NTNU
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Assessment and Control of Methods for Flow Measurement Systems

Master of Civil and Environmental Engineering

Pauli Petter Nordvåg

Civil and Environmental Engineering
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Supervisor: Sveinung Sægrov, IBM
Co-supervisor: Maryam Beheshti, IBM
Tone Muthana, IBM

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

Abstract

This Master thesis is about the Palmer-Bowlus flume measuring open channel flow rates of waste water at Risvollan. Risvollan is a study catchment in Trondheim Norway, with a measuring station to investigate hydrological parameters through the year. The waste water measurement system consists of the flume (primary device), and a pressure gauge (secondary device). The Department of Civil and Environmental Engineering at the Norwegian University of Technology and Science (NTNU) wanted to confirm if the initial stage-discharge relation for the flume is valid, in order to use the data with confidence in accomplished and future studies. The objective for the thesis is to assure quality of the measurement system which is in use, and to document procedures and accuracy of tracer dilution measurements in waste water.

In order to validate the present stage-discharge curve, different methods was applied. The results from each method was presented as stage-discharge curves. The stage-discharge curve for each method was compared to the initial. The methods used were a theoretical desk-top method, tracer dilution method as an in-place calibration, and a laboratory method with in situ condition.

The study was limited to the primary measuring device, id est the Palmer-Bowlus flume. For the laboratory calibration a 1:1 model of the flume from Risvollan and belonging components had to constructed. In order to construct the model, casting techniques had to be studied to create a replica of the flume from Risvollan. Casting frame, installation of flume, measurement of in situ conditions and other practical assignments had to be carried out in order to reach the goal.

A comprehensive literature review concerning configurations of Palmer-Bowlus flumes, flow rate measurement for waste water, and casting techniques was carried out. The study compared different configurations of Palmer-Bowlus flumes found in literature, and compared them with the flume at Risvollan.

For the the theoretical method, tracer dilution and laboratory method the mean deviation from the initial stage-discharge curve was 0.35, 0.68 and 0.11 l/s respectively. The measurement range for each method varies, but covered the range of operation for the flume (5.0-9.0 cm). The results from the laboratory calibration confirms the initial stage-discharge curve for water levels between 4.0 cm up to 15.0 cm. It was also the method with highest expectation in terms of accuracy and repeatability. However, the full measurement range for the flume (4.0-21.0 cm) was not completed due to limitations in the model used for the laboratory calibration. These limitations can be exposed by doing small configurations to the flume itself. Further, new measurements can be conducted for the whole measurement range.

In the tracer dilution measurements there was found to be a systematic error in the measurements. Some of the sources of errors were discovered, but could not be quantified. In the measurements the sources of errors needs to be isolated to increase the accuracy of the measurements. The optimal injection point for tracer was found to be at a distance of approximately 8 times larger than what was recommended.

Sammendrag

Denne masteroppgaven handler om Palmer-Bowlus målerenna for frispeilsstrømning som måler vannføringen av avløpsvann på Risvollan. Risvollan er et forskningsfelt i Trondheim Norge, med en målestasjon som undersøker hydrologiske parametre gjennom året. Måleutstyret for avløpsvann består av selve målerenna (primærapparat), og en trykkmåler (sekundærapparat). Institutt for bygg- og miljøteknikk ved Norges teknisk-naturvitenskapelige universitet (NTNU) ønsket å kvalitetssikre gyldigheten til den opprinnelige vannføringskurva for målerenna for å kunne bruke tidligere data med fortrolighet i gjennomførte og fremtidige studier. Formålet med oppgaven er å kvalitetssikre målesystemet som er i bruk og å dokumentere prosedyrer og nøyaktighet ved bruk av sporstoff i avløpsvann.

Forskjellige metoder var anvendt for å kunne bekrefte gyldigheten til den opprinnelige vannføringskurva. Resultatene til hver metode var presentert som vannføringskurver. Vannføringskurva til hver metode var sammenlignet med den opprinnelige. De anvendte metodene var en teoretisk metode, vannføringsmåling ved hjelp av sporstoff for kalibrering på målestedet, og en kalibrering i laboratoriumet med like betingelser som på målestedet.

Studiet var avgrenset til primærapparatet, det vil si Palmer-Bowlus målerenna. For kalibrering i laboratorium ble en 1:1 model av målerenna med tilhørende konstruert. Støpemetoder ble studert for å lage en kopi av målerenna fra Risvollan. Forskalingsarbeid, installering av målerenne, målinger av måleområdets betingelser og andre praktiske oppgaver måtte gjennomføres for å oppnå kalibrering i laboratoriumet.

Et omfattende litteraturstudium ble gjennomført med hensyn på konfigurasjoner av Palmer-Bowlus målerenner, vannføringsmålinger i avløp og støpemetoder. Studiet sammenligner forskjellige konfigurasjoner av Palmer-Bowlus målerenner som finnes i litteratur, og sammenligner de med konfigurasjonene til målerenna på Risvollan.

For den teoretiske metoden, sporstoff metoden og laboratorium metoden var middelavviket fra den opprinnelige vannføringskurva henholdsvis 0.35, 0.68 og 0.11 l/s. Måleområdet for hver metode varierte, men driftsområdet til målerenna (5.0-9.0 cm) lå innenfor måleområdet for hver metode. Målingene fra laboratorium kalibreringen bekrefter gyldigheten til den opprinnelige vannføringskurva for vannstander mellom 4.0 til 15.0 cm. Det var også metoden med høyest forventning med tanke på nøyaktighet og repeterbarhet.

Det var ikke mulig å få bekreftet vannføringskurva for hele måleområdet (4-21 cm) i laboratoriumet på grunn av begrensninger i modellen. Disse begrensningene kan justeres ved å gjøre små konfigurasjoner på målerenna og U-kanalen oppstrøms. Videre kan nye målinger bli gjennomført for hele måleområdet.

I sportstoffmålingene ble det oppdaget en systematisk feil i målingene da de konsekvent ga høyere vannføring enn den opprinnelige vannføringskruva for samme vannstand. Noen av feilkildene ble oppdaget, men de var ikke mulige å kvantifisere. I sporstoffmålinger må feilkilder isoleres for å øke nøyaktigheten i måleutstyret. Det optimale injeksjonspunktet for sporstoff ble funnet til å være 8 ganger større enn anbefalinger.

Preface

This Master Thesis is submitted to the Norwegian University of Science and Technology (NTNU) in Trondheim for fulfillment of the requirements for the degree of Master of Science (MSc).

The thesis is a part of a 5-year integrated masters' which was conducted at the Department of Civil and Environmental Engineering. The Thesis was carried out in the Spring of 2017 with Professor Sveinung Sægrov as main supervisor and Associate Professor Tone Merete Muthanna and PhD Candidate Maryam Beheshti as co-supervisors.

Many people have advised, supported and motivated me during my Master Thesis. I would like to thank my main supervisor Sveinung Sægrov for his support, guidance and for always having the door to his office open, as well my co-supervisor Maryam Beheshti for instructions with tracer dilution measurements and supporting literature. A special thanks goes to PhD Candidate Christy Ushanth Navaratnam for support related to the casting technique and physical modeling. I would also like to thank Professor Knut Alfredsen for advise related to tracer dilution measurements. His engineering approach to science was valuable. I would also like to thank my friend and colleague Lars Solberg for a great team effort when doing the tracer dilution measurements.

I would like to Trondheim Municipality with Roger Pedersen for helping with redirecting the flow at Risvollan. Without their support the reproduced flume could not have been made. I am grateful for the technical support in the Hydraulic Laboratory of NTNU for the support of constructing the model in the Laboratory.

Last but not least I thank my common-law wife for proofreading the thesis and for the support when I needed it.

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Chapter 1

Introduction

1.1 Background

Flow measurement is an important tool for evaluating capacity and condition of sewage pipes [35, p. 3]. Flow measurements are necessary for calibrating run-off models and estimating infiltration and leakages in sewage pipes. Infiltration and leakages are critical problems in the long-term for sustainable urban water management, and can have serious impacts on the environment, social and economic impacts on cities and sewer systems [15]. The object of flow measurements are to detect leakage of untreated waste water and infiltration of extraneous water. Based on the measurements a survey can be made to localize the areas of leakage or infiltration. Therefore, accurate measurements are a necessity to implement accurate rehabilitation measures in terms of cost-benefit.

The Norwegian University of Science and Technology (NTNU) has a research station located at Risvollan. Risvollan is one of the study catchments in Trondheim, Norway with a good database and a measuring station to investigate hydrological parameters throughout the year [15]. One of the station's function is to measure the waste water flow rate from Risvollan. The flow rate measurements are done with a Palmer-Bowlus flume. The Palmer-Bowlus flumes is a simple and effective waste water flow measuring device for open channel flow [25, p. 41]. It differs from the more used Venturi flume mainly in that it does not require a drop along its bottom profile. The Palmer-Bowlus flume can therefore be inserted directly into an existing circular or U-shaped conduit with minimal site requirements other than suitable slope. The flume develops critical flow in the throat section which makes the flow rate a unique function of the measured upstream head for a given throat shape and upstream channel geometry [11]. This function can be obtained theoretically, from experiments or from manufacturers.

1.2 Thesis statement and Objectives

The Palmer-Bowlus flume at Risvollan is made out of stainless steel, and was installed directly into the channel. There are uncertainties related to the initial stage-discharge relation for the flume, and therefore the measurement data. There was also expressed uncertainty around geometry of the flume as it appear to be deformed. The purpose for this thesis was to assure quality of the measurement system which is in use, and to assure quality of the initial stage-discharge curve for the Palmer-Bowlus flume at Risvollan. Different methods have been used and the basis for the measurements and calculations were the Palmer-Bowlus flume at Risvollan. The results are presented as stage-discharge curves for each method. Further, the results of each method was compared with the initial stage-discharge curve. The different methods applied were a theoretical method, tracer dilution and laboratory experiments. The results may also influence the general practice for flow measurements. The geometry of the flume was measured from a reproduced flume that was made from a negative imprint of the flume at Risvollan.

Specified task:

1. Study different methods for calibrating the Palmer-Bowlus flume at Risvollan, and create a stage-discharge relation for each method
2. Complete tracer dilution measurements in the laboratory and the field to document procedures and precision
3. Create a 1:1 scale model of the Palmer-Bowlus flume at Risvollan with in situ conditions

1.3 Limitations in the Thesis

The main objective with the Thesis was to find out if the initial stage-discharge curve at Risvollan is valid. Different methods were used to compare the initial stage-discharge curve for the Palmer-Bowlus flume at Risvollan.

Other problems connected to the Risvollan measuring station has not been assessed in this thesis. Problems connected to the waste water and infiltration has not been evaluated or calculated. The dimensioning discharge of waste water from the connecting area upstream the measuring station has not been calculated. Downstream conditions of the Palmer-Bowlus flume has not been evaluated. The flume is constricted to the upstream conditions.

The secondary measurement equipment at Risvollan was not studied or calibrated. However, it was discovered that the system needs to be maintained and calibrated.

For tracer dilution measurements, the objective was to document procedures and accuracy of the flow measurements. The influence of the length between the injection of tracer and measurement point of conductivity was studied. Other sources of error in the measurements was not investigated, but are discussed in the Discussion section.

1.4 The Structure of the Report

Chapter 2 includes a literature review of the Palmer-Bowlus flume concerning its historical background, different designs, shapes and installation conditions from several different sources. The terms are compared to each other and in context of the flume at Risvollan. It includes a presentation of tracer dilution measurements and casting techniques used to reproduce the Palmer-Bowlus flume at Risvollan.

Chapter 3 describes the theory behind flow measuring flumes for open channel systems. The theory includes hydraulics in open-channel flow and flumes, and is described in context of the flume at Risvollan. A brief summary of theory from tracer dilution measurements is included.

Chapter 4 presents the field and laboratory work done to create the reproduced flume at Risvollan. It describes how the flow measurements in the laboratory was done.

Chapter 5 describes methods for calibrating the Palmer-Bowlus flume at Risvollan. The methods included are a theoretical desktop method, tracer dilution as an in-place calibration and a laboratory calibration with in situ conditions.

Chapter 6 presents the calculated and measured results of the methods, with belonging stage-discharge curves.

A summary of the methods and casting technique is given in Chapter 7.

Conclusions based on the results and the discussion are made in Chapter 8.

Chapter 9 describes further work that should be carried out concerning the measurement flume at the laboratory and the secondary measurement system at Risvollan.

1.5 Contributions

- The main contribution for the thesis was to verify the initial stage-discharge curve for the flume at Risvollan as valid
- The development of procedures to achieve accurate tracer dilution measurements in waste water
- Finding the accuracy of tracer dilution measurements in waste water flow
- Creating illustrations, denoted [PPN], of the flume at Risvollan with the design tool AutoCAD. These can be used further in association with the Palmer-Bowlus flume at Risvollan. A great deal of time has been invested in designing the figures, and should be included in the final evaluation of the thesis
- Field and laboratory work: Creating a framework to make the negative imprint. Making a 1:1 model in the laboratory channel
- Creating a plan for making reproduced flumes, including error and success criteria
- Made a replica of Palmer-Bowlus flume at Risvollan with same dimensions and roughness. The flume should be included further in teaching at NTNU
- Maintenance work at Risvollan; flushing of the flume conduit. Establishing new routines for maintenance work

Chapter 2

Literature Review

There are various types of flumes and areas of application, such as irrigation, flow measurements and for waste water treatment. A flume is by definition, a section of a river or pipe of open-channel flow where the flume structure both raises the channel bottom and narrows it [18, p. 2]. In waste water, flumes can be used to monitor the flow in the waste water system. It can be used to detect leakage of untreated waste water, or infiltration of extraneous water which gives higher operational costs [15]. Monitoring flow in waste water can be done proactively to reduce the chance of inconvenient events [26]. Measuring waste water flow is in addition the basis for municipal charge to the subscribers [35, p. 4]. This Chapter presents a comprehensive literature review about the different configurations of the Palmer-Bowlus flume. The Literature Review is related to the thesis statements in terms of the flume, and with focus on different methods for calibrating Palmer-Bowlus flumes for measuring open channel flow.

2.1 General Terminology

Terminology used in the thesis and in Figure 2.1 and 2.2, are presented in this section. The definitions are in accordance with the measurement system at Risvollan, and is found from literature [10]. Usually, terminology is defined in a more general manner.

1. Palmer-Bowlus flume: A fixed hydraulic structure in open channels which creates a flow pattern that can be sensed by a secondary instrument to measure flow

2. Approach channel: The channel upstream the flume where head measurements are done

3. Converging transition: Entrance to the flume where subcritical flowing water is accelerated and guided into the throat without flow separation. The flow becomes rapidly varied flow

4. Flume throat: The constricted portion of the flume where flow accelerated due to contraction of both sidewalls and a rise of bottom

5. Gauging station : A site in a channel placed at an appropriate distance upstreams the flume which measures the water depth with a secondary instrument

6. Secondary instrument: Device that measures the flow depth upstream the flume. Able to convert the measured depth to an indicated flow rate

7. Control section: The section of the flume throat were the water depth is equal to the critical water depth

8. Diverging transition and tailwater channel: The water elevation downstream the flume where the flow velocity is gradually reduced to a subcritical velocity

9. Froude number: Dimensionless parameter expressing the ratio between the inertia and the gravitational forces in a liquid

10. Hydraulic jump: The sudden change of flow from supercritical to subcritical flow

11. Critical flow: Open channel flow in which the total energy head is a minimum for a given discharge. The Froude number is equal to a unity under this condition

12. Subcritical flow: Open channel flow in which the Froude number is less than a unity, meaning deeper and lower velocity of flow than critical flow for the same flow rate

13. Supercritical flow: Open channel flow in which the Froude number is greater than a unity, meaning shallower and higher velocity of flow than critical flow for the same flow rate

14. Draw-down curve: Water level drop due to constriction in the channel geometry

15. Head/water level: Depth of flow referenced to the channel bottom or the floor of the throat measured at an appropriate location upstream of the flume

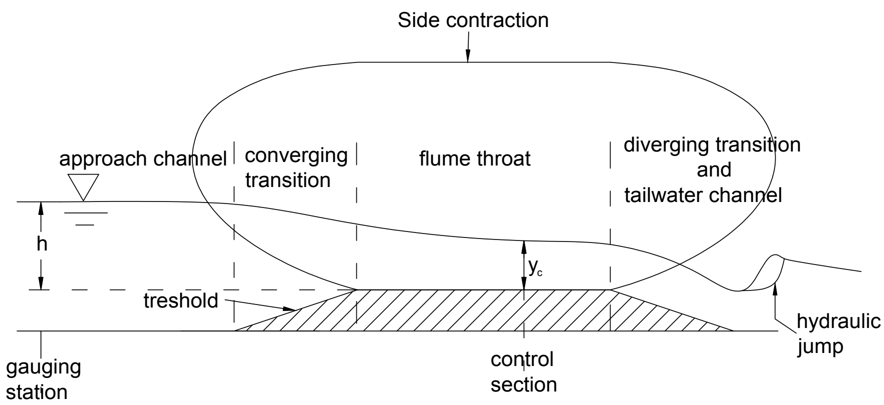

Figure 2.1: General terminology Palmer-Bowlus flume [PPN], vertical side view

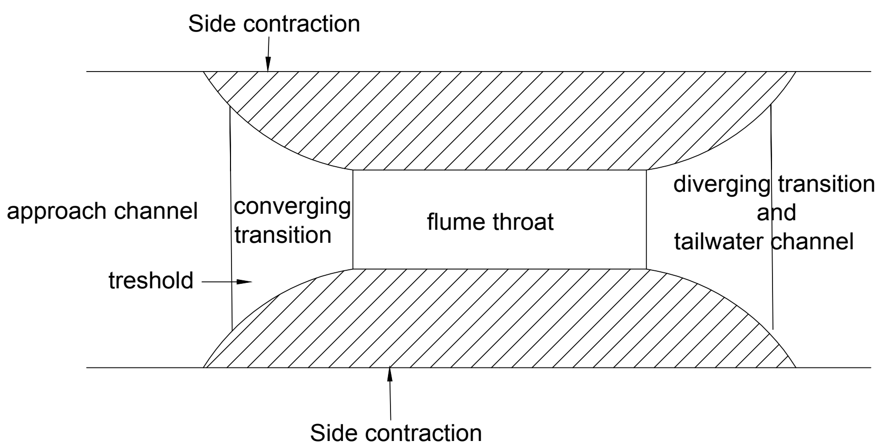

Figure 2.2: General terminology Palmer-Bowlus flume, horizontal view [PPN]

2.2 The Design and Shape of Palmer-Bowlus Flumes

This section describes the fundamental features of a Palmer-Bowlus flume. Differences in design will be discussed. Figure 2.3 shows the typical variations in design of Palmer-Bowlus flumes for installation in round and rectangular conduits. The most common design used in practice and discussed in literature is the flume type B. The Palmer-Bowlus flume at Risvollan has the same design as type B. Therefore, throughout the thesis, the focus will be on type B.

> "There is no standardized shape for Palmer-Bowlus flumes and they can be designed to fit specific hydraulic situations." [11]

The Palmer-Bowlus flume is in the standard [11], defined as a long-throated flume formed by constricted sidewalls and a bottom rise. The standard does not set out specific sizes and flow rates, but gives a general design of the flume as illustrated in Figure 2.4. There is a big variety of flume shapes used in practice. Prefabricated flumes can be ordered from manufacturers [33] or designed and constructed after the standard [11] or other literature [32, 35]. The shapes of some flumes can be found in Appendix A. In general for Palmer-Bowlus flumes, the dimensions are proportional to the conduit internal diameter, D.

Length of the Throat Section Palmer and Bowlus recommended that the length of the throat section should be at least equal to the internal diameter as illustrated Figure 2.4 [32]. This dimensions were found to be used also in [11], [25, p. 44], [32], [35, p. 156] including prefabricated flumes from manufacturers [33, 9]. Another common understanding in literature, is that the longitudinal throat floor should be installed so that it is horizontal to the ground, preferably within a slope of 0 to 0.001 m/m [11].

Dimensions of the Cross-Section The differences in shape between Palmer-Bowlus flumes is usually found in the contraction of the sidewalls and height of the threshold in the throat section of a flume. Several sources of literature, including [25, 22], suggest the shape of the contracted cross-section to be as in Figure 2.5, where the width in the threshold part equals half of the diameter. While other literature gives the width of the threshold as $t = {}^{5D}/_{12}$ [32] down to $t = {}^{D}/_{4}$ [35, p. 156]. There are also differences in the height of the threshold of the flume. [25, 22] sets the threshold height to $t = {}^{D}/_{6}$. Other values for the height of threshold found was $t = {}^{D}/_{12}$ [32], while the lowest value was $t = {}^{D}/_{20}$ [35, p. 156]. Values of the same dimensions are probably collected from other literature and reused. This is the case for Figure 2.5 (left), which appears as a copy from older literature [25, Figure 3.3-5].

Entrance to the Control Section Palmer, H. K. and Bowlus, F. D. recommended that the transition between downstream and upstream be sloped a minimum of approximately 1:3 (laterally:longitudinally) (1936 as cited in [32]). A threshold with the height of ${}^{D}/_{6}$ and transition length of ${}^{D}/_{2}$ will give a ratio of one to three.

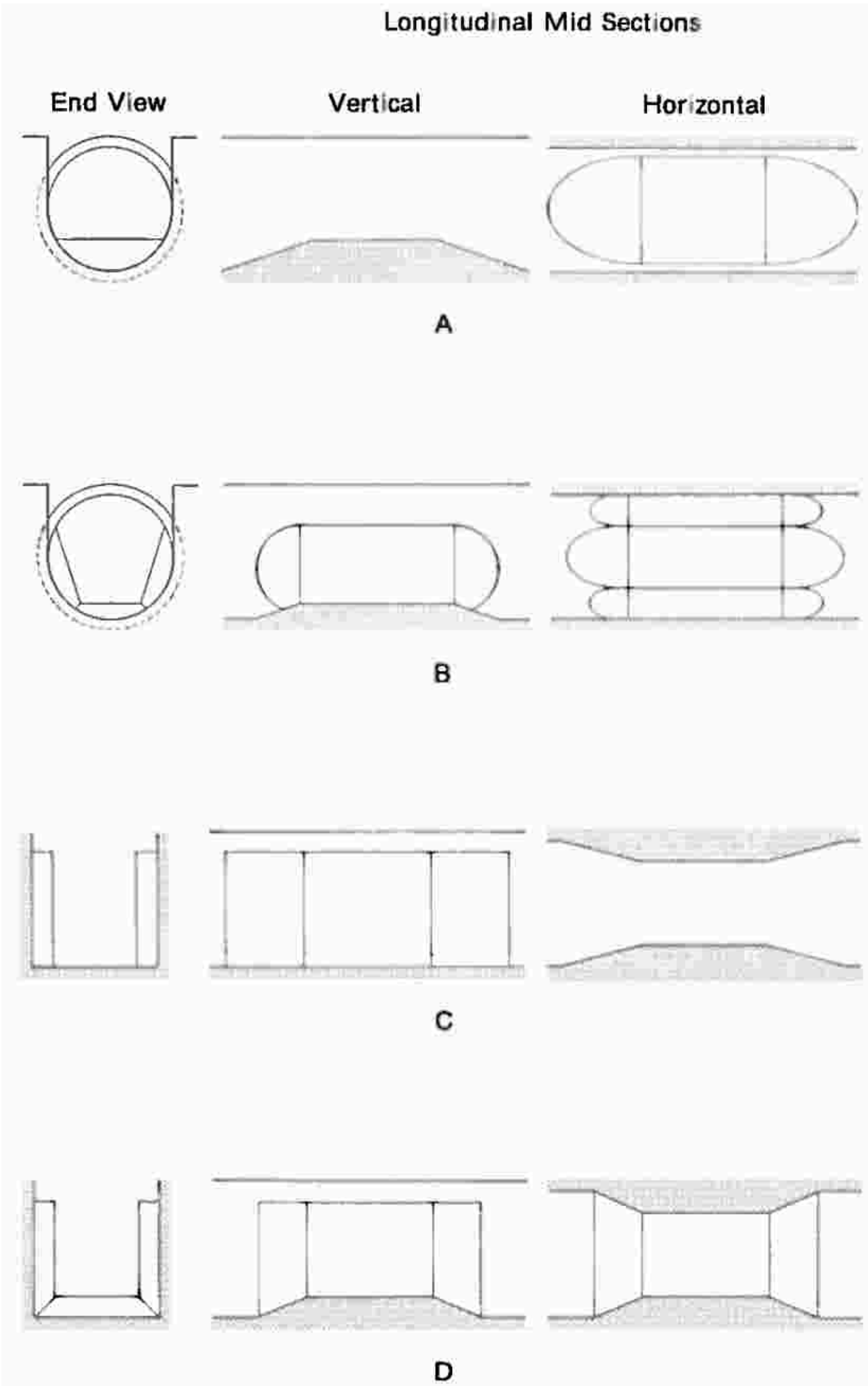

Figure 2.3: Various cross sectional and longitudinal shapes of Palmer-Bowlus flumes [25, p. 43]

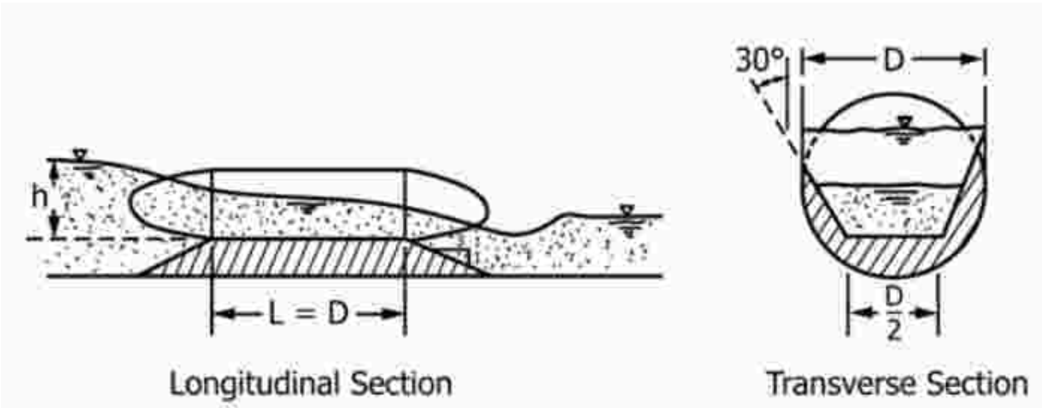

Figure 2.4: Typical construction of a Palmer-Bowlus flume for sewer [11]

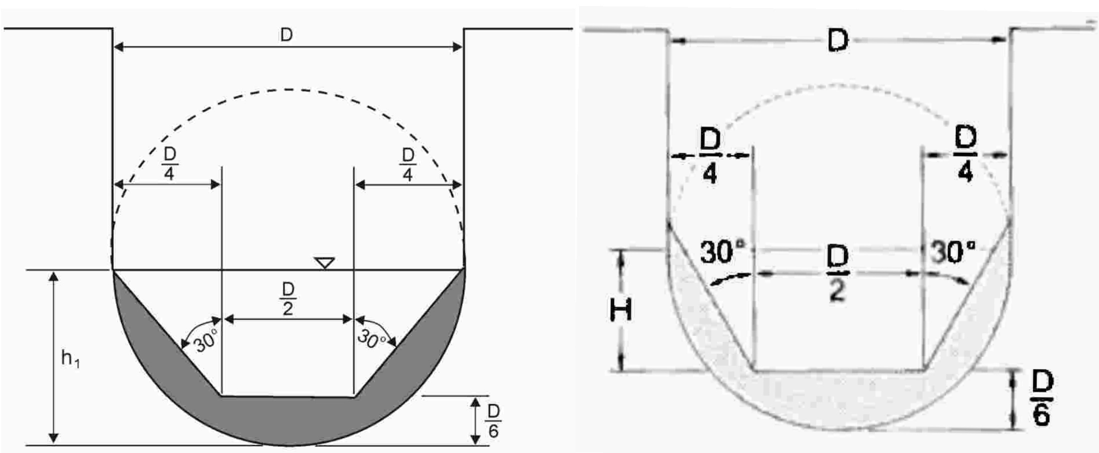

Figure 2.5: Common cross section of Palmer-Bowlus flume, from [22] (left) and [25] (right)

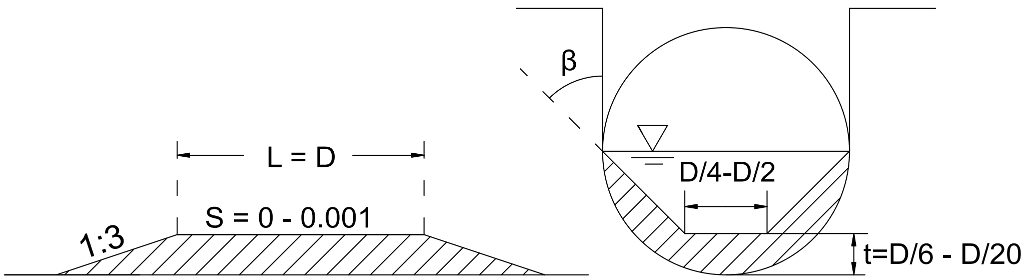

Figure 2.6: Dimensions for Palmer-Bowlus flume used in practice [PPN]

Summary As studied, the dimensions used in practice for Palmer-Bowlus flume vary. A brief summary of possible dimensions is presented in Figure 2.6. The dimensions are a summary from literature found in [11, 16, 22, 25, 32, 35, 33]. The slope of the side constrictions will vary according to the selected width of the throat bottom, height of threshold and height of contracted walls. As presented in Figure 2.6, the contracted walls are one half of the diameter. Not one of the studied literature mentioned or suggested a height of the control section. However, the angel β will usually never be bigger then 41.6^o when the throat bottom width is set to the minimum value of $W = {}^{D}/_{4}$, and the threshold height is set to the maximum $t = {}^{D}/_{6}$, see Figure 2.6 to the right.

Figure 2.7 gives the design and dimensions of the Palmer-Bowlus flume installed at Risvollan. The initial drawing of the Palmer-Bowlus flume can be found in the Appendix A.3. Table 2.1 compares the dimensions for Palmer-Bowlus flume found in literature and the dimensions for the flume at Risvollan. As the table concludes, the flume at Risvollan differ for the entrance slope to the threshold section and to the slope of the throat. For the entrance slope, this is a recommendation given by Palmer, H. K. and Bowlus, F. D. (1936 cited in [32]). The recommendation is set to assure a small head loss and to secure good sediment and debris passing. The threshold at Risvollan would probably give higher head loss and poorer debris passing than the flume in Figure 2.6 where the entrance slope is 1:3. However, the flume at Risvollan has been in operation since 1986 [23], and there has not been detected any major self-cleansing problems.

For the small stream wise slope in the throat, the error can be minimized by referencing the head measurement to the elevation of of the downstream end of the throat. Errors due to small transverse slope can be minimized by referencing the head measurement to the throat floor elevation at the longitudinal centerline [11, 11.5.3].

Table 2.1: Comparison of dimensions found in literature of Palmer-Bowlus flumes and the flume at Risvollan

Section	Dimensions from literature	Dimension from Risvollan	Remarks
Length of Throat	$L = D$	$L \sim D$	In range
Width	$W = {}^{D}/_{4} - {}^{D}/_{2}$	$W = {}^{D}/_{3}$	In range
Height threshold	$t = {}^{D}/_{6} - {}^{D}/_{20}$	$t = {}^{D}/_{15}$	In range
Entrance slope	$1:3$	$16.7:30$	Not in range
Slope of throat	0 - $0.001{}^{m}/_{m}$	$S = 0.020{}^{m}/_{m}$	Not in range

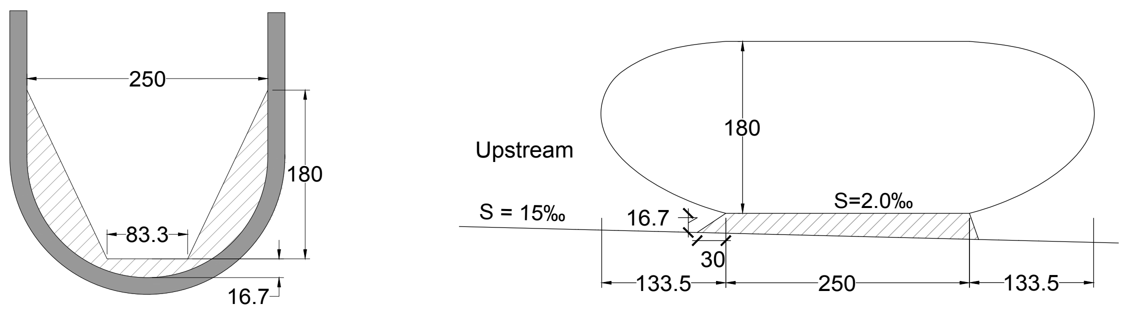

Figure 2.7: Cross section (left) and longitudinal section (right) of the Palmer-Bowlus flume at Risvollan [PPN]

2.3 Installation Conditions

In order for the Palmer-Bowlus flume to function sufficiently, there are some installation conditions that has to be fulfilled. These conditions will be presented in the following paragraphs and evaluated further in the Results chapter.

Approach Channel Conditions In artificial channels, the flow in the approach channel should be smooth and free for disturbances. The cross section should be uniform and the channel straight. Eq. 3.10 and 3.11 are valid under these assumptions. The Standard for Palmer-Bowlus flume suggest a length of 25 times the diameter ($L \geq 25D$) for no major disturbances upstream the flume entrance [11, 25], while other suggest $L \geq 6D$ as sufficient [35]. Other standards for flumes and weirs suggest for artificial channels a distance of $L \geq 10D$ [2, 3]. For the flume at Risvollan, there does not seem to be any problems to fulfill the most conservative requirement as the cross section of the pipeline is uniform and straight for approximately 5 meters upstream the flume, see Appendix B.2. However, the length of the approach channel will be of concern when building the model in the laboratory. To save resources and expenses, a short channel will be made.

The flow conditions in the approach channel should be subcritical in order for the flow measurement to function [11, 33, 25, 35, and more]. This requirement is particular for all flow measuring flumes for open-channel flow [18, p. 32]. Subcritical flow conditions is achieved when the Froude number is less than a unity. However, for Palmer-Bowlus flumes, there is an agreement that the

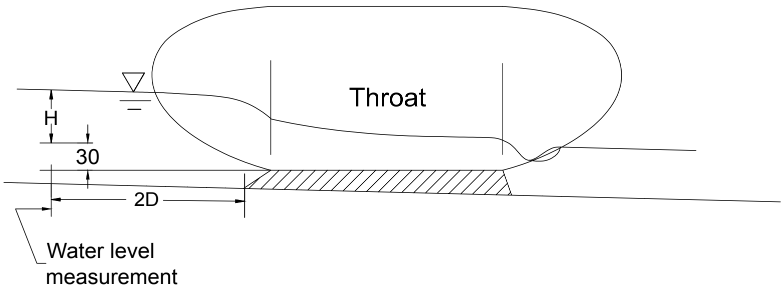

Figure 2.8: Distance between the point of water level measurement and flume at Risvollan [PPN] (not in scale)

Froude number upstream should be: $Fr = \frac{V}{\sqrt{g^{A_i/B_i}}} \leq 0.5$ [11, 35, 33]. The requirement is set to avoid surface disturbances at the head measurement location, and is valid for flumes that are not calibrated individually [35, p. 160].

If the flow in the upstream channel is supercritical, a hydraulic jump should be forced to occur at least 30 pipe diameters upstream [11, 29]. [25, p. 47] state that the upper limit to maintain subcritical flow in the upstream section of a Palmer-Bowlus flume is a slope around $20 - 30‰$ for smaller flume sizes and a lesser slope for larger flume sizes. The flume in this Thesis has an upstream channel of about 15‰, which is within the requirement.

Maximum and minimum head upstream the flume is varying in literature. The Standard for Palmer-Bowlus flume recommends the maximum head equal to one half of the throat length [11], which equals about 13 cm for the flume at Risvollan. Other recommendations suggest the maximum head upstream equal to 0.73D [25, p. 47] which is 19 cm at Risvollan, and 0.85D in [32] which is 22 cm at Risvollan. However, at Risvollan the requirement is not a problem; the maximum measured head there is about 11 cm. The minimum recommended head upstream is in the standard set to $\frac{h}{L} \geq 0.1$ [11], which gives a minimum head of 2.55 cm at Risvollan. Again, other literature [35, p. 163] suggests other values. However, from the ISO standards for flumes [3], $h_{min} = 2.6$ cm seems sufficient at Risvollan.

Gauging Station A Palmer-Bowlus flume measuring system consists of a flume and a head measuring device. Palmer-Bowlus flume is defined as a long throated flume. The throat is an area of transition from subcritical to super-

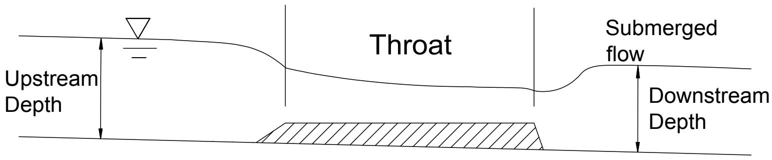

Figure 2.9: Submerged flow in a Palmer-Bowlus flume [PPN]

critical, therefore the head should not be measured in this section of the flume. The point of measurement is upstream the throat section and the level reading is compensated for the height of the ramp [33]. Older and newer literature sets $D/2$ as a sufficient distance upstream for measuring the water level [25, p. 46], [22, p. 761], [35, p. 156], while the Standard for Palmer-Bowlus flume suggests the head h to be measured at an upstream distance equal to the maximum head. At Risvollan, the secondary instrument measuring the flow depths is installed in a stilling well approximately two times the diameter upstream the flume, as shown in Figure 2.8. This distance is sufficient in order to avoid a draw-down curve at the point of flow depth measurement.

As mentioned, the zero elevation for measuring the water level is from the flume floor. If the water level is measured from the bottom of the channel and up, the actual level and flow will be overestimated. The stilling basin's datum at Risvollan is 30 mm above the bottom of the flume throat [23]. This can be reviewed in Appendix B.1 and is illustrated in Figure 2.8.

Outlet Conditions Palmer-Bowlus flumes must be installed to avoid being submerged by the tailwater. If the flume is submerged, the flow rate cannot be related to a single upstream head, and can therefore not be measured. Figure 2.9 illustrates submerged flow for the Palmer-Bowlus flume. The standard justifies the flow through a flume as unsubmerged when observing a hydraulic jump downstream of the throat [11]. Other criteria in the Standard are defined more conservatively; the flow is not submerged if the tailwater depth is under the critical depth in the throat [11, 25]. Data from Risvollan gives water depth between 5 and 9 cm during normal operations. When observing these water depths for the flume at Risvollan in situ and in the laboratory, there are no sign of submergence.

The maximum water level before the flume becomes submerged should be tested through experiments in the laboratory. This was not conducted in this thesis due to water level measurements constricted to 15.7 cm. See Chapter 9 for further evaluation of this boundary.

Summary of the flume at Risvollan

- Minimum and maximum head upstream; measured from the flume bottom and up: $h = [2.6 - 22.5cm]$
- Head measurement location: $L > D/2$ from flume contraction

Figure 2.10: Prefabricated Palmer-Bowlus flume in operation from Open-Channel-Flow [8]

- Length of no major disturbances in the approaching channel: $L \geq 6D$

2.4 Stage-Discharge Relation for Palmer-Bowlus flume

There are two possibilities for installing a Palmer-Bowlus flume into a sewer. A prefabricated flume can be bought from a manufacturer [8] and placed into the sewer. Prefabricated flumes are available with different configurations to fit directly into the site specifications.

When ordering a commercial prefabricated flume, the manufacturer usually provides a stage-discharge curve for the flume. When provided, the manufacturer must specify the method for obtaining information [11, p. 4], which could be based on laboratory experiments or from theory. Figure 2.10 is a photo of a prefabricated Palmer-Bowlus flume in operation, from the manufacturer Open-Channel-Flow (OFC) [8].

The flume at Risvollan is a prefabricated flume from [37]. The initial drawing of the flume can be found in Appendix B.3. The upstream section and the throat section of the flume is made out of prefabricated stainless steel, while the downstream section is molded into the channel, see Figure 2.11. Like all Palmer-Bowlus flumes, the flume at Risvollan is upstream controlled.

For flumes constructed into a channel like the one at Risvollan, an in-place calibration of the flume is recommended for highest accuracy [11, p. 5] [35, p. 159]. The initial stage-discharge curve for the flume at Risvollan is given in the

Figure 2.11: Drained Palmer-Bowlus flume at Risvollan [Photo PPN]

Results section 6.1, while the initial plot is found in Appendix B.5.

2.5 Methods for Calibrating Palmer-Bowlus Flume

> "An in-place calibration of the flume is recommended for highest accuracy... [11, p. 5]"

The Standard for Palmer-Bowlus flumes suggests the following methods for in-place calibration; velocity area traverse, tracer dilution, tracer velocity, volumetric and comparison with a reference flow meter. Velocity area method is mainly used to find the flow rate in rivers or conduits of bigger cross section. This method is also restricted to cleaner water due to debris in waste water flow. Tracer velocity is a method which measures the time it takes for a tracer to pass through a pipe while concentrations are recorded with a fluorometer over time. When the injection of the tracer is done correctly, the fluorometer determines the velocity in the channel [12, p. 13]. Further, the flow can be determined from the Continuity equation (3.2). Tracer dilution method measures the concentration of a given tracer injected upstream the measuring point. A known concentration of tracer is injected into a channel. Calibrating with comparison of a reference flow meter is possible with flow monitoring systems like FlowShark Pulse. A v-notch weir could also be used as a reference flow meter. However, v-notch weirs are not suitable for doing flow measurements in waste water channel due to sedimentation build up upstream. This will give incorrect water level measurements and therefore a stage-discharge relation which cannot be used [35, p. 95].

For highest accuracy in-place calibrations are recommended [11][35, p. 305]. In this thesis the tracer dilution method, a theoretical method, and a laboratory calibration has been carried out.

Tracer Dilution One commonly used method to measure the flow in open channels is tracer dilution. This method consists of adding a known amount of concentrated tracer at a constant rate to the flow stream. Tracers are water-soluble substances and the concentration of these can be used to measure the discharge. These techniques have proven to be some of the most powerful tools to characterize water flow [27, p. 31]. Although the method is mostly used for rivers [6], it can be used for measuring flow rates in sewage pipelines. The method is used for flow rates from some few l/s up to 20 000 m^3/s. The boundaries for flow rates is related to flow conditions and the length of the channel [35, p. 237].

Dilution measurements can be applied by two main principles:

1. Constant-rate injection method [5]

2. Integration method (sudden injection) [6]

The two methods differ in the injection time. For method 1 a constant amount of tracer is injected into the flow at a constant rate for a known period. While for method 2 the tracer should be injected for a short duration. Both methods require a constant flow rate Q in the channel throughout the measuring period. In waste water pipelines with relatively few subscribers, the local flow rate variations may affect the results of such measurements. In this thesis method 2 was used. This was also the method of interest described in the thesis. Measurements with method 1 was not done due the requirement of constant flow rate Q. Therefore, method 2 has the best conditions for success.

There are various tracers that can be used. In this Thesis the tracer used is limited by the equipment available, which is conductivity sensors for NaCl. Other tracers that could be used are salts like lithium chloride, sodium chloride, potassium iodide or radioactive isotopes. In municipalities the background concentration of NaCl in waste water can be high and vary rapidly in concentration [35, p. 247]. This could affect the results from the measurements. The benefits by using NaCl are that it is cost-efficient and that the salt is not hazardous.

> "Calibration - Establishing a relation between the input and the output value for a measurement instrument [35, p. 300]"

For tracer dilution and laboratory calibration the input signal is the discharge, while the output signal is the water depth. Calibration is carried out by varying the input signal, while measuring the input and output signal. This is known as calibration measurements. The equipment used in calibration measurements should be of higher accuracy than the equipment that is calibrated [35, p. 302]. Tracer dilution measurements will in waste water pipelines have a measurement uncertainty between 5 - 20% [35, p. 237], while the Palmer-Bowlus flume has an uncertainty between 3 - 5% [35, p. 163] in the measurements within operational discharge values.

Accuracy and reliability of the calibration increases with increasing calibration measurements. The methods for laboratory calibration and tracer dilution are described in Section 5.1 and 5.3 respectively, while the theoretical method is presented in Section 5.2.

Figure 2.12: Accuracy and repeatability [7]

2.6 Measurement System and Accuracy

In this subsection definitions concerning accuracy of measurement will be defined. Methods for determining the accuracy and errors of different measurement methods will be studied. The literature is collected from [35, chap. 3. and Attachment D]

Measurement Accuracy - Definitions Flow measurements will contain errors in the measurements. It is necessary to have knowledge about the probability of the measurement error. The relationship between a measured value and the error is given as

$$X = x + v$$

where X is the measured value, x is the true value (always unknown) and v is the measurement error (always unknown). The value of the measurement error has to be calculated based on basis of assumptions since the measurement error is unknown. Therefore, measuring uncertainty is used instead of measuring error when results are evaluated.

The measuring uncertainty e is defined as

$$X - e < x < X + e$$

The measuring uncertainty is defined as an area where it is probable for the true value to lie within. For flow measurement the measuring uncertainty is recommended to be linked to the 95% probability. The measuring range for tracer dilution method will be discussed further in Section 5.4.

Accuracy describes the quality of a measuring instrument or a measuring method. The accuracy is usually given as the maximal expected error for a given measuring area.

Repeatability describes the accordance between measurement results achieved when using the same measurement method under equal conditions. To achieve equal conditions for flow measurements, use the same operator, measuring instruments, and measuring cite. See Figure 2.12 for illustration of accuracy and repeatability.

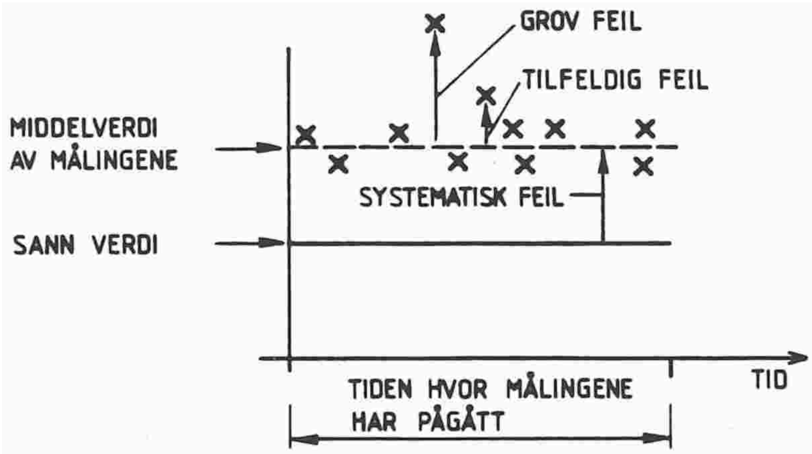

Figure 2.13: Error classes [35, p. 19]

Error Class Error class is divided into three classes (Norwegian) [35, p. 18]:

- Major error (Norwegian: grov feil)
- Systematic error (Norwegian: systematisk feil)
- Irregular error (Norwegian: tilfeldig feil)

Figure 2.13 illustrates how the error classes are defined in measurements. A more precise definition will be presented in the next paragraph.

Major errors are human errors made by the user, or errors from the uncalibrated measurement instrument. Major errors will not be included when calculating the mean value from the measurements.

Systematic errors follow certain laws such as the impact for each measurement can be calculated, if the error is known. Systematic errors are divided into two groups:

1. Constant systematic errors
2. Variable systematic errors

An irregular error results from a long string of independent occurrence which leads to different measurement results for the same input values. When the number of measurements is large, the irregular errors will correspond to a Gaussian distribution.

2.7 Flume Casting Technique

The method for creating a replica of the Palmer-Bowlus flume at Risvollan was based on [36]. The results from the paper concludes that the casting technique reproduces surfaces with high accuracy without altering hydraulic roughness characteristics. The exact same materials as in the paper were used in this Thesis to create the replica of the flume at Risvollan.

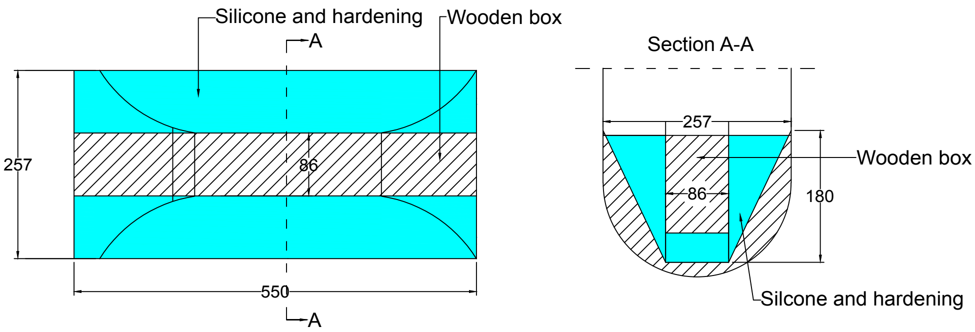

Figure 2.14: Plan and cross-sectional view of the negative imprint from [PPN]

A bi-component silicone combined with a wooden box was used to create the negative imprint (mould) of the flume, see Figure 2.14. The wooden box was placed in the middle of the flume to occupy space in order to use less silicone. The silicone used was fairly expensive, but the detail level was high.

A two-component Polyurethane Resin (PUR) was used to create the corresponding cast of the flume. To make the cast, the negative imprint had to be placed into a compacted box. Then resin could be poured over the negative imprint in order to produce the replica to the flume, see Figure 2.15.

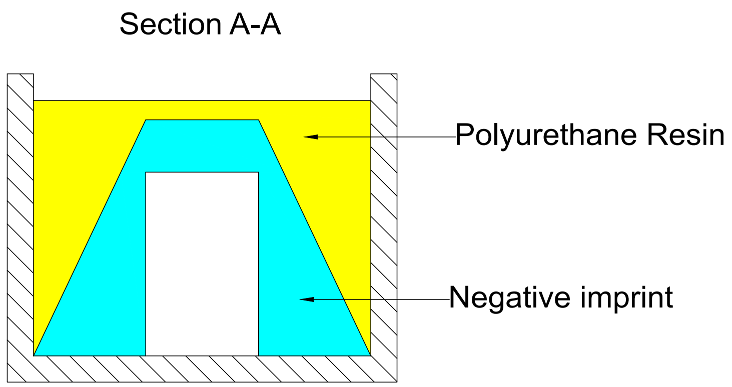

Figure 2.15: Cross sectional view from reproducing the flume from the negative imprint [PPN]

Chapter 3

Theoretical Background

The first two sections of Chapter 3 gives a brief introduction of open-channel flow found in literature [19, 21, 35]. Section 3.3 and 3.5 gives the theoretical foundation for two of the three different methods used to calibrate the Palmer-Bowlus flume at Risvollan; the theoretical desk-top method, and the method for in-place calibration respectively.

3.1 Open Channel Flow

Open channel flow is defined to be flow in any channel in which the liquid flows with a free surface [25, p. 5]. A free surface means that the liquid surface is subjected to atmospheric pressure. Examples of this are rivers, canals, flumes and other uncovered conduits. Sewers flowing partially full and not under pressure are classified as open channels.

> "Flow conditions in open channels are complicated by the fact that the position of the free surface is likely to change with respect to time and space and also by the fact that the depth of flow, the discharge, and the slopes of the channel bottom and of the free surface are interdependent [19, p. 3]."

Open channel flow can be classified into many different types and is described in various ways. The following classifications are made according to the change in flow depth with respect to time and space [19, p. 4].

Steady and Unsteady Flow Steady and unsteady flow describe the flow with respect to time. Flow in an open channel is steady if the depth of flow does not change with time or during a given time interval of the flow, denoted as $\frac{dV}{dt} = 0$. The flow is unsteady if the depth of flow changes with time, denoted as $\frac{dV}{dt} \neq 0$. In most open channel problems it is necessary to study flow behaviour only under steady conditions [19, p. 5].

Uniform and Varied Flow Uniform and non-uniform flow describe the flow with respect to space. Flow in an open-channel is uniform if the depth of flow is the same at every section of the channel, denoted as $\frac{dV}{dx} = 0$. Uniform flow may be steady or unsteady, depending on whether or not the depth changes

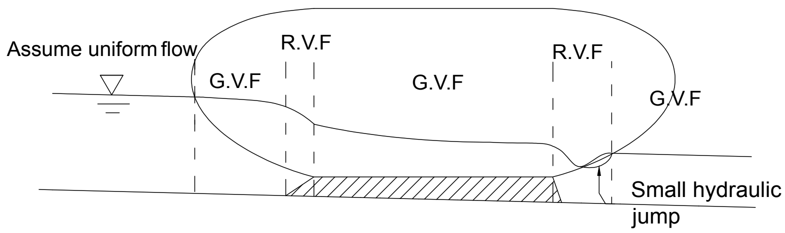

Figure 3.1: Fluid path for a Palmer-Bowlus flume [PPN]

with time. The flow is varied if the depth of flow changes along the length of the channel, denoted as $\frac{dV}{dx} \neq 0$. Varied flow may be further classified as either rapidly or gradually varied. Rapidly varied flow changes abruptly over a comparatively short distance, while gradually varied flow changes more slowly over a longer reach.

In this thesis, the flow behavior in the Palmer-Bowlus flume at Risvollan will be studied under steady conditions, meaning calculations and experiments will be carried out as steady flow. In laboratory this is easy to achieve by setting the discharge to a fixed value which will give a constant depth in a considered time interval.

Figure 3.1 classifies the different sections in the Palmer-Bowlus flume and the flow types occurring during operation.

3.2 Hydraulics in Flumes

This section gives a brief overview of the theoretical background for flow measurements in flumes in order to evaluate the flow patterns. In flumes it is the flow pattern that determines the head-discharge relationship [18, p. 197]. In order to calibrate flumes, this information is crucial. For more detailed information of the derivation of equations, literature from [19, 18, 21] should be studied.

Continuity Equation For any flow, the discharge Q at a channel section is expressed by [19, p. 5]

$$Q = VA \tag{3.1}$$

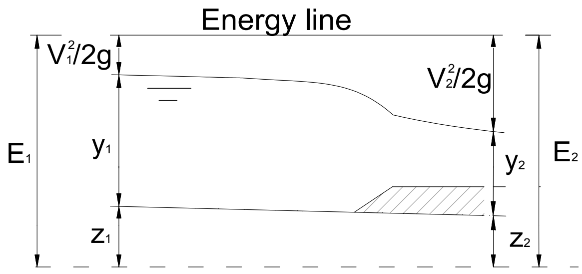

Figure 3.2: Energy in steady open-channel flow [PPN]

where V is the average velocity and A is the flow in the cross sectional area normal to the direction of the flow. In conduits with steady flow, the discharge is constant throughout the reach, and is expressed by

$$Q = V_1 A_1 = V_2 A_2 = \text{constant} \tag{3.2}$$

where the subscripts 1 and 2 are the different channel sections. Eq. 3.2 is the continuity equation for continuous steady flow.

Energy Equation The energy equation for steady open-channel flow is [21, p. 514]

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V_2^2}{2g} + h_f \tag{3.3}$$

where z is the height of the datum, y is the water depth, α is the energy-coefficient, g is the acceleration due to gravity and h_f is energy loss due to friction. When $\alpha_1 = \alpha_2 = 1$ and if the distance between 1 and 2 is short and the energy loss due to friction and turbulence may be neglected, Equation. 3.3 becomes [19, p. 40]

$$z_1 + y_1 + \frac{V_1^2}{2g} = z_2 + y_2 + \frac{V_2^2}{2g} = \text{constant} \tag{3.4}$$

which is known as the Bernoulli energy equation. $V^2/2g$ is the velocity head of a flow, and Figure 3.2 illustrates how the velocity head and water depth varies when water flows through the flume. Eq. 3.4 is valid when the streamlines in the water are less arc-shaped [35, atch. C3], meaning they follow the bed slope. When streamlines curves a lot, centripetal acceleration has significant affect on the energy conditions. In the presented flume, the streamlines will have an arc-shape which will affect the results of Bernoulli's equation for calculating the head-discharge relation.

Specific Energy Specific energy in a channel section is defined as the energy per cubic of water at any section of a channel measured with respect to the channel bottom [19, p. 41]. According to each of the segments in Equation 3.4 with $z = 0$, the specific energy in a channel of small slope can be written

$$E = y + \frac{Q^2}{2gA^2} \tag{3.5}$$

which indicates that the specific energy is equal to the sum of the depth of water and the velocity head.

Froude Number The flow upstream a Palmer-Bowlus flume has to be subcritical in order to function [11]. The flow is subcritical when the Froude number is less than a unity. There is an agreement in different literature that the Froude number should be less than 0.5 to avoid surface disturbances at the head measurement location [11, 33]. This is a requirement for flumes that are not calibrated individually [35, p. 160]. The Froude number in open channel flow is given as

$$Fr = \frac{U}{\sqrt{gd_i}} \tag{3.6}$$

where U is the flow velocity and d_i is the water level. The calculation of the Froude number for the upstream channel of the flume at Risvollan, is given in Appendix B.7, Table B.2 with Figure B.6 as basis for the calculation. The Manning's coefficient n is set to 0.017 [19, p. 110]. The theoretical calculations gave Froude numbers around a unity. The Froude numbers based on discharge values from the initial stage-discharge curve were all below 0.5, which is recommended to avoid surface disturbances at the head measurement location.

3.3 Bernoulli

Bernoulli's equation can be used to set up the stage-discharge curve for a Palmer-Bowlus flume. The discharge can be made from theoretical calculations from Bernoulli's equation and the method was found in literature [35, p. 158-159]. The Bernoulli's equation for a Palmer-Bowlus flume is

$$y_i + \frac{V_i^2}{2g} = y_c + \frac{V_c^2}{2g} + t \tag{3.7}$$

where V_i is the average flow velocity in the upstream section, V_c is the critical flow velocity in the flume, y_i is the water in upstream section, y_c critical depth in the flume, and t is the height of the threshold. Figure 3.3 illustrates the points i and c where the equation is used. The water level is measured at point i and the flow goes through critical flow in c. Equation 3.7 is valid under the following assumptions:

- The streamlines are parallel with the bed in the throat section
- Energy loss due to friction can be neglected between the entrance and throat
- The discharge coefficient C_D is constant when the discharge varies

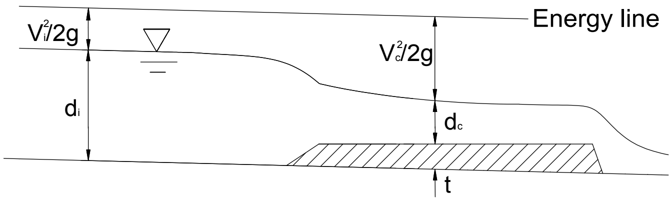

Figure 3.3: The sections in Palmer-Bowlus flume were Bernoulli is calculated [PPN]

Literature [14, p. 106] specifies that short-throated flumes are not long enough to develop parallel flow conditions where critical depth occurs. Therefore theoretically derived calibrations are difficult to obtain without making assumptions such as the following. This is also stated in [18, p. 2]: "Short throat cause three-dimensional flow for which no valid theory is available and thus limit the predictability of hydraulic behavior." However, the Palmer-Bowlus flume is classified as a long-throated flume [11], and Eq. 3.7 should be valid for the flume at Risvollan.

At critical flow

$$\frac{Q^2}{g} = \frac{A_c^3}{B_c} \tag{3.8}$$

where A_c is the cross section area and B_c is the water surface width at the point where the flow is critical. The velocity head at the point of critical flow becomes

$$\frac{V_c^2}{2g} = \frac{Q^2}{A_c^2 2g} = \frac{A_c}{2B_c} \tag{3.9}$$

Eq. 3.7 can be expressed as

$$d_i = t + d_c + \frac{A_c}{2B_c} - \frac{Q^2}{2gA_i^2} \tag{3.10}$$

where A_i is the cross sectional area in the upstream section.

3.4 Discharge Relations

The volumetric flow rate, Q, through a Palmer-Bowlus flume is [11]

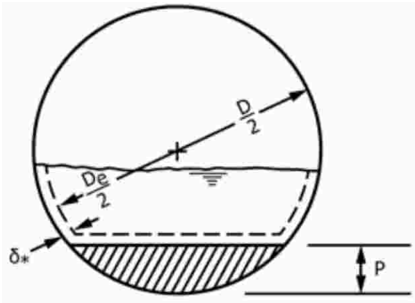

Figure 3.4: Development of boundary layer due to viscous friction [11]

$$Q = (2/3)^{\frac{1}{2}} \, (2g/3)^{\frac{1}{2}} \, C_D C_S C_V B h^{\frac{3}{2}} \tag{3.11}$$

where B is the width of the flume at the bottom, h is water level upstream the flume and C_D, C_S and C_V are the discharge coefficient, throat shape coefficient, and velocity-approach coefficient respectively. Eq. 3.11 has not been used in this Thesis to find the stage-discharge curve for the flume at Risvollan. One of the limiting conditions described in the Standard [11, 7.2.3.5], is not fulfilled for the flume at Risvollan. A calculation for the equation will not be done in this Thesis, but the effect of the limiting condition not being fulfilled will be studied in Eq. 3.10 and discussed further in the Discussion section. These two equations both assume this condition to be fulfilled and are therefore similar. Therefore, only one theoretical calculation will be carried out.

Discharge Coefficient The discharge coefficient C_D, as described in [11], approximates the effect of viscous friction on the theoretical discharge by allowing for the development of a boundary layer of displacement thickness δ_* along the bottom and sides of the throat:

$$C_D = (B_e/B) \, (1 - \delta_*/h)^{\frac{3}{2}} \tag{3.12}$$

where B is the throat width, B_e is the effective throat width (see [11]), h is the water level and $\delta_* = 0.003L$. The discharge coefficient will increase with increasing water levels. Figure 3.4 shows how the boundary layer with thickness δ_*along the bottom and sides will develop.

[35, p. 157] states that the flow rate for Palmer-Bowlus flumes are seldom written as Equation 3.11. However, the discharge coefficient is relevant for the Bernoulli's method, and therefore mentioned here.

3.5 Tracer Dilution

Tracer dilution measurement can be used to find the flow rate in channels. It can also be used as an in-place calibration method to fixed measurement stations for flow [35, p. 238]. In the following subsection the theory behind measurement of flow in channels by the dilution method is presented as in [6].

A solution of a tracer is injected for a short duration into a cross-section at the entry to the measuring reach of the channel. At a second cross section downstream of the reach, samples are taken over a period of time t. The sampling time t has to be sufficiently long enough to assure that the whole of the tracer has passed the second cross section. This gives the following mass balance [6]

$$M = C_1 V = Q \int_0^t (C_2 - C_0)dt \tag{3.13}$$

where M is the mass of the tracer injected, C_1 is the concentration of the injected tracer, V is the volume of solution injected, Q is the volume rate of flow in the stream, C_2 is the concentration of tracer at the point of sampling during a period of time dt in grams per liter, and C_0 is the background concentration of tracer in situ in grams per liter. Equation 3.13 gives the flow rate of the channel

$$Q = \frac{C_1 V}{\int_0^t (C_2 - C_0)dt} \tag{3.14}$$

The integral of Equation 3.14 can be determined by measuring the concentrations C_0, C_1 and C_2 independently [6]. Measurements of the concentrations will be done by a conductivity recorder [24], which during measurements creates the curve

$$C_2 - C_0 = f(t) \tag{3.15}$$

The integral of the curve is determined graphically. Requirements for the measurements:

- The discharge Q is constant during the period of measurements
- Leakage between the location of release and measuring is not of significance
- The amount of extraneous water in the measuring section is so small that is does not affect the concentration of dilution in the measuring location

The requirement of constant discharge Q during measurement period, is the main reason that the Integration method is used. The water levels and the flow rates in the waste water channel at Risvollan varies rapidly. The constant-rate injection method has longer injection times t, and should not be used in conduits were the flow rates may change rapidly.

Chapter 4

Field and Laboratory Work

4.1 Flume Casting Technique

This chapter deals with the work concerning the casting technique that was used to create the replica of the flume at Risvollan. The laboratory set up will be presented as well.

Casting Frame The first step for reproducing the flume was to make a casting frame. The casting frame had to fit inside the waste water channel and block the silicone from leaking when creating the negative imprint. Figure 4.1 shows the casting frame made by the Author. The parts are made of plywood, and would be assembled once it was placed in the channel. A lot of time was invested to make the ends fit sufficiently in the channel. The box of plywood in the middle was mainly made to occupy space when making the negative imprint to save silicone. The ends was fasten with screws onto the box to hold them in place.

Field Work In order to create the negative imprint, the flume area had to be dry. The flow through the flume had to be closed and redirected to avoid flooding. Trondheim municipality installed a pipe plug into the pipe upstreams the flume. The plug was filled with air once it was placed into the pipe to block the flow completely. The flow was redirected on the side of the flume and released downstream the flume. Figure 4.2 shows the pipe plug. When the flume was dry the casting frame was placed into the channel. Gaps between the channel and the ends of the casting frame where sealed off to avoid leakages from the silicone when pouring it into the casting frame. The silicone was left to dry for approximately eight hours. Then the negative imprint was removed carefully. Figure 4.3 shows the silicone while drying inside the casting frame, and the result of the negative imprint.

Casting A tight box of plywood was made to reproduce the flume from Risvollan of the negative imprint. Figure 4.4 shows the box with the negative imprint in it. Then polyurethane resin (PUR) was poured into the box and left to dry for 12 hours. Afterwards the box and the negative imprint was removed. The result of the reproduced flume is seen in Figure 4.5.

Figure 4.1: The casting frame [Photo PPN]

Figure 4.2: Left: The pipe plug with hose to redirect the flow. Right: The pipe plug in operation [Photo PPN]

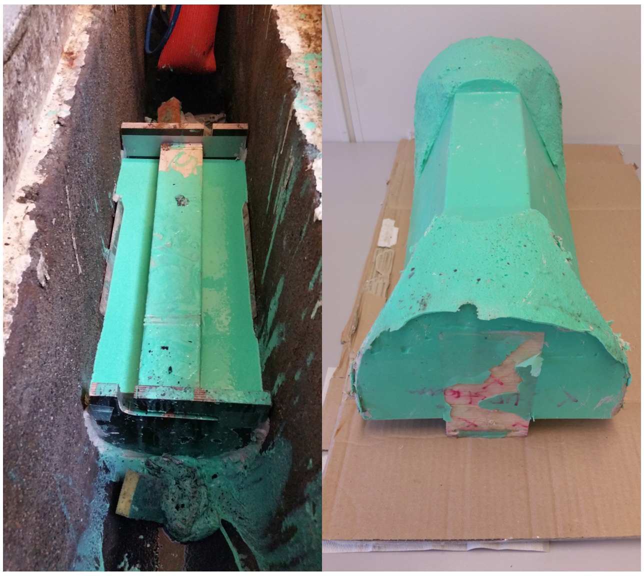

Figure 4.3: Left: Producing the negative imprint. Right: The result of the negative imprint [Photo PPN]

Figure 4.4: Creating the reproduced flume. Left: Box of plywood with negative imprint inside. Right: PUR poured and drying over the negative imprint to create the flume replica [Photo PPN]

Figure 4.5: The reproduced Palmer-Bowlus flume from Risvollan [Photo PPN]

Issues During Molding Experiments using the bi-component silicone was done in the laboratory before making the negative imprint in the field. The experiments conducted gave results of the time for the material to harden, and the level viscosity of in the material. The work gave positive results to continue the work in the field. In the field unexpected problems appeared. When the silicone was mixed with the hardener, the viscosity did not increase as rapidly as in the laboratory. When the molding material was filled into the framework, a lot of leakages appeared. The viscosity was high and a lot of molding material was wasted, see Figure 4.6. Another problem was leakage of ground water from the upstream part of the flume. The leakage came from the pipe joints which could not be blocked by the pipe plug. The ground water was cold and leaked into the molding area. The cold air temperature combined with the cold ground water made the hardening time roughly four times longer than in the laboratory tests, i.e. 3 hours.

Before the rest of the silicone could be filled into the casting frame, the issues had to be fixed. Fortunately the leakage of groundwater upstream the flume was blocked when the leaked silicone hardened. The temperature in the room was increase to approximately 20^oC by a heater which was brought to the site from the laboratory.

Figure 4.6: Silicone and hardening leaking from the framework [Photo PPN]

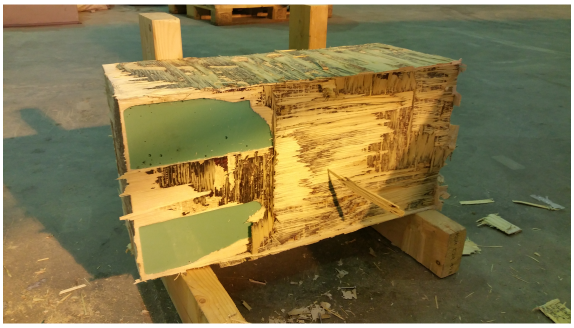

Figure 4.7: Plywood stuck onto PUR

Issues During Casting When removing the box of plywood from the reproduced flume, the PUR was stuck to the plywood as seen in Figure 4.7. The plywood was impossible to separate from the PUR by hand, and had to be polished mechanically.

4.2 Laboratory set up

The laboratory calibration measurements of the reproduces flume from Risvollan was done in a flume stationed in the Hydraulic Laboratory of the Norwegian University of Science and Technology (NTNU). The flume is called the C-flume. The discharge to the flume was delivered by a pump with a capacity of flow rates from roughly 1 to 150 l/s. The pipe delivering the discharge was equipped with Siemens Sitrans Mag 5000 discharge meters and controlled by a valve. The pump circulates water from a basin through the flume and back to the basin. The basin needs to be filled before every test due to major leakages in the basin.

Constructing the Model Before the model could be placed in the flume, some changes had to be done. An Ogee crested weir had to be removed, and a belonging drainage pipe had to be installed back onto the basin. Figure 4.8 is the technical drawing of the model installed into the C-flume. Due to lack of time, the channel upstream the flume was adjusted to 65 cm instead of $L > 6D$. This can be justified that the objective of the Thesis was to confirm the initial stage-discharge curve, and not to do a full calibration for replacing the existing stage-discharge curve. For higher flow rates the inlet of the U-channel created surface waves and a draw down curve in the flow profile. The surface waves made it difficult to measure the water depth precisely when the flow rate was increased.

The slope upstream the flume at Risvollan was measured in the field by the Author with laser. In the technical report of Risvollan measurement station [34], a slope of 10‰ was planned to be built. However, measurements done by the Author found the slope to be around 15‰. The slope of U-channel in the model was set to 15‰. This is within the upstream slope limits of $10 - 30$‰ set by literature [3, 35, 11]. The slope of the flume throat in the model was set to the in situ conditions, $S = 0.020$ (1.25^o).

Measurement Equipment To measure the water depth in the U-channel in the model, a point gauge with an accuracy of 1 micrometer was used and installed as illustrated in Figure 4.8. The datum surface for the point gauge was set at the downstream end of the throat and at the longitudinal centerline as described in [11, 11.5.3]. The datum was also set at the channel bottom, in order to compare the different stage-discharge curves for each datum. When the zero elevation was set, the water level at different flow rates was found.

Figure 4.9 shows the model installed into C-flume. The model was assembled into the C-flume by the Author. Some of the components in the model was made by the belonging staff in the laboratory with assistance from the Author.

Test Runs Before the calibration measurements was performed, test runs were carried out. Figure 4.10 shows the stage-discharge curve for a test run. There were major leakages between the pump and the flume during the measurements. This gave higher discharge values to the related water depth. The leakages came from areas were the flume material is wood. The wood had to be saturated before it would stop leaking. Water was pumped into the flume for some time in order to stop the flume from leaking. After a couple of days the wood was saturated and the calibration measurements could be carried out.

The water level for the test run is not calibrated after the flume, meaning the zero elevation level is not at the flume throat. The results given in Figure 4.10 will not be used further, and illustrates how leakages affect the results of the stage-discharge curves.

Figure 4.11 gives all the results from the calibration when the C-flume had stop leaking. A full calibration is to measure 20 different water depths 5 times [35, p. 311]. The input, the discharge, had to be stable for each of the 20 measurements. This was not possible as the pump gave varied discharge rates for the same frequency and valve opening. Also, the objective of the thesis was to confirm the initial stage-discharge curve. The result of the stage-discharge curve would therefore be made from one single measurement in the laboratory.

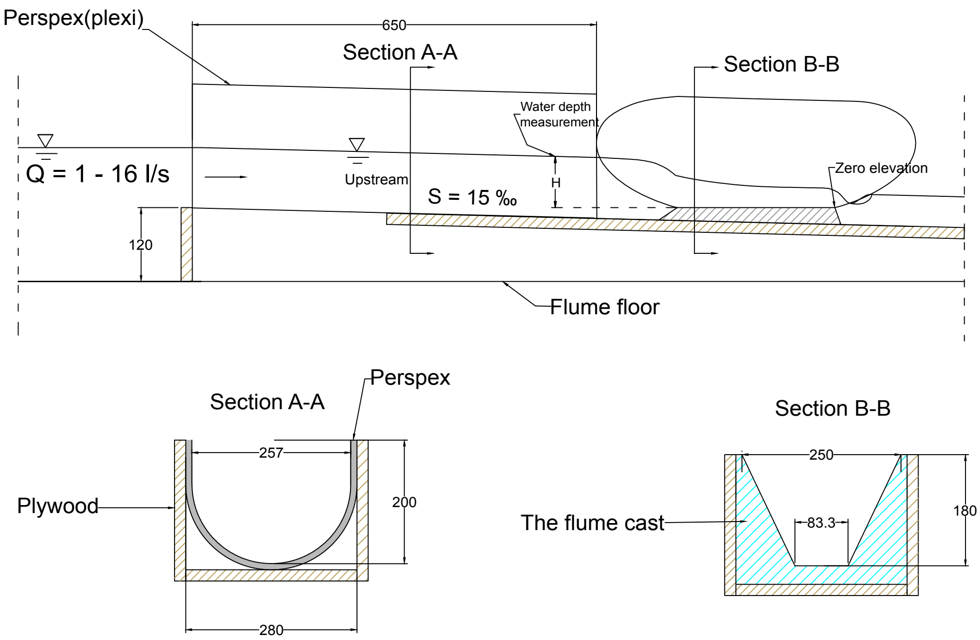

Figure 4.8: Technical drawing of the model for flow rate measurements at Risvollan with in situ conditions [PPN]

Figure 4.9: The model installed into the C-flume [Photo PPN]

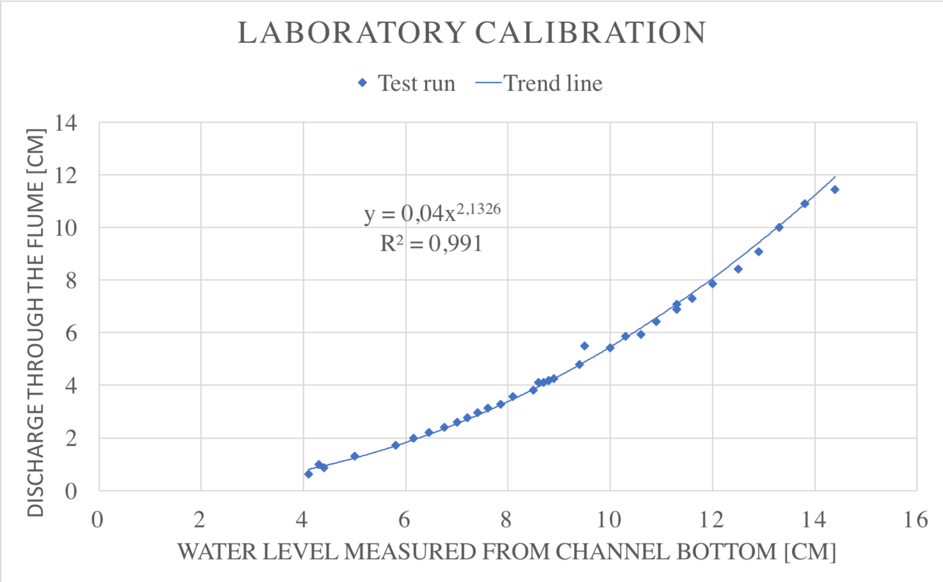

Figure 4.10: Stage-discharge curve from test run calibration in the laboratory

The repeatability for the measurements was done by comparing the final stage-discharge curve for the laboratory calibration to one other stage-discharge curve made in the laboratory. The the mean deviation between them was found. If the mean deviation was small, the stage-discharge curve for the laboratory calibration was valid. Note that the configurations in the model is not sufficient to do a full calibration of the flume as water will flow over the flume for water levels above 16.0 cm. Potential configurations that could be done on the model will be discussed in Chapter 9.

Figure 4.11 was the second test run done in the laboratory, and it is not used as the final calibrated curve. The R-squared is 0.998 and the data scatter a bit from the trend line in the smallest and highest discharge values. The smallest values scatter due to unsteady flow. The Author experienced that the time for steady flow to develop was much longer for low flow than higher flows. This gave higher flows for lower measured water depths. For higher flows the imprecision is due to inexperience and surface wave development on the water surface in the flume and the U-channel.

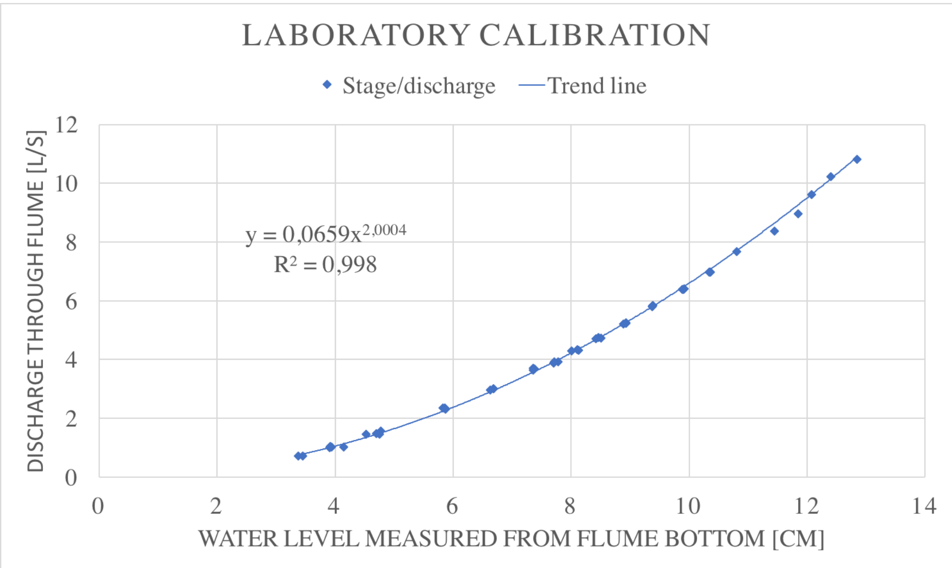

Figure 4.11: Results from stage-discharge run in the laboratory

Chapter 5

Quantitative Method

The Quantitative Method Chapter presents the initial stage-discharge curve at Risvollan and the three methods used to calibrate the flume and how the stage-discharge curves were found for each method. The theory behind the theoretical and tracer dilution method is presented in Section 3.3 and 3.5 respectively. There are various methods available for calibration of flumes, and the methods can be split into two groups: in situ and laboratory calibration [38, p. 291]. For this thesis a theoretical method, tracer dilution and laboratory calibration were used to calibrate the flume. Tracer dilution measurements is a calibration method which is done in situ. Section 5.4 and 5.5 presents statistics used to process data and to compare the methods.

5.1 Laboratory Calibration of Flume

A calibration of the reproduced flume from Risvollan was done in the laboratory. In the laboratory a model of 1:1 was built. The conditions in the laboratory was recreated to resemble the once in situ. Since the Palmer-Bowlus flume is mainly controlled upstream, the upstream slope of the flume in the laboratory has to be identical to the one in situ. The downstream slope of the flume was not considered in this set-up, but should be considered with respect to submergence of the flume. For the flume at Risvollan however, there was not experienced any problems connected to submergence under operational conditions. For more information concerning the laboratory set up, see Section 4.2.

As mentioned, in full calibration of a flow measurement instrument, the calibration measurements should be based on 20 different flow rates and 5 times for each flow rate, distributed across the entire measurement range [35, p. 311]. Due to imprecision in the pump, the stage discharge curve is only based on one measurement. The flow rates in the calibration was set from 1 l/s to 16 l/s. 1 l/s was the minimal discharge the pump could provide, and for discharge above 16 l/s there would be overflow in the flume. On a daily basis the flow through the flume will be around 1.2 - 8.0 l/s. However, the measuring range for the flume at Risvollan is higher than 16 l/s, meaning that the flume is not verified for the entire measurement range.

The discharge rate was controlled with a pump. The pump did not provide a steady discharge rate and could vary with ± 0.13 l/s, so a rough value had to be chosen from the display of the discharge meter. The water was then guided through the flume while measuring the water depth at a known flow rate. The water level was measured once the flow through the point of measurement was steady. The water level was measured with a point gauge.

Assumptions made for the laboratory calibration:

- Water quality will not affect the measurement: For the laboratory calibration fresh water was used compared to waste water from the site
- Stable flow pattern: The U-channel of Plexiglas in the laboratory will create the same flow pattern as the one in the site despite difference in material

5.2 Bernoulli's Equation

Bernoulli's equation (Eq. 3.4) can be used for a theoretical desktop method for calibrating Palmer-Bowlus flumes. The theory behind this method is presented in section 3.3. Equation below is the same as Eq. 3.10 from section 3.3. Since A_i is a function of d_i, the equation cannot be solved directly. The equation can be solved by loops developed in any coding language. For this thesis the equation was solved by Iterative solution in excel as presented in [13]. The literature [13] gives the method for using iterative solving in excel, and the process will not be presented further here.

$$d_i = t + d_c + \frac{A_c}{2B_c} - \frac{Q^2}{2gA_i^2}$$

As described in [35, p. 159], the stage-discharge curve for Bernoulli's is found from an iterative four step process:

1. Choose a value for d_c and calculate A_c and B_c by knowing the geometrical relation
$$B_c\,(d_c) = 0.0833 + d_c\,[m]$$
$$A_c\,(d_c) = (0.0833 \cdot d_c) + \left({}^1\!/{}_2 d_c^2\right)[m]$$
2. Calculate the discharge Q by using Eq. 3.8
$$Q = \sqrt{9.81 \cdot \frac{A_c^3}{B_c}}$$
3. Set an input value for d_i, and calculate the output value for d_i from the Eq. 3.10. By solving the equation with iteration in Excel, the input value and output value will become the same
$$d_i = t + d_c + \frac{A_c}{2B_c} - \frac{Q^2}{2gA_i^2}$$
4. Repeat the procedure for a new value of d_i to make the stage-discharge curve for Q/d_i

The method for Bernoulli is presented in [35, p. 158-159], and does not specify in which measuring area the method is valid for. The standard sets the minimum water level the theoretical calculation is valid for to 0.05 m. In this Thesis, the stage-discharge relation was calculated in the measuring range $h = [5.0 - 21.0]$ cm for Bernoulli's.

5.3 Tracer Dilution

The tracer dilution measurements was carried out with instruments from Sommer Messtechnik called the TQ-system. See [24] for more information about the instruments and software.

The method to determine the flow rate in a waste water channel from tracer dilution measurements is described in the following with Figure 5.1 as basis:

1. Inject the tracer solution with a known mass M at point A in one stake
2. The sensors downstream in point B measures the background concentration C_0 of NaCl in the waste water
3. The dilution concentration C_2 is measured at point B and the flow rate is calculated from Equation 3.14 by the software. Point B is downstream point A by a length of L

It is important to inject the tracer as quickly as possible in the waste water flow [24]. The user manual from [24], suggests $L \sim 50 \cdot B$ for middle tortuous flow as a rule of thumb. At Risvollan this is equivalent to about 13 meters since the internal diameter of the channel is 250 mm. For the experiments conducted in the presented thesis, the length L was dependent on available injection points upstream the measuring point. The injection points were in distances of 22, 59 and 98 meters as illustrated in Figure 5.2. Measurements from different injection points could give an indication on how the distance L will affect the results.

The discharge for tracer dilution measurements are found by

$$Q = \frac{C_1 V}{\int_0^t (C_2 - C_0)dt} = \frac{C_1 V}{C_2 - C_0}$$

where $C_2 - C_0$ is determined graphically by the software TQ-commander with the mass of NaCl (here: M) as input, see Equation 3.15.

The TQ-system has three conductivity sensors. The conducted measurements used two to three of the sensors. To find the optimal number and placement of the sensors, different placement was tried, as is illustrated in Figure 5.3.

5.4 Processing Data

In order to sort data from the tracer dilution measurements the Gaussian method (normal distribution) was used. Physical measurements in hydraulics is adequately explained with a normal distribution [40, p. 172]. Errors in scientific measurements are extremely well approximated by a normal distribution. Figure 5.4 shows the Probability density function (PDF) for the Standard Normal distribution curve. The PDF specifies the probability for a random variable to fall within a defined range of values.

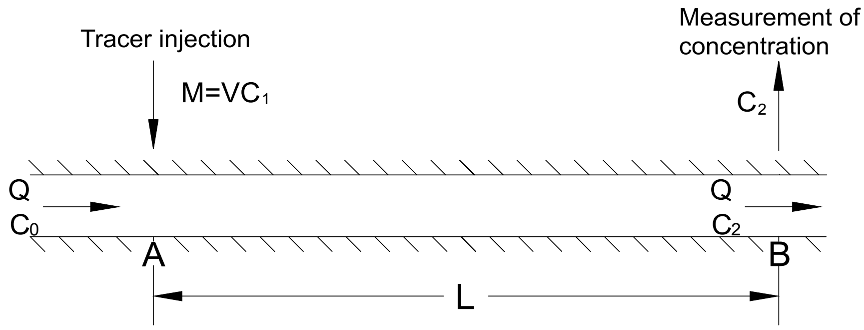

Figure 5.1: Measurement of flow rate with integration method [PPN]

The normal curve is completely determined when μ and σ are specified. μ is the mean of a defined population sample, while σ is called the standard deviation. The standard deviation gives information about how wide the distribution is, and specifies the probability for a random variable to fall within a range. The width of each distribution gives information about how divergent the observation data will be. In this section, the PDF will be used to sort data from the tracer dilution measurements, in order to achieve better results. For more information about the normal distribution, see [40, chapter 6].

The measurement uncertainties for flow rate measurements should be connected to 95% probability [4]. If a population sample is assumed to be normally distributed, there is a 95% probability that a measured value lies within the defined interval of the population sample. If the width for a PDF is set to 2σ, a value will have 95.4% probability of laying within the interval.

Tracer Dilution Method For the tracer dilution measurement the data was grouped for every fifth millimeter, meaning values from 5.8-6.2 mm, 6.3-6.8 mm, etc. was put into the same group. Each group was defined as one population sample. Further the mean discharge and the standard deviation was calculated for each group, defining the normal distribution for each group. The width of the distribution was set to 2σ. The probability for a random value X to fall within this interval is 0.954, and can be expressed as

$$P(\mu - 2\sigma < X < \mu + 2\sigma) = 0.954 \tag{5.1}$$

The values that did not fall within $X = \{\mu - 2\sigma, \mu + 2\sigma\}$, was sorted out and not included in further calculations.

5.5 Mean Deviation

For each method used in the thesis the mean deviation from the initial stage discharge curve was calculated. The trend line equation for each method was used to calculate discharge for water levels in a defined interval. Then the trend line equation for the initial stage-discharge curve was used to calculate discharge for water levels in the same defined interval for each method. The mean deviation from the initial was found by [31]

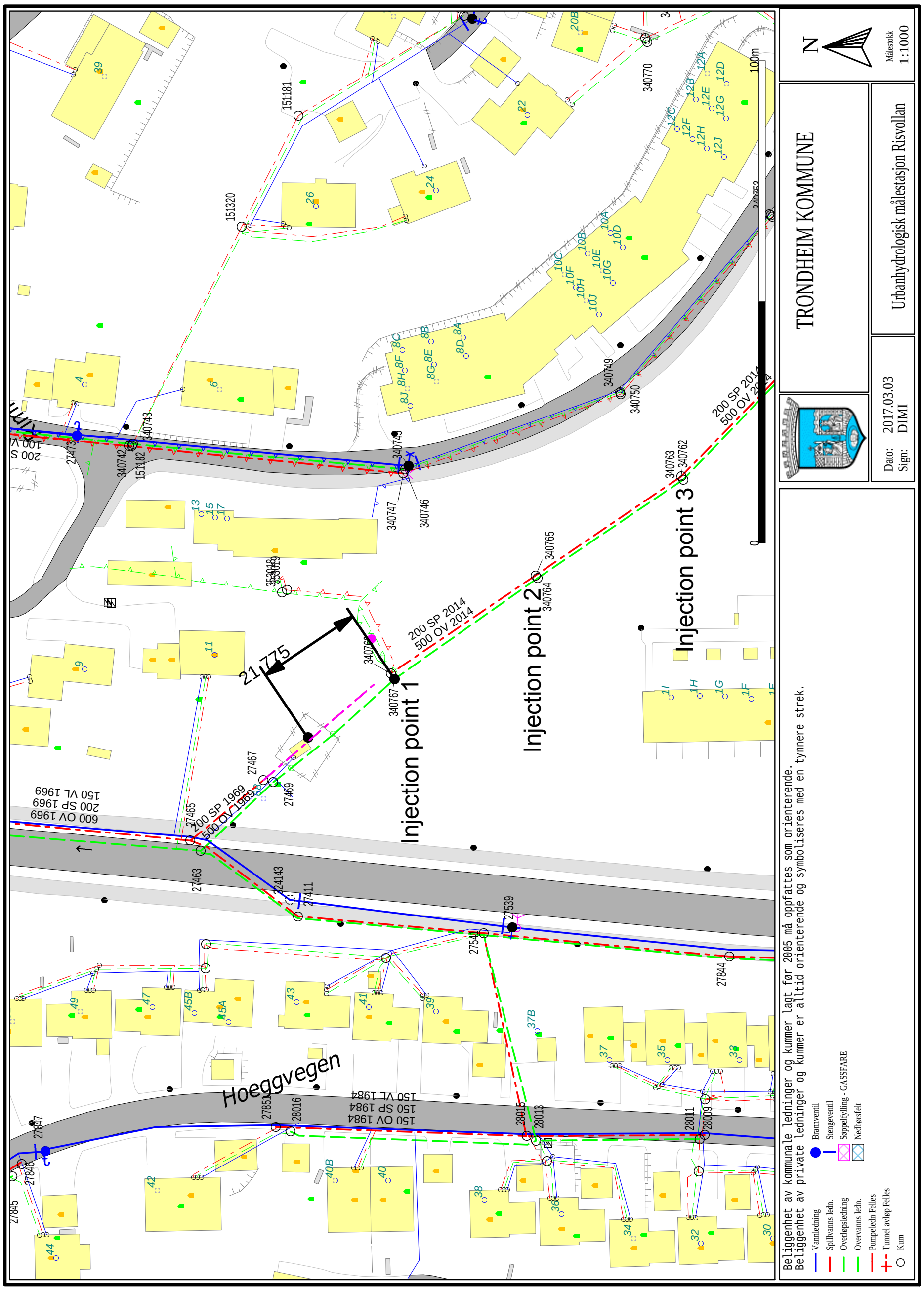

Figure 5.2: Injection points upstream measurement point at Risvollan [28]

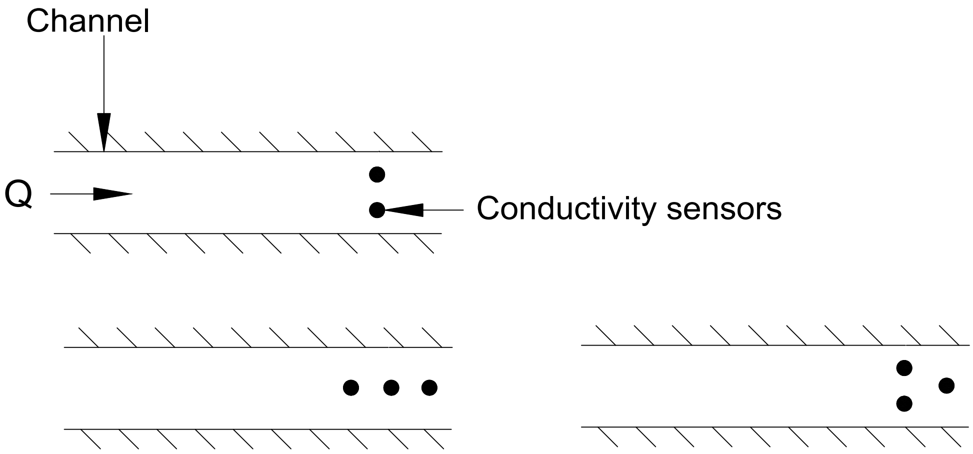

Figure 5.3: Placement of sensors in waste water channel at Risvollan [PPN]

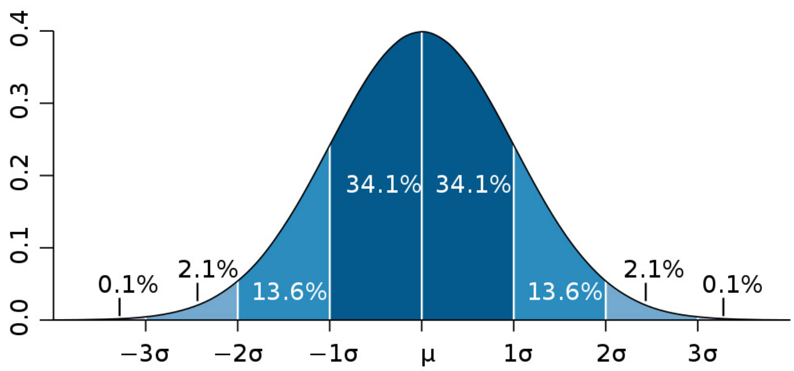

Figure 5.4: Probability density function (pdf) for the Standard Normal distribution [20]

$$m = \frac{1}{n}\left(|Q_{1,\text{ inital}} - Q_{1,\text{ method}}| + \ldots + |Q_{\text{n, inital}} - Q_{\text{n, method}}|\right) \tag{5.2}$$

where m is the mean deviation, n is the number of discharge calculations and Q is the discharge values calculated from the trend line equations. Eq. 5.2 gives the difference between the average initial discharge and the average discharge from a method for a defined interval of water depths and can be written as

$$m = |\overline{Q}_{\text{initial}} - \overline{Q}_{\text{method}}| \tag{5.3}$$

where $\overline{Q}_{\text{initial}}$ is the average initial discharge and $\overline{Q}_{\text{method}}$ is the average discharge in a defined interval. The relative error was also calculated. The relative standard deviation (RSD) is the ratio between the mean deviation and the average initial discharge [30]

$$\text{RSD} = \frac{m}{\overline{Q}_{\text{initial}}} \cdot 100 \tag{5.4}$$

and was given in percent. The ratio between the initial and the different methods was also expressed at different water levels to find out how the accuracy of the measurement methods varied at different water levels:

$$r = \frac{|Q_{\text{i, inital}} - Q_{\text{i, method}}|}{Q_{\text{i, inital}}} \tag{5.5}$$

Due to the differences in the measurement intervals, it is not right to compare the different deviations from each method with each other. For tracer dilution measurements the deviation was found for a interval defined for water depths at 6.0 to 9.0 cm, while for Bernoulli is was from 5.0 to 21.0 cm. Also the RSD will decrease for higher water levels as the $\overline{Q}_{\text{initial}}$ will increase. However, the mean deviation calculated from the initial for each value will give an estimate for how accurate the method is. The calculations of mean deviation from the initial was done in excel and the spreadsheets for each method can be found in Appendix E.

Chapter 6

Results

This chapter deals with the results from the methods used to calibrate the Palmer-Bowlus flume at Risvollan. The basis for the results are from measured data and are presented as stage-discharge curves. The results included are the initial stage-discharge curve, stage discharge-curve from the presented methods, and a stage-discharge curve from a SINTEF report. Each method had different measuring ranges and they have different datum to measure the water level from. As mentioned, the water depth for Palmer-Bowlus flumes should be measured from the throat bottom. However, some of the results are measured from the channel bottom. The datum for each method will be stated in each section. The initial stage-discharge curve will be compared to the other curves in order to find out how the different methods for calibrating the flume differ.

6.1 Initial Stage-Discharge Curve

Figure 6.1 shows the initial stage-discharge curve currently in use. The data is from a log-plot found in an Appendix from the belonging database to Risvollan. The plot is given in Appendix B.5. The values for the stage-discharge relation is collected directly from the plot as no belonging table for the data was found. Table 6.1 gives the initial values collected from the plot. The measuring range is from $d_i = [3.0 - 21.0]$ cm.

It is unknown what datum the initial stage-discharge curve for Risvollan uses to measure the water depth from. Here however, it is set to measure from the channel bottom. Note that the datum for measuring the water level is from the flume bottom and not from the channel bottom as in this case.

Table 6.1: Initial values from the data plot, see Figure B.5

d_i $[cm]$	3.0	3.2	3.55	3.78	4.22	4.58	4.9	5.5	5.8	6.5
Q $[l/s]$	0.26	0.3	0.4	0.5	0.7	0.8	1.0	1.3	1.5	2.0
d_i $[cm]$	7.2	7.9	8.5	8.9	9.4	9.8	10.3	10.8	11.7	12.4
Q $[l/s]$	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	7.0	8.0
d_i $[cm]$	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0	21	
Q $[l/s]$	9.0	10.0	12.0	14.0	15.4	17.8	20.0	22.0	26.0	

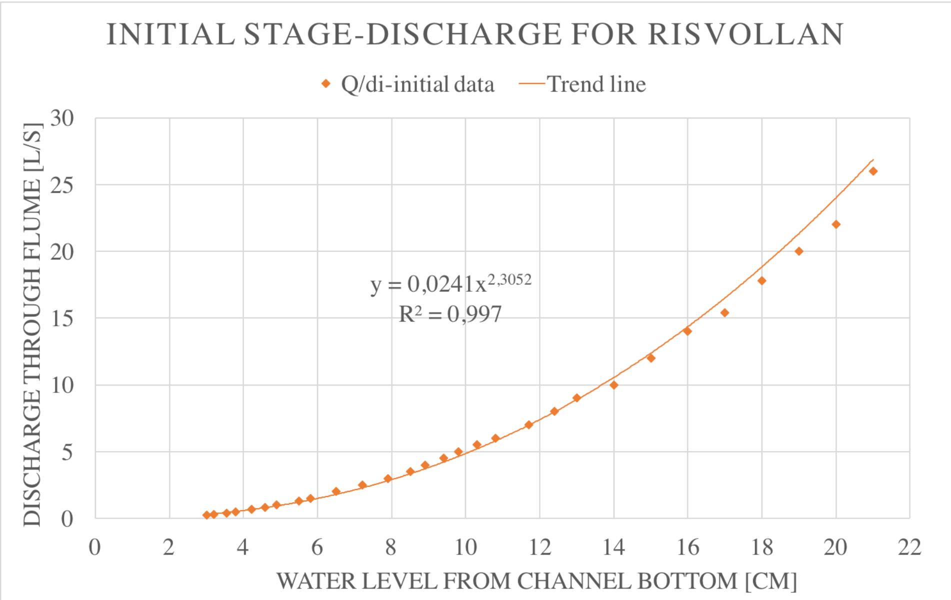

Figure 6.1: Initial stage-discharge curve for Risvollan

6.2 Stage-Discharge from Laboratory Calibration

This section presents the data from the laboratory calibration with the set up described in Section 4.2. The tables made in excel from each calibration can be found in Appendix C.

The results for the calibration is given in Figure 6.2. Note that the results are only with one measurement for each input value. The correlation in the data is good. This is due to patience and waiting for the flow to become steady when doing the measurement for each input value. The flow had to settle and become steady for the frequency set at the pump. For low flow rates this could take up to 5 minutes. Note that the flow is assumed steady. The discharge rates from the pump would vary at fixed frequencies.

A stage-discharge curve was also made when the datum was set to the channel bottom, see Figure 6.3. This measurement was done to compare the different stage-discharge curves for the method were the datum is the channel bottom.

The trend lines to the two discharge-curves with datum at the flume bottom and channel bottom gave an equation to convert the water level from the channel bottom to flume bottom. The equation is

$$h_i = h_{measured} - \left(\left(4.9177Q^{0.4409}\right) - \left(3.8199Q^{0.5074}\right)\right) \tag{6.1}$$

where h_i is the water level from the flume bottom, $h_{measured}$ is the water level from the channel bottom, and Q is the measured discharge through the flume. Equation $4.9177Q^{0.4409}$ and $3.8199Q^{0.5074}$ are the inverse equations of the trend lines from Figure 6.2 and 6.3, respectively. Equation 6.1 is only valid for flow rates between 1 l/s to 16 l/s and for a Palmer-Bowlus flume with the same configurations as the flume at Risvollan.

The repeatability of the measurement system was checked by doing two

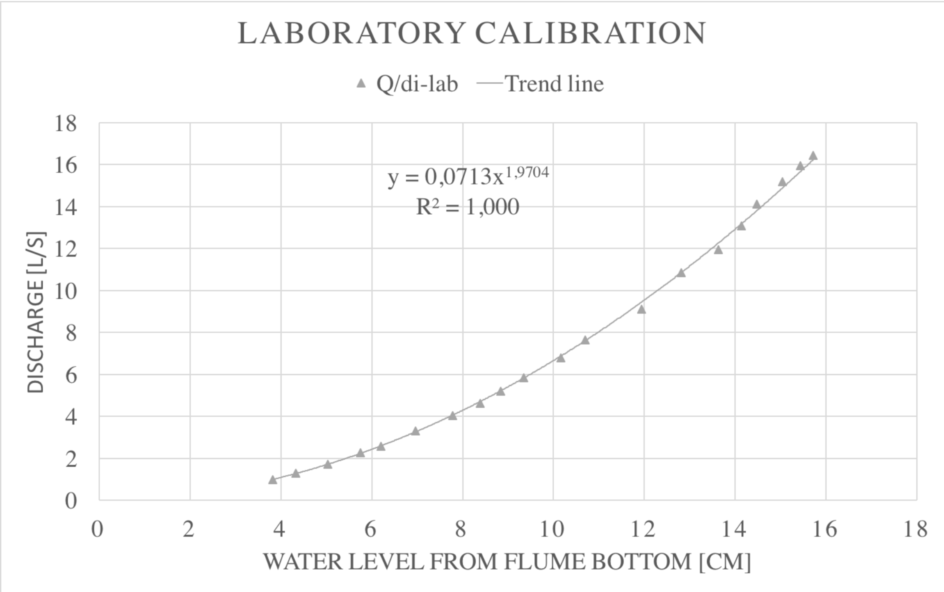

Figure 6.2: Laboratory calibration with the flume bottom as datum

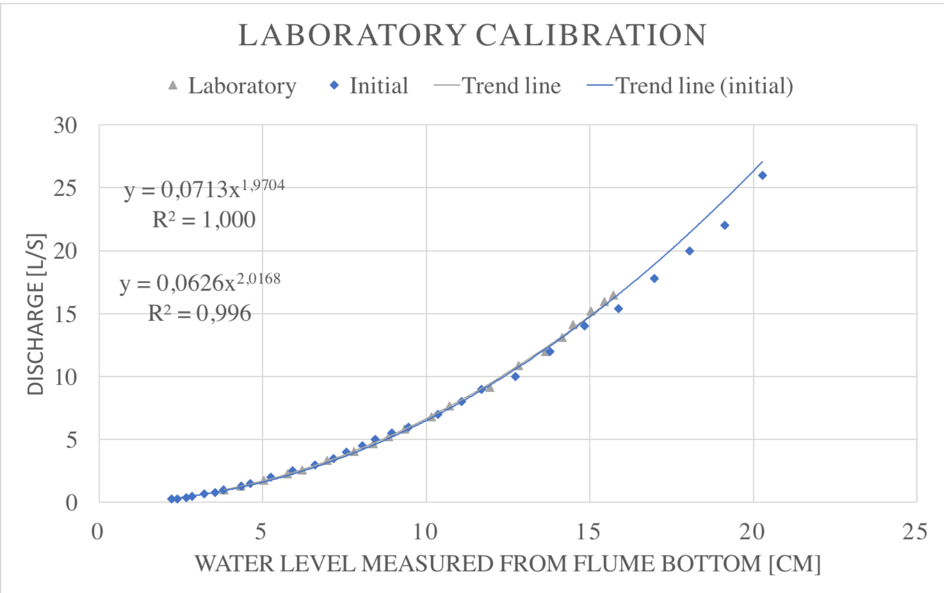

Figure 6.3: Laboratory calibration with the channel bottom as datum

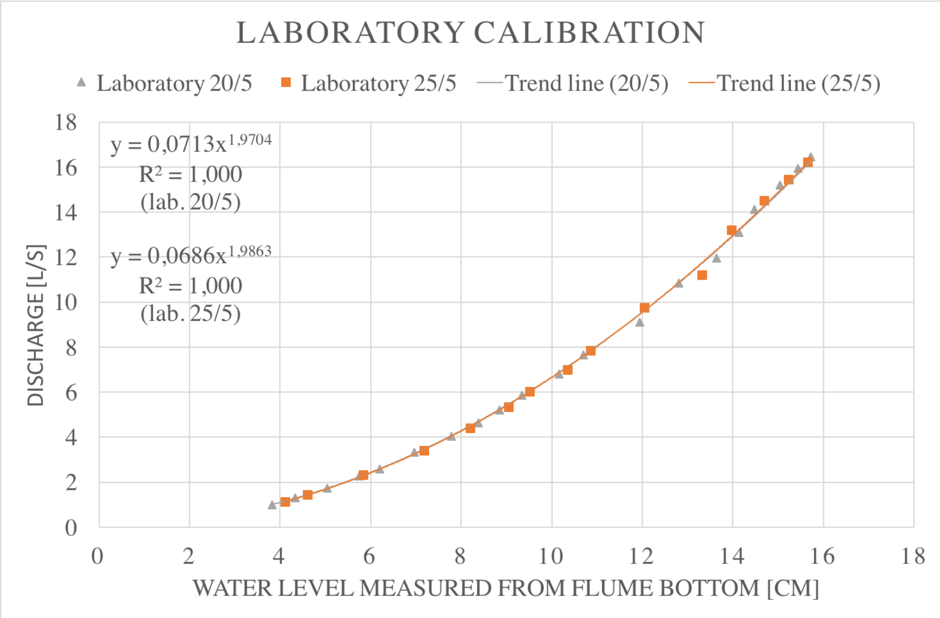

Figure 6.4: Repeatability of laboratory calibration

calibrations. The result was a mean deviation of 0.03 l/s between the trend line equation for each. This is very accurate as the pump would vary with ±013 l/s at fixed frequencies. The result from the calculation can be found in Appendix E.6, while the comparison of the stage-discharge curves is shown in Figure 6.4.

6.3 Theoretical Stage-Discharge

Figure 6.5 shows the results of the stage-discharge curve calculated from the Bernoulli's method as presented in Section 4.1. The results from the spreadsheet calculations of the stage-discharge relation done in Excel can be found in Appendix B.6.

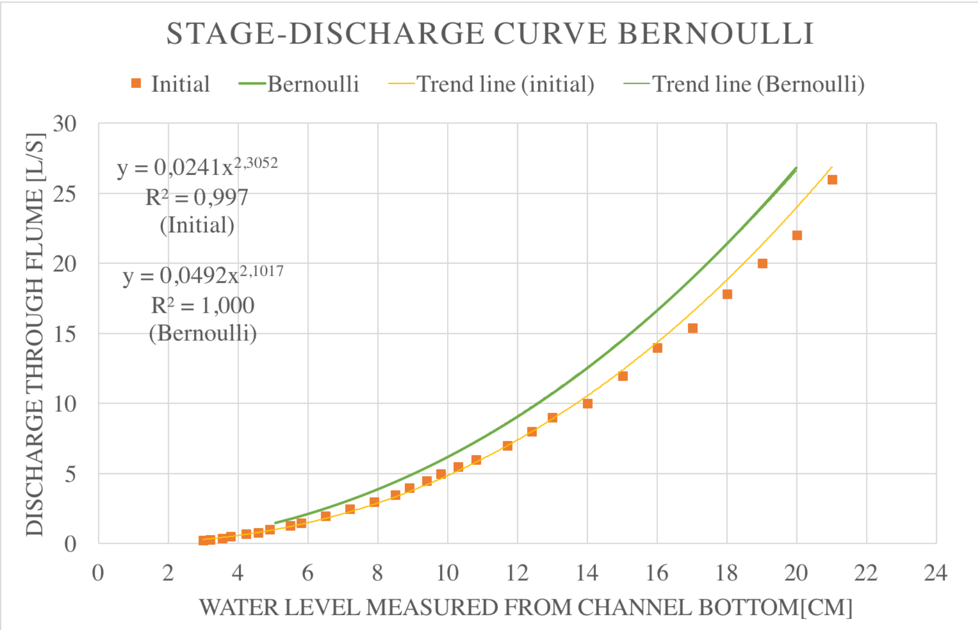

Figure 6.5: Stage-Discharge through Palmer-Bowlus flume calculated from Bernoulli's equation

6.4 Stage-Discharge from SINTEF

SINTEF made a report of stage-discharge curves for Palmer-Bowlus flume in 1994 [39]. The data is found in Appendix B.4. The report gives stage-discharge data for a Palmer-Bowlus flume with the exact same configurations as the flume at Risvollan. For comparison, see Figure B.4 and Figure B.5 in the Appendix.

Figure 6.6 illustrates how the stage-discharge from SINTEF matches with the initial for water levels between 4-20 cm. The mean deviation from the initial is 0.18 l/s in the interval between 4-20 cm. From a water level of about 16 cm, the curves diverge slightly. The corresponding stage-discharge values for the plot is given in Table 6.2.

Note: The water level is measured from the channel bottom as datum.

Table 6.2: Stage-Discharge data used for Palmer-Bowlus flume at Risvollan [39]

d_i $[cm]$	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
$Q[l/s]$	0.58	1.58	3.08	5.0	7.39	10.31	13.83	18.11	23.31

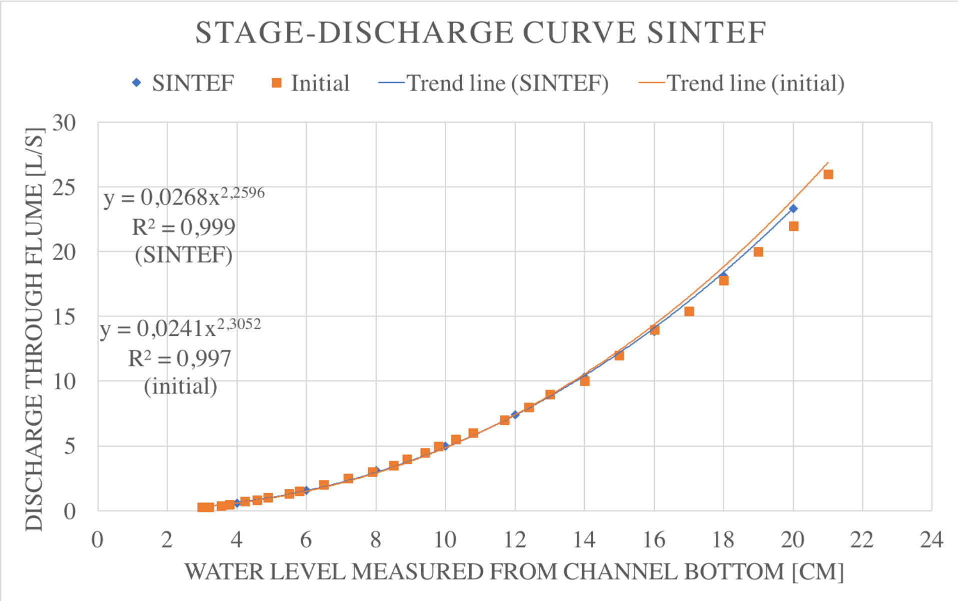

Figure 6.6: Stage-Discharge through Palmer-Bowlus flume from Risvollan

6.5 Results from Tracer Dilution

In this section the results obtained and processed from tracer dilution measurements at Risvollan are presented.

Unsorted Data Appendix D.1 contains the data of all 47 tracer dilution measurements done at Risvollan. Figure 6.7 is the corresponding plot to the table. The data from measurement number 1, 31 and 41 found in Appendix D.1 is not included in the figure and will not be used further as they are clearly not within the measurement range. Figure 6.8 show the plot of the average value for each measurement. In the measurements the number of sensors used was between two and three. In each measurement the mean flow was calculated between the sensors.

Sorted Data The measurement data is sorted in order to select the data that should be used further to discuss the results. Table 6.3 gives an overview of all the initial data from sensor A, B and C in the measurement. The measurements are grouped in seven groups, were the data within an interval of 0.5 cm are joined together (5.8 - 6.2 cm, 6.3 - 6.8 cm etc.). The values marked with red and yellow are excluded. The average flow from the remaining data is calculated for each group. Values marked with red are errors observed during measurements. The observed errors in the measurements are discussed in Section 7.1. The values marked in yellow are values outside the interval, given as two times the standard deviation, see Equation 5.1. Thus values that are larger or smaller by two times the standard deviation from the average discharge are excluded from the mean discharge calculation.

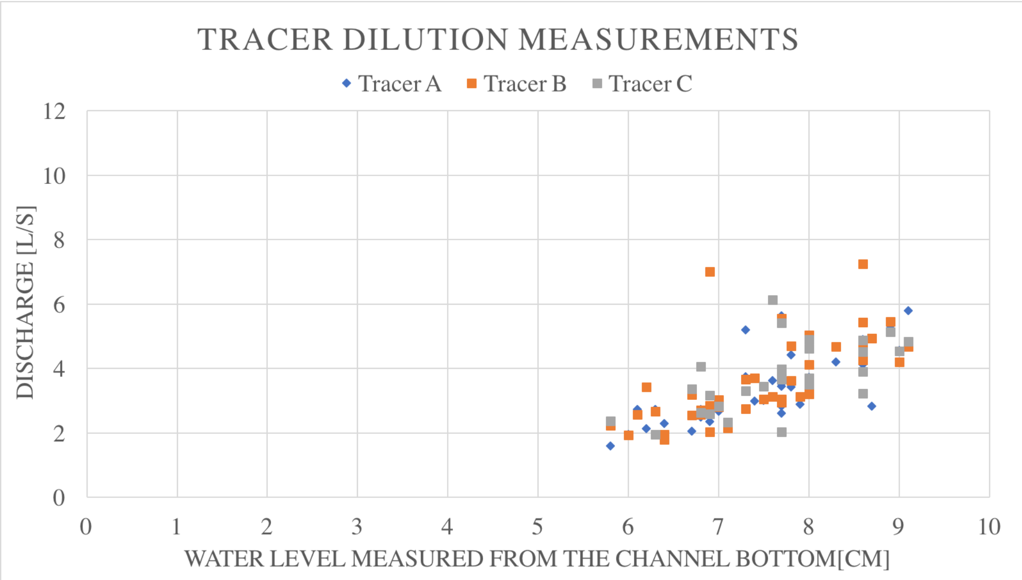

Figure 6.7: All tracer dilution measurements from Risvollan

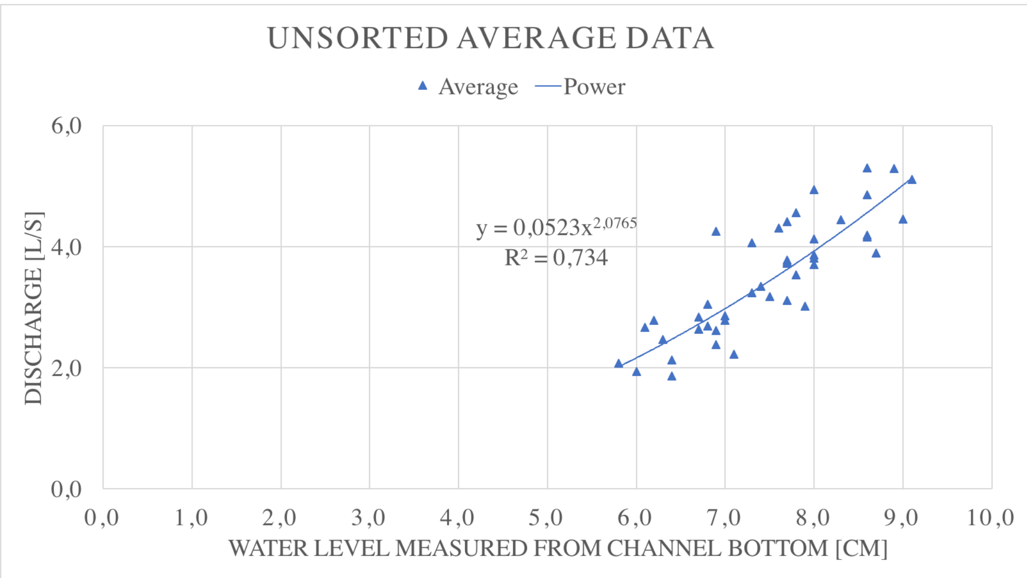

Figure 6.8: Trend line of the average data from tracer dilution measurements

Table 6.3: Tracer dilution measurement data from Risvollan. Values marked in red are errors observed in the field, while values marked in yellow are outside the defined confidence interval

Initial Data					Adjusted Data				
Water level (cm)	Group level	A	B	C	Deleted data	Comment	Water depth	Q average	2 * Standard dev
5,8	5,8 - 6,2	1,60	2,23	2,37	A	Toilet paper A			
6,0	5,8 - 6,2	1,95	1,93	-					
6,1	5,8 - 6,2	2,73	2,58	-					
6,2	5,8 - 6,2	2,13	3,44	-	B	Outside interval	6,0	2,27	1,00
6,3	6,3- 6,7	2,74	2,67	1,96					
6,4	6,3- 6,7	2,29	1,95	-					
6,4	6,3- 6,7	1,92	1,80	-					
6,7	6,3- 6,7	2,56	2,55	3,37					
6,7	6,3- 6,7	2,06	3,20	-			6,5	2,42	1,03
6,8	6,8 - 7,2	11,41	3,05	-	A	Toilet paper A			
6,8	6,8 - 7,2	2,50	2,58	4,07	C	Outside interval			
6,8	6,8 - 7,2	2,73	2,71	2,63					
6,9	6,8 - 7,2	2,54	7,02	3,17	B	Outside interval			
6,9	6,8 - 7,2	2,36	2,85	2,60					
6,9	6,8 - 7,2	27,83	33,22	-	A and B	Injection fail			
6,9	6,8 - 7,2	2,72	2,04	-					
7,0	6,8 - 7,2	2,67	3,04	2,83					
7,0	6,8 - 7,2	2,74	2,82	-					
7,1	6,8 - 7,2	2,17	2,16	2,34			7,0	2,65	0,84
7,3	7,3 - 7,7	5,20	3,67	3,31		Toilet paper A			
7,3	7,3 - 7,7	3,74	2,75	-					
7,4	7,3 - 7,7	2,99	3,70	-					
7,5	7,3 - 7,7	3,01	3,05	3,45					
7,6	7,3 - 7,7	3,62	3,14	6,14	C	Cloth C			
7,7	7,3 - 7,7	2,84	2,96	5,42	C	Outside interval			
7,7	7,3 - 7,7	3,54	3,81	3,99					
7,7	7,3 - 7,7	2,61	3,06	3,66					
7,7	7,3 - 7,7	3,45	3,74	3,95					
7,7	7,3 - 7,7	5,64	5,56	2,03	A and B	Outside interval	7,5	3,31	1,72
7,8	7,8 - 8,2	4,43	4,70	-					
7,8	7,8 - 8,2	3,44	3,62	-					
7,9	7,8 - 8,2	40,70	82,94	79,35	A, B and C	Injection fail			
7,9	7,8 - 8,2	2,89	3,13	-					
8,0	7,8 - 8,2	3,51	4,12	-					
8,0	7,8 - 8,2	4,86	5,04	4,91					
8,0	7,8 - 8,2	3,72	4,93	3,71					
8,0	7,8 - 8,2	4,65	3,41	3,51					
8,0	7,8 - 8,2	3,25	3,22	4,62	A and B	Toilet paper A and B	8,0	4,07	1,40
8,3	8,3 - 8,7	4,20	4,68	-					
8,6	8,3 - 8,7	3,89	5,44	3,24					
8,6	8,3 - 8,7	4,12	7,25	4,52		Toilet paper A and B			
8,6	8,3 - 8,7	4,33	4,26	3,90					
8,6	8,3 - 8,7	4,90	4,77	4,88					
8,7	8,3 - 8,7	2,83	4,95	-	A	Outside interval	8,5	4,46	1,41
8,9	8,8 - 9,2	5,27	5,46	5,15					
9,0	8,8 - 9,2	4,57	4,21	4,55					
9,1	8,8 - 9,2	5,80	4,68	4,85			9,0	4,95	1,01

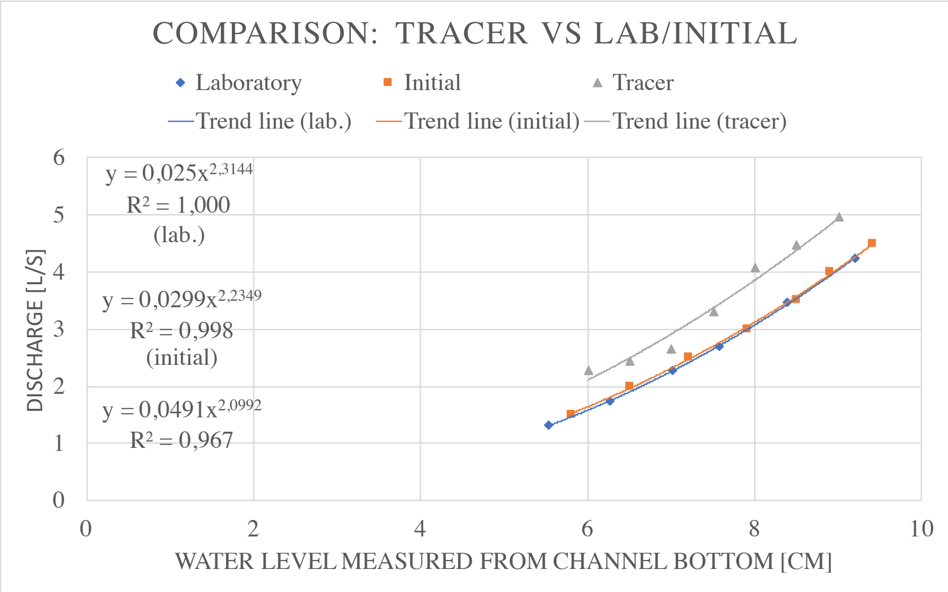

Figure 6.9: Comparison of stage-discharge curves for tracer vs initial and laboratory

Figure 6.9 shows the stage-discharge curves for the initial data, laboratory calibration and tracer dilution in water levels between approximately 5.8-9.2 cm. The trend line for the the tracer dilution measurements lies as a parallel displacement from the other two trend lines.

Injection Point Table 6.4 shows the data from all measurements sorted after injection point 1, 2 and 3 (marked in green). The deleted values are errors observed during measurements (marked in red). These values are not included when calculating the mean discharge for each group. The values marked in yellow are outside the confidence interval, but are included when calculating the average discharge. The average discharge is calculated from the same water levels at each injection point. Figure 6.10 shows a comparison of the measured average water flow for each of the injection points and the discharge values from the initial stage-discharge curve. Table 6.5 gives an overview of the results. The mean deviation from the initial is calculated for water levels between 6.0 to 9.0 cm. There is a clear correlation between the injection point and the mean deviation. The further away the tracer is injected from the measurement point, a decrease in the mean deviation from the initial is observed.

6.6 Secondary Instrumentation

The secondary system at Risvollan monitors the water depth at real time for every minute. The sensor is placed inside a stilling well, 50 cm from the start of the flume contraction. For the tracer dilution measurements the manual water depth measurements were supposed to be compared to the secondary device at Risvollan in order to determine a reasonable water level for the measurements.

Table 6.4: Data from tracer dilution measurement sorted from injection point of tracer

Initial Data					Adjusted Data			
		Tracer name and flow rate (L/s)						
Water level (cm)	Injection point	A	B	C	Deleted data	Comment	Water depth	Q average
5,8	1	1,60	2,23	2,37	A	Toilet paper A	5,8	2,30
6,9	1	2,54	7,02	3,17	B			
6,9	1	2,36	2,85	2,60			6,9	2,70
7,3	1	5,20	3,67	3,31		Toilet paper A	7,3	3,49
7,7	1	2,84	2,96	5,42			7,7	3,74
8,0	1	4,86	5,04	4,91			8,0	4,94
8,6	1	3,89	5,44	3,24				
8,6	1	4,12	7,25	4,52	A and B	Toilet paper A and B	8,6	4,27
8,9	1	5,27	5,46	5,15			8,9	5,29
6,8	2	11,41	3,05	-	A	Toilet paper A	6,8	
6,8	2	2,50	2,58	4,07			6,8	3,05
7,4	2	2,99	3,70	-			7,4	3,35
7,6	2	3,62	3,14	6,14	C	Cloth C	7,6	3,38
7,7	2	2,61	3,06	3,66				
7,7	2	3,45	3,74	3,95			7,7	3,41
7,8	2	4,43	4,70	-			7,8	4,57
8,0	2	3,51	4,12	-				
8,0	2	4,65	3,41	3,51			8,0	3,84
8,3	2	4,20	4,68	-			8,3	4,44
8,6	2	4,33	4,26	3,90			8,6	4,16
8,7	2	2,83	4,95	-			8,7	3,89
9,0	2	4,57	4,21	4,55			9,0	4,44
9,1	2	5,80	4,68	4,85			9,1	5,11
6,0	3	1,95	1,93	-			6,0	1,94
6,1	3	2,73	2,58	-			6,1	2,66
6,2	3	2,13	3,44	-			6,2	2,79
6,3	3	2,74	2,67	1,96			6,3	2,46
6,4	3	2,29	1,95	-				
6,4	3	1,92	1,80	-			6,4	1,99
6,7	3	2,56	2,55	3,37				
6,7	3	2,06	3,20	-			6,7	2,75
6,8	3	2,73	2,71	2,63			6,8	2,69
6,9	3	2,72	2,04	-			6,9	2,38
7,0	3	2,67	3,04	2,83				
7,0	3	2,74	2,82	-			7,0	2,82
7,1	3	2,17	2,16	2,34			7,1	2,22
7,3	3	3,74	2,75	-			7,3	3,25
7,5	3	3,01	3,05	3,45			7,5	3,17
7,7	3	3,54	3,81	3,99				
7,7	3	5,64	5,56	2,03			7,7	4,10
7,8	3	3,44	3,62	-			7,8	3,53
7,9	3	2,89	3,13	-			7,9	3,01
8,0	3	3,72	4,93	3,71				
8,0	3	3,25	3,22	4,62	A and B	Toilet paper A and B	8,0	4,25
8,6	3	4,90	4,77	4,88			8,6	4,85

Table 6.5: Comparison of injection point

Injection point	1	2	3
Length upstream	22 meter	58 meter	98 meter
Trend line equation	$0.0718x^{2.0175}$	$0.1135x^{1.7078}$	$0.0493x^{2.0733}$
R-squared	0.858	0.766	0.757
Mean deviation from the initial	1.68 l/s	1.01 l/s	0.70 l/s
Number of measurement values	27	36	55
# of observed errors	5	2	2
# of values outside confidence interval	2	2	3

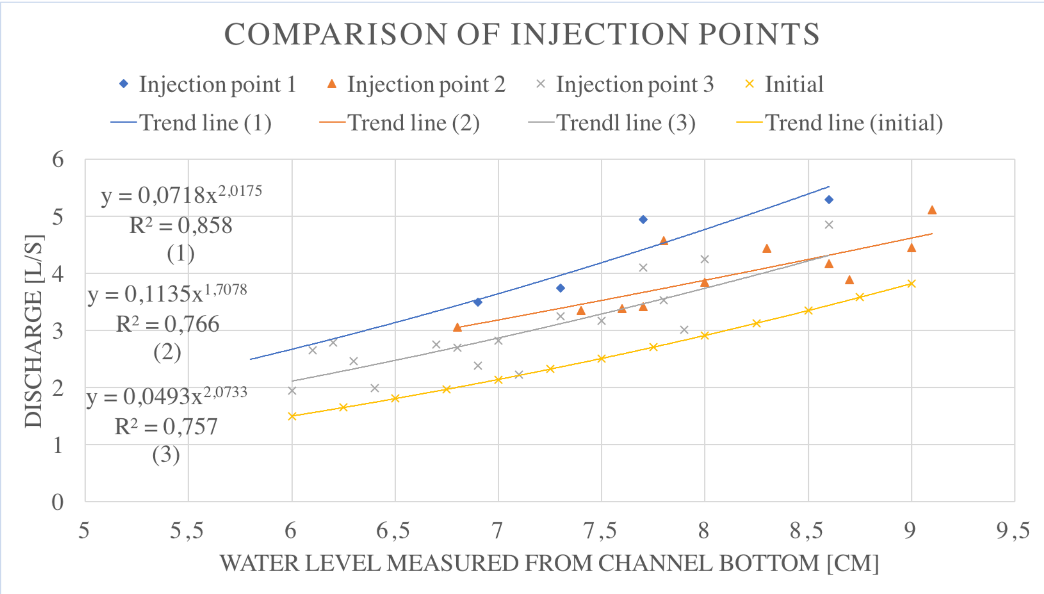

Figure 6.10: Comparison of the stage-discharge(average) data from different injection points

Figure 6.11 shows the water depth measured 30. of March 2017 by the sensor. This day tracer dilution measurements were done, and the conclusion was that the device was clearly out of operation that day. The device measures the water level as almost stable at 7.5 cm, while the water level should be varying between approximately 4.0 cm to 10.0 cm. The same trend was observed at other days for the tracer dilution measurements.

Figure 6.12 shows water level measurements for a longer period. The device is measuring incorrectly compared to the manual water level measurements done for the tracer dilution measurements. The highest measured water level is 0.5 cm, while it should be around 10 cm.

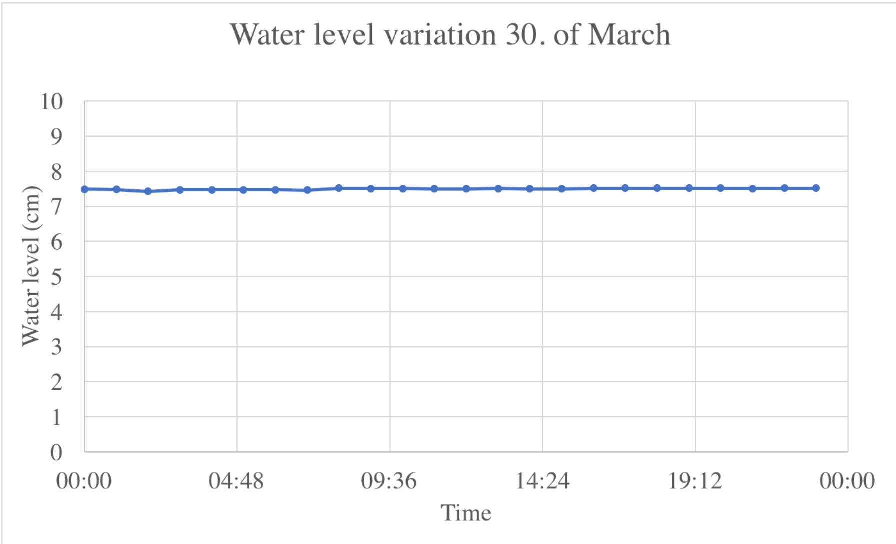

Figure 6.11: Water level measurements 30. of March from the secondary device at Risvollan

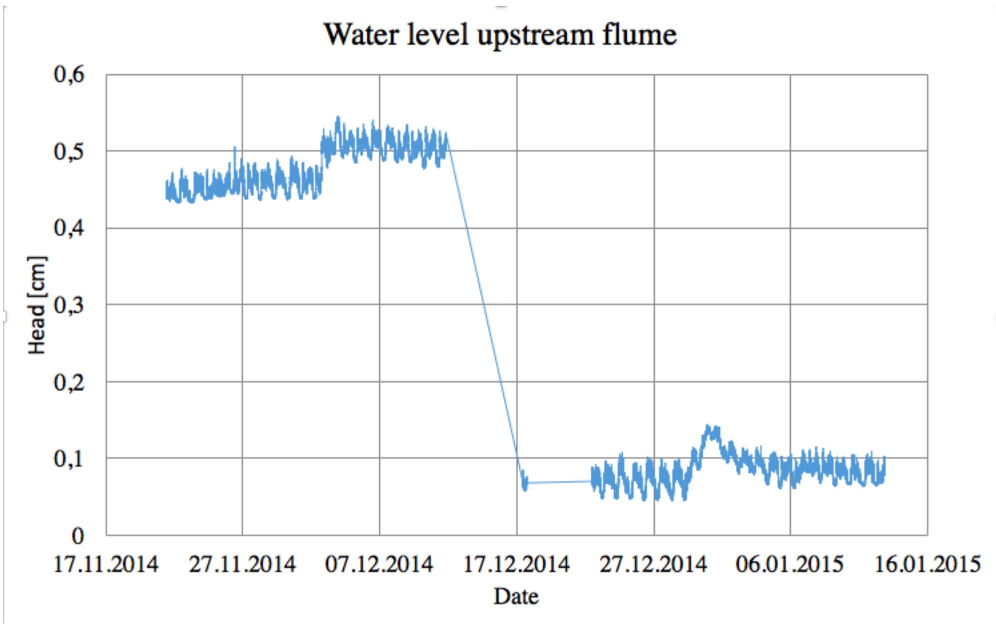

Figure 6.12: Water level measurements from 17.9.2014 to 16.1.2015

Chapter 7

Discussion

This chapter discuss the results from each of the methods used to create a stage-discharge curve for the Palmer-Bowlus flume at Risvollan. For each method a Excel spread sheet was made to calculate the mean deviation from the initial stage-discharge curve for each method. These sheets can be found in the Appendix E. For each method there will be presented a graph which describes the ratio between the initial and the different methods to see how the accuracy of the measurement methods varies at different water levels. Section 5.5 shows the approach for the calculations. The basis of the deviations will be studied and discussed on the basis of assumptions made for the methods and potential sources of error.

7.1 Initial Data

The initial data for the stage-discharge curve for the flume at Risvollan was found from a log-plot in the corresponding database. The basis of the log-plot is not known. The corresponding stage-discharge curve from the log-plot was compared to the rest of the methods.

According to the log-plot the water level is measured from the channel bottom for the flow measurements at Risvollan. When the mean deviation from the initial stage-discharge curve was compared with the laboratory stage-discharge curve with the channel bottom as datum, the mean deviation was 0.11 l/s in the measuring range from 4.5-17.0 cm. The trend line for the initial stage-discharge corresponds good with the calibrated from the laboratory that used the channel bottom as datum, see Figure 6.3. From this it can be concluded that the stage-discharge data from Risvollan probably measure the water depth at the wrong datum.

7.2 Laboratory Calibration

In the laboratory calibration the mean deviation from the initial stage-discharge curve was 0.11 l/s for water levels between 4.5-17.0 cm when measuring from the channel bottom. The deviation decreased with increasing water depth, see Figure 7.1. It was surprising that the deviation from the initial stage-discharge data was so low for higher water levels, as surface waves developed and made it

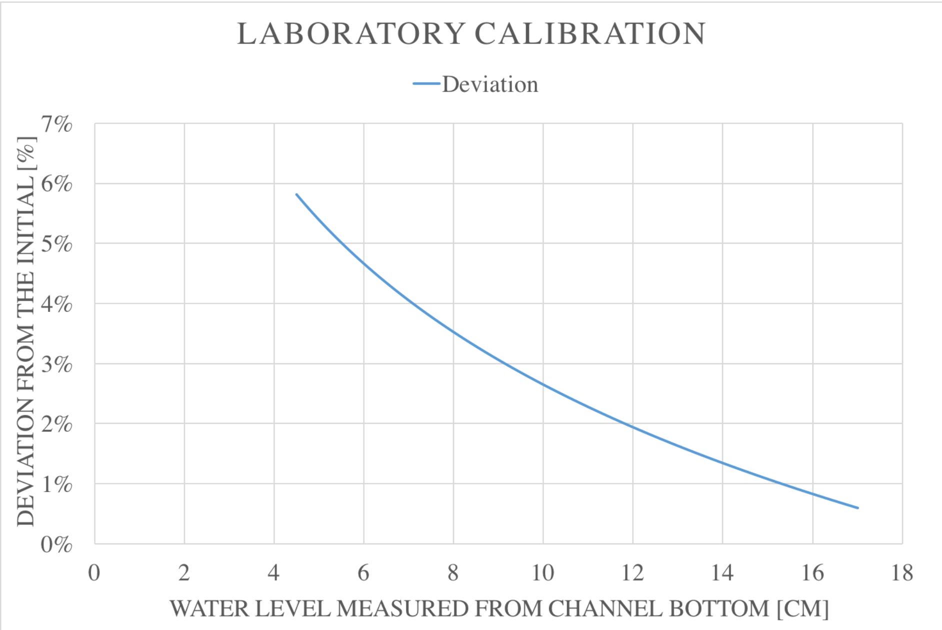

Figure 7.1: Deviation from the initial stage-discharge curve

harder to read of the height, see Figure 7.2. For water levels from about 15.0 cm, the stage-discharge values differed slightly from the trend line. This was anticipated in the Literature Review, section 2.3, since the length of the channel upstream will influence on the flow pattern. The inlet of the channel gives a draw down curve of the flow while developing surface waves. Therefore, for more accurate water level measurements a channel without any major disturbances in a length of $L = 6D$ should have been set when measuring water levels from approximately 10.0 cm.

For small water levels the deviation from the initial stage-discharge trend line was about 5% for the laboratory calibration. This could be caused by the inaccuracy in the pump. The pump would not stabilize on one specific discharge value when it was in operation. For low discharges this would have an larger effect on the measurement accuracy. For a frequency of 48% at the pump, the discharge could vary between 1.05-1.20 l/s. However, it could also be due to the initial stage-discharge curves. For theoretical calculations of stage-discharge curves, the accuracy will be poorer, especially in the external parts of the measuring range [35, p. 163]. The basis of calculation for the initial stage-discharge curve is unknown, and it could be done from theoretical calculations.

In terms of accuracy and repeatability, the laboratory calibration was successful. The accuracy was high as the equation for the trend line has an R-squared of $R^2 = 1.000$ when applying three decimals. The repeatability was tested by doing an extra calibration in the laboratory. The mean deviation between the trend line equations was 0.03 l/s. It could be argued that more tests should have been done to evaluate the repeatability.

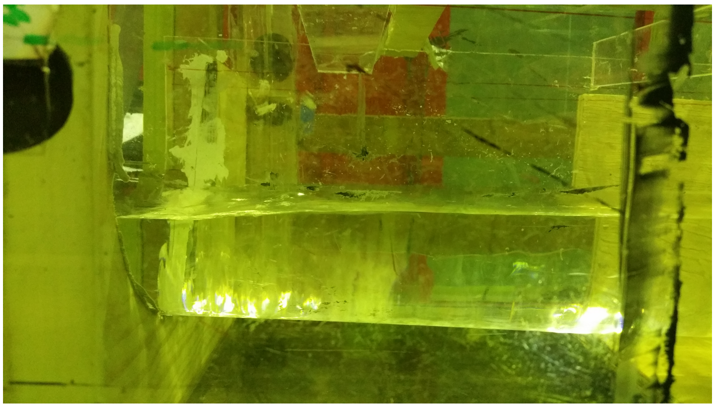

Figure 7.2: Surface waves developing

7.3 Bernoulli

For theoretical calculations of the stage-discharge curve, the mean deviation from the initial stage-discharge curve was 1.77 l/s for water levels from 5.0-21.0 cm. Figure 7.4 shows how the discharge values from Bernoulli differ from the initial at different water levels in percent. The deviation is largest for low measurements, as stated in [35, p. 163].

The theory from [35, p. 158-159] states that Bernoulli uses the channel bottom as datum to measure the water depth. Figure 7.3 shows that the trend line for Bernoulli corresponds better with the trend line for the laboratory experiments where the datum is at the flume bottom. Figure 7.4 shows how the discharge values from Bernoulli differ from the initial at different water levels in percent. The mean deviation for Bernoulli from the laboratory trend line equation is 0.35 l/s, compared to 1.77 l/s from the initial which uses the channel bottom as datum. On the basis of this observation, the assumptions from Bernoulli will be compared to both datums.

As mentioned in the Quantitative Method Chapter, the basis of calculation for Bernoulli is based on three assumptions [35, p. 158]:

1. In the throat section the flow pattern is parallel to the bottom
2. The head loss in the entrance and throat section are neglected
3. The discharge coefficient C_d is constant when the discharge varies

The first assumption did not match what was observed in the field and the laboratory. The water flow pattern in the throat section was at a higher downwards slope than the flume bottom. This could be due to the fact that the throat at Risvollan and in the laboratory had slope of 0.02 m/m. This is not within the recommendations of 0-0.001 m/m as recommended in [11, 35, 32, 22]. For higher slope in the flume, the critical water level in the flume will be lower. This is the case for all conduits. If the downwards slope is increased for a fixed cross section at the same discharge, the water level would decrease. The Bernoulli's method does not take to account this effect. For Bernoulli the critical water level in the flume is higher than in the real situation. Equivalently the water

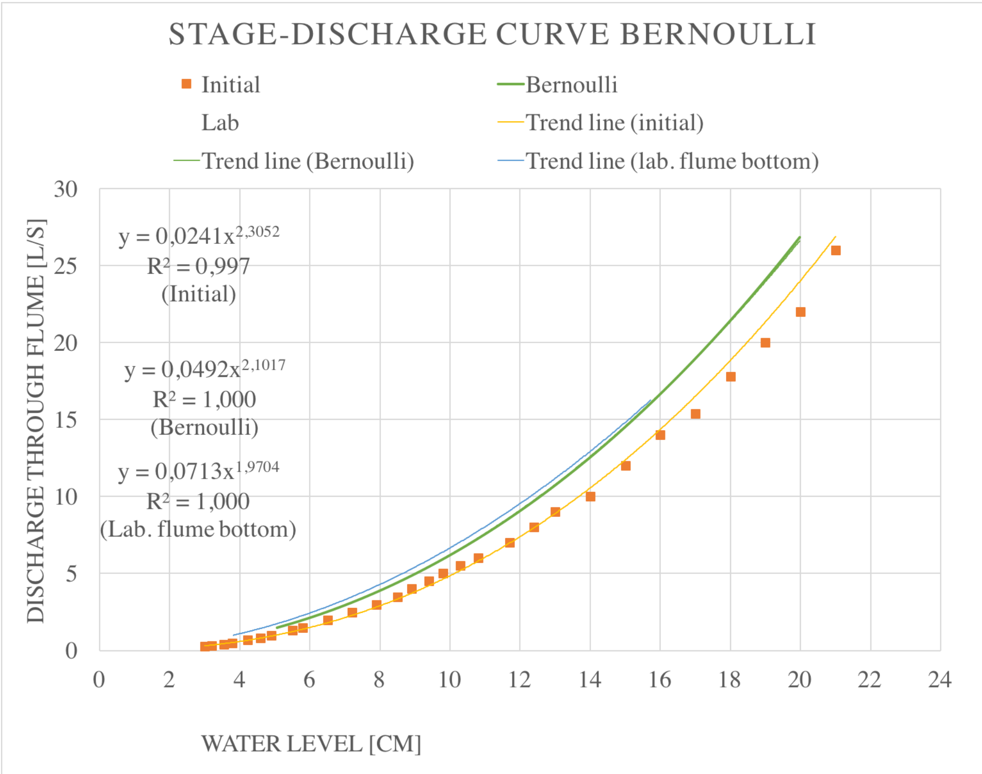

Figure 7.3: Discharge through Palmer-Bowlus flume from the initial, Bernoulli and laboratory calibration with flume bottom as datum

level upstream the flume will be higher for Bernoulli. If Bernoulli took into account the effect of slope in the throat it would give lower water levels for the same discharge. If the slope effect in the throat was taken into account, the trend line to Bernoulli in Figure 7.3 would move towards the laboratory trend line which uses the flume bottom as datum.

From [35, p. 161], the head loss through the flume is set to $0.15 - 0.2d_i[m]$. For low water levels, the head loss will have an impact on the flow. Equation 3.5 illustrates that when there is a decrease in the energy line, an equivalent decrease in the discharge will be experienced. Equivalently, the discharge values for Bernoulli should have been lower for the whole measuring range, and especially at low flow rates. Lower discharge for the same water level would imply a stage-discharge curve for Bernoulli which was more equal to the initial.

The discharge coefficient C_d approximates the effect of viscous friction on the theoretical stage discharge by allowing for the development of a boundary layer of a certain displacement thickness along the bottom and sides of the throat [11]. In Bernoulli the constant is assumed to be constant. The boundary layer gives an different width, called the effective throat width denoted B_e. As seen from Eq. 3.12, the discharge coefficient will always be under a unity. This means the development of boundary layer will decrease the discharge for the same water level, see Eq. 3.11. Bernoulli's method from [35, p. 158-159] does not state the value of the coefficient. However as shown in Eq. 6.5, Bernoulli assumes no friction loss between the measurement point upstream the flume and the point of critical flow in the flume. Therefore it can be concluded that Bernoulli does not take into account the viscous friction as it is equal to a unity for the Bernoulli's method. Bernoulli underestimates this effect and the result is that the method gives higher discharge values for the same water levels. This would imply a stage discharge curve more equal to the initial.

7.4 SINTEF

The stage-discharge measurement from the SINTEF-report is used as an independent source for finding the stage-discharge relation. The report was published in 1994 while the flume was installed in 1984. As stated, the report is for a Palmer-Bowlus flume with the same configurations as the one at Risvollan, see Appendix B.4. The mean deviation from the initial stage-discharge curve is 0.18 l/s. Figure 7.5 shows how the discharge values from SINTEF differ from the initial at different water levels in percent. The ratio is highest at the low and high water levels, which is typical for stage-discharge curves that are calculated theoretically [35, p. 163]. The SINTEF-report states that the calibration was done from theoretical calculations.

7.5 Tracer Dilution

The results from the tracer dilution measurements will in this section be discussed in the light of the results. Practical consequences and the accuracy for tracer dilution measurements will also be discussed.

Figure 6.9 gives the comparison of the sorted average tracer dilution measurements. The parallel displacement of the tracer trend line compared to the

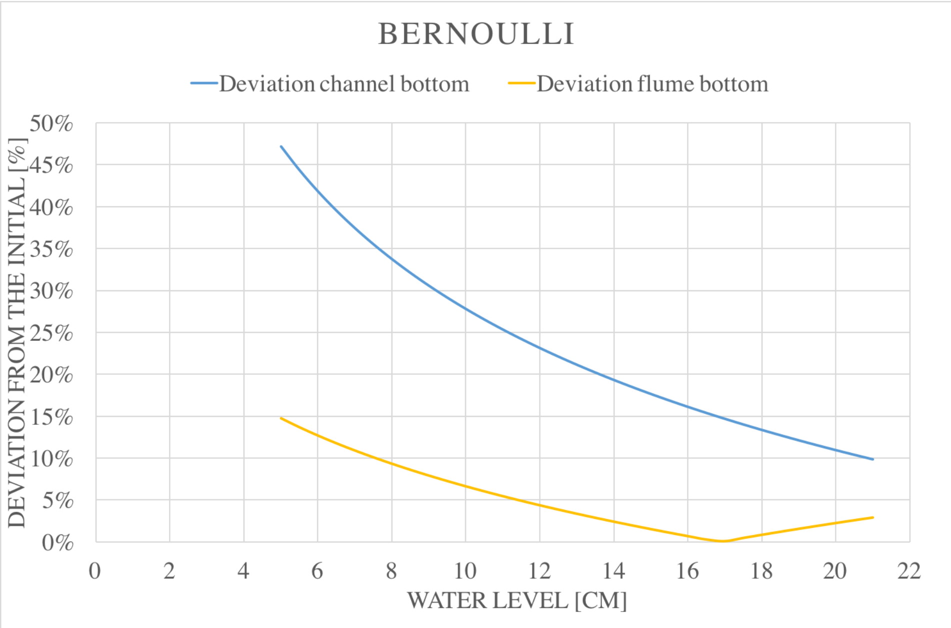

Figure 7.4: Deviation from the initial stage-discharge curve for Bernoulli at different datums

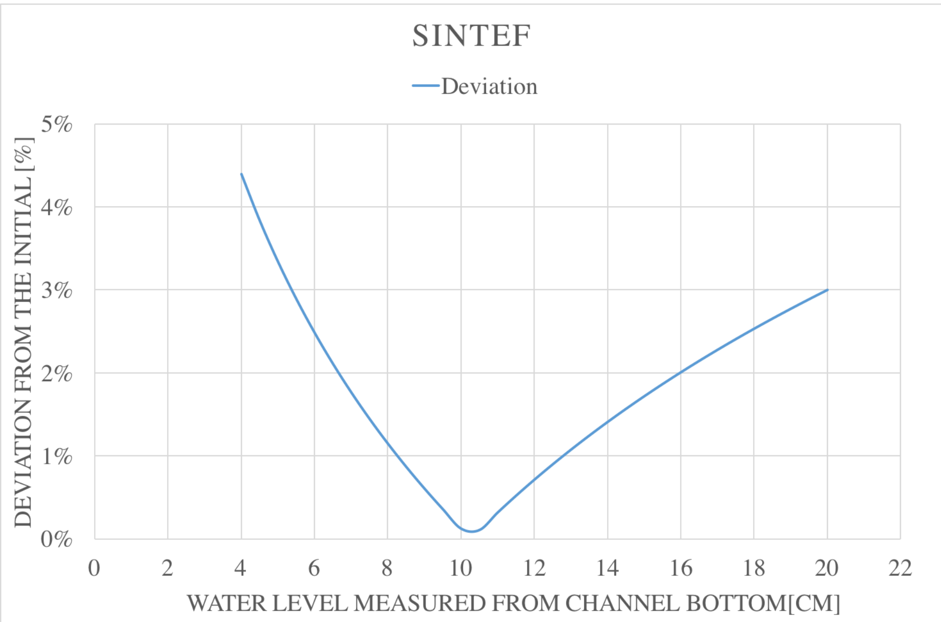

Figure 7.5: Deviation from the initial stage-discharge curve

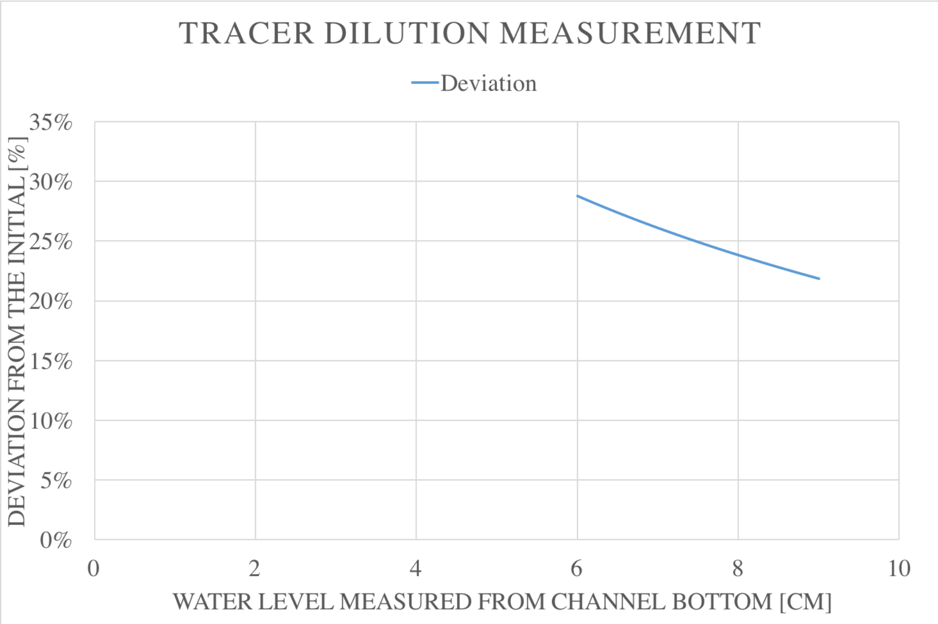

Figure 7.6: Deviation from the initial stage-discharge curve

other two indicates a systematic error in the tracer dilution measurements. Figure 2.13 shows the error classes studied in section 2.6 from [35, p. 18]. For tracer dilution measurements, major errors and irregular errors can be sorted out from the measurements statistically and by observed errors. The systematic errors, in this case, cannot be sorted out since the source of error is unknown. It is unknown whether the error is constant or variable systematic error, or a combination of the two. At least there has to be a systematic error, since the other two groups can be sorted out.

Accuracy In terms of accuracy the tracer dilution method is poor as the mean deviation from the initial stage-discharge curve was 0.68 l/s, and had a RSD of approximately 25%. Concerning repeatability, results deviate at similar water levels. Poor accuracy and repeatability means that many measurements needs to be done in order to achieve results that can be used for some extent.

The RSD from the initial data and tracer was exactly 25% for water levels between 6.0-9.0 cm, meaning that the dilution measurements gave on average a 25% larger discharge value than the initial for the same water depth. In [35, p. 237], the uncertainty of tracer dilution measurements is about 5 - 20% for waste water pipelines. In this thesis the measurement uncertainty lies beyond this for the mentioned water levels.

Figure 7.6 shows that the deviation from the initial stage-discharge values, decreased with increasing water level. This could signify that the accuracy of the method is higher for higher discharges and water levels.

Injection Point In tracer dilution measurements the boundaries for measuring is related to flow conditions and the length of the channel [35, p. 237]. The flow in the sewage at Risvollan will have a Reynolds number lower than river flow, meaning it will be less turbulent and the length needed for the NaCl to be mixed would be longer. Therefore, the injection point of the tracer (NaCl) upstream the conductivity sensors are of interest. Figure 6.10 shows a comparison of the measured average water flow for each of the three injection points. All data are included except for the data from measurement 1, 31 and 41.

Table 6.5 gives an overview of the results. The results show no relation between R-squared and length. The R-squared is actually decreasing when the length between the measurement and injection point is increased, but the trend is not clear. However, there is a trend between the length and number of successful measurements. The longer distance between the measurement and the injection point L, the higher the possibility to obtain a measurement value within the defined confidence interval.

From Figure 6.10, the trend line for injection point 3 is the most similar to the initial trend line. The mean deviation from the initial trend line equation was 0.70 l/s for injection point 3. The mean deviation from the initial calculated for each injection point can be found in Appendix E.7. In other words, injection point 3 gives lower discharge values than the other two injection points. When it is known that the tracer dilution measurements gave higher discharge values than what was actually observed for the given water level, injection point 3 would give measurements results that corresponded better to the calibrated stage-discharge curve for the flume.

Amount of Tracer A quantity of NaCl of 5 kg is generally required to measure the flow rate of Q = 1 m^3/s [24]. The solution should be mixed with 250 grams NaCl per liter water. For flow rates around 4-6 l/s, that is equal to a solution of approximately 2,5 grams NaCl in a solution of 1 cl water. This amount was not practical to use in these measurements. Also the base conductivity should be doubled by the input of the salt solution. In the measurements carried out, the amount of NaCl used were from 150 grams to 500 grams were used. The concentrations of NaCl was about 200 g/l. Figure 7.7 shows the results from a solution of 150 grams NaCl injected into the channel, and illustrates that the injected solution was about 8 times larger than the background concentration of NaCl. A solution containing 150 grams or less of NaCl is sufficient for a sewage with discharge values between 2-6 l/s.

Source of Bias There are many sources of error when doing these types of measurements. In this paragraph some of the experienced sources will be discussed.

- Formation of debris on conductivity sensors

In waste water there is a great deal of debris such as toilet paper and other fabrics. Under some of the measurements done in the presented Thesis, toilet paper and other debris got stuck inside and onto the conductivity sensors, see Figure 7.8. For some reason the conductivity sensors with debris attached gave higher discharge values than the sensors without debris. This problem was observed already during the first measurement. As seen in Appendix D.1 measurement 1, sensor A shows a discharge too high for the given water depth, while sensor B gave a more reasonable value compared to the stage-discharge values

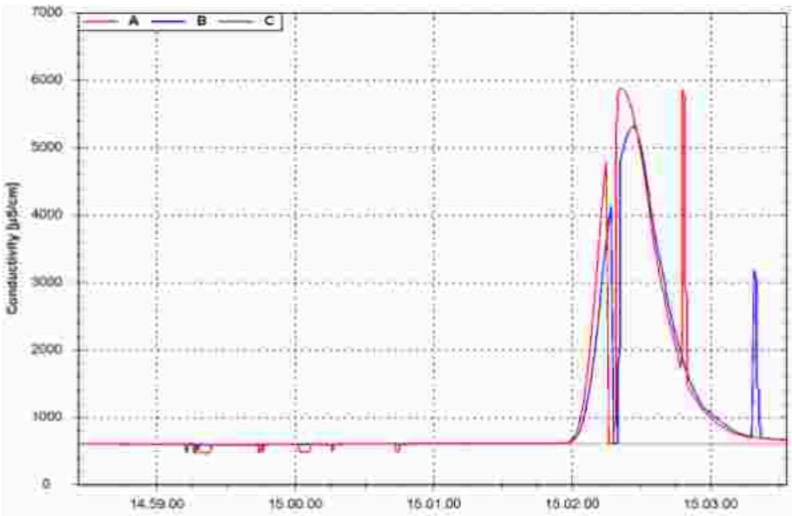

Figure 7.7: Tracer dilution measurement done with 150 grams of NaCl

from the other methods. When investigating the problem, there was found toilet paper on sensor A. While continuing the measurements, this problem was experienced several times and with the same outcome. Therefore it is important to remove any debris that gets attached to the sensors before and during the measurements.

- The placement of sensors

To eliminate the placement of sensors as a source of error, the placement should have been the same for all measurements. However, the placement and the number of sensors had to be adjusted during the measurements mainly because of debris. Figure 5.3 show the different placement and the number of sensors used for the measurements. We found that two sensors abreast were enough in a narrow channel like the one at Risvollan. More than two sensors increased the chance for debris getting stuck in/onto the sensors, and disturbed the measurement. The data from two sensors was also sufficient enough in terms of accuracy when calculating the mean discharge for a measurement.

- Injecting the tracer

It is important that the input amount of tracer set in the software is the same as the actual amount of tracer that is injected to the channel. The software calculates the discharge from the input amount of tracer and the measured conductivity as given in Equation 3.14. In measurement 31, Appendix D.1, all three sensors gave too high discharge values. After injecting the tracer there was still a lot of undissolved tracer inside the bucket. This led to lower concentration of tracer in the channel, while the input amount of tracer was larger. Lower tracer concentrations would imply higher discharge values and therefore failed measurements.

- The variation in water consumption

Figure 7.8: Debris stuck on conductivity sensors

Areas with fewer subscribers will have larger variations in water use. This was also the case at Risvollan. The water consumption had a peak in the morning and afternoon causing the water level to rise rapidly while doing the measurements. It was difficult to determine the water depth due to the large variations in water consumption. The variations could vary up to 1.0 centimeter. For tracer dilution measurements the discharge has to be constant during the measurements.

- Imprecision when determining the water depth

The water depth in the measurements were done with a folding rule. The Palmer-Bowlus flume had a pressure sensor to measure the water level, but it was out of operation when the tracer dilution measurements were carried out. The most accurate way to determine the depth would have been a pressure sensor that measured the water level at real time and continuously. Then the time of measured water depth could be compared to the time of conductivity measurements.

- NaCl stuck in the system

Branch points inside manholes in waste water pipelines can disturb tracer dilution measurements. Figure 7.9 shows paper stuck in the bottom of a manhole. The paper may block parts of the tracer concentration and disturb the measurements. Some of the tracers may get stuck here, leading to lower measured concentration which would result in higher discharge values.

- Background concentration of NaCl

Figure 7.9: Piece of paper stuck in the bottom of a node

In municipal waste water the background concentration of NaCl can be high and vary rapidly [35, p. 247]. The measurement showed small variations in NaCl concentrations, see Figure 7.7. However, these variations were small compared to the concentrations of injected tracers. Literature suggest lithium chloride (LiCl) to be used as tracer instead of natrium chloride (NaCl) [35, p. 248].

7.6 Flume Casting Technique

The reproduced Palmer-Bowlus flume had the exact same dimensions as the one in the field. The detail level in terms of surface roughness was high. The reproduced flume had the same roughness as the one in the field, and the laboratory measurements could be carried out with confidence. However, careful preparations should be done prior to creating a reproduced flume. The following paragraphs present lists with recommendations that should be followed when reproducing a flume with a bi-component silicone and two-component Polyurethane Resin.

Creating the Negative Imprint

- Calculate the right volume needed to create the negative imping. If possible, fill the middle of the negative imprint with wood or some other cheap material.
- Test the molding material before creating the negative imprint in the field. Simulate the same temperature conditions.
- Invest time in making the casting frame. Make sure it fits and use material (clay) to block potential cracks.
- Make the molding area as dry as possible before injecting the molding material.

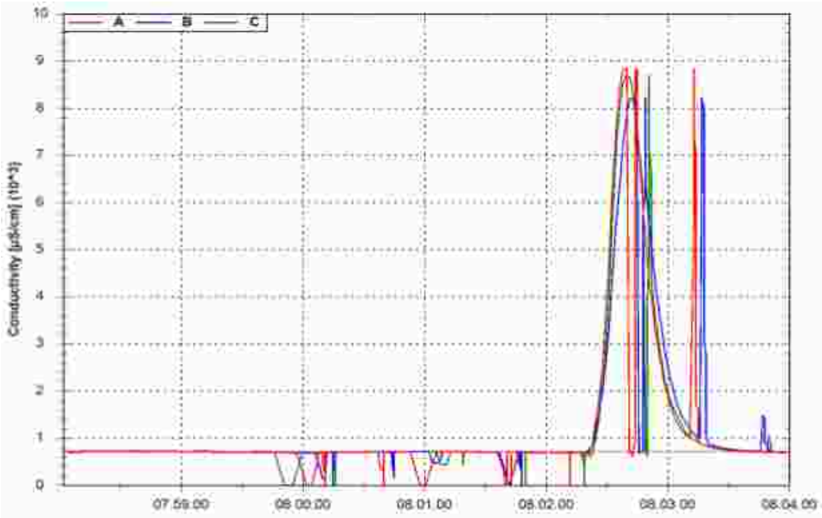

Figure 7.10: Variations in background concentration

- If available, use an air compressor to blow the flume free for dust and smaller stones.
- It is preferable to mix the bi-component silicone in room temperature. Higher room temperature will give the casting material higher viscosity faster, making it easier to work with.
- Create the negative imprint by molding layers of approximately three centimeters at the time. Wait for each layer to dry and then add the next one. This will reduce the pore pressure causing less leakage.

Creating the Reproduced Flume

- Calculate the right volume of PUR needed to create the cast.
- The box for making the cast should be made out of plywood. Preferably of plywood with smooth surface.
- The box has to be completely tight. Polyurethane Resin has low viscosity and will leak through very small cracks.
- Rub the box for creating the cast with a parting agent. Margarine from the super market can be used. The parting agent will avoid the PUR from getting stuck onto the plywood, making it easier to separate them from each other.

Chapter 8

Conclusion

8.1 Calibration Methods

Initial Stage-Discharge Curve The initial stage-discharge curve was confirmed from the laboratory calibration and the SINTEF report. Both confirms that the datum of the measured water level in the initial data is at the channel bottom. The SINTEF report confirms the data for water levels from 4.0-20.0 cm with a mean deviation of 0.18 l/s. The laboratory calibration confirms the data for water levels from 4.0 to 15 cm with a mean deviation of 0.11 l/s. Both is within the operation range for the flume (5.0-10cm).

If the secondary device at Risvollan measure the water level from the channel bottom as the initial data, the initial stage-discharge curve needs to be adjusted. Also the secondary device has been measuring the water level incorrectly for a longer period of time. This could mean that earlier data is lost.

Laboratory Calibration The measurements from the laboratory calibration was good in terms of accuracy and repeatability. The calibration confirmed the initial data used in earlier research [15]. To confirm water levels beyond 15 cm, a longer U-channel upstream the flume should be installed in the model, see Chapter 9. The laboratory calibration also confirms that the Froude number in the upstream channel of the flume is below 0.5, which means that there is no surface disturbances at the head measurement location.

Theoretical Calibration Bernoulli does not take into account the effect of the three assumptions made in the method. When the flume channel is not in range for a slope of 0.001, the flow pattern in the flume is not parallel to the bottom. This affects the water level upstream the flume. For Bernoulli the water level is higher for the same discharge values. For the other two assumptions, Bernoulli's overestimation of the stage discharge curve. However, for the assumption of constant discharge coefficient C_D and neglected head loss in the flume the effect is minimal. For the discharge coefficient there was found to be a reduce in relative standard deviation RSD from 23 to 21% from the initial calculated for the channel bottom as datum. Head loss in the entrance will mainly affect the stage-discharge values at low flow rates. The effect of not having a parallel flow to the bottom in the throat section cannot be quantified.

On the basis of the discussion in Section 7.3, Bernoulli's method calculates the discharge from the the flume bottom as datum and not from the channel bottom as presented in [35, p. 158-159]. This was confirmed by the laboratory experiments with mean deviation of 0.35 l/s for flume bottom and 1.77 l/s for channel bottom.

8.2 Tracer Dilution

Tracer dilution measurements cannot be used to calibrate the Palmer-Bowlus flume at Risvollan in terms of accuracy. The main issue is connected to the systematic error in the measurements. On a consistent basis the measurements gave higher discharge values and the systematic error could not be quantified. The higher measured discharge values is a result of lower measured NaCl concentrations in the measurement point. This could mean that some of tracer injected got stuck in the system and deteriorated the results. The user manual also states that measurements are restricted for drains below 5 m^3/s [24].

Another problem is the unstable flow rates. While doing tracer dilution measurements the flow rate has to be stable. In the measurements the water level could change with 1.0 cm in few minutes.

Literature suggests lithium chloride (LiCl) to be used as tracer instead of natrium chloride (NaCl) due to high background concentrations of NaCl [35, p. 247]. However, the results were not dependent on the selection of tracer. The errors in the measurements while using NaCl as a tracer, would also appear for LiCl. In a personal discussion with Professor Knut Alfredsen 28. of April 2017, he informed that small particles in the waste water will disturb the measurements, giving several peaks in a measurement. In tracer dilution measurements in fresh water, there is just one consistent peak.

It was found that tracer dilution measurements can be used if data is sorted in some degree. The process of sorting data gave indication of were the injection point should be. The best results were achieved from the injection point furthest away. This injection point was 98 meters ($L = 381 \cdot D$), while the manual [24] suggested above 13 meter ($L = 50 \cdot D$) as a sufficient injection point. In other words, the injection point should be further away from the point of measurement in sewage than in rivers. Note that for tracer dilution measurements at Risvollan two conductivity sensors are enough and a concentration of about 150 grams NaCl should be used.

For better tracer dilution measurements, isolate potential sources of error:

- Use two conductivity sensors and place them next to each other in the channel
- Use the same amount of tracer. For Risvollan approximately 150 grams of NaCl in the solution is sufficient

In the measurement use a point gauge from the Hydraulic Laboratory to measure the water level or fix/calibrate the secondary device. The traveling time for the NaCl solution should be calculated from injection point 3 to the measuring point by using dyeing materials for waste water [35, p. 239]. The travel time indicates when the measurement of the conductivity in the channel should be stopped in order to get the measurement right.

8.3 Flume Casting Technique

The bi-component silicone gave the exact same dimensions and roughness of the flume in-situ. Making a replica by dimensions found in the field takes time and requires precise tools to do the measurements. However, with strict planning and precautions the casting can be completed. In this Thesis the replica had the exact same dimensions as the flume at Risvollan. The roughness was almost exactly the same as the one in the field.

Chapter 9

Recommendations and Supplementary Work

Measurement Datum Secondary System The datum of water level measurement has to be investigated. From the laboratory calibration is was found that the water level is measured from the channel bottom from the stage-discharge data given from the initial. If this is the case for the secondary system at Risvollan, the data needs to be adjusted.

Upstream Conditions The length of the channel upstream was a bit short in the presented model compared to recommendations given in literature [11, 17, 35, 32]. However, for the range of operation it was sufficient (5.0-10 cm). To find the stage-discharge relation above 10 cm, new laboratory experiments should be conducted with a longer approach channel, preferably $L > 6D$ or longer. Then these results could be compared to this Thesis to see how they differ from the model in the presented thesis.

Downstream Conditions If the upstream channel in the model is replaced by a longer one, the old channel should be placed downstream the flume to study the downstream conditions. The interesting observation would be to find out at what flow rate and water level the flume section would become submerged. When submerged, flow measurements cannot be done. Compare the results to relevant literature.

Throat Conditions The Palmer-Bowlus flume is defined as a long-throated flume, where the flow pattern through the flume will become parallel with the bottom flume. In this thesis this was not the case. This could be because the slope of the throat which was 0.02 m/m. All relevant literature about Palmer-Bowlus flume presented in the Literature Review [11, 17, 18, 35, 33, etc.], stats that the slope of the throat should be within 0-0.001, but the literature did not state why. A sensitivity analysis could be done in the Hydraulic Laboratory to find out how the slope in the throat section affects the results by varying the slope from 0 - 0.02 m/m.

Self Cleansing Self cleansing of bigger particles could be tested. Place coarse of different sizes upstream the flume and see how they are able to pass through the flume.

Tracer Dilution Measurements In order to reduce systematic error it would be beneficial to increase the the number of measurements from point 3 and isolate potential sources of error:

- Use to conductivity sensors and place them next to each other in the channel
- Do not use more the 150 grams of NaCl in the solution as the
- Use a point gauge from the laboratory to measure the water level or fix/calibrate the secondary device
- Calculate the traveling time for the NaCl solution from injection point 3 to the measuring point by using dyeing materials for waste water [35, p. 239]

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Appendix A

Different Shapes of Palmer-Bowlus Flumes

A.1 ISCO Open Channel Flow Measurement Handbook

A.2 Water Environment Federation

A.3 Initial Drawing of Palmer-Bowlus flume

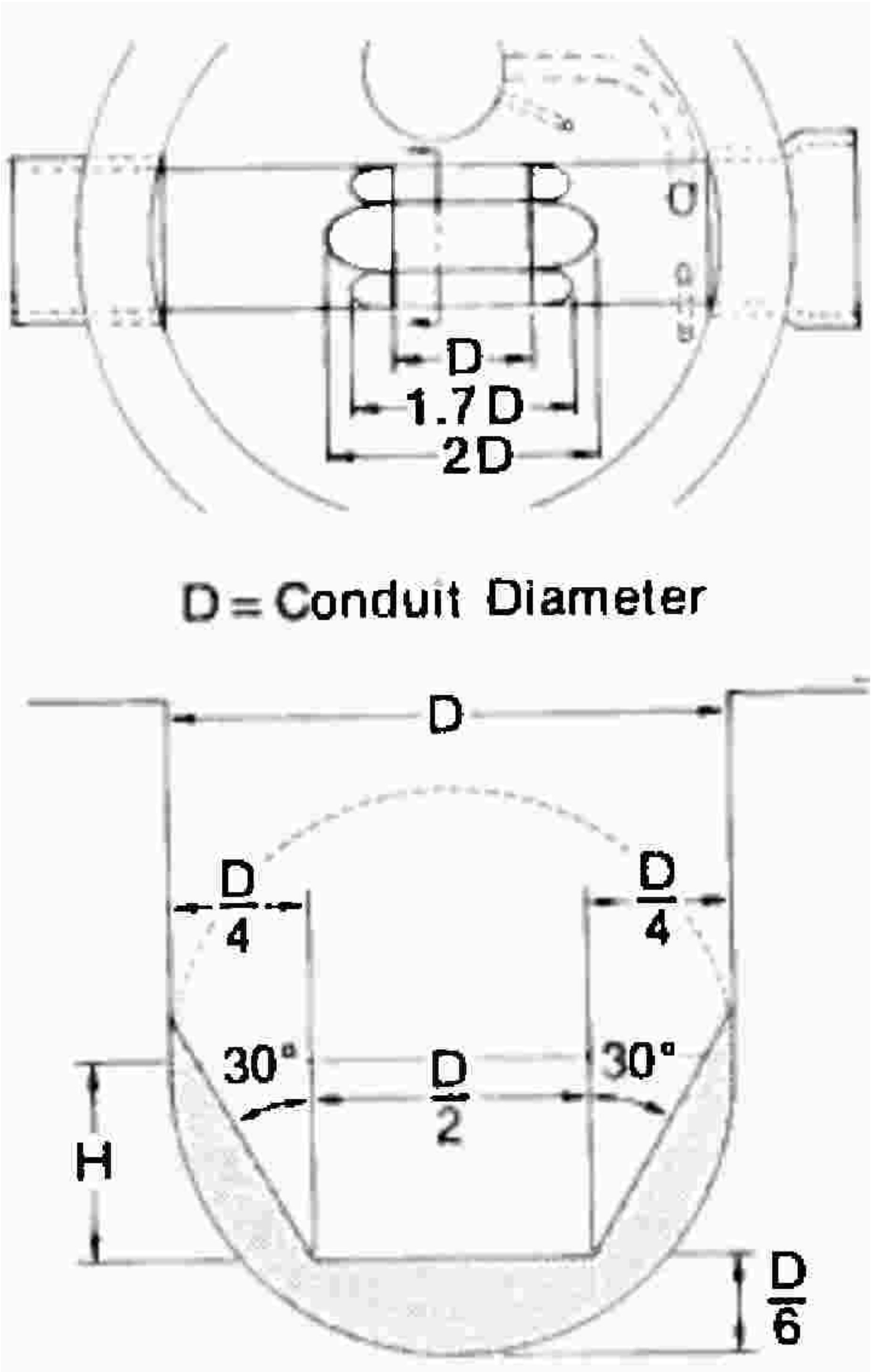


Figure A.1: Dimension of a Palmer-Bowlus flume as illustrated in [25, p. 44]

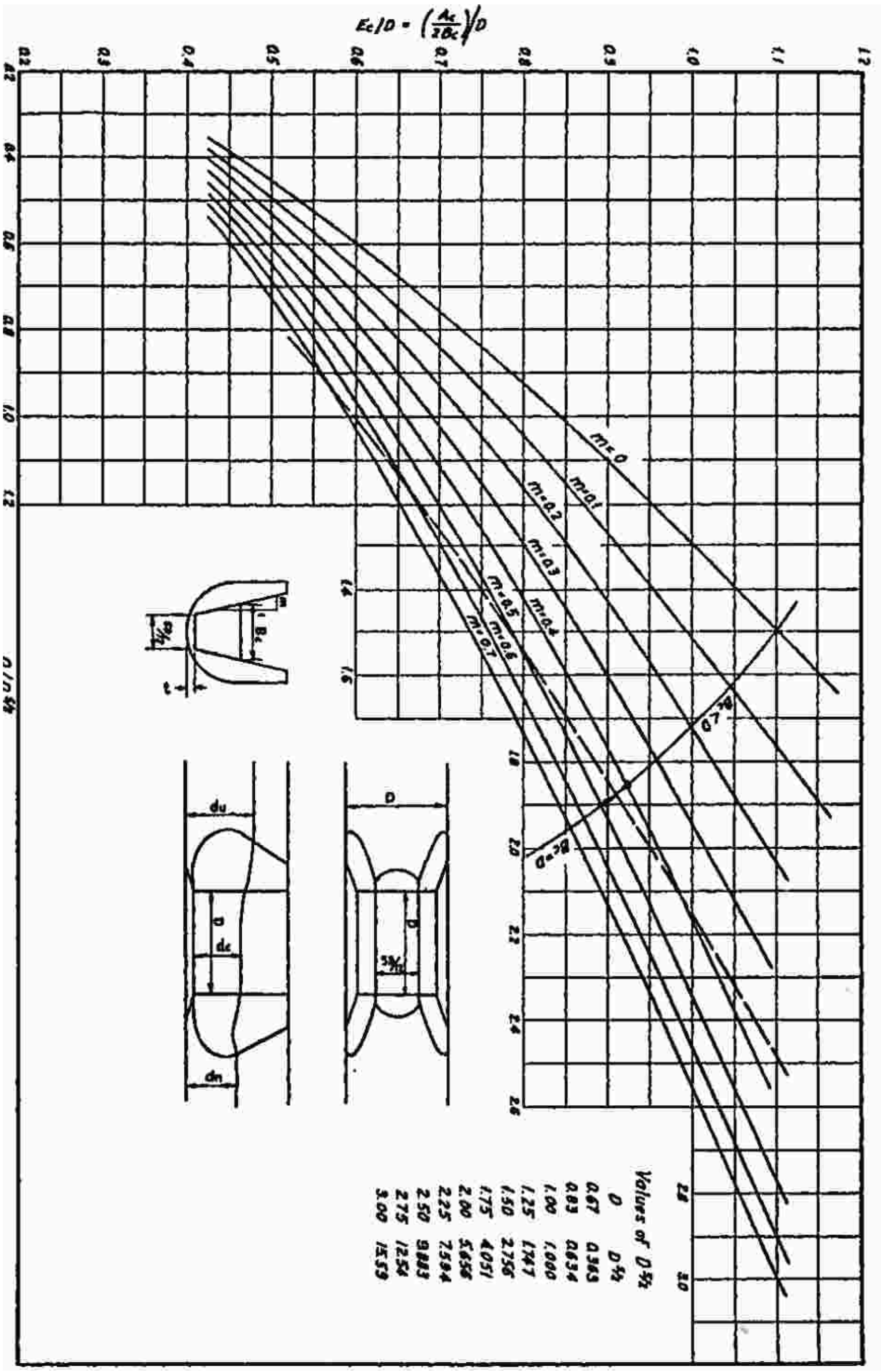


Figure A.2: Total energy curves for flow in trapezoidal channels and shape of Palmer-Bowlus flume [32]

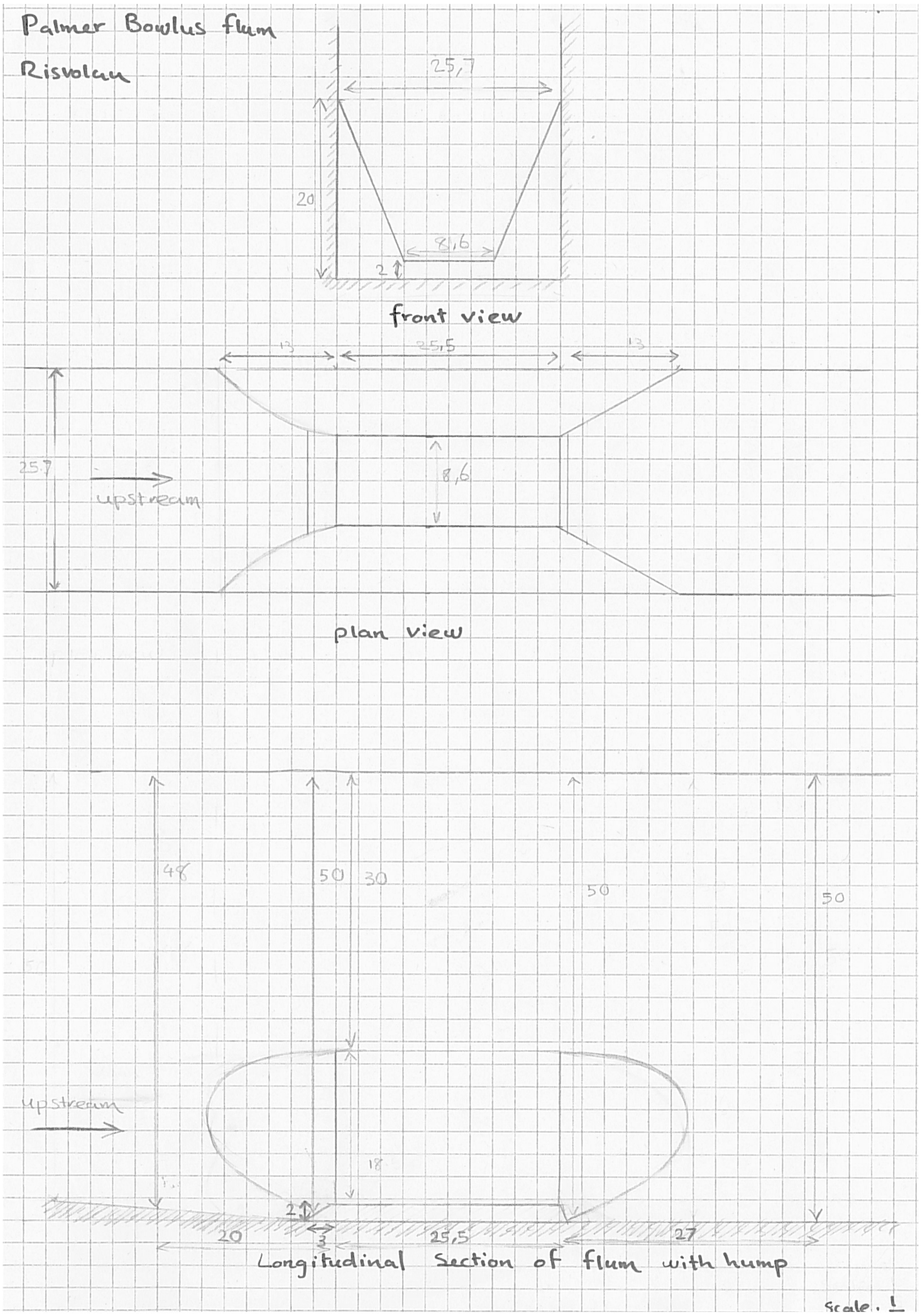


Figure A.3: Initial drawing of the Palmer-Bowlus flume at Risvollan

Appendix B

Palmer-Bowlus Flume at Risvollan

B.1 Floor and section drawing from Risvollan

B.2 Initial Floor and Section drawing from Risvollan

B.3 The government pollution control [Statens forurensningstilsyn]

B.4 Stage-discharge Values for Palmer-Bowlus flume type 2

B.5 Initial Stage-Discharge curve for Palmer-Bowlus flume at Risvollan

B.6 Theoretical Calculation of Flume from Bernoulli

B.7 Calculation of Froude Number for the Channel at Risvollan

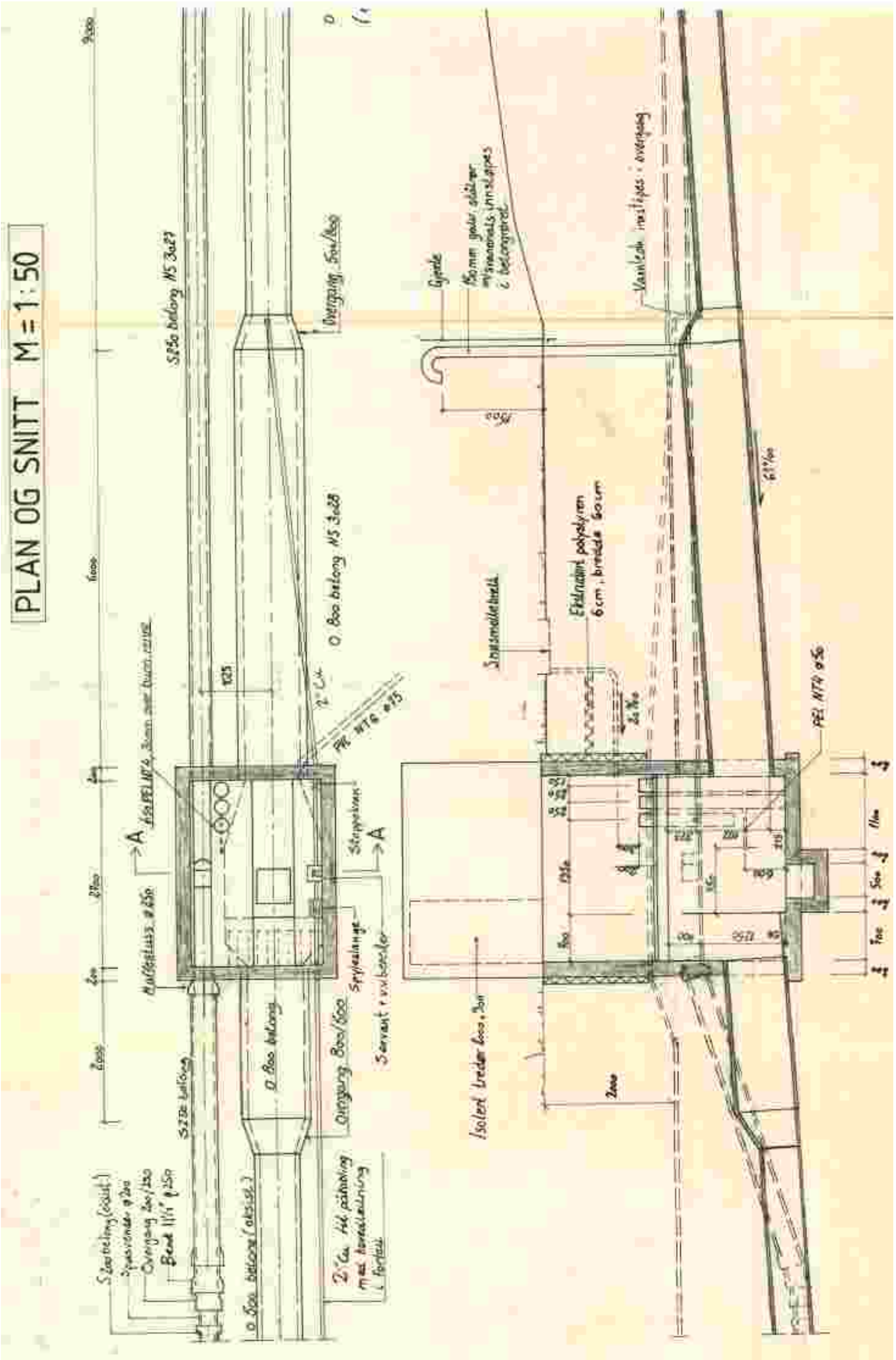


Figure B.1: Overview drawing from Risvollan measurement station [23]

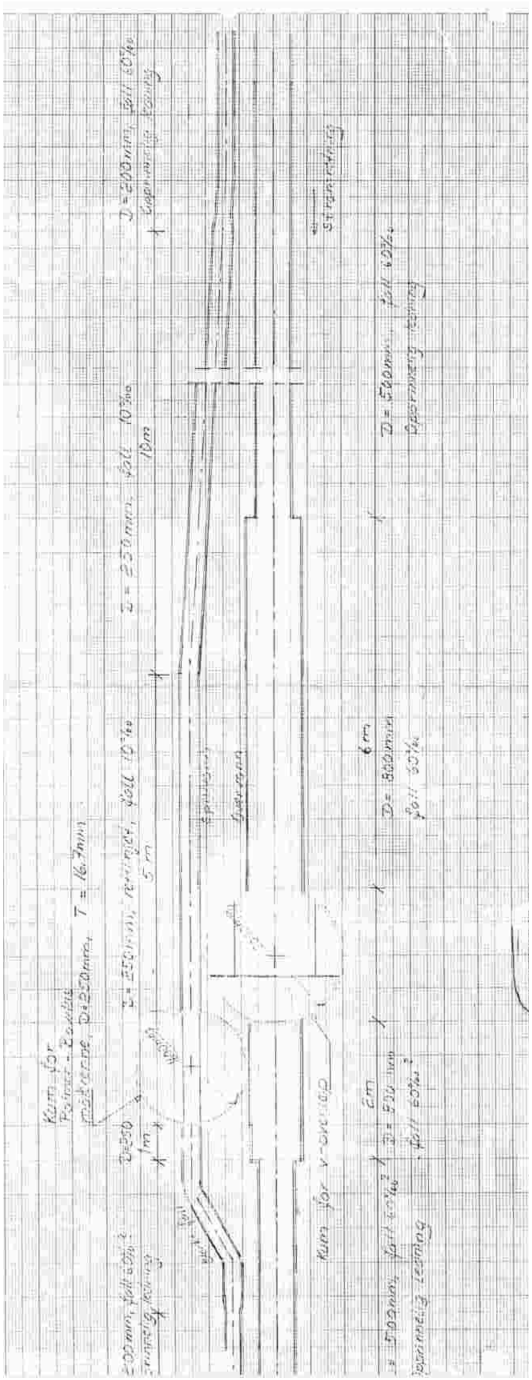
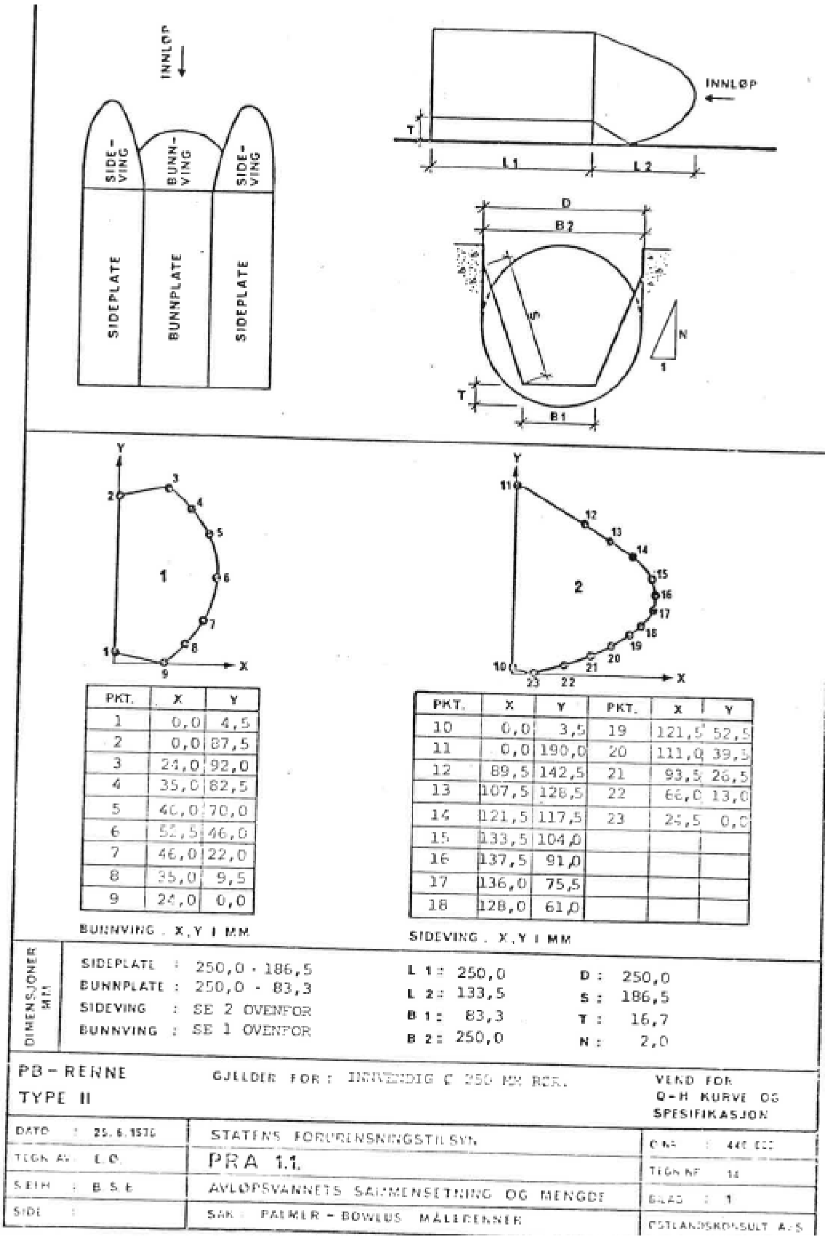


Figure B.2: Initial overview drawing from Risvollan measurement station [23]



PKT.	X	Y
1	0,0	4,5
2	0,0	87,5
3	24,0	92,0
4	35,0	82,5
5	40,0	70,0
6	52,5	46,0
7	46,0	22,0
8	35,0	9,5
9	24,0	0,0

BUNNVING . X,Y I MM

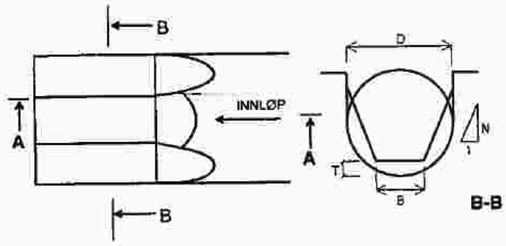
PKT.	X	Y	PKT.	X	Y
10	0,0	3,5	19	121,5	52,5
11	0,0	190,0	20	111,0	39,5
12	89,5	142,5	21	93,5	26,5
13	107,5	128,5	22	66,0	13,0
14	121,5	117,5	23	24,5	0,0
15	133,5	104,0			
16	137,5	91,0			
17	136,0	75,5			
18	128,0	61,0			

SIDEVING . X,Y I MM

Figure B.3: Dimensions of the Palmer Bowlus flumes at Risvollan for D=250mm, type 2 [39].

PALMER BOWLUS MÅLERENNE

(Håndbok i vannføringsmålinger ISBN 82-595-6443-2)

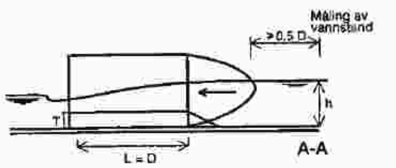


TYPE II

N = 2
B = 1/3 D
T = 1/15 D

VANNFØRINGSFORMEL:

$$Q = \sqrt{g}\; C_s\; C_d\; C_v\; B\; h^{1,5} \quad (m^3/s)$$



g = tyngdeakselerasjon (9,8 m/s²)
C_s = koeffisient tverrsnittsform
C_d = vannføringskoeffisient
C_v = koeffisient som øker med økende hastighetshøyde
B = bunnbredde hals (m)
h = målt høyde (m)

D (mm)	150	200	250	300	350	400	450	500	600	700	800
h (m)	Q_1 (m³/h)	Q_2 (m³/h)	Q_3 (m³/h)	Q_4 (m³/h)	Q_5 (m³/h)	Q_6 (m³/h)	Q_7 (m³/h)	Q_8 (m³/h)	Q_9 (m³/h)	Q_{10} (m³/h)	Q_{11} (m³/h)
0,04	2,1	2,1	2,1	1,8	1,7	1,4	2,6	1,0	0,0	0,0	0,0
0,06	5,1	5,5	5,7	5,7	5,8	5,5	5,6	4,6	3,9	3,3	3,9
0,08	9,3	10,3	11,1	11,5	11,9	11,9	11,6	11,1	10,4	9,8	9,3
0,10	15,2	16,6	18,0	19,1	19,9	20,4	20,3	20,3	20,0	19,5	18,5
0,12	23,4	24,7	26,6	28,4	29,9	30,9	31,5	32,1	32,4	32,3	31,2
0,14		34,9	37,1	39,6	41,7	43,5	44,9	46,2	47,6	48,1	47,3
0,16		48,0	49,8	52,7	55,5	58,2	60,5	62,6	65,3	66,7	66,7
0,18		64,7	65,2	68,1	71,6	74,9	78,3	81,2	85,5	88,1	89,2
0,20			83,9	86,2	90,0	94,0	98,3	102	108	112	115
0,25				147	149	153	159	165	176	184	191
0,30					231	233	237	244	259	273	286
0,35						340	341	346	362	381	399
0,40							478	475	487	509	532
0,45								641	641	660	686
0,50									830	840	866
0,55										1054	1074
0,60										1307	1316
0,65											1596
0,70											1923

Beregningsforutsetninger:

- Underkritisk strømning innløp (bunnhelning < 2 - 4 ‰)
- Vannrett bunn renne
- h < 0,9 D (rørdiameteren)
- Tilløpskanal rettlinjet L_t > 6 D

F:\HOME\KLOMSOYN\VEIT\RAPPORT\605557

Figure B.4: SINTEF NHL Rapport: Stage-Discharge Values for Risvollan

SPESIFIKASJON

- De angitte dimensjoner er innvendige mål. Ved bygging av målerennen må det tas hensyn til godstykkelsen av det materialet som benyttes.

- For bestemmelse av godstykkelsen,t, kan følgende retningslinjer benyttes for de forskjellige rørdiametre, D :

  t = 3 mm for D ≤ 350 mm
  t = 4 mm for 350 mm < D ≤ 600 mm
  t = 5 mm for 600 mm < D ≤ 800 mm
  t = 6 mm for 800 mm < D ≤1000 mm

- Som rennemateriale kan det ved bruk i kommunalt avløpsvann benyttes rustfritt stål, SIS 2333, glassfiberarmert polyester (isoftalsyrepolyester) el.l. Materialvalg for aggressivt avløpsvann må vurderes spesielt i hvert tilfelle.

- Målepunkt : innen 0,5·D foran innløpstrakt.

Q – H KURVE (VANNFØRINGSKURVE)

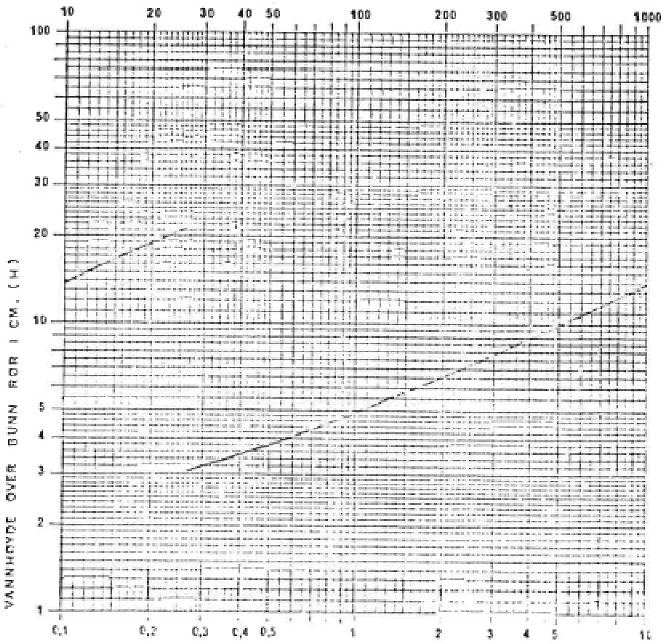


Figure B.5: Initial stage-discharge curve for Risvollan

Table B.1: The spreadsheet for iterative solving of d_i calculated from Bernoulli's

Spreadsheet for calculating the flowrate through the PB-flume with Bernoullis							
						Iteration of head upstreams the flume	
						Input	Output
dc [m]	Bc [m]	Ac [m2]	Q [m3/s]	Q [l/s]		di [m]	di=t+dc+(Ac/2Bc)-(Q^2/2gAi^2)
0,005	0,08830	0,00043	0,00009	0,09366		0,02404	0,02404
0,010	0,09330	0,00088	0,00027	0,26905		0,03104	0,03104
0,015	0,09830	0,00136	0,00050	0,50214		0,03776	0,03776
0,020	0,10330	0,00187	0,00079	0,78551		0,04429	0,04429
0,025	0,10830	0,00240	0,00112	1,11552		0,05066	0,05066
0,030	0,11330	0,00295	0,00149	1,49016		0,05692	0,05692
0,035	0,11830	0,00353	0,00191	1,90825		0,06307	0,06307
0,040	0,12330	0,00413	0,00237	2,36915		0,06915	0,06915
0,045	0,12830	0,00476	0,00287	2,87256		0,07516	0,07516
0,050	0,13330	0,00542	0,00342	3,41835		0,08111	0,08111
0,055	0,13830	0,00609	0,00401	4,00661		0,08701	0,08701
0,060	0,14330	0,00680	0,00464	4,63749		0,09287	0,09287
0,065	0,14830	0,00753	0,00531	5,31125		0,09869	0,09869
0,070	0,15330	0,00828	0,00603	6,02820		0,10447	0,10447
0,075	0,15830	0,00906	0,00679	6,78870		0,11022	0,11022
0,080	0,16330	0,00986	0,00759	7,59313		0,11595	0,11595
0,085	0,16830	0,01069	0,00844	8,44193		0,12165	0,12165
0,090	0,17330	0,01155	0,00934	9,33553		0,12733	0,12733
0,095	0,17830	0,01243	0,01027	10,27439		0,13299	0,13299
0,100	0,18330	0,01333	0,01126	11,25897		0,13863	0,13863
0,105	0,18830	0,01426	0,01229	12,28975		0,14425	0,14425
0,110	0,19330	0,01521	0,01337	13,36721		0,14985	0,14985
0,115	0,19830	0,01619	0,01449	14,49185		0,15544	0,15544
0,120	0,20330	0,01720	0,01566	15,66415		0,16102	0,16102
0,125	0,20830	0,01823	0,01688	16,88462		0,16658	0,16658
0,130	0,21330	0,01928	0,01815	18,15373		0,17213	0,17213
0,135	0,21830	0,02036	0,01947	19,47199		0,17767	0,17767
0,140	0,22330	0,02146	0,02084	20,83989		0,18319	0,18319
0,145	0,22830	0,02259	0,02226	22,25793		0,18871	0,18871
0,150	0,23330	0,02375	0,02373	23,72659		0,19422	0,19422
0,155	0,23830	0,02492	0,02525	25,24638		0,19972	0,19972
0,160	0,24330	0,02613	0,02682	26,81777		0,20521	0,20521
0,165	0,24830	0,02736	0,02844	28,44126		0,21069	0,21069
0,170	0,25330	0,02861	0,03012	30,11733		0,21616	0,21616
0,175	0,25830	0,02989	0,03185	31,84646		0,22163	0,22163
0,180	0,26330	0,03119	0,03363	33,62913		0,22709	0,22709

Table B.2: Theoretical calculation of the Froude number from the channel upstrem the flume at risvollan

Manning's coefficient n	0,0170	
Slope	0,0150	m/m
Diameter	0,25	m
Radius	0,1250	m

di (m)	Area (m2)	Pw	Rh = A/Pw	Q (m3/s)	U - velocity	Froude number	Discharge from initial	Area	U - velocity	Froude number
0,030	0,003	0,176	0,0180	0,0017	0,511	0,941	0,0003	0,0033	0,091	0,168
0,049	0,006	0,229	0,029	0,0046	0,699	0,994	0,0010	0,0068	0,146	0,211
0,085	0,014	0,311	0,0470	0,0138	0,942	1,030	0,0035	0,0147	0,238	0,261
0,117	0,022	0,376	0,0590	0,0248	1,102	1,029	0,007	0,0225	0,311	0,290
For water depth > Radius, the area is equal to a half circle and a rectangel with height di-r										
0,130	0,025	0,402	0,0640	0,0297	1,153	1,021	0,009	0,0258	0,349	0,309
0,160	0,033	0,463	0,0710	0,0411	1,242	0,991	0,014	0,0332	0,422	0,337
0,190	0,040	0,529	0,0750	0,0515	1,288	0,943	0,019	0,0400	0,475	0,348

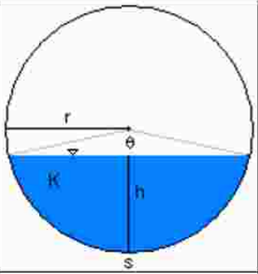
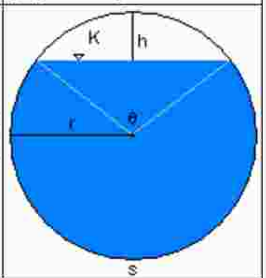
step	solve for	*if flow depth* < *radius*	*if flow depth* ≥ *radius*
			
1	circular segment height	$h = d$	$h = 2r - d$
2	central angle	$\theta = 2\arccos\left(\frac{r-h}{r}\right)$	$\theta = 2\arccos\left(\frac{r-h}{r}\right)$
3	circular segment area	$K = \frac{r^2(\theta - \sin\theta)}{2}$	$K = \frac{r^2(\theta - \sin\theta)}{2}$
4	arc length	$s = r \times \theta$	$s = r \times \theta$
5	flow area	$A = K$	$A = \pi r^2 - K$
6	wetted perimeter	$P_W = s$	$P_W = 2\pi r - s$
7	hydraulic radius	$R_h = \frac{A}{P_W}$	$R_h = \frac{A}{P_W}$

Figure B.6: Equations for solving the wetted area for partially full pipe when flow depth < radius [1]

Appendix C

Laboratory Calibration Data

C.1 Test Run Data

C.2 Laboratory Calibration 16. May

C.3 Laboratory Calibration 20. May

C.4 Laboratory Calibration 20. May

Table C.1: Data from the test run from laboratory calibration

DATE	12.mai DAY 1		
Distance to water surface	Water depth (cm)	Discharge (l/s)	Comment
20,60	4,10	0,63	
20,30	4,40	0,87	
20,40	4,30	1,00	Major leakages
19,70	5,00	1,30	
18,90	5,80	1,72	
18,55	6,15	1,99	
18,25	6,45	2,20	
17,95	6,75	2,41	
17,70	7,00	2,59	
17,50	7,20	2,78	
17,30	7,40	2,96	
17,10	7,60	3,14	
16,85	7,85	3,27	
16,60	8,10	3,57	
16,20	8,50	3,82	
16,10	8,60	4,10	Major leakages
16,00	8,70	4,12	Major leakages
15,90	8,80	4,19	
15,90	8,80	4,19	
15,80	8,90	4,25	
15,30	9,40	4,78	
15,20	9,50	5,50	Major leakages
14,70	10,00	5,43	
14,40	10,30	5,87	Major leakages
14,10	10,60	5,93	
13,80	10,90	6,42	
13,40	11,30	6,89	
13,40	11,30	7,09	
13,10	11,60	7,30	
12,70	12,00	7,85	
12,20	12,50	8,42	
11,80	12,90	9,08	
11,40	13,30	10,00	
10,90	13,80	10,90	
10,30	14,40	11,45	

Table C.2: Laboratory Calibration

DATE		12.mai Second Run			
Valve opening	Pump frequency	Measurement number	Discharge (l/s)	Water depth (cm)	Water Depth (mm)
2	48	1	0,71	3,371	33,710
		2	0,72	3,450	34,500
		3			
		4			
		5			
2	49	1	1,00	3,907	39,070
		2	1,02	4,144	41,440
		3	1,03	3,935	39,350
		4	1,05	3,918	39,180
		5			
2	51	1	1,46	4,523	45,230
		2	1,57	4,774	47,740
		3	1,46	4,749	47,490
		4	1,49	4,702	47,020
		5			
2	56	1	2,35	5,854	58,540
		2	2,36	5,827	58,270
		3	2,30	5,870	58,700
		4			
		5			
2	61	1	3,00	6,679	66,790
		2	3,00	6,681	66,810
		3	2,96	6,630	66,300
		4			
		5			
2	67	1	3,71	7,360	73,600
		2	3,69	7,382	73,820
		3	3,65	7,352	73,520
		4			
		5			
2	69	1	3,93	7,778	77,780
		2	3,92	7,714	77,140
		3	3,89	7,704	77,040
		4			
		5			
2	73	1	4,33	8,108	81,080
		2	4,32	8,126	81,260
		3	4,30	8,012	80,120
		4			
		5			
2	77	1	4,76	8,462	84,620
		2	4,74	8,507	85,070
		3	4,71	8,423	84,230
		4			
		5			
2	82	1	5,25	8,930	89,300
		2	5,23	8,925	89,250
		3	5,21	8,886	88,860
		4			
		5			

Table C.3: Laboratory calibration, page 2

2	88	1	5,84	9,380	93,800
		2	5,81	9,374	93,740
		3	5,80	9,370	93,700
		4			
		5			
2	94	1	6,40	9,920	99,200
		2	6,39	9,911	99,110
		3	6,38	9,886	98,860
		4			
		5			
2	100	1	6,98	10,361	103,610
		2	6,97	10,350	103,500
		3	6,97	10,336	103,360
		4			
		5			
3	60	1	7,67	10,804	108,040
		2			
		3			
		4			
		5			
3	62	1	8,38	11,447	114,470
		2			
		3			
		4			
		5			
3	64	1	8,97	11,852	118,520
		2			
		3			
		4			
		5			
3	66	1	9,62	12,080	120,800
		2			
		3			
		4			
		5			
3	68	1	10,23	12,404	124,040
		2			
		3			
		4			
		5			
3	70	1	10,82	12,848	128,480
		2			
		3			
		4			
		5			
3		1			
		2			
		3			
		4			
		5			

Table C.4: Stage-discharge measurements with the flume bottom as datum

	DATE	Third Run		
Valve opening	Pump frequency	Discharge (l/s)	Water depth (cm)	Water Depth (mm)
2	48	1,00	3,823	38,23
2	49	1,29	4,327	43,27
2	51	1,73	5,034	50,34
2	54	2,27	5,752	57,52
2	56	2,58	6,2	62,00
2	61	3,32	6,969	69,69
2	67	4,05	7,784	77,84
2	72	4,63	8,382	83,82
2	77	5,20	8,839	88,39
2	83	5,85	9,345	93,45
2	92	6,79	10,161	101,61
2	100	7,65	10,702	107,02
3	63	9,11	11,941	119,41
3	69	10,85	12,812	128,12
3	73	11,96	13,633	136,33
3	77	13,08	14,141	141,41
3	81	14,12	14,481	144,81
3	85	15,20	15,034	150,34
3	88	15,95	15,434	154,34
3	90	16,45	15,716	157,16

Table C.5: Stage-discharge measurements with the channel bottom as datum

	DATE	Third Run		
Valve opening	Pump frequency	Discharge (l/s)	Water depth (cm)	Water Depth (mm)
2	48	0,79	4,479	44,79
2	48	1,04	5,108	51,08
2	49	1,31	5,528	55,28
2	51	1,74	6,265	62,65
2	54	2,27	7,005	70,05
2	56	2,69	7,565	75,65
2	61	3,45	8,388	83,88
2	67	4,23	9,189	91,89
2	72	4,86	9,744	97,44
2	77	5,42	10,333	103,33
2	83	6,11	10,827	108,27
2	92	7,10	11,69	116,90
2	100	8,00	12,309	123,09
3	64	9,20	13,086	130,86
3	69	10,69	13,919	139,19
3	73	11,85	14,793	147,93
3	77	12,97	15,426	154,26
3	81	14,00	15,663	156,63
3	85	15,05	16,231	162,31
3	88	15,80	16,701	167,01
3	90	16,30	17,004	170,04

Appendix D

Tracer Dilution Data

D.1 Measurement Data from Tracer Dilution

Measurement #	Time	Water level (cm)	Tracer Amount	Injection point	Tracer name and flow rate (L/s)			Average flow	Deviation from each tracer (%)		
					A	B	C		A	B	C
1	15:30	6,8	500	2	11,41	3,05	-	7,23	57,80	57,80	-
2	16:00	7,4	500	2	2,99	3,70	-	3,34	10,60	10,60	-
3	16:30	7,8	500	2	4,43	4,70	-	4,56	3,00	3,00	-
4	17:00	8,3	500	2	4,20	4,68	-	4,44	5,40	5,40	-
5	17:30	8,7	500	2	2,83	4,95	-	3,89	27,30	27,30	-
6	18:00	8,0	500	2	3,51	4,12	-	3,81	8,00	8,00	
7	06:00	5,8	300	1	1,60	2,23	2,37	2,07	22,70	8,00	14,70
8	06:30	8,6	300	1	3,89	5,44	3,24	4,19	7,20	29,90	22,70
9	07:00	8,0	300	1	4,86	5,04	4,91	4,94	1,60	2,10	0,50
10	07:30	8,9	300	1	5,27	5,46	5,15	5,29	0,40	3,10	2,70
11	08:00	8,6	300	1	4,12	7,25	4,52	5,30	22,20	36,90	14,70
12	08:30	6,9	300	1	2,54	7,02	3,17	4,25	40,20	65,50	25,20
13	08:45	6,9	300	1	2,36	2,85	2,60	2,61	9,30	9,50	0,20
14	09:00	7,7	300	1	2,84	2,96	5,42	3,74	24,10	20,90	44,90
15	09:30	7,3	300	1	5,20	3,67	3,31	4,06	28,20	9,70	18,50
16	10:00	6,8	500	2	2,50	2,58	4,07	3,05	18,20	15,30	33,40
17	10:30	8,0	500	3	3,72	4,93	3,71	4,12	9,70	19,70	10,00
18	11:00	7,7	500	3	3,54	3,81	3,99	3,78	6,50	0,90	5,60
19	11:30	8,0	500	2	4,65	3,41	3,51	3,86	20,50	11,50	9,00
20	14:30	7,7	500	2	2,61	3,06	3,66	3,11	16,00	1,60	17,60
21	15:00	7,6	150	2	3,62	3,14	6,14	4,30	15,70	27,10	42,80
22	15:30	7,7	500	2	3,45	3,74	3,95	3,72	7,00	0,70	6,30
23	15:45	8,6	500	2	4,33	4,26	3,90	4,16	4,00	2,30	6,30
24	16:00	9,0	500	2	4,57	4,21	4,55	4,45	2,70	5,20	2,40
25	16:15	9,1	500	2	5,80	4,68	4,85	5,11	13,50	8,40	5,10
26	06:15	6,8	300	3	2,73	2,71	2,63	2,69	1,60	0,80	2,40
27	06:30	7,7	300	3	5,64	5,56	2,03	4,41	27,80	26,00	53,80
28	07:00	8,6	300	3	4,90	4,77	4,88	4,85	1,00	1,60	0,60
29	07:30	7,5	300	3	3,01	3,05	3,45	3,17	5,10	3,70	8,80
30	08:00	8,0	300	3	3,25	3,22	4,62	3,70	12,00	12,80	24,90
31	08:30	7,9	300	3	40,70	82,94	79,35	67,66	39,90	22,60	17,30
32	09:00	6,7	300	3	2,56	2,55	3,37	2,83	9,30	9,80	19,10
33	09:30	7,0	300	3	2,67	3,04	2,83	2,85	6,20	6,90	0,60
34	10:00	7,1	150	3	2,17	2,16	2,34	2,22	2,30	2,80	5,10
35	10:30	6,3	300	3	2,74	2,67	1,96	2,46		8,70	20,10
36	11:00	6,0	500	3	1,95	1,93	-	1,94	11,40	0,60	-
37	11:30	6,4	500	3	2,29	1,95	-	2,12	0,60	7,90	-
38	12:00	6,7	300	3	2,06	3,20	-	2,63	21,70	21,70	-
39	13:00	6,1	300	3	2,73	2,58	-	2,66	2,70	2,70	-
40	13:30	6,4	300	3	1,92	1,80	-	1,86	3,20	3,20	-
41	14:00	6,9	200	3	27,83	33,22	-	30,53	8,80	8,80	-
42	14:30	6,9	300	3	2,72	2,04	-	2,38	14,30	14,30	-
43	15:00	6,2	150	3	2,13	3,44	-	2,78	23,50	23,50	-
44	15:30	7,0	500	3	2,74	2,82	-	2,78	1,50	1,50	-
45	16:00	7,8	300	3	3,44	3,62	-	3,53	2,50	2,50	-
46	16:15	7,3	300	3	3,74	2,75	-	3,24	15,30	15,30	-
47	16:30	7,9	300	3	2,89	3,13	-	3,01	4,00	4,00	-

Table D.1: All data from Tracer Dilution measurements at Risvollan

Appendix E

Calculations of Mean Deviation

E.1 Laboratory

E.2 Bernoulli: Datum Channel Bottom

E.3 Bernoulli: Datum Flume Bottom

E.4 Tracer Dilution

E.5 SINTEF

E.6 Two Laboratory Calibrations

E.7 Tracer Dilution: Injection Points

Table E.1: The mean deviation for the laboratory calibration calculated from the initial

Mean deviation from the initial			Water level measured from channel bottom				Mean Deviation (l/s)		0,11
h	Q lab	Q initial	Delta Q	Ratio (%)	h	Q lab	Q initial	Delta Q	Ratio
4,50	0,82	0,77	0,04	5,81 %	10,80	5,95	5,81	0,14	2,35 %
4,60	0,86	0,81	0,05	5,72 %	10,90	6,07	5,94	0,14	2,31 %
4,70	0,90	0,85	0,05	5,63 %	11,00	6,20	6,06	0,14	2,28 %
4,80	0,95	0,90	0,05	5,55 %	11,10	6,33	6,19	0,14	2,24 %
4,90	0,99	0,94	0,05	5,47 %	11,20	6,46	6,32	0,14	2,21 %
5,00	1,04	0,98	0,05	5,39 %	11,30	6,59	6,45	0,14	2,17 %
5,10	1,09	1,03	0,05	5,31 %	11,40	6,72	6,58	0,14	2,14 %
5,20	1,13	1,08	0,06	5,23 %	11,50	6,86	6,72	0,14	2,10 %
5,30	1,18	1,13	0,06	5,15 %	11,60	6,99	6,85	0,14	2,07 %
5,40	1,24	1,18	0,06	5,08 %	11,70	7,13	6,99	0,14	2,04 %
5,50	1,29	1,23	0,06	5,01 %	11,80	7,27	7,13	0,14	2,00 %
5,60	1,34	1,28	0,06	4,93 %	11,90	7,41	7,27	0,14	1,97 %
5,70	1,40	1,33	0,06	4,86 %	12,00	7,55	7,41	0,14	1,94 %
5,80	1,45	1,39	0,07	4,79 %	12,10	7,70	7,55	0,14	1,91 %
5,90	1,51	1,44	0,07	4,73 %	12,20	7,84	7,70	0,14	1,87 %
6,00	1,57	1,50	0,07	4,66 %	12,30	7,99	7,84	0,14	1,84 %
6,10	1,63	1,56	0,07	4,59 %	12,40	8,14	7,99	0,14	1,81 %
6,20	1,69	1,62	0,07	4,53 %	12,50	8,28	8,14	0,14	1,78 %
6,30	1,75	1,68	0,07	4,47 %	12,60	8,44	8,29	0,15	1,75 %
6,40	1,82	1,74	0,08	4,40 %	12,70	8,59	8,44	0,15	1,72 %
6,50	1,88	1,80	0,08	4,34 %	12,80	8,74	8,60	0,15	1,69 %
6,60	1,95	1,87	0,08	4,28 %	12,90	8,90	8,75	0,15	1,66 %
6,70	2,01	1,93	0,08	4,22 %	13,00	9,06	8,91	0,15	1,63 %
6,80	2,08	2,00	0,08	4,16 %	13,10	9,21	9,07	0,15	1,60 %
6,90	2,15	2,07	0,08	4,10 %	13,20	9,37	9,23	0,14	1,57 %
7,00	2,23	2,14	0,09	4,05 %	13,30	9,54	9,39	0,14	1,54 %
7,10	2,30	2,21	0,09	3,99 %	13,40	9,70	9,55	0,14	1,51 %
7,20	2,37	2,28	0,09	3,94 %	13,50	9,86	9,72	0,14	1,48 %
7,30	2,45	2,36	0,09	3,88 %	13,60	10,03	9,89	0,14	1,45 %
7,40	2,52	2,43	0,09	3,83 %	13,70	10,20	10,06	0,14	1,43 %
7,50	2,60	2,51	0,09	3,78 %	13,80	10,37	10,23	0,14	1,40 %
7,60	2,68	2,59	0,10	3,72 %	13,90	10,54	10,40	0,14	1,37 %
7,70	2,76	2,66	0,10	3,67 %	14,00	10,71	10,57	0,14	1,34 %
7,80	2,84	2,74	0,10	3,62 %	14,10	10,89	10,74	0,14	1,32 %
7,90	2,93	2,83	0,10	3,57 %	14,20	11,06	10,92	0,14	1,29 %
8,00	3,01	2,91	0,10	3,52 %	14,30	11,24	11,10	0,14	1,26 %
8,10	3,10	2,99	0,10	3,47 %	14,40	11,42	11,28	0,14	1,23 %
8,20	3,19	3,08	0,11	3,42 %	14,50	11,60	11,46	0,14	1,21 %
8,30	3,27	3,17	0,11	3,38 %	14,60	11,78	11,64	0,14	1,18 %
8,40	3,36	3,26	0,11	3,33 %	14,70	11,96	11,83	0,14	1,16 %
8,50	3,46	3,35	0,11	3,28 %	14,80	12,15	12,01	0,14	1,13 %
8,60	3,55	3,44	0,11	3,24 %	14,90	12,34	12,20	0,13	1,10 %
8,70	3,64	3,53	0,11	3,19 %	15,00	12,53	12,39	0,13	1,08 %
8,80	3,74	3,62	0,11	3,15 %	15,10	12,72	12,58	0,13	1,05 %
8,90	3,84	3,72	0,12	3,10 %	15,20	12,91	12,78	0,13	1,03 %
9,00	3,93	3,82	0,12	3,06 %	15,30	13,10	12,97	0,13	1,00 %
9,10	4,03	3,92	0,12	3,02 %	15,40	13,30	13,17	0,13	0,98 %
9,20	4,13	4,02	0,12	2,97 %	15,50	13,49	13,37	0,13	0,95 %
9,30	4,24	4,12	0,12	2,93 %	15,60	13,69	13,56	0,13	0,93 %
9,40	4,34	4,22	0,12	2,89 %	15,70	13,89	13,77	0,12	0,90 %
9,50	4,45	4,32	0,12	2,85 %	15,80	14,09	13,97	0,12	0,88 %
9,60	4,55	4,43	0,12	2,81 %	15,90	14,29	14,17	0,12	0,85 %
9,70	4,66	4,54	0,13	2,77 %	16,00	14,50	14,38	0,12	0,83 %
9,80	4,77	4,65	0,13	2,73 %	16,10	14,71	14,59	0,12	0,81 %
9,90	4,88	4,76	0,13	2,69 %	16,20	14,91	14,80	0,12	0,78 %
10,00	5,00	4,87	0,13	2,65 %	16,30	15,12	15,01	0,11	0,76 %
10,10	5,11	4,98	0,13	2,61 %	16,40	15,33	15,22	0,11	0,74 %
10,20	5,22	5,09	0,13	2,57 %	16,50	15,55	15,44	0,11	0,71 %
10,30	5,34	5,21	0,13	2,53 %	16,60	15,76	15,65	0,11	0,69 %
10,40	5,46	5,33	0,13	2,49 %	16,70	15,98	15,87	0,11	0,67 %
10,50	5,58	5,45	0,13	2,46 %	16,80	16,20	16,09	0,10	0,64 %
10,60	5,70	5,57	0,13	2,42 %	16,90	16,41	16,31	0,10	0,62 %
10,70	5,82	5,69	0,14	2,38 %	17,00	16,64	16,54	0,10	0,60 %
							Relative error (accuracy)		1,69 %

Table E.2: The mean deviation for the laboratory calibration calculated from the initial with the channel bottom as datum

Comparison of Bernoulli				
Water level (cm)	Initial	Bernoulli	Delta Q	Ratio
5,0	0,98	1,45	0,46	47 %
5,5	1,23	1,77	0,54	44 %
6,0	1,50	2,13	0,63	42 %
6,5	1,80	2,51	0,71	39 %
7,0	2,14	2,94	0,80	37 %
7,5	2,51	3,40	0,89	35 %
8,0	2,91	3,89	0,98	34 %
8,5	3,35	4,42	1,07	32 %
9,0	3,82	4,98	1,17	31 %
9,5	4,32	5,58	1,26	29 %
10,0	4,87	6,22	1,35	28 %
10,5	5,45	6,89	1,44	27 %
11,0	6,06	7,60	1,54	25 %
11,5	6,72	8,34	1,62	24 %
12,0	7,41	9,12	1,71	23 %
12,5	8,14	9,94	1,80	22 %
13,0	8,91	10,79	1,88	21 %
13,5	9,72	11,68	1,96	20 %
14,0	10,57	12,61	2,04	19 %
14,5	11,46	13,58	2,12	18 %
15,0	12,39	14,58	2,19	18 %
15,5	13,37	15,62	2,26	17 %
16,0	14,38	16,70	2,32	16 %
16,5	15,44	17,81	2,38	15 %
17,0	16,54	18,97	2,43	15 %
17,5	17,68	20,16	2,48	14 %
18,0	18,87	21,39	2,52	13 %
18,5	20,10	22,66	2,56	13 %
19,0	21,37	23,96	2,59	12 %
19,5	22,69	25,31	2,62	12 %
20,0	24,05	26,69	2,64	11 %
20,5	25,46	28,11	2,65	10 %
21,0	26,92	29,57	2,66	10 %
Mean deviation	1,77		Ratio (accuracy)	23,48 %

Table E.3: The mean deviation for the laboratory calibration calculated from the initial with the channel bottom as datum

Comparison of Bernoulli from flume bottom				
Water level (cm)	Initial	Bernoulli	Delta Q	Ratio
5,0	1,70	1,45	0,25	15 %
5,5	2,05	1,77	0,28	14 %
6,0	2,43	2,13	0,31	13 %
6,5	2,85	2,51	0,34	12 %
7,0	3,30	2,94	0,36	11 %
7,5	3,78	3,40	0,38	10 %
8,0	4,29	3,89	0,40	9 %
8,5	4,84	4,42	0,42	9 %
9,0	5,41	4,98	0,43	8 %
9,5	6,02	5,58	0,44	7 %
10,0	6,66	6,22	0,44	7 %
10,5	7,33	6,89	0,44	6 %
11,0	8,04	7,60	0,44	5 %
11,5	8,77	8,34	0,43	5 %
12,0	9,54	9,12	0,42	4 %
12,5	10,34	9,94	0,40	4 %
13,0	11,17	10,79	0,38	3 %
13,5	12,03	11,68	0,35	3 %
14,0	12,92	12,61	0,31	2 %
14,5	13,85	13,58	0,27	2 %
15,0	14,81	14,58	0,23	2 %
15,5	15,79	15,62	0,17	1 %
16,0	16,81	16,70	0,12	1 %
16,5	17,87	17,81	0,05	0 %
17,0	18,95	18,97	0,02	0 %
17,5	20,06	20,16	0,10	0 %
18,0	21,21	21,39	0,18	1 %
18,5	22,38	22,66	0,27	1 %
19,0	23,59	23,96	0,37	2 %
19,5	24,83	25,31	0,48	2 %
20,0	26,10	26,69	0,59	2 %
20,5	27,40	28,11	0,71	3 %
21,0	28,73	29,57	0,84	3 %
Mean deviation	0,35		Ratio (accura	5,05 %

Table E.4: The mean deviation for the tracer dilution calibration calculated from the initial

Water level (cm)	Q tracer (l/s)	Q inital (l/s)	Delta Q (l/s)	Ratio (accuracy)
6,00	2,11	1,64	0,47	28,8 %
6,25	2,30	1,80	0,50	28,1 %
6,50	2,50	1,96	0,54	27,4 %
6,75	2,70	2,13	0,57	26,7 %
7,00	2,92	2,31	0,60	26,1 %
7,25	3,14	2,50	0,64	25,5 %
7,50	3,37	2,70	0,67	24,9 %
7,75	3,61	2,91	0,71	24,4 %
8,00	3,86	3,12	0,74	23,8 %
8,25	4,12	3,34	0,78	23,3 %
8,50	4,39	3,57	0,82	22,8 %
8,75	4,66	3,81	0,85	22,3 %
9,00	4,95	4,06	0,89	21,9 %
Mean Deviation	0,68		Relative error	24,5 %

Table E.5: The mean deviation for SINTEF calculated from the initial

h	Q SINTEF	Q initial	Delta Q	Deviation from intial	Qreal/Qtheoretical
4,0	0,6145	0,5887	0,0259	4,39 %	0,96
4,5	0,8019	0,7723	0,0296	3,83 %	0,96
5,0	1,0175	0,9847	0,0328	3,33 %	0,97
5,5	1,2620	1,2266	0,0354	2,89 %	0,97
6,0	1,5362	1,4990	0,0372	2,48 %	0,98
6,5	1,8407	1,8028	0,0380	2,11 %	0,98
7,0	2,1763	2,1386	0,0377	1,76 %	0,98
7,5	2,5435	2,5073	0,0361	1,44 %	0,99
8,0	2,9428	2,9095	0,0333	1,14 %	0,99
8,5	3,3748	3,3459	0,0289	0,86 %	0,99
9,0	3,8401	3,8171	0,0230	0,60 %	0,99
9,5	4,3391	4,3238	0,0153	0,35 %	1,00
10,0	4,8723	4,8665	0,0058	0,12 %	1,00
10,5	5,4402	5,4458	0,0056	0,10 %	1,00
11,0	6,0432	6,0623	0,0191	0,31 %	1,00
11,5	6,6817	6,7164	0,0347	0,52 %	1,01
12,0	7,3562	7,4088	0,0526	0,71 %	1,01
12,5	8,0670	8,1398	0,0728	0,89 %	1,01
13,0	8,8146	8,9100	0,0955	1,07 %	1,01
13,5	9,5992	9,7199	0,1207	1,24 %	1,01
14,0	10,4214	10,5699	0,1485	1,41 %	1,01
14,5	11,2814	11,4605	0,1791	1,56 %	1,02
15,0	12,1795	12,3920	0,2125	1,71 %	1,02
15,5	13,1162	13,3650	0,2488	1,86 %	1,02
16,0	14,0917	14,3799	0,2881	2,00 %	1,02
16,5	15,1064	15,4369	0,3305	2,14 %	1,02
17,0	16,1606	16,5367	0,3761	2,27 %	1,02
17,5	17,2545	17,6794	0,4249	2,40 %	1,02
18,0	18,3886	18,8656	0,4770	2,53 %	1,03
18,5	19,5630	20,0956	0,5326	2,65 %	1,03
19,0	20,7781	21,3698	0,5916	2,77 %	1,03
19,5	22,0342	22,6885	0,6543	2,88 %	1,03
20,0	23,3315	24,0520	0,7205	3,00 %	1,03
	Mean deviation	0,1807	Accuracy (Ratio)	1,97 %	

Table E.6: Mean deviation between two separate laboratory calibration

Repeatability				
Water level (cm)	Lab. 20/5	Lab25/5	Delta Q	Accuracy
4,2	1,21	1,19	0,02	1,59 %
4,5	1,38	1,36	0,02	1,48 %
5,0	1,70	1,68	0,02	1,31 %
5,5	2,05	2,03	0,02	1,16 %
6,0	2,43	2,41	0,02	1,02 %
6,5	2,85	2,82	0,03	0,89 %
7,0	3,30	3,27	0,03	0,77 %
7,5	3,78	3,75	0,02	0,66 %
8,0	4,29	4,27	0,02	0,56 %
8,5	4,84	4,81	0,02	0,46 %
9,0	5,41	5,39	0,02	0,37 %
9,5	6,02	6,00	0,02	0,28 %
10,0	6,66	6,65	0,01	0,20 %
10,5	7,33	7,32	0,01	0,12 %
11,0	8,04	8,03	0,00	0,05 %
11,5	8,77	8,77	0,00	0,02 %
12,0	9,54	9,55	0,01	0,09 %
12,5	10,34	10,35	0,02	0,16 %
13,0	11,17	11,19	0,02	0,22 %
13,5	12,03	12,06	0,03	0,28 %
14,0	12,92	12,97	0,04	0,34 %
14,5	13,85	13,90	0,05	0,39 %
15,0	14,81	14,87	0,07	0,44 %
15,5	15,79	15,87	0,08	0,50 %
Mean deviation	0,03		Ratio	0,38 %

Table E.7: Deviation from the initial calculated for injection point 1, 2 and 3

Water level (cm)	Injection point 1	Injection point 2	Injection point 3	Q initial	Delta Q1	Delta Q2	Delta Q3	RSD1	RSD2	RSD3
6,00	2,67	2,42	2,02	1,50	1,17	0,92	0,52	78 %	61 %	35 %
6,25	2,90	2,60	2,20	1,65	1,25	0,95	0,56	76 %	58 %	34 %
6,50	3,13	2,78	2,39	1,80	1,33	0,97	0,59	74 %	54 %	33 %
6,75	3,38	2,96	2,58	1,97	1,42	0,99	0,62	72 %	51 %	31 %
7,00	3,64	3,15	2,79	2,14	1,50	1,01	0,65	70 %	47 %	30 %
7,25	3,91	3,34	3,00	2,32	1,59	1,03	0,68	68 %	44 %	29 %
7,50	4,18	3,54	3,21	2,51	1,68	1,04	0,71	67 %	41 %	28 %
7,75	4,47	3,75	3,44	2,70	1,77	1,04	0,74	65 %	39 %	27 %
8,00	4,77	3,96	3,67	2,91	1,86	1,05	0,77	64 %	36 %	26 %
8,25	5,07	4,17	3,92	3,12	1,95	1,05	0,79	62 %	34 %	25 %
8,50	5,39	4,39	4,17	3,35	2,04	1,04	0,82	61 %	31 %	25 %
8,75	5,71	4,61	4,42	3,58	2,13	1,03	0,85	60 %	29 %	24 %
9,00	6,04	4,84	4,69	3,82	2,23	1,02	0,87	58 %	27 %	23 %
						Mean deviation:		1,68	1,01	0,70