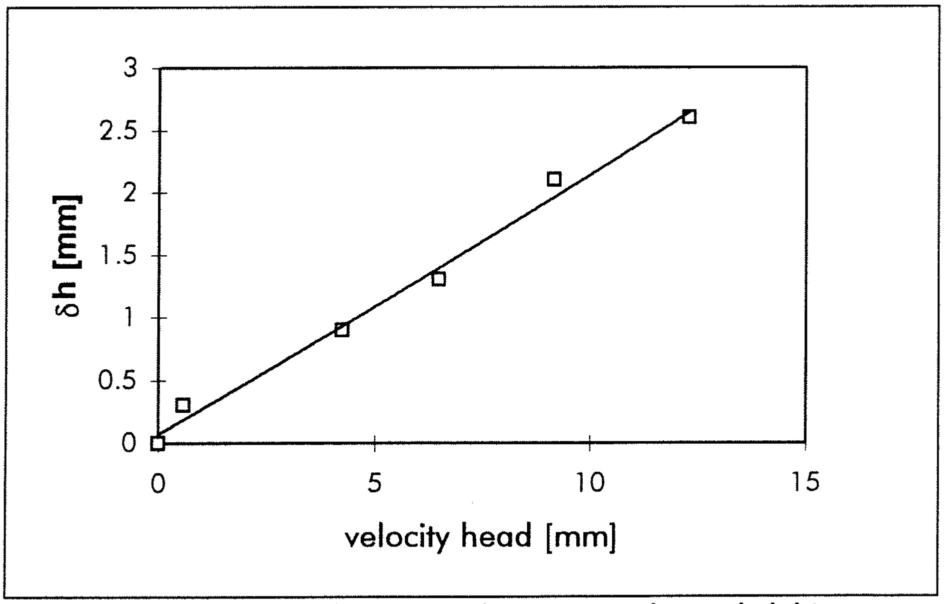


Figure D.1 Difference between point gauge and wave height gauge measurement

The deviation can be clarified by the following:
Point gauges are placed upon the water surface and will therefore not influence the flow. Wave height gauges are placed in the flow. For a zero flow rate the point gauge and the wave height gauge will result in equal water level measurement, but for larger flow rates the set up of water against the wave height gauge will increase due to a gain of velocity head just upstream of the wave height gauges. Therefore the δh increases from 0 up to approximately 2.5 mm for velocity heads up to 12mm (and in this case a discharge of 60 l/s).

Appendix E Measurement: Horizontal shift of sliding gate

This final measurement is executed to find out what the influence is of a horizontal shift of the sliding gate upon the discharge coefficient for free orifice flow. The gate is shifted in downstream direction over 10 cm's. The location of the weir of the Crump-De Gruyter is not changed.

Since the measurement will be used to calculate the discharge coefficient for free orifice flow (formula 3.5), the discharge Q, the orifice opening w_{cdg} and the upstream water level h_1 will be measured.

The h_1 level point gauge was temporarily removed from the laboratory canal during the adjustment of the Crump-De Gruyter structure. Before the measurements, the point gauge is placed at its original location and its reference levels are determined again.

Gauge	Reference crest level [cm]		Reference bottom level [cm]	
	crest level	max. error	bottom level	max. error
point gauge: h_1 level	13.51	0.03	3.39	0.01

Table E.1 Reference levels of the h_1 point gauge

The basic data of the measurements of the Crump-De Gruyter structure operating under free orifice flow conditions can be viewed in Table E.2.

$h_{rehbock}$ level [cm]	h_1 level [cm]	w_{cdg} [cm]
Q = ± 19 l/s		
20.64	24.37	5.2
20.62	26.15	4.4
20.59	29.82	3.6
20.51	39.70	2.7
Q = ± 35 l/s		
24.50	29.48	7.6
24.47	31.46	6.7
24.45	34.92	5.8
24.35	40.02	5.0
Q = ± 51 l/s		
27.80	33.62	9.8
27.78	34.87	9.1
27.75	37.18	8.4
27.70	40.12	7.6

E.2 Basic data of measurements: horizontal shift of sliding gate

The processed data can be viewed in Table E.3:

Q [m³/s]	h_{1weir} [m]	$h_{1bottom}$ [m]	w_{cdg} [m]
0.0191	0.1086	0.2098	0.052
0.0190	0.1264	0.2276	0.044
0.0189	0.1631	0.2643	0.036
0.0186	0.2619	0.3631	0.027
0.0349	0.1597	0.2609	0.076
0.0348	0.1795	0.2807	0.067
0.0347	0.2141	0.3153	0.058
0.0342	0.2651	0.3663	0.050
0.0511	0.2011	0.3023	0.098
0.0510	0.2136	0.3148	0.091
0.0509	0.2367	0.3379	0.084
0.0506	0.2661	0.3673	0.076

E.3 Processed data: horizontal shift of sliding gate

The discharge coefficient of the Crump-De Gruyter structure before and after the horizontal shift of the sliding gate can be viewed in figure E.1. It is important to note from this figure that the influence of the new position of the sliding gate can be neglected. The discharge coefficient before and after the shift are practically equal.

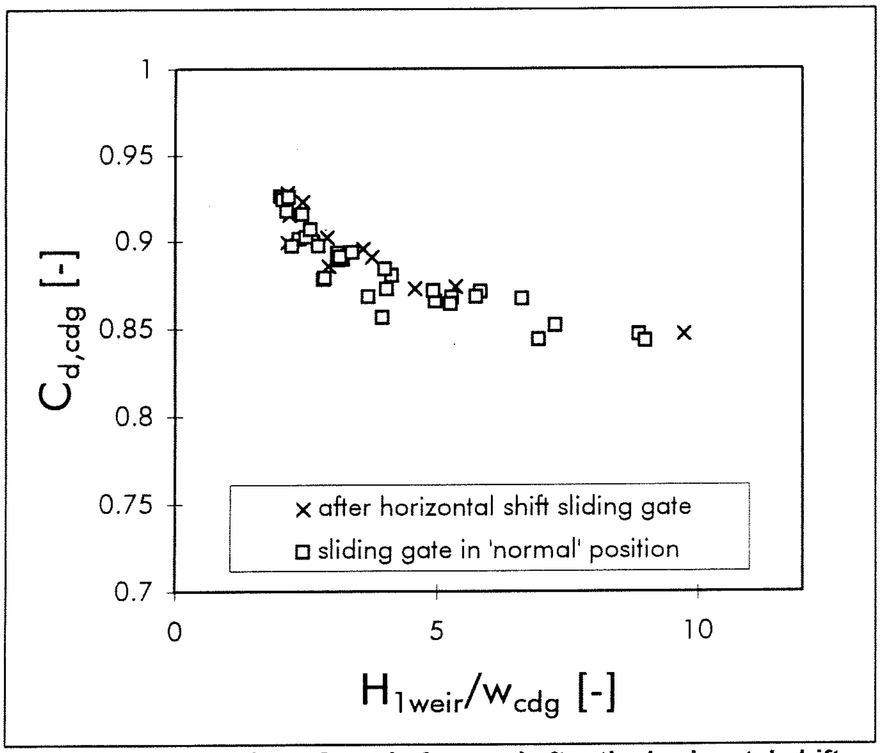
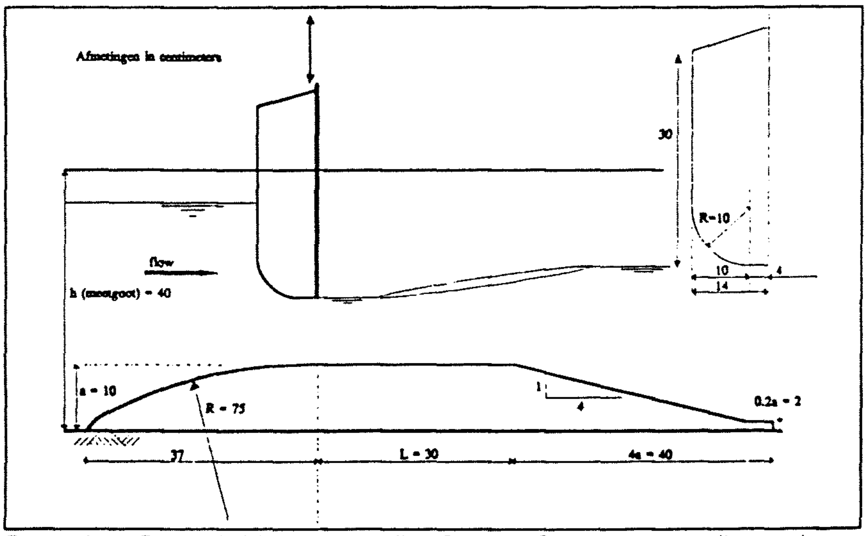
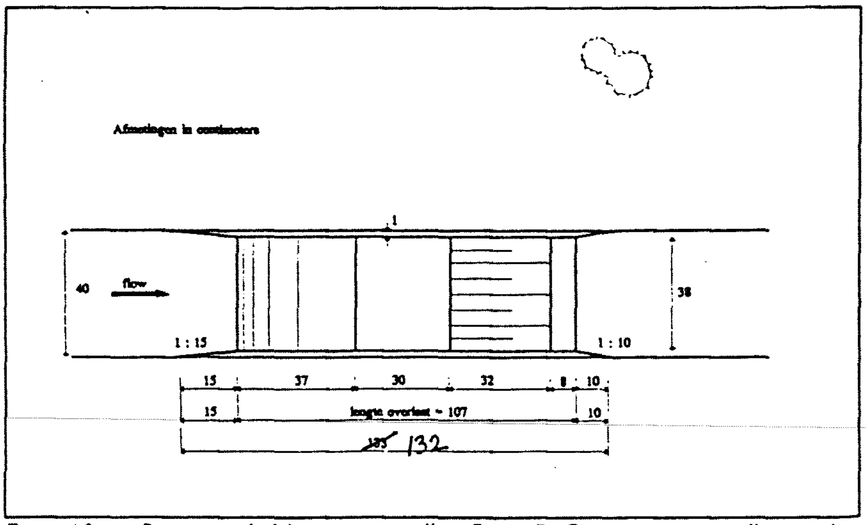


Figure E.1. Comparison $C_{d,cdg}$ before and after the horizontal shift

Appendix F Drawing of Crump-De Gruyter model used by Spaan

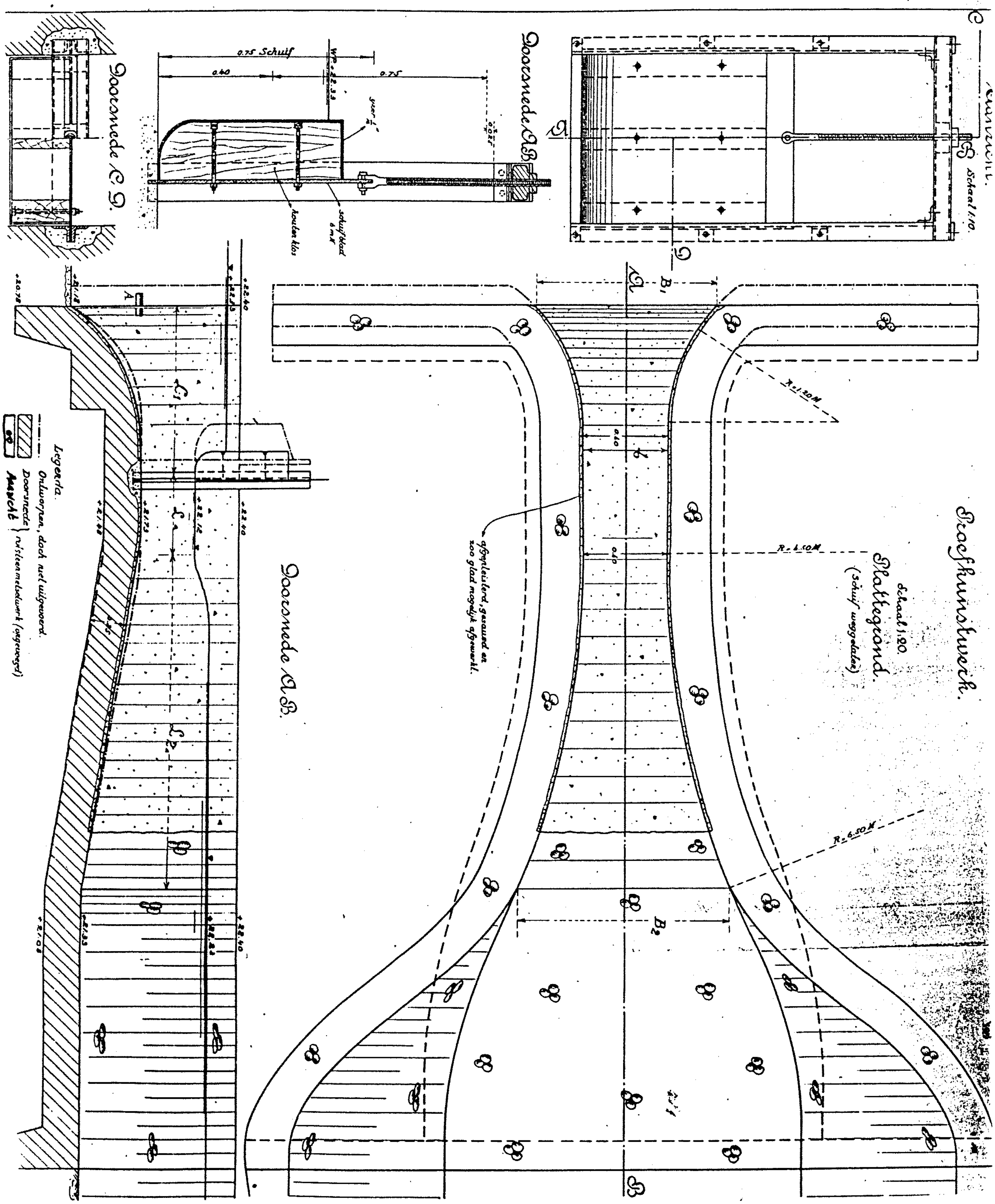


Figuur 4.1 Zijaanzicht laboratoriumopstelling Crump-De Gruyter meet-en regelkunstwerk



Figuur 4.2 Bovenaanzicht laboratoriumopstelling Crump-De Gruyter meet-en regelkunstwerk

Appendix G Drawing of Crump-De Gruyter model used by Gruyter



Appendix H Basic data from the measurements

The basic data from the six experiments (which are defined in the measurement protocol in section 2.6.2) are given in this section. All measured water levels are readings on the point gauges (or static pressure tube in case of h_3 measurement using a Pitot tube). To derive water levels above the laboratory canal bottom or water levels above the weir crest, the reference bottom level or respectively the reference weir crest level (table 3.2) have to be subtracted from the measured water levels. To make the data more accessible, it is processed in appendix I.

The accuracy of measurement is determined by the accuracy of the measurement equipment (Appendix A) and the flow conditions. The accuracy of measurement is given by the number of digits in the tables. In some cases water level fluctuations were too large. In these cases the measurements are replaced by a '****' sign.

H.1 Experiment I: Free- and submerged weir flow

$h_{rehbock}$ level [cm]	h_1 level [cm]	h_{2a} level [cm]	h_{2b} level [cm]	h_3 level [cm]		w_{cdg} [cm]
				Pitot tube	Point gauge	
Q = ± 19 l/s and an increasing downstream water level						
20.70	23.49	10.8	7.1	-1.9 .. -2.0	****	****
20.70	23.50	10.8	7.1	0.5	****	****
20.71	23.49	10.8	7.1	2.7 .. 2.8	****	****
20.71	23.57	11.1	****	5.1 ..5.2	****	****
20.69	23.68	11.3	****	5.3 ..5.4	****	****
20.69	23.81	11.7	10.0	5.6	****	****
20.69	24.06	12.2	****	5.8 .. 5.9	****	****
20.70	24.35	12.8	10.8	6.2	****	****
20.69	27.44	16.9	14.9	****	30.33	****
20.66	31.05	20.79	18.81	****	34.02	****
20.61	34.39	24.27	22.29	****	37.38	****
Q = ± 19 l/s and a decreasing downstream water level						
20.70	23.49	10.8	7.1	-2.3 .. -2.4	****	****
20.70	23.49	10.8	7.1	0.1 .. 0.2	****	****
20.71	23.49	10.8	7.1	2.2 .. 2.3	****	****
20.71	23.54	11.0	7.9	4.9	****	****
20.71	23.57	11.1	8.9	5.2	****	****
20.70	23.72	11.5	****	5.6 .. 5.7	****	****
20.71	24.01	12.1	****	5.9 .. 6.0	****	****
20.71	24.14	12.5	10.5	6.2	****	****
20.71	27.34	16.76	14.8	****	30.24	****
20.65	30.70	20.43	18.46	****	33.67	****
20.61	34.39	24.27	22.29	****	37.38	****
Q = ± 27 l/s and an increasing downstream water level						
22.71	25.72	12.5	8.3	1.1 .. 1.2	****	****
22.70	25.73	12.5	8.3	2.6 .. 2.7	****	****
22.70	25.74	12.6	8.4	5.0 .. 5.1	****	****
22.70	25.78	12.7	****	7.0	****	****
22.70	25.82	12.8	****	7.1	****	****
22.69	25.89	12.9	****	7.3 .. 7.4	****	****
22.70	26.01	13.3	****	7.6 .. 7.7	****	****
22.68	26.26	13.9	****	8.0 .. 8.1	****	****
22.66	29.34	18.4	16.5	11.3 .. 11.4	****	****
22.64	32.44	21.98	20.00	****	35.36	****

22.61	35.13	24.35	22.87	****	38.08	****
Q = ± 35 l/s and an increasing downstream water level						
24.51	27.78	14.2	9.5	2.1	****	****
24.50	27.79	14.2	9.5	3.9 .. 4.0	****	****
24.51	27.78	14.2	9.6	6.1	****	****
24.52	27.80	14.3	10.0	8.2	****	****
24.52	27.82	14.3	****	8.6 .. 8.7	****	****
24.53	27.85	14.5	****	8.9 .. 9.0	****	****
24.53	27.95	14.6	****	9.2	****	****
24.52	28.15	15.0	****	9.6 .. 9.7	****	****
24.50	30.51	19.1	17.1	12.4 .. 12.5	****	****
24.48	32.88	22.0	20.1	****	35.70	****
24.44	35.27	24.7	22.8	****	38.17	****
Q = ± 43 l/s and an increasing downstream water level						
26.26	29.73	15.7	10.7	4.1	****	****
26.29	29.72	15.7	10.7	6.1 ..6.2	****	****
26.30	29.74	15.8	10.9	8.5	****	****
26.33	29.78	15.9	****	9.9	****	****
26.30	29.83	16.0	****	10.3 .. 10.4	****	****
26.31	29.84	16.0	****	10.5 .. 10.6	****	****
26.28	29.94	16.2	****	10.8 .. 10.9	****	****
26.28	30.06	16.5	****	11.3 .. 11.4	****	****
26.28	31.67	****	****	13.6	****	****
26.25	33.50	22.2	20.2	15.4	****	****
26.22	35.20	24.2	22.3	****	38.03	****
Q = ± 51 l/s and an increasing downstream water level						
27.75	31.35	17.0	11.8	5.6 .. 5.7	****	****
27.76	31.35	17.0	11.8	7.9 .. 8.0	****	****
27.75	31.41	17.1	11.9	9.8	****	****
27.80	31.45	17.2	12.5	11.5	****	****
27.79	31.45	17.3	12.5	11.7	****	****
27.76	31.48	17.4	12.8	11.9	****	****
27.75	31.54	17.4	****	12.1 .. 12.2	****	****
27.75	31.73	17.8	****	12.6 .. 12.7	****	****
27.79	32.74	19.8	****	14.3 .. 14.4	****	****
27.75	34.29	22.2	20.4	15.9	****	****
27.72	35.65	24.2	22.3	17.5 ..17.6	****	****
two extra measurements under free flow conditions for comparison results with results from Spaan						
17.77	20.17	****	****	****	****	****
19.11	21.72	****	****	****	****	****

Table H.1 basic data of experiment I: Free- and submerged weir flow

H.2 Experiment II: Free weir and free orifice flow

$h_{rehbock}$ level [cm]	h_1 level [cm]	h_{2a} level [cm]	h_{2b} level [cm]	h_3 level [cm] Pitot tube	h_3 level [cm] Point gauge	w_{cdg} [cm]
Q = ± 19 l/s and a decreasing gate opening						
20.58	23.37	11.1	7.0	****	****	7.9
20.66	23.51	10.7	7.1	****	****	7.1
20.63	23.51	9.9	7.0	****	****	6.3
20.65	24.05	9.1	6.7	****	****	5.5
20.64	24.87	8.6	6.3	****	****	4.9
20.61	26.06	8.1	6.2	****	****	4.5
20.61	28.79	7.5	6.0	****	****	3.9
20.58	31.39	7.1	5.8	****	****	3.4
20.50	35.27	6.7	****	****	****	3.0
20.52	38.31	6.5	****	****	****	2.8
Q = ± 19 l/s and an increasing gate opening						
20.68	23.46	11.2	7.1	****	****	8.0
20.69	23.43	10.5	7.1	****	****	7.1
20.68	23.61	9.7	6.9	****	****	6.2
20.66	24.01	9.2	6.6	****	****	5.6
20.68	24.70	8.7	6.4	****	****	5.1
20.66	26.20	8.1	6.2	****	****	4.5
20.64	28.14	7.7	6.0	****	****	4.0
20.60	30.83	7.2	5.8	****	****	3.5
20.57	35.01	6.8	5.6	****	****	3.1
20.54	38.68	6.4	****	****	****	2.8
Q = ± 27 l/s and a decreasing gate opening						
22.71	25.72	13.0	8.4	****	****	9.8
22.72	25.73	12.1	8.4	****	****	8.7
22.69	26.00	11.2	8.1	****	****	7.6
22.69	26.97	10.1	7.6	****	****	6.5
22.67	28.80	9.3	7.3	****	****	5.7
22.66	30.15	9.0	7.1	****	****	5.3
22.64	32.70	8.4	6.9	****	****	4.8
22.62	35.06	8.1	6.7	****	****	4.4
22.60	37.30	7.8	6.6	****	****	4.1
22.58	39.28	7.6	6.4	****	****	3.9
Q = ± 35 l/s and a decreasing gate opening						
24.59	27.79	****	****	****	****	11.6
24.55	27.78	13.8	9.7	****	****	10.3
24.55	28.08	12.7	9.4	****	****	9.3
24.57	29.01	11.5	8.8	****	****	8.0
24.53	30.78	10.6	8.4	****	****	7.1
24.51	32.93	10.0	8.1	****	****	6.4
24.45	36.40	9.2	7.8	****	****	5.6
24.40	40.11	8.7	****	****	****	5.1
24.40	41.51	8.6	****	****	****	4.9
Q = ± 43 l/s and a decreasing gate opening						
26.24	29.60	****	****	****	****	13.1
26.23	29.56	15.7	10.8	****	****	12.4
26.23	29.75	14.6	10.6	****	****	11.1
26.22	30.01	14.0	10.4	****	****	10.5
26.21	30.28	13.4	10.2	****	****	10.0
26.23	30.75	12.9	9.9	****	****	9.5
26.20	31.30	12.5	9.7	****	****	9.0

26.20	32.72	11.7	9.4	****	****	8.2
26.16	35.60	10.9	9.0	****	****	7.3
26.12	39.12	10.1	8.6	****	****	6.5
Q = ± 51 l/s and a decreasing gate opening						
27.77	31.28	****	****	****	****	14.5
27.80	31.30	16.8	****	****	****	13.5
27.80	31.40	16.3	****	****	****	13.0
27.76	31.65	15.3	****	****	****	11.9
27.75	32.07	14.7	11.2	****	****	11.2
27.77	32.63	14.1	10.9	****	****	10.6
27.73	33.74	13.2	10.5	****	****	9.7
27.73	35.74	12.4	10.1	****	****	8.9
27.68	38.41	11.6	****	****	****	8.1
27.65	39.28	11.4	****	****	****	7.8

Table H.2 Basic data of experiment II: Free weir and free orifice flow

H.3 Experiment III: Free and submerged orifice flow

$h_{rehbock}$ level [cm]	h_1 level [cm]	h_{2a} level [cm]	h_{2b} level [cm]	h_3 level [cm] Pitot tube	h_3 level [cm] Point gauge	w_{cdg} [cm]
Q = ± 19 l/s and an increasing downstream water level						
20.69	26.87	8.0	6.2	-1.4	****	4.3
20.69	26.87	8.0	6.2	0.8 .. 0.9	****	4.3
20.70	26.90	8.0	6.2	3.3	****	4.3
20.70	26.91	8.0	****	5.6 .. 5.7	****	4.3
20.70	26.91	8.0	****	5.9 .. 6.0	****	4.3
20.69	27.5	****	****	6.1 .. 6.2	****	4.3
20.69	28.0	****	****	6.4 .. 6.5	****	4.3
20.71	28.2	****	****	6.5 .. 6.7	****	4.3
20.66	32.4	****	****	9.1 .. 9.2	****	4.3
20.62	35.3	****	****	11.3 .. 11.4	****	4.3
20.62	38.7	****	****	14.3 .. 14.4	****	4.3
Q = ± 19 l/s and a decreasing downstream water level						
20.73	26.87	8.0	6.1	-1.8 .. -1.9	****	4.3
20.70	26.88	8.0	6.1	0.1	****	4.3
20.72	26.91	8.0	6.2	2.8 .. 2.9	****	4.3
20.71	26.91	8.0	****	5.0	****	4.3
20.72	26.91	8.0	****	5.6 .. 5.7	****	4.3
20.71	26.91	8.0	****	5.9 .. 6.0	****	4.3
20.72	27.7	****	****	6.1 .. 6.2	****	4.3
20.71	28.2	****	****	6.4 .. 6.5	****	4.3
20.67	32.8	****	****	9.4 .. 9.5	****	4.3
20.63	35.8	****	****	11.8 .. 11.9	****	4.3
20.62	38.7	****	****	14.3 .. 14.4	****	4.3
Q = ± 27 l/s and an increasing downstream water level						
22.71	29.73	9.1	7.2	0.9	****	5.5
22.71	29.74	9.1	7.2	3.6	****	5.5
22.72	29.77	9.1	7.2	5.8	****	5.5
22.72	29.78	9.1	****	7.9	****	5.5
22.72	29.79	9.1	****	8.2 .. 8.3	****	5.5
22.68	30.5	****	****	8.7	****	5.5
22.68	31.2	****	****	9.0	****	5.5
22.67	31.6	****	****	9.3	****	5.5
22.66	34.2	****	****	10.9 .. 11.0	****	5.5
22.64	36.8	****	****	12.6	****	5.5
22.61	38.9	****	****	14.3 .. 14.4	****	5.5
Q = ± 35 l/s and an increasing downstream water level						
24.52	32.96	10.0	8.1	4.0	****	6.4
24.52	32.95	10.0	8.1	5.9	****	6.4
24.52	32.96	10.0	8.1	8.0	****	6.4
24.49	32.96	10.0	****	10.0 .. 10.1	****	6.4
24.52	32.95	10.0	****	10.3 .. 10.4	****	6.4
24.53	34.0	****	****	11.0	****	6.4
24.52	34.3	****	****	11.2 .. 11.4	****	6.4
24.49	35.0	****	****	11.6 .. 11.8	****	6.4
24.46	36.2	****	****	12.5 .. 12.6	****	6.4
24.44	37.3	****	****	13.1 .. 13.2	****	6.4
24.44	38.9	****	****	14.0 .. 14.1	****	6.4
Q = ± 43 l/s and an increasing downstream water level						
26.25	31.38	12.5	9.7	5.0 .. 5.1	****	8.9
26.26	31.39	12.5	9.7	7.5	****	8.9

26.25	31.38	12.5	9.9	9.4 .. 9.5	****	8.9
26.24	31.4	12.5	****	10.4 .. 10.5	****	8.9
26.23	31.6	12.6	****	11.8	****	8.9
26.20	32.4	****	****	12.1 .. 12.2	****	8.9
26.22	32.7	****	****	12.3 .. 12.4	****	8.9
26.21	33.0	****	****	12.6 .. 12.7	****	8.9
26.22	34.9	****	****	13.8 .. 13.9	****	8.9
26.18	36.5	****	****	14.9	****	8.9
26.15	38.7	****	****	16.3 .. 16.4	****	8.9
Q = ± 51 l/s and an increasing downstream water level						
27.77	33.90	13.2	10.5	6.4	****	9.7
27.78	33.95	13.2	10.5	8.4 .. 8.5	****	9.7
27.78	33.95	13.2	****	10.7 .. 10.8	****	9.7
27.76	34.1	13.2	****	13.0	****	9.7
27.77	34.2	13.3	****	13.3 .. 13.4	****	9.7
27.78	34.3	13.3	****	13.5 .. 13.6	****	9.7
27.78	35.3	****	****	14.2 .. 14.3	****	9.7
27.74	35.8	****	****	14.6 .. 14.7	****	9.7
27.75	37.3	****	****	15.6 .. 15.8	****	9.7
27.71	39.8	****	****	16.4 .. 16.6	****	9.7

Table H.3 Basic data of experiment III: Free- and submerged orifice flow

H.4 Experiment IV: Free weir- and submerged orifice flow

$h_{rehbock}$ level [cm]	h_1 level [cm]	h_{2a} level [cm]	h_{2b} level [cm]	h_3 level [cm]		w_{cdg} [cm]
				Pitot tube	Point gauge	
Q = ± 19 l/s and an increasing downstream water level						
20.57	23.31	11.1	7.0	-0.7 .. -0.8	****	7.7
20.55	23.31	11.1	7.0	2.3 .. 2.4	****	7.7
20.56	23.34	11.1	****	4.8 .. 4.9	****	7.7
20.55	25.95	****	****	7.6 .. 7.7	****	7.7
20.52	29.04	****	****	10.4	****	7.7
20.50	30.91	****	****	12.0	****	7.7
20.49	32.50	****	****	13.4	****	7.7
20.46	34.20	****	****	14.9	****	7.7
20.46	35.66	****	****	16.3 .. 16.4	****	7.7
20.46	37.13	****	****	17.8	****	7.7
20.43	38.85	****	****	19.3 .. 19.4	****	7.7
Q = ± 19 l/s and a decreasing downstream water level						
20.57	23.30	11.1	7.0	-0.8 .. -0.9	****	7.7
20.57	23.30	11.1	7.0	1.9 .. 2.0	****	7.7
20.56	23.34	11.1	****	4.8 .. 4.9	****	7.7
20.54	25.74	****	****	7.5	****	7.7
20.52	28.82	****	****	10.3	****	7.7
20.51	30.62	****	****	11.8 .. 11.9	****	7.7
20.50	32.28	****	****	13.3 .. 13.4	****	7.7
20.48	33.87	****	****	14.8	****	7.7
20.47	35.49	****	****	16.3 .. 16.4	****	7.7
20.45	37.35	****	****	18.1	****	7.7
20.43	38.85	****	****	19.3 .. 19.4	****	7.7
Q = ± 27 l/s and an increasing downstream water level						
22.73	25.74	****	****	0.5	****	9.9
22.72	25.74	****	****	4.0	****	9.9
22.74	26.08	****	****	7.7 .. 7.8	****	9.9
22.69	29.14	****	****	11.2	****	9.9
22.65	33.32	****	****	14.3 .. 14.4	****	9.9
22.65	34.35	****	****	15.2	****	9.9
22.63	35.23	****	****	16.0	****	9.9
22.62	36.12	****	****	16.7 .. 16.8	****	9.9
22.62	36.92	****	****	17.4 .. 17.5	****	9.9
22.60	37.89	****	****	18.4	****	9.9
22.62	38.54	****	****	19.0 .. 19.1	****	9.9
Q = ± 35 l/s and an increasing downstream water level						
24.48	27.64	****	****	2.9 .. 3.0	****	11.5
24.48	27.66	****	****	4.9 .. 5.0	****	11.5
24.49	27.71	14.7	****	8.0	****	11.5
24.49	28.32	15.2	****	10.0	****	11.5
24.47	30.58	****	****	12.2 .. 12.3	****	11.5
24.40	32.05	****	****	13.5	****	11.5
24.41	33.50	****	****	14.8	****	11.5
24.41	34.95	****	****	15.8 .. 15.9	****	11.5
24.42	36.33	****	****	17.0	****	11.5
24.41	37.86	****	****	18.3	****	11.5
24.41	39.28	****	****	19.6	****	11.5
Q = ± 43 l/s and an increasing downstream water level						
26.19	29.55	****	****	3.7	****	13.0
26.21	29.55	****	****	6.4 .. 6.5	****	13.0

26.23	29.57	****	****	9.7 .. 9.8	****	13.0
26.18	30.65	16.9	****	12.3 .. 12.4	****	13.0
26.18	31.68	****	****	14.9	****	13.0
26.18	34.65	****	****	15.8	****	13.0
26.15	35.82	****	****	16.7 .. 16.8	****	13.0
26.15	36.78	****	****	17.5	****	13.0
26.10	37.70	****	****	18.3	****	13.0
26.08	38.85	****	****	19.3	****	13.0
26.08	39.65	****	****	20.0	****	13.0
Q = ± 51 l/s and an increasing downstream water level						
27.76	31.80	****	****	6.2 .. 6.3	****	14.7
27.77	31.30	****	****	8.6	****	14.7
27.77	31.36	****	****	11.6 .. 11.7	****	14.7
27.76	32.19	18.3	****	13.8 .. 13.9	****	14.7
27.71	35.25	****	****	16.5	****	14.7
27.70	36.25	****	****	17.4	****	14.7
27.68	37.29	****	****	18.2 .. 18.3	****	14.7
27.66	38.5	****	****	19.2 .. 19.3	****	14.7
27.64	40.2	****	****	20.6 .. 20.7	****	14.7
27.62	40.9	****	****	21.3	****	14.7
27.62	41.5	****	****	21.8 .. 21.9	****	14.7

Table H.4 Basic data of experiment IV: Free weir- and submerged orifice flow

H.5 Experiment V: Submerged weir- and submerged orifice flow

$h_{rehbock}$ level [cm]	h_1 level [cm]	h_{2a} level [cm]	h_{2b} level [cm]	h_3 level [cm]		w_{cdg} [cm]
				Pitot tube	Point gauge	
Q = ± 19 l/s and an increasing downstream water level						
20.64	25.88	14.8	13.2	7.9	****	11.6
20.63	26.84	16.3	****	9.0	****	11.6
20.63	27.93	****	****	10.1	****	11.6
20.62	29.09	****	****	11.2	****	11.6
20.61	30.57	****	****	12.4 .. 12.5	****	11.6
20.60	31.78	****	****	13.7 .. 13.8	****	11.6
20.59	33.40	****	****	15.2	****	11.6
20.57	35.22	****	****	17.0	****	11.6
20.55	36.77	****	****	18.4	****	11.6
20.54	38.14	****	****	19.7	****	11.6
20.52	39.59	****	****	21.1 .. 21.2	****	11.6
Q = ± 19 l/s and a decreasing downstream water level						
20.66	25.65	14.6	****	7.8	****	11.6
20.65	26.16	15.4	****	8.4	****	11.6
20.64	27.77	****	****	10.1	****	11.6
20.62	29.09	****	****	11.2	****	11.6
20.61	30.17	****	****	12.2 .. 12.3	****	11.6
20.60	31.82	****	****	13.9	****	11.6
20.59	33.56	****	****	15.5 .. 15.6	****	11.6
20.58	35.17	****	****	17.0 .. 17.1	****	11.6
20.55	36.75	****	****	18.6	****	11.6
20.55	38.37	****	****	20.0 .. 20.1	****	11.6
20.52	39.59	28.4	26.6	21.1 .. 21.2	****	11.6
Q = ± 27 l/s and an increasing downstream water level						
22.70	28.76	17.6	15.6	10.7	****	14.3
22.67	30.36	****	****	12.5 ..12.6	****	14.3
22.65	32.05	****	****	14.1 .. 14.2	****	14.3
22.64	33.71	****	****	15.7	****	14.3
22.62	35.22	****	****	17.0 .. 17.1	****	14.3
22.60	36.22	****	****	18.1	****	14.3
22.60	37.19	****	****	18.9 .. 19.0	****	14.3
22.62	38.39	****	****	20.0	****	14.3
22.58	39.49	****	****	21.1	****	14.3
22.58	40.89	****	****	22.3 .. 22.4	****	14.3
22.58	41.87	****	****	23.3	****	14.3
Q = ± 35 l/s and an increasing downstream water level						
24.59	31.31	20.1	****	13.4	****	16.7
24.59	32.38	****	****	14.5	****	16.7
24.56	33.37	****	****	15.5	****	16.7
24.59	34.42	****	****	16.4 .. 16.5	****	16.7
24.56	35.52	****	****	17.5	****	16.7
24.57	36.56	****	****	18.4 .. 18.5	****	16.7
24.55	37.69	****	****	19.5	****	16.7
24.55	38.68	****	****	20.4	****	16.7
24.54	39.73	****	****	21.3 .. 21.4	****	16.7
24.51	40.82	****	****	22.3 .. 22.4	****	16.7
24.50	41.46	****	****	23.0 .. 23.1	****	16.7
Q = ± 43 l/s and an increasing downstream water level						
26.23	33.90	****	****	15.9 ..16.0	****	19.2
26.25	34.65	****	****	16.7 .. 16.8	****	19.2

Appendix I Data processing

The basic data from Appendix H consists of readings on point gauges and a static pressure tube. For deriving water levels above the laboratory canal bottom or weir crests, the reference bottom- or weir crest level have to be subtracted from the basic data. In this appendix the data from appendix H is processed.

The variables in the data processing are defined by:

Q	=	discharge	[m^3/s]
$h_{1\ weir}$	=	upstream water level above weir crest	[m]
$h_{1\ bottom}$	=	upstream water level above the channel bottom	[m]
$h_{2a\ weir}$	=	water depth above weir crest (see figure 3.1 and table 3.1)	[m]
$h_{2b\ weir}$	=	water depth above weir crest (see figure 3.1 and table 3.1)	[m]
$h_{3\ weir}$	=	downstream water level above weir crest	[m]
$h_{3\ bottom}$	=	downstream water level above channel bottom	[m]
w_{cdg}	=	vertical orifice opening	[m]

The maximum errors in the variables are given in table I.1. The maximum errors in the calculated variables are given in appendix B. The maximum error in the orifice opening can be found in appendix A.

	Q [m^3/s]	$h_{1\ weir}$ [m]	$h_{1\ bottom}$ [m]	$h_{2a\ weir}$ [m]	$h_{2b\ weir}$ [m]	$h_{3\ weir}$ [m]	$h_{3\ bottom}$ [m]	w_{cdg} [m]
max. error	1.5%	$8\ 10^{-4}$	$6\ 10^{-4}$	$6\ 10^{-4}$	$6\ 10^{-4}$	$1.2\ 10^{-3}$	$1.2\ 10^{-3}$	$1\ 10^{-3}$

Table I.1 Maximum errors in the calculated variables

I.1 Experiment I: Free- and submerged weir flow

Q [m^3/s]	$h_{1\ weir}$ [m]	$h_{1\ bottom}$ [m]	$h_{2a\ weir}$ [m]	$h_{2b\ weir}$ [m]	$h_{3\ weir}$ [m]	$h_{3\ bottom}$ [m]	w_{cdg} [m]
increasing downstream water level							
0.0193	0.0991	0.2010	0.072	0.055	0.023	0.124	****
0.0193	0.0992	0.2011	0.072	0.055	0.047	0.148	****
0.0194	0.0991	0.2010	0.072	0.055	0.070	0.171	****
0.0194	0.0999	0.2018	0.075	****	0.094	0.195	****
0.0193	0.1010	0.2029	0.077	****	0.096	0.197	****
0.0193	0.1023	0.2042	0.081	0.084	0.098	0.199	****
0.0193	0.1048	0.2067	0.086	****	0.101	0.202	****
0.0193	0.1077	0.2096	0.092	0.092	0.104	0.205	****
0.0193	0.1386	0.2405	0.133	0.133	0.1374	0.2382	****
0.0192	0.1747	0.2766	0.172	0.172	0.1743	0.2751	****
0.0190	0.2081	0.3100	0.207	0.207	0.2079	0.3087	****
decreasing downstream water level							
0.0193	0.0991	0.2010	0.072	0.055	0.019	0.120	****
0.0193	0.0991	0.2010	0.072	0.055	0.044	0.145	****
0.0194	0.0991	0.2010	0.072	0.055	0.065	0.166	****
0.0194	0.0996	0.2015	0.074	0.063	0.091	0.192	****
0.0194	0.0999	0.2018	0.075	0.073	0.094	0.195	****
0.0193	0.1014	0.2033	0.079	****	0.099	0.120	****
0.0194	0.1043	0.2062	0.085	****	0.102	0.203	****
0.0194	0.1056	0.2075	0.089	0.089	0.104	0.205	****
0.0192	0.1376	0.2395	0.132	0.132	0.1365	0.2373	****
0.0191	0.1712	0.2731	0.168	0.168	0.1708	0.2716	****
0.0190	0.2081	0.3100	0.207	0.207	0.2079	0.3087	****
increasing downstream water level							
0.0271	0.1214	0.2233	0.089	0.067	0.054	0.155	****

0.0271	0.1215	0.2234	0.089	0.067	0.069	0.170	****
0.0271	0.1216	0.2235	0.090	0.068	0.093	0.194	****
0.0271	0.1220	0.2239	0.091	****	0.112	0.213	****
0.0271	0.1224	0.2243	0.092	****	0.113	0.214	****
0.0271	0.1231	0.2250	0.093	****	0.116	0.217	****
0.0271	0.1243	0.2262	0.097	****	0.119	0.220	****
0.0270	0.1268	0.2287	0.103	****	0.123	0.224	****
0.0269	0.1576	0.2595	0.148	0.149	0.156	0.257	****
0.0269	0.1886	0.2905	0.184	0.184	0.1877	0.2885	****
0.0267	0.2155	0.3174	0.208	0.212	0.2149	0.3157	****
increasing downstream water level							
0.0350	0.1420	0.2439	0.106	0.079	0.063	0.164	****
0.0349	0.1421	0.2440	0.106	0.079	0.082	0.183	****
0.0350	0.1420	0.2439	0.106	0.080	0.103	0.204	****
0.0350	0.1422	0.2441	0.107	0.084	0.124	0.225	****
0.0350	0.1424	0.2443	0.107	****	0.129	0.230	****
0.0351	0.1427	0.2446	0.109	****	0.132	0.233	****
0.0351	0.1437	0.2456	0.110	****	0.134	0.235	****
0.0350	0.1457	0.2476	0.114	****	0.139	0.240	****
0.0349	0.1693	0.2712	0.155	0.155	0.167	0.268	****
0.0348	0.1930	0.2949	0.184	0.185	0.1911	0.2919	****
0.0346	0.2169	0.3188	0.211	0.212	0.2158	0.3166	****
increasing downstream water level							
0.0433	0.1615	0.2634	0.121	0.091	0.083	0.184	****
0.0434	0.1614	0.2633	0.121	0.091	0.104	0.205	****
0.0435	0.1616	0.2635	0.122	0.093	0.127	0.228	****
0.0436	0.1620	0.2639	0.123	****	0.141	0.242	****
0.0435	0.1625	0.2644	0.124	****	0.146	0.247	****
0.0435	0.1626	0.2645	0.124	****	0.148	0.249	****
0.0434	0.1636	0.2655	0.126	****	0.151	0.252	****
0.0434	0.1648	0.2667	0.129	****	0.156	0.257	****
0.0434	0.1809	0.2828	****	****	0.178	0.279	****
0.0432	0.1992	0.3011	****	****	0.196	0.297	****
0.0431	0.2162	0.3181	****	****	0.2144	0.3152	****
increasing downstream water level							
0.0509	0.1777	0.2796	0.134	0.102	0.099	0.200	****
0.0509	0.1777	0.2796	0.134	0.102	0.122	0.223	****
0.0509	0.1783	0.2802	0.135	0.103	0.140	0.241	****
0.0511	0.1787	0.2806	0.136	0.109	0.157	0.258	****
0.0511	0.1787	0.2806	0.137	0.109	0.159	0.260	****
0.0509	0.1790	0.2809	0.138	0.112	0.161	0.262	****
0.0509	0.1796	0.2815	0.138	****	0.164	0.265	****
0.0509	0.1815	0.2834	0.142	****	0.169	0.270	****
0.0511	0.1916	0.2935	0.162	****	0.186	0.287	****
0.0509	0.2071	0.3090	0.186	0.188	0.201	0.302	****
0.0507	0.2207	0.3226	0.206	0.207	0.218	0.319	****
two extra measurements under free flow conditions for comparison results with results from Spaan							
0.0098	0.0659	0.1678	****	****	****	****	****
0.0139	0.0814	0.1833	****	****	****	****	****

Table I.2 Processed data from experiment I: Free- and submerged weir flow

I.2 Experiment II: Free weir- and free orifice flow

Q [m³/s]	$h_{1\,weir}$ [m]	$h_{1\,bottom}$ [m]	$h_{2a\,weir}$ [m]	$h_{2b\,weir}$ [m]	$h_{3\,weir}$ [m]	$h_{3\,bottom}$ [m]	w_{cdg} [m]
decreasing gate opening and downstream water level well below weir crest Cr.deGr.							
0.0189	0.0979	0.1998	0.075	0.054	****	****	0.079
0.0192	0.0993	0.2012	0.071	0.055	****	****	0.071
0.0191	0.0993	0.2012	0.063	0.054	****	****	0.063
0.0191	0.1047	0.2066	0.055	****	****	****	0.055
0.0191	0.1129	0.2148	0.050	****	****	****	0.049
0.0190	0.1248	0.2267	0.045	0.046	****	****	0.045
0.0190	0.1521	0.2540	0.039	****	****	****	0.039
0.0189	0.1781	0.2800	0.035	0.042	****	****	0.034
0.0186	0.2169	0.3188	0.031	****	****	****	0.030
0.0187	0.2473	0.3492	0.029	****	****	****	0.028
increasing gate opening and downstream water level well below weir crest Cr.deGr.							
0.0193	0.0988	0.2007	0.076	0.055	****	****	0.080
0.0193	0.0985	0.2004	0.069	0.055	****	****	0.071
0.0193	0.1003	0.2022	0.061	0.053	****	****	0.062
0.0192	0.1043	0.2062	0.056	0.050	****	****	0.056
0.0193	0.1112	0.2131	0.051	0.048	****	****	0.051
0.0192	0.1262	0.2281	0.045	0.046	****	****	0.045
0.0191	0.1456	0.2475	0.041	0.044	****	****	0.040
0.0190	0.1725	0.2744	0.036	0.042	****	****	0.035
0.0189	0.2143	0.3162	0.032	0.040	****	****	0.031
0.0187	0.2510	0.3529	0.028	****	****	****	0.028
decreasing gate opening and downstream water level well below weir crest Cr.deGr.							
0.0271	0.1214	0.2233	0.094	0.068	****	****	0.098
0.0272	0.1215	0.2234	0.085	0.068	****	****	0.087
0.0271	0.1242	0.2261	0.076	0.065	****	****	0.076
0.0271	0.1339	0.2358	0.065	0.060	****	****	0.065
0.0270	0.1522	0.2541	0.057	0.057	****	****	0.057
0.0269	0.1657	0.2676	0.054	0.055	****	****	0.053
0.0269	0.1912	0.2931	0.048	0.053	****	****	0.048
0.0268	0.2148	0.3167	0.045	0.051	****	****	0.044
0.0267	0.2372	0.3391	0.042	0.050	****	****	0.041
0.0266	0.2570	0.3589	0.040	0.048	****	****	0.039
decreasing gate opening and downstream water level well below weir crest Cr.deGr.							
0.0353	0.1421	0.2440	****	****	****	****	0.116
0.0351	0.1420	0.2439	0.102	0.081	****	****	0.103
0.0351	0.1450	0.2469	0.091	0.078	****	****	0.093
0.0352	0.1543	0.2562	0.079	0.072	****	****	0.080
0.0351	0.1720	0.2739	0.070	0.0.68	****	****	0.071
0.0350	0.1935	0.2954	0.064	0.065	****	****	0.064
0.0347	0.2282	0.3301	0.056	0.062	****	****	0.056
0.0345	0.2653	0.3672	0.051	****	****	****	0.051
0.0345	0.2793	0.3812	0.050	****	****	****	0.049
decreasing gate opening and downstream water level well below weir crest Cr.deGr.							
0.0432	0.1602	0.2621	****	****	****	****	0.131
0.0431	0.1598	0.2617	0.121	0.092	****	****	0.124
0.0431	0.1617	0.2636	0.110	0.090	****	****	0.111
0.0431	0.1643	0.2662	0.104	0.088	****	****	0.105
0.0430	0.1670	0.2689	0.098	0.086	****	****	0.100
0.0431	0.1717	0.2736	0.093	0.083	****	****	0.095
0.0430	0.1772	0.2791	0.089	0.081	****	****	0.090
0.0430	0.1914	0.2933	0.081	0.078	****	****	0.082
0.0428	0.2202	0.3221	0.073	0.074	****	****	0.073

0.0426	0.2554	0.3573	0.065	0.070	****	****	0.065
decreasing gate opening and downstream water level well below weir crest Cr.deGr.							
0.0510	0.1770	0.2789	****	****	****	****	0.145
0.0511	0.1772	0.2791	0.132	****	****	****	0.135
0.0511	0.1782	0.2801	0.127	****	****	****	0.130
0.0509	0.1807	0.2826	0.117	****	****	****	0.119
0.0509	0.1849	0.2868	0.111	0.096	****	****	0.112
0.0510	0.1905	0.2924	0.105	0.093	****	****	0.106
0.0508	0.2016	0.3035	0.096	0.089	****	****	0.097
0.0508	0.2216	0.3235	0.088	0.085	****	****	0.089
0.0505	0.2483	0.3502	0.080	****	****	****	0.081
0.0503	0.2570	0.3589	0.078	****	****	****	0.078

Table I.3 Processed data from experiment II: Free weir and free orifice flow

I.3 Experiment III: Free- and submerged orifice flow

Q [m³/s]	$h_{1\ weir}$ [m]	$h_{1\ bottom}$ [m]	$h_{2a\ weir}$ [m]	$h_{2b\ weir}$ [m]	$h_{3\ weir}$ [m]	$h_{3\ bottom}$ [m]	w_{cdg} [m]
increasing downstream water level and $h_{1\ weir}/w \geq 3$							
0.0193	0.1329	0.2348	0.044	0.046	0.028	0.129	0.043
0.0193	0.1329	0.2348	0.044	0.046	0.051	0.152	0.043
0.0193	0.1332	0.2351	0.044	0.046	0.075	0.176	0.043
0.0193	0.1333	0.2352	0.044	****	0.099	0.200	0.043
0.0193	0.1333	0.2352	0.044	****	0.102	0.203	0.043
0.0193	0.1392	0.2411	****	****	0.104	0.205	0.043
0.0193	0.1442	0.2461	****	****	0.107	0.208	0.043
0.0194	0.1462	0.2481	****	****	0.108	0.209	0.043
0.0192	0.1882	0.2901	****	****	0.134	0.235	0.043
0.0190	0.2172	0.3191	****	****	0.156	0.257	0.043
0.0190	0.2512	0.3531	****	****	0.186	0.287	0.043
decreasing downstream water level and $h_{1\ weir}/w \geq 3$							
0.0194	0.1329	0.2348	0.044	0.045	0.024	0.125	0.043
0.0193	0.1330	0.2349	0.044	0.045	0.043	0.144	0.043
0.0194	0.1333	0.2352	0.044	0.046	0.071	0.172	0.043
0.0194	0.1333	0.2352	0.044	****	0.092	0.193	0.043
0.0194	0.1333	0.2352	0.044	****	0.099	0.200	0.043
0.0194	0.1333	0.2352	0.044	****	0.102	0.203	0.043
0.0194	0.1412	0.2431	****	****	0.104	0.205	0.043
0.0194	0.1462	0.2481	****	****	0.107	0.208	0.043
0.0192	0.1922	0.2941	****	****	0.137	0.238	0.043
0.0191	0.2222	0.3241	****	****	0.161	0.262	0.043
0.0190	0.2512	0.3531	****	****	0.186	0.287	0.043
increasing downstream water level and $h_{1\ weir}/w \geq 3$							
0.0271	0.1615	0.2634	0.055	0.056	0.051	0.152	0.055
0.0271	0.1616	0.2635	0.055	0.056	0.078	0.179	0.055
0.0272	0.1619	0.2638	0.055	0.056	0.100	0.201	0.055
0.0272	0.1620	0.2639	0.055	****	0.121	0.222	0.055
0.0272	0.1621	0.2640	0.055	****	0.125	0.226	0.055
0.0270	0.1692	0.2711	****	****	0.129	0.230	0.055
0.0270	0.1762	0.2781	****	****	0.132	0.233	0.055
0.0270	0.1802	0.2821	****	****	0.135	0.236	0.055
0.0269	0.2062	0.3081	****	****	0.152	0.253	0.055
0.0269	0.2322	0.3341	****	****	0.168	0.269	0.055
0.0267	0.2532	0.3551	****	****	0.186	0.287	0.055
increasing downstream water level and $h_{1\ weir}/w \geq 3$							
0.0350	0.1938	0.2957	0.064	0.065	0.082	0.183	0.064
0.0350	0.1937	0.2956	0.064	0.065	0.101	0.202	0.064
0.0350	0.1938	0.2957	0.064	0.065	0.122	0.223	0.064
0.0349	0.1938	0.2957	0.064	****	0.143	0.244	0.064
0.0350	0.1937	0.2956	0.064	****	0.146	0.247	0.064
0.0351	0.2042	0.3061	****	****	0.152	0.253	0.064
0.0350	0.2072	0.3091	****	****	0.155	0.256	0.064
0.0349	0.2142	0.3161	****	****	0.159	0.260	0.064
0.0347	0.2262	0.3281	****	****	0.168	0.269	0.064
0.0346	0.2372	0.3391	****	****	0.174	0.275	0.064
0.0346	0.2532	0.3551	****	****	0.183	0.284	0.064
increasing downstream water level and $h_{1\ weir}/w \geq 2$							
0.0432	0.1780	0.2799	0.089	0.081	0.093	0.194	0.089
0.0433	0.1781	0.2800	0.089	0.081	0.117	0.218	0.089
0.0432	0.1780	0.2799	0.089	0.083	0.137	0.238	0.089
0.0432	0.1782	0.2801	0.089	****	0.147	0.248	0.089

0.0431	0.1802	0.2821	0.090	****	0.160	0.261	0.089
0.0430	0.1882	0.2901	****	****	0.164	0.265	0.089
0.0431	0.1912	0.2931	****	****	0.166	0.267	0.089
0.0430	0.1942	0.2961	****	****	0.169	0.270	0.089
0.0431	0.2132	0.3151	****	****	0.181	0.282	0.089
0.0429	0.2292	0.3311	****	****	0.191	0.292	0.089
0.0427	0.2512	0.3531	****	****	0.206	0.307	0.089
increasing downstream water level and $h_{1\,weir}/w \geq 2$							
0.0510	0.2032	0.3051	0.096	0.089	0.106	0.207	0.097
0.0510	0.2037	0.3056	0.096	0.089	0.127	0.228	0.097
0.0510	0.2037	0.3056	0.096	****	0.150	0.251	0.097
0.0509	0.2052	0.3071	0.096	****	0.172	0.273	0.097
0.0510	0.2062	0.3081	0.097	****	0.176	0.277	0.097
0.0510	0.2072	0.3091	0.097	****	0.178	0.279	0.097
0.0510	0.2172	0.3191	****	****	0.185	0.286	0.097
0.0508	0.2222	0.3241	****	****	0.189	0.290	0.097
0.0509	0.2372	0.3391	****	****	0.199	0.300	0.097
0.0507	0.2622	0.3641	****	****	0.207	0.308	0.097

Table I.4 Processed data from experiment III: Free- and submerged orifice flow

I.4 Experiment IV: Free weir- and submerged orifice flow

Q [m³/s]	$h_{1\ weir}$ [m]	$h_{1\ bottom}$ [m]	$h_{2a\ weir}$ [m]	$h_{2b\ weir}$ [m]	$h_{3\ weir}$ [m]	$h_{3\ bottom}$ [m]	w_{cdg} [m]
increasing downstream water level							
0.0189	0.0973	0.1992	0.075	0.054	0.035	0.136	0.077
0.0188	0.0973	0.1992	0.075	0.054	0.066	0.167	0.077
0.0188	0.0976	0.1995	0.075	****	0.091	0.192	0.077
0.0188	0.1237	0.2256	****	****	0.119	0.220	0.077
0.0187	0.1546	0.2565	****	****	0.146	0.247	0.077
0.0186	0.1733	0.2752	****	****	0.162	0.263	0.077
0.0186	0.1892	0.2911	****	****	0.176	0.277	0.077
0.0185	0.2062	0.3081	****	****	0.191	0.292	0.077
0.0185	0.2208	0.3227	****	****	0.206	0.307	0.077
0.0183	0.2355	0.3374	****	****	0.220	0.321	0.077
0.0190	0.2527	0.3546	****	****	0.236	0.337	0.077
decreasing downstream water level							
0.0189	0.0972	0.1991	0.075	0.054	0.034	0.135	0.077
0.0189	0.0972	0.1991	0.075	0.054	0.062	0.163	0.077
0.0188	0.0976	0.1995	0.075	****	0.091	0.192	0.077
0.0187	0.1216	0.2235	****	****	0.117	0.218	0.077
0.0187	0.1524	0.2543	****	****	0.145	0.246	0.077
0.0186	0.1704	0.2723	****	****	0.161	0.262	0.077
0.0186	0.1870	0.2889	****	****	0.176	0.277	0.077
0.0185	0.2029	0.3048	****	****	0.190	0.291	0.077
0.0185	0.2191	0.3210	****	****	0.206	0.307	0.077
0.0184	0.2377	0.3396	****	****	0.223	0.324	0.077
0.0183	0.2527	0.3546	****	****	0.236	0.337	0.077
increasing downstream water level							
0.0272	0.1216	0.2235	****	****	0.047	0.148	0.099
0.0272	0.1216	0.2235	****	****	0.082	0.183	0.099
0.0273	0.1250	0.2269	****	****	0.120	0.221	0.099
0.0271	0.1556	0.2575	****	****	0.154	0.255	0.099
0.0269	0.1974	0.2993	****	****	0.186	0.287	0.099
0.0269	0.2077	0.3096	****	****	0.194	0.295	0.099
0.0268	0.2165	0.3184	****	****	0.202	0.303	0.099
0.0268	0.2254	0.3273	****	****	0.210	0.311	0.099
0.0268	0.2334	0.3353	****	****	0.217	0.318	0.099
0.0267	0.2431	0.3450	****	****	0.226	0.327	0.099
0.0268	0.2496	0.3515	****	****	0.233	0.334	0.099
increasing downstream water level							
0.0348	0.1406	0.2425	****	****	0.072	0.173	0.115
0.0348	0.1408	0.2427	****	****	0.092	0.193	0.115
0.0349	0.1413	0.2432	0.111	****	0.122	0.223	0.115
0.0349	0.1474	0.2493	0.116	****	0.142	0.243	0.115
0.0348	0.1700	0.2719	****	****	0.165	0.266	0.115
0.0345	0.1847	0.2866	****	****	0.177	0.278	0.115
0.0345	0.1992	0.3011	****	****	0.190	0.291	0.115
0.0345	0.2137	0.3156	****	****	0.201	0.302	0.115
0.0346	0.2275	0.3294	****	****	0.212	0.313	0.115
0.0345	0.2428	0.3447	****	****	0.225	0.326	0.115
0.0345	0.2570	0.3589	****	****	0.238	0.339	0.115
increasing downstream water level							
0.0429	0.1597	0.2616	****	****	0.079	0.180	0.130
0.0430	0.1597	0.2616	****	****	0.107	0.208	0.130
0.0431	0.1599	0.2618	****	****	0.140	0.241	0.130
0.0429	0.1707	0.2726	0.133	****	0.166	0.267	0.130

0.0429	0.1810	0.2829	****	****	0.191	0.292	0.130
0.0429	0.2107	0.3126	****	****	0.200	0.301	0.130
0.0427	0.2224	0.3243	****	****	0.210	0.311	0.130
0.0427	0.2320	0.3339	****	****	0.217	0.318	0.130
0.0425	0.2412	0.3431	****	****	0.225	0.326	0.130
0.0424	0.2527	0.3546	****	****	0.235	0.336	0.130
0.0424	0.2607	0.3626	****	****	0.242	0.343	0.130
increasing downstream water level							
0.0509	0.1772	0.2791	****	****	0.105	0.206	0.147
0.0510	0.1772	0.2791	****	****	0.128	0.229	0.147
0.0510	0.1778	0.2797	****	****	0.159	0.260	0.147
0.0509	0.1861	0.2880	0.147	****	0.181	0.282	0.147
0.0507	0.2167	0.3186	****	****	0.207	0.308	0.147
0.0506	0.2267	0.3286	****	****	0.216	0.317	0.147
0.0505	0.2371	0.3390	****	****	0.225	0.326	0.147
0.0504	0.2492	0.3511	****	****	0.235	0.336	0.147
0.0503	0.2662	0.3681	****	****	0.249	0.350	0.147
0.0502	0.2732	0.3751	****	****	0.255	0.356	0.147
0.0502	0.2792	0.3811	****	****	0.261	0.362	0.147

Table I.5 Processed data from experiment IV: Free weir- and submerged orifice flow

I.5 Experiment V: Submerged weir- and submerged orifice flow

Q [m³/s]	$h_{1\ weir}$ [m]	$h_{1\ bottom}$ [m]	$h_{2a\ weir}$ [m]	$h_{2b\ weir}$ [m]	$h_{3\ weir}$ [m]	$h_{3\ bottom}$ [m]	W_{cdg} [m]
increasing downstream water level							
0.0191	0.1230	0.2249	0.112	0.116	0.121	0.222	0.116
0.0191	0.1326	0.2345	0.127	****	0.132	0.233	0.116
0.0191	0.1435	0.2454	****	****	0.143	0.244	0.116
0.0190	0.1551	0.2570	****	****	0.154	0.255	0.116
0.0190	0.1699	0.2718	****	****	0.167	0.268	0.116
0.0190	0.1820	0.2839	****	****	0.180	0.281	0.116
0.0189	0.1982	0.3001	****	****	0.194	0.295	0.116
0.0189	0.2164	0.3183	****	****	0.212	0.313	0.116
0.0188	0.2319	0.3338	****	****	0.226	0.327	0.116
0.0187	0.2456	0.3475	****	****	0.239	0.340	0.116
0.0187	0.2601	0.3620	0.248	0.249	0.254	0.355	0.116
decreasing downstream water level							
0.0192	0.1207	0.2226	0.110	****	0.120	0.221	0.116
0.0191	0.1258	0.2277	0.118	****	0.126	0.227	0.116
0.0191	0.1419	0.2438	****	****	0.143	0.244	0.116
0.0190	0.1551	0.2570	****	****	0.154	0.255	0.116
0.0190	0.1659	0.2678	****	****	0.165	0.266	0.116
0.0190	0.1824	0.2843	****	****	0.181	0.282	0.116
0.0189	0.1998	0.3017	****	****	0.198	0.299	0.116
0.0189	0.2159	0.3178	****	****	0.213	0.314	0.116
0.0188	0.2317	0.3336	****	****	0.228	0.329	0.116
0.0188	0.2479	0.3498	****	****	0.243	0.344	0.116
0.0187	0.2601	0.3620	****	****	0.254	0.355	0.116
increasing downstream water level							
0.0271	0.1518	0.2573	0.140	0.140	0.149	0.250	0.143
0.0270	0.1678	0.2697	****	****	0.168	0.269	0.143
0.0269	0.1847	0.2866	****	****	0.184	0.285	0.143
0.0269	0.2013	0.3032	****	****	0.199	0.300	0.143
0.0268	0.2164	0.3183	****	****	0.213	0.314	0.143
0.0267	0.2264	0.3283	****	****	0.223	0.324	0.143
0.0267	0.2361	0.3380	****	****	0.232	0.333	0.143
0.0268	0.2481	0.3500	****	****	0.242	0.343	0.143
0.0266	0.2591	0.3610	****	****	0.253	0.354	0.143
0.0266	0.2731	0.3750	****	****	0.266	0.367	0.143
0.0266	0.2829	0.3848	****	****	0.275	0.376	0.143
increasing downstream water level							
0.0353	0.1773	0.2792	0.165	****	0.176	0.277	0.167
0.0353	0.1880	0.2899	****	****	0.187	0.288	0.167
0.0352	0.1979	0.2998	****	****	0.197	0.298	0.167
0.0353	0.2084	0.3103	****	****	0.207	0.308	0.167
0.0352	0.2194	0.3213	****	****	0.217	0.318	0.167
0.0352	0.2298	0.3317	****	****	0.227	0.328	0.167
0.0351	0.2411	0.3430	****	****	0.237	0.338	0.167
0.0351	0.2510	0.3529	****	****	0.246	0.347	0.167
0.0351	0.2615	0.3634	****	****	0.256	0.357	0.167
0.0350	0.2724	0.3743	****	****	0.266	0.367	0.167
0.0349	0.2788	0.3807	****	****	0.273	0.374	0.167
increasing downstream water level							
0.0431	0.2032	0.3051	****	****	0.202	0.303	0.192
0.0432	0.2107	0.3126	****	****	0.210	0.311	0.192
0.0432	0.2184	0.3203	****	****	0.218	0.319	0.192
0.0430	0.2260	0.3279	****	****	0.225	0.326	0.192

0.0429	0.2332	0.3351	****	****	0.232	0.333	0.192
0.0430	0.2422	0.3441	****	****	0.240	0.341	0.192
0.0429	0.2491	0.3510	****	****	0.246	0.347	0.192
0.0428	0.2588	0.3607	****	****	0.255	0.356	0.192
0.0427	0.2661	0.3680	****	****	0.262	0.363	0.192
0.0427	0.2736	0.3755	****	****	0.268	0.369	0.192
0.0426	0.2847	0.3866	****	****	0.279	0.380	0.192
increasing downstream water level							
0.0507	0.2212	0.3231	0.180	****	0.218	0.319	0.207
0.0506	0.2250	0.3269	****	****	0.223	0.324	0.207
0.0507	0.2332	0.3351	****	****	0.231	0.332	0.207
0.0504	0.2392	0.3411	****	****	0.237	0.338	0.207
0.0503	0.2461	0.3480	****	****	0.243	0.344	0.207
0.0503	0.2522	0.3541	****	****	0.248	0.349	0.207
0.0503	0.2581	0.3600	****	****	0.254	0.355	0.207
0.0503	0.2656	0.3675	****	****	0.261	0.362	0.207
0.0502	0.2712	0.3731	****	****	0.266	0.367	0.207
0.0502	0.2777	0.3796	****	****	0.273	0.374	0.207
0.0501	0.2867	0.3886	****	****	0.281	0.382	0.207

Table I.6 Processed data from experiment V: Submerged weir- and submerged orifice flow

I.6 Experiment VI: Submerged weir- and free orifice flow

Q [m³/s]	$h_{1\ weir}$ [m]	$h_{1\ bottom}$ [m]	$h_{2a\ weir}$ [m]	$h_{2b\ weir}$ [m]	$h_{3\ weir}$ [m]	$h_{3\ bottom}$ [m]	w_{cdg} [m]
decreasing gate opening							
0.0189	0.1242	0.2261	0.114	0.117	0.124	0.225	0.117
0.0190	0.1250	0.2269	****	****	0.124	0.225	0.095
0.0189	0.1302	0.2321	****	****	0.124	0.225	0.073
0.0189	0.1532	0.2551	****	****	0.124	0.225	0.050
0.0185	0.2672	0.3691	****	****	0.123	0.224	0.027
increasing gate opening							
0.0189	0.1238	0.2257	0.115	0.116	0.124	0.225	0.116
0.0190	0.1250	0.2269	****	****	0.124	0.225	0.096
0.0190	0.1302	0.2321	****	****	0.124	0.225	0.074
0.0189	0.1492	0.2511	****	****	0.124	0.225	0.052
0.0185	0.2672	0.3691	****	****	0.123	0.224	0.027
decreasing gate opening							
0.0273	0.1526	0.2545	0.141	****	0.151	0.252	0.144
0.0273	0.1540	0.2559	****	****	0.152	0.253	0.116
0.0272	0.1592	0.2611	****	****	0.152	0.253	0.094
0.0271	0.1802	0.2821	****	****	0.152	0.253	0.067
0.0268	0.2792	0.3811	****	****	0.150	0.251	0.040
decreasing gate opening							
0.0347	0.1779	0.2798	****	****	0.175	0.276	0.168
0.0347	0.1792	0.2811	****	****	0.177	0.278	0.141
0.0347	0.1852	0.2871	****	****	0.177	0.278	0.112
0.0347	0.2032	0.3051	****	****	0.177	0.278	0.084
0.0342	0.2612	0.3631	****	****	0.175	0.276	0.058
decreasing gate opening							
0.0431	0.2026	0.3045	0.190	****	0.201	0.302	0.191
0.0431	0.2037	0.3056	****	****	0.201	0.302	0.163
0.0430	0.2092	0.3111	****	****	0.201	0.302	0.134
0.0429	0.2232	0.3251	****	****	0.201	0.302	0.106
0.0427	0.2592	0.3611	****	****	0.201	0.302	0.078
decreasing gate opening							
0.0510	0.2227	0.3246	****	****	0.219	0.320	0.209
0.0508	0.2238	0.3257	****	****	0.220	0.321	0.185
0.0507	0.2272	0.3291	****	****	0.220	0.321	0.156
0.0507	0.2362	0.3381	****	****	0.219	0.320	0.131
0.0506	0.2582	0.3601	****	****	0.219	0.320	0.105

Table I.7 Processed data from experiment VI: Submerged weir- and free orifice flow

During measurements I up to VI, it is checked if hysteresis phenomenon occurred. This phenomenon was not found.