UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

The Influence of Large Roughness Elements on the Velocity Distribution in Streams

Mhairi Riddet

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering

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Declaration

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of Candidate)

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Abstract

Producing a local control can significantly increase the variation in velocity of the flow surrounding rocks (large roughness elements) in a river, which is important as fish and invertebrates require variation in velocity in their habitat in order to survive and to breed. Thus the creation of a local control in a rehabilitated river will be useful for encouraging the formation of a natural habitat in that river. This report details research carried out on the velocity distribution around two protruding cylinders, representing large roughness elements, placed perpendicular to the flow in a laboratory flume. The research is conducted mainly by two-dimensional computer modelling in RiverFLO-2D, which is verified by laboratory experiments. The results of the computer modelling confirm that a greater variation in velocity occurs when a local control is present, and also produce guidelines for producing a local control in the specific case studied. These guidelines include placing two obstructions side-by-side in a flow whose base Froude Number is greater than 0.6. To increase the maximum Froude Number once a local control is created, the obstructions may be moved closer together. This will also increase the variation in velocity around the obstructions.

Table of Contents

List of Tables

List of Figures

1 INTRODUCTION

Variation in a habitat is important in encouraging fauna and flora to repopulate rehabilitated rivers. A specific aspect of variation that needs to be created is the variation in velocities in a river, which can be achieved by adding obstacles to a reach of river. It is expected that a greater variation will be created in the river if the obstacles placed in the flow were to control the flow – i.e. create a section of river where the flow transitions from subcritical flow to supercritical flow (i.e. from relatively deep, slow flow to relatively fast, shallow flow, which will create flow variation). This creates some of the habitat conditions that certain fauna and flora need in order to thrive, therefore creating an environmental habitat closer to the natural habitat of the rehabilitated river.

Thus the purpose of this research is to investigate means of creating a control in flow and therefore induce a variation in velocity at a point in the river.

This research report documents experiments and computer models developed to investigate how to create a control in a river by adding large roughness elements into the flow. The research then investigates whether a local control has a significant effect on creating variation in velocity around two cylinders protruding from and placed perpendicular to the flow in a river (represented here by a laboratory flume).

1.1 Layout of Report

This research report begins by introducing the topic of ecohydraulics and explains the significance of the research in terms of river rehabilitation. It explains some of the background to the research and what other researchers have done previously in the field.

Having established the context and significance of the research, the experimental work performed in the Hydraulics Laboratory of the Civil Engineering Department of the University of the Witwatersrand is explained. This experimental work is then linked to numerical work done in a computer program called RiverFLO-2D. The numerical modelling done is then explained and the models built are shown.

The data obtained from the experimental work and, largely, from the computer modelling performed is then discussed and significant observations are pointed out. The conclusions of this research are drawn from the observations made from the results of this data. Recommendations for the use of the conclusions drawn and also for further research are then discussed.

1.2 Definitions of Important Terms

Base flow

This is the undisturbed flow in a river or flume – i.e. the flow that occurs when no obstructions are present in the river.

Critical velocity

The velocity at which a local control is formed for a specific slope and discharge, i.e. the velocity at which the Froude Number is equal to one for a particular geometry. Velocities that fall below the critical velocity are in the subcritical range, while velocities that fall above the critical velocity are in the supercritical range. The critical velocity is calculated by using Q = vA, with A = b times y_c, where y_c is the critical depth of the flow, which can be calculated by taking the cube root of the discharge per metre (squared) divided by the width of the cross section.

Ecohydraulics

Interdisciplinary research conducted involving geomorphology, hydrology, hydraulics and river ecology (Harvey and Clifford 2009).

Flow Direction

Unless otherwise noted, the direction of the flow in figures is either towards the top of the page or towards the right of the page, depending on the orientation of the figure.

Froude Number

The Froude number is a non-dimensional flow characteristic that is calculated by taking the velocity of the flow and dividing it by the square root of gravity multiplied by the square root of the flow depth. This quantity is useful in determining the type of flow present in a river or stream, i.e. subcritical flow or supercritical flow. The Froude Number can either be local – i.e. the quantity is calculated with the velocity and depth at a point – or it can be averaged across a section.

Histogram

A histogram is a graphical representation of data showing the number of data points that fall into a specified category. In this report, the histograms will have a representation of the velocity on the x axis, with the frequency (or number of data points in a velocity category) on the y axis. A data point is put into a specific category on the x axis if it is within the category range on the x axis.

Large roughness elements

Large roughness elements are elements obstructing the stream flow (such as boulders or large rocks in natural rivers, or objects used to model these in flumes, such as cylinders or hemispheres) that are at least as high as the flow depth.

Local control

A local control in the flow is caused by an obstacle in the flow that induces a change in the flow regime from subcritical flow to supercritical flow.

Low flow

A low flow is a flow in a river that is shallow in depth (less than 0.5m according to Kleynhans's flow classifications (James and King (Eds) 2010)). This should not be confused with seasonal low flows, which may have large depths in comparison to those investigated in this report.

Pseudouniform flow

This is a type of flow around large roughness elements where the large roughness elements do not have a significant visual impact on the flow – i.e. an observer of the flow does not notice significant changes in the depth or velocity and there is no local control.

Slope

The slope in this research refers to the slope of the bed of the flume, which is the same as the slope of the water surface when there is uniform flow in the flume.

Subcritical flow

The flow in a river/stream/flume that is characterised by relatively slow velocities and relatively large flow depths. This type of flow has a greater percentage of energy stored as potential energy than as kinetic energy, as its depth is large compared to its velocity. The Froude number for this type of flow is less than 1.0.

Supercritical flow

The flow in a river/stream/flume that is characterised by relatively fast velocities and relatively shallow flow depths. In this type of flow, most of the energy is present in the flow as kinetic energy because of the faster velocities, while a smaller percentage is stored as potential energy due to the shallower flow depths. The Froude number for this type of flow is greater than 1.0.

Velocity

The velocity is generally measured in metres per second. This may refer either to longitudinal or transverse velocity, depending on which is explicitly defined in the text. In the figures of the flumes, the highest velocity is shown in red and the lower velocities are shown in blue, with the range of velocities shown in the colour scale between red and blue.

Zone of influence

The zone of influence of a large roughness element in a river is the extent to which it significantly disturbs the flow in the river around it, for example, the zone of influence may be defined as the zone downstream of a large roughness element that has a velocity that is appreciably different from the uniform velocity. For the purposes of this report, the zone of influence will be defined as that portion of the flow that has a velocity that deviates by more than 10% from the base velocity of the flow.

2 BACKGROUND

This research is aimed at investigating the variations in flow characteristics of low flows around large roughness elements. The background and motivations for doing this research are detailed below.

2.1 Motivation

The motivation for undertaking this research is primarily for the purpose of river rehabilitation. The flow in many rivers has been disrupted through human activity, for example the building of dams and other flood mitigation measures, and they are therefore not in a condition close to their natural state, as rivers do not necessarily recover easily from sustained disturbance to their flow (King, Tharme, and de Villiers 2000; Shen and Diplas 2008; Crowder and Diplas 2006). As well as this, rehabilitating river environments is becoming an important aspect of ecohydrological research (Lee, Kil, and Jeong 2010), while river management is increasingly stressing the need for integration between the physical and biological aspects of rivers (Clifford et al. 2006; Rodriguez et al. 2004).

For this reason, legislation has been put in place to protect rivers in South Africa. This legislation stipulates that when the river's natural resources are harvested, the environment depending on that river must be protected. This is accomplished by maintaining a minimum flow, sometimes known as the ecological reserve. The ecological reserve is 'the water required to protect the aquatic ecosystems of a water resource' (DWAF 1998). This requires a certain flow to be present in rivers, both natural and rehabilitated, which requires, very simplistically, a certain velocity and depth to be present in a river. These two flow characteristics have been shown to be important in developing and defining fish habitats (Guay et al. 2000; James and King (Eds) 2010; Dolinsek, Grant, and Biron 2007; Shields and Rigby 2005; Harvey and Clifford 2009; Stewart, Anderson, and Wohl 2005; Rodriguez et al. 2004). Also, the two-dimensional velocity distribution or point velocity in rivers and streams is important in defining fish habitats, as spatial variation in the velocity and complex flow patterns in a river are important requirements for both fish and invertebrate habitat (Lamouroux, Souchon, and Herouin 1995; Crowder and Diplas 2006). This concept will be discussed in further detail below.

Thus ecologists and hydraulicians have started to investigate methods of rehabilitating rivers in such a way that they encourage fish and invertebrates to reproduce by creating suitable habitats for them – i.e. habitats that are close to their natural habitats (Shen and Diplas 2008). This is done by ensuring that the ecological reserve is maintained. Practically, this is often achieved by installing morphological features and meander bends, as this encourages a physical environment that is closer to the natural habitat for fish and invertebrates (Bockelmann 2004).

In order to provide this natural physical habitat and to encourage the natural fauna and flora to re-establish, it is becoming generally accepted that a non-uniform velocity distribution in two or three dimensions – i.e. physical heterogeneity – is required in the stream or river as this is important in creating habitats for fish and invertebrates (Crowder and Diplas 2000). Part of this physical heterogeneity is the variation in point velocities and flow depths in a river, which have a significant impact on hydrodynamic habitat (Jonker 2002). Several different approaches have been used to describe the various habitats that fish and invertebrates need in order to survive. The approaches that this research will focus on are flow classes and numerical modelling.

2.1.1 Flow classes

Flow classes are a semi-quantitative method of classifying the flow in natural rivers. The method divides the flow in a river into four broad classes, as described in Table 1.

Table 1: Flow classes for fish (Kleynhans 1999)

Class	Velocity	Depth	Description
SS	Slow (<0.3m/s)	Shallow (<0.5m)	Shallow pools and backwaters
SD	Slow (<0.3m/s)	Deep (>0.5m)	Deep pools and backwaters
FS	Fast (>0.3m/s)	Shallow (<0.3m)	Shallow runs, rapids and riffles
FD	Fast (>0.3m/s)	Deep (>0.3m)	Deep runs, rapids and riffles

These flow classes are now used widely in the assessment of the ecological reserve in South Africa. They should, however, be used with caution, as not all fish perceive hydraulic environments in the same way and therefore the required habitat of some fish and invertebrates may need to be assessed in different ways (James and King (Eds) 2010). Also, linking physical properties such as those described in flow classes or biotopes or morphological units to actual biological functioning tends to be a complex process – i.e. describing the habitat using only depth and velocity may not be sufficient to fully describe the requirements of the fish or invertebrates in that river or stream (Clifford et al. 2006). Having said this, for the purposes of this report, flow classes – i.e. only the depth and, more specifically, velocity of the flow – are adequate for use as simple descriptors of hydraulic habitat.

2.1.2 Numerical modelling

In terms of numerical modelling to represent this spatial variation in velocity, two-dimensional models have been shown to adequately quantify the spatial variation and combinations of flow patterns that are important to stream fauna and flora (Crowder and Diplas 2000). The two-dimensional modelling program to be used in this research is RiverFLO-2D, with Argus ONE used for pre- and post-processing. This program will be described in greater detail in later chapters.

These tools of flow classes and numerical modelling will aid in an investigation into methods to provide the non-uniform flow distribution necessary to create natural habitats would be useful in rehabilitating rivers. This investigation will look specifically at the placing of large roughness elements in the flow to obtain the desired non-uniform flow distribution. Specifically, the research will include investigating how the spacing between two cylinders (representing large roughness elements) will affect the flow conditions, as well as how the longitudinal spacing of the large roughness element pairs will affect the flow conditions, as previous research has shown that both these variables affect the flow characteristics in the river (Bathurst 1985; Ferro 2003).

2.2 Previous Research

Various researchers have investigated the two-dimensional velocity distribution in streams. Some of these are discussed below.

2.2.1 Statistical investigations

Dingman (1989) investigated the probability distribution of the flow in several natural streams. The velocities in these streams were investigated in two-dimensions and were found to follow a power law probability distribution. It was concluded that a grid of velocity measurements of around 0.2m was sufficient to describe the velocity distributions in these streams (Dingman 1989). From these measurements, the mean cross sectional velocity and the fraction of the cross section with velocities in a certain range could be determined. This has some limited use in describing habitats, but a more detailed description of the velocity distribution may be useful for habitat building.

Research along the same lines has been conducted into describing the two-dimensional velocity distribution in a natural stream by using statistical and probabilistic methods. It was shown that these methods are a good means of determining the approximate two-dimensional velocity distribution when a numerical simulation would not be possible (Lamouroux, Souchon, and Herouin 1995). It was also found in this research that two-dimensional distributions are useful in describing fish habitat, as mentioned previously.

Other researchers have used various statistical distributions to describe the two-dimensional velocity distributions. Jonker (2002) fitted Weibull and Extreme distributions to pool units, plane bed morphological units and rapid and riffle morphological units, which described the velocity distributions for those morphological units. Different distributions were used for different morphological units, depending on the goodness of fit of the distribution. The concept of whether different flow patterns produce different distributions of velocities and different descriptive statistics will be investigated in this research, specifically looking at the difference induced by a local control.

Harvey and Clifford (2009) also investigated the statistical distribution of two-dimensional flows. They found that flows with higher turbulence are likely to have a higher standard deviation in their velocities. This may have significance in terms of fitting distributions to two-dimensional velocity distributions.

Clifford et al (2006) also found that the distribution of velocity changes with stage and discharge. They find a single peak distribution at a low discharge and a more bimodal distribution at high discharges. Thus within the same morphological unit, there is a possibility of obtaining different flow classes and fairly large variation in velocities, depending on the discharge. This research will attempt to demonstrate this.

2.2.2 Descriptive investigations

Crowder and Diplas (2000) investigated the flow of rivers around large boulders using two-dimensional modelling. They modelled situations that they had investigated in the field and made several observations. These observations concluded that boulders significantly affect the flow in a river and therefore the habitat conditions around the boulder. They also found that the boulder affects flow up to 8 times the boulder’s diameter downstream of the boulder, and also that boulders tend to increase the velocity of the flow. These effects will be investigated in this research, also with specific focus on a local control.

In terms of creating a local control, it is thought that slope has an effect on whether there is a local control in a stream or not (Miller and Cluer (Eds) 1998). This research also investigates the effect that slope has on flow conditions and whether the slope does have an effect on the creation of a local control or not.

Obstructions are often used in channels to create more natural or varied spatial velocity distributions (Rutherfurd, Jerie, and Marsh 2000). Obstructions are used because they have been seen to induce these variations in velocity. For instance, pools are created upstream of obstructions, which create a decrease in velocity (Harrison and Keller 2007).

Dolinsek et al (2007) also studied obstructions in streams, specifically boulders in the substratum of the stream. They found that the addition of boulders increased the variability in depth and velocity and therefore increased the abundance of fauna in the stream. This study thus suggested that adding boulders to a rehabilitated stream would have a positive effect on the habitat quality in that stream.

Rodriguez et al (2004) note that low velocity areas are often found in the wakes of boulders or large woody debris – i.e. large roughness elements. These areas typically provide shelter for fish and are therefore usually included in their habitat requirements.

Rutherfurd et al (2000) compiled a list of guidelines for placing obstructions such as boulders in streams in order to maximise the velocity variation. The size of boulders is suggested to be greater than the depth of flow, but less than roughly a fifth of the width of the river, with placement that is not within the zone of influence of other boulders, to maximise the effect that they will have on the flow. It is suggested that the boulders should be placed in groups to enhance the variation in velocity. This research will attempt to confirm these guidelines.

2.2.3 Investigations using numerical models

Various numerical modelling programs are currently being used for hydrodynamic analyses, including one-dimensional models, such as HEC-RAS, two-dimensional models, such as RiverFLO-2D and River2D, and three-dimensional models, which are less widely used and considerably more complex than the one- or two-dimensional models. These different types of models are applied in various different circumstances in order to analyse different quantities. For the analysis of the spatial variation of velocities and flow complexities around large roughness elements, a one-dimensional model is not adequate; however, a two-dimensional model generally provides enough detail in these cases, provided that details of the flow complexity near the river bed are not required (Crowder and Diplas 2006; Shen and Diplas 2008; Harrison and Keller 2007;

Boavida et al. 2010; Stewart, Anderson, and Wohl 2005). In summary, a two-dimensional numerical model should be able to represent the main processes controlling the flow for a specific situation (Rodriguez et al. 2004).

Miller and Cluer (1998) used a two-dimensional numerical model to investigate the flow characteristics in a stream. They noted that boundary roughness or resistance is not as important as a determinant of flow conditions in a model's output as the specification of topographic detail is. A similar observation was made by Crowder and Diplas (2000), who mention that good bathymetry data is essential in obtaining the correct flow patterns in a model.

Harrison and Keller (2007) also investigated various river geometries using a numerical two-dimensional flow modelling program called River2D. They found that the velocity distribution in a river is more even when the flows are higher and fewer obstacles protrude through the flow. This seems to indicate a more even distribution when the obstacles do not have as significant an effect on the flow – i.e. when there is no local control present. They also found a high degree of variability in velocity distribution when complex topography was input into the model, which indicates that a two-dimensional description (whether this be statistical or, in as in this case, numerical) of the velocity when the topography becomes complex is essential.

Shields and Rigby (2005) also make an observation regarding the flow complexity and variation around obstacles. They mention, from running numerous numerical models of a river and obtaining certain habitat criteria (such as depth and velocity), that habitat criteria obtained vary much more with geometry than they do with discharge, which implies that geometry is important in creating a suitable habitat with enough variation to encourage a natural environment to form. This also means that geometry has to be very carefully modelled in order to ensure that the habitat is represented correctly by the numerical model (Legleiter et al. 2011).

Boavida et al (2010) modelled four different conditions in a two-dimensional numerical hydrodynamic model. The conditions they modelled were the natural state of the river, the river with 3 islands placed longitudinally, the river with two bays cut into opposite banks and the river with 4 alternating deflector triangles. They found that the islands had the most significant effect on the flow (they created the greatest diversity of depths) and were therefore a good option for improving flow conditions for habitats. This implies that obstacles that protrude from the flow are good for creating physical heterogeneity in the flow. This study did not take into account existing habitat conditions that may have affected the flow in the river.

Lee et al (2010) also ran various simulations using a two-dimensional hydrodynamic numerical model, with geometry that had a single boulder as well as multiple boulders as well as a contraction in the flow. They found that a single boulder did not significantly change the flow conditions around it, but multiple boulders had a more noticeable impact. The contraction, however, produced even better results than multiple boulders.

There has, however, been little investigation into the specific velocity distribution around large roughness elements when the flow becomes controlled by the large roughness elements.

2.3 Objectives of Current Research

The main objective of this research is to:

- Investigate the velocity distribution of flows around large roughness elements, especially when the large roughness elements control the flow

This will be done specifically by:

- Investigating various velocity distributions by changing the placement of two cylinders in a flume
- Investigating the extent of the effect that the cylinders have on the flow – i.e. the zone of influence of the cylinders – under various flow conditions

2.4 Limitations

The limitations to this research include:

- Only one case study was conducted – studying the effect of transverse spacing between two cylinders with a diameter equal to 0.11m. This case study was largely done with a numerical model of the flume in the civil engineering laboratory at the University of the Witwatersrand.
- The numerical models built had restrictions on the number of elements can be accommodated by the student version of RiverFLO-2D that was used for this research.

3 LABORATORY WORK

Laboratory experimentation was carried out to investigate the two-dimensional distribution of velocity at mid-depth around large roughness elements, which were simulated by cylinders in the flumes in the civil engineering laboratory. Two sets of experiments were carried out – pilot studies in the smaller Flume B and detailed experiments in the larger Flume C. These are described below.

3.1 Pilot studies – Flume B

3.1.1 Description of flume

Flume B is a recirculating flume that is 0.38m wide and 10m long. The discharge in the flume is controlled by valves at the flume head and is measured electronically with sensors that are situated in the inflow pipes of the flume. The discharge can also be measured using the V-notch weir located at the end of the flume.

The slope of Flume B is adjusted with a motorized jack that changes the height of the outlet. This height is measured at the flume outlet with a measuring tape that has the zero slope (i.e. when the flume's bed is level) marked clearly on it. The zero slope was checked by surveying the flume and ensuring that the inlet and outlet were at the same level.

There is a tailgate at the outlet of Flume B with a variable height that can be used to control the depth and velocity of the flow upstream. The tailgate was set to ensure either uniform flow or flow with a local control, depending on which was necessary.

The Manning's n coefficient of the flume is 0.010 ± 0.0015, which has been determined from studying uniform flow conditions in the flume and calibrating the data obtained. Details of this calibration procedure and the verification of the model used to represent the flume can be found in the Computer Modelling chapter. The Manning's n value is assumed to be the same for the floor of the flume and the walls of the flume.

3.1.2 Velocity measurement

In Flume B, the velocity was measured with a propeller velocimeter, which measures the velocity with a small propeller at the end of a probe. The velocity of the flow is measured by converting the propeller rotation from Hertz, or cycles per second, into a velocity in cm/s by using a conversion curve (this is provided with the equipment). The propeller is held in the flow by hand and can easily be moved to measure velocities anywhere in the flume. The reading of the propeller rotation in Hertz is displayed on the StreamFlo current amplifier shown in Figure 1 with the velocity probe and propeller.

Figure 1: Velocimeter probe with StreamFlo current amplifier that displays readings from the velocimeter in Hertz

The propeller measures the velocity in one direction at a time only and was only used to measure the longitudinal velocity in the flume at mid-depth of the flow. The velocity was measured at mid-depth as the flows were generally too shallow to allow for accurate measurement of the velocity at 0.4 times the depth.

3.1.3 Experiments conducted

In order to investigate the flow velocities around large roughness elements, two cylinders of either 0.11m diameter or 0.050m diameter, depending on the flume used, were put into the flume to simulate emergent rocks in a river. The flow velocities around the cylinders were then measured in order to determine the two-dimensional velocity distribution around the large roughness elements, as shown in Figure 2.

Figure 2: 2 cylinders (diameter = 0.11m) showing varying flow depth around them in flume B

In the pilot studies, three different flow cases were investigated: two different spacings of the cylinders, with two different slopes and different discharges. This was done so that at least one flow case was pseudouniform and at least one has a local control, as shown in Table 2.

Table 2: Geometries investigated during pilot study in Flume B

Experiment Number	Slope	Discharge (m^3/s)	Spacing between cylinders (m)	Type of flow
1	0.00020	0.00817	0.034	Pseudouniform
2	0.0020	0.00775	0.034	Local control
3	0.0020	0.00644	0.212	Local control

Velocity measurements were taken with the propeller velocimeter in a grid around the cylinders, with the measurements becoming fewer as the distance from the cylinder increased. The grid for measurement started as a roughly 50mm by 50mm grid for a length of flume of 300mm directly surrounding the cylinders, which then expanded to a grid spacing of roughly 200mm along the length of the flume, with 4 to 5 measurements across the 0.38m width of the flume. The total area of the measurements was 1.5m to 2m along the length of the flume, with the measurements stopping when the velocities measured across the flume and along the length from one section to another became very similar.

The velocities from these experiments were plotted as histograms and two-dimensional velocity plots using a combination of Excel spreadsheets and Matlab – the Excel spreadsheets were used to create the histograms and the same data were exported to Matlab to create the two-dimensional velocity contour plots. The data points for the histogram plots were sorted in Excel into regular grids of 100mm along the length of the flume and roughly 50mm across the width of the flume for 2.5m. Where the points did not fit exactly into the grid, they were averaged using the four closest points (upstream and downstream as well as across the width of the flume). The results of these plots are shown below.

3.1.3.1 Experiment number 1

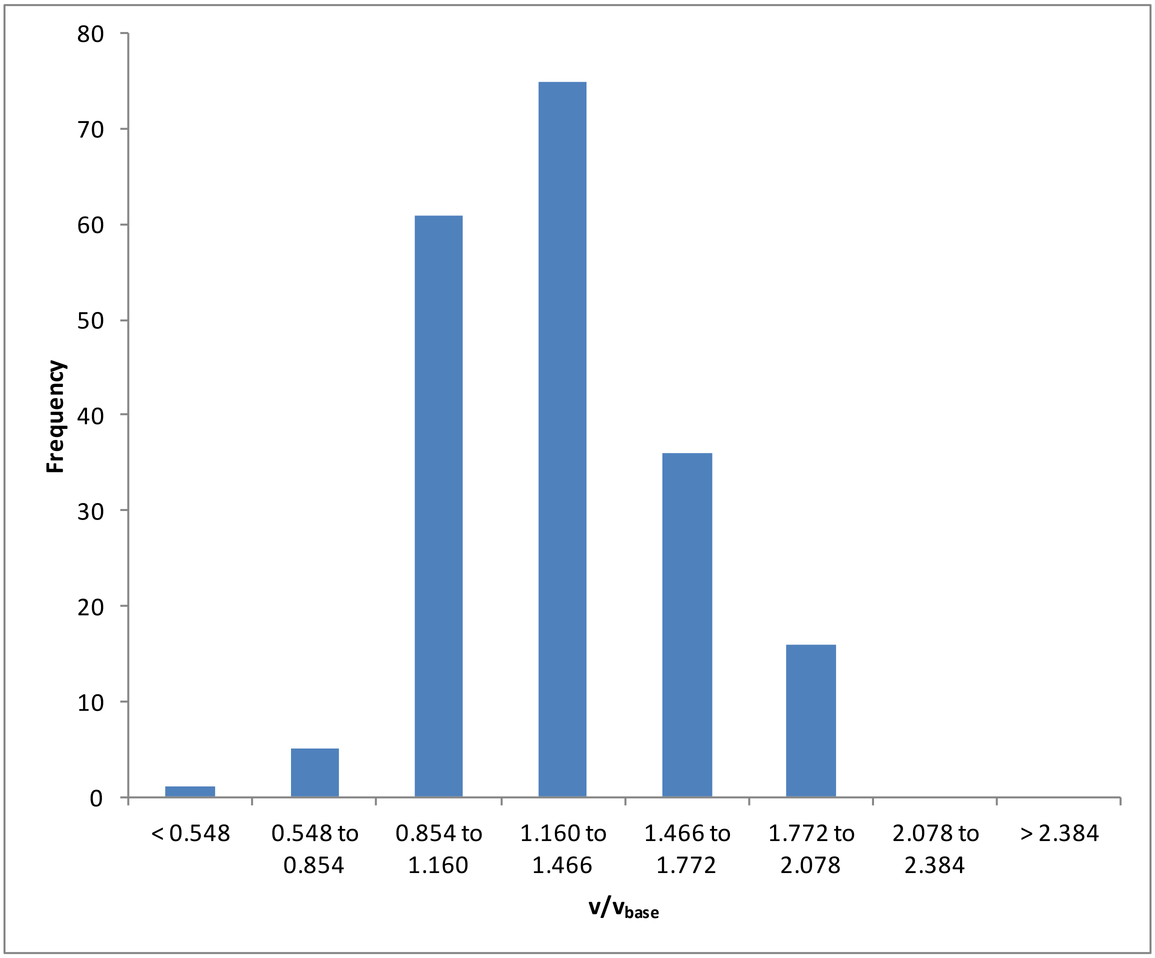

Figure 3: Histogram describing velocity distribution for experiment one

The histogram in Figure 3 shows the distribution of velocity over the area investigated – one metre upstream from the cylinders to 1.5m downstream from the cylinders. The velocity is in the form of v/v_{base} (where v is the velocity at a point and v_{base} is the uniform or base velocity of the flume for the experiment considered). Displaying the velocity like this gives an indication of the spread of velocities in terms of the uniform velocity, and thus the range of velocities in terms of the uniform velocity. Most of the velocities for this experiment are found around the base velocity of 0.268m/s. The velocities here exhibit a peaked distribution, with little skew either to the left or to the right, and the flow observed was pseudouniform – i.e. no velocities exceeded the critical velocity of 0.595m/s (v/v_{base} = 2.22). Localised patches of faster flow can be observed in the two-dimensional velocity plot in Figure 4, but most of the velocities are within the range of 0.20m/s to 0.50m/s. This is around the velocity associated with uniform flow in the flume for this slope and discharge, i.e 0.406m/s.

The zone of influence of the cylinders in this case is seen to be roughly 8 times the diameter of the cylinders and the range of velocities of the flow just upstream of the cylinders to just downstream of the cylinders is roughly 0.30m/s.

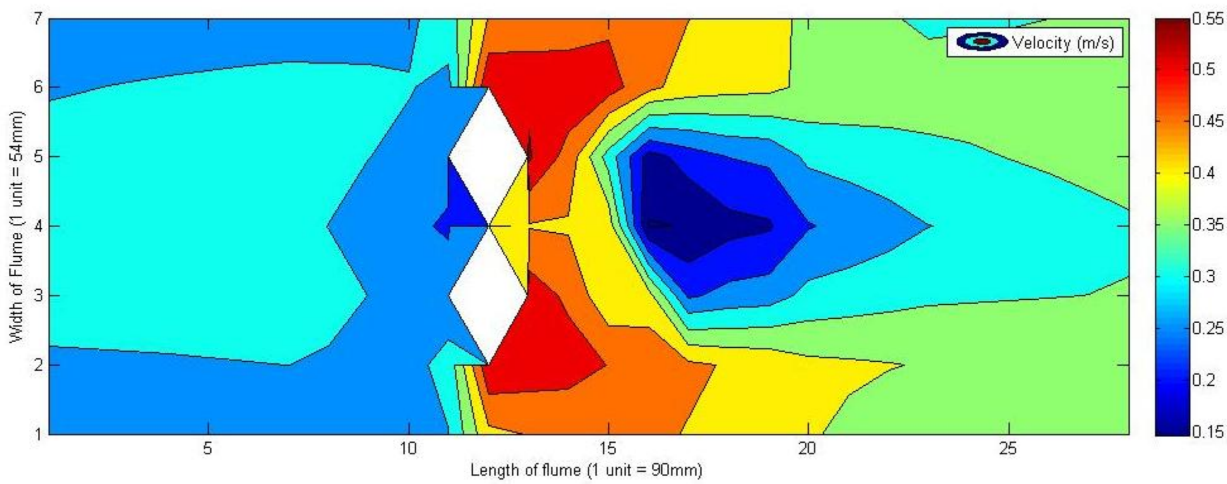

Figure 4: Two-dimensional velocity distribution for experiment one

3.1.3.2 Experiment number 2

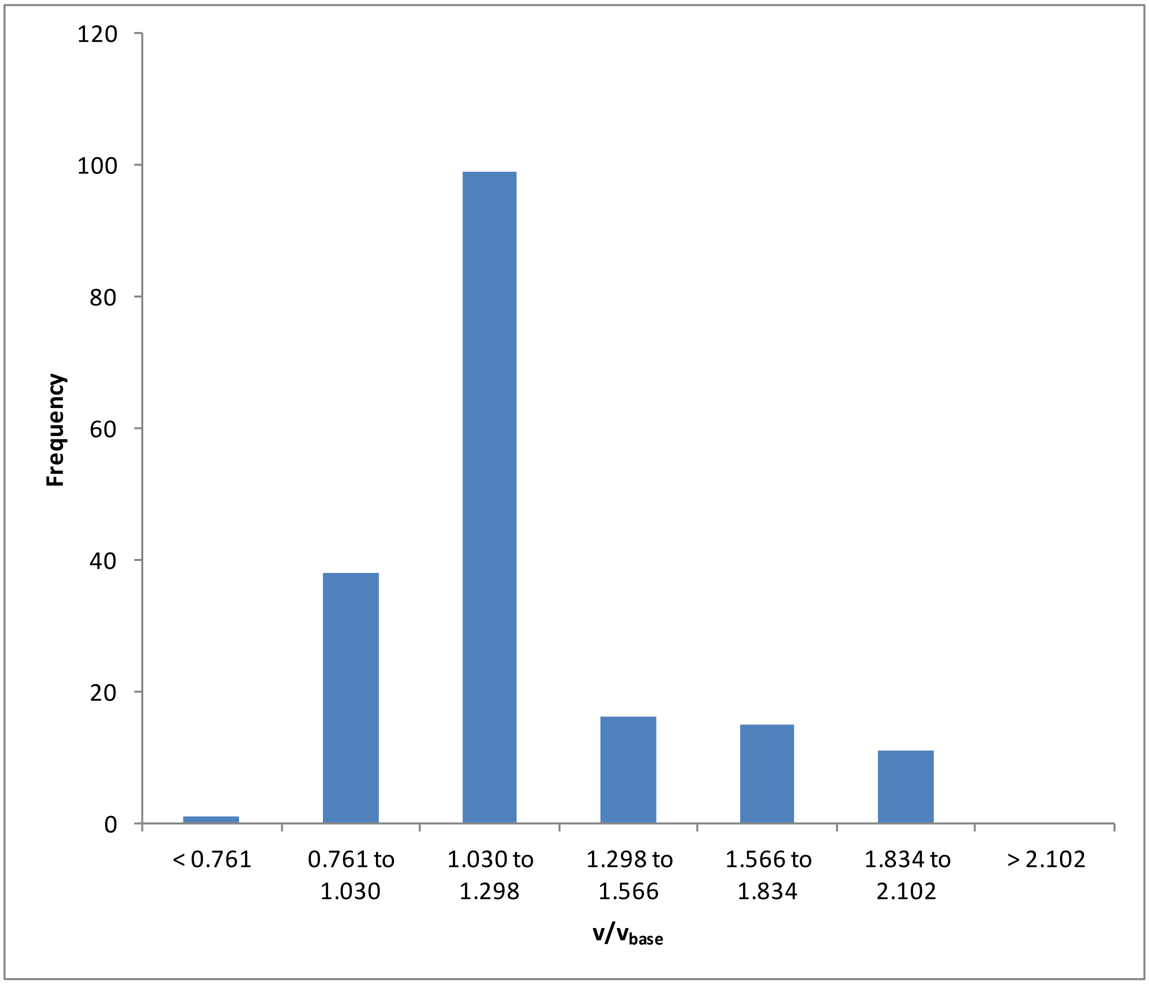

Figure 5: Histogram describing velocity distribution for experiment two

The histogram for experiment 2 in Figure 5 displays a different distribution of velocities than that of experiment 1, with a skew towards the lower ranges of velocities. Many of the velocities for this case are grouped around and just above the uniform flow velocity, which is 0.399m/s. The two-dimensional velocity plot for this case (Figure 6) shows a larger range of velocities than is displayed for experiment 1 – in this case the range of velocities is roughly 0.50m/s from just upstream of the cylinders to downstream of them, which is a 0.20m/s difference in velocity range. The flow type observed in this case was locally controlled as the velocities measured exceeded the critical velocity of 0.585m/s (v/v_{base} = 1.47). In this case there are, in fact, two local controls between the cylinders and the walls and not one local control in between the cylinders.

Also, the zone of influence of the cylinders is very slightly larger for this case than it is for experiment 1, with the zone being roughly 10 times the diameter of the cylinder, whereas the zone of influence was roughly 8 times the diameter of the cylinder for experiment 1. The change in zone of influence will be further investigated later in this report.

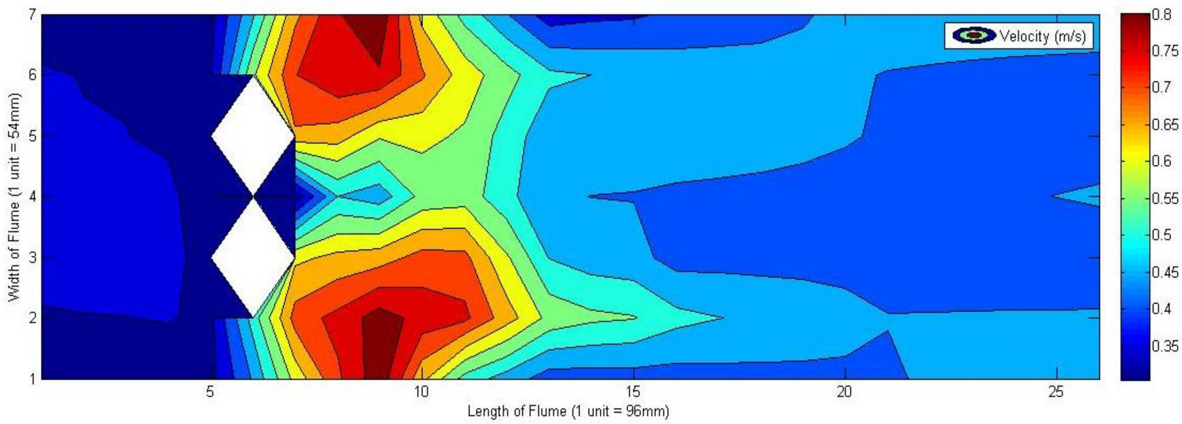

Figure 6:Two-dimensional velocity distribution for experiment 2

3.1.3.3 Experiment number 3

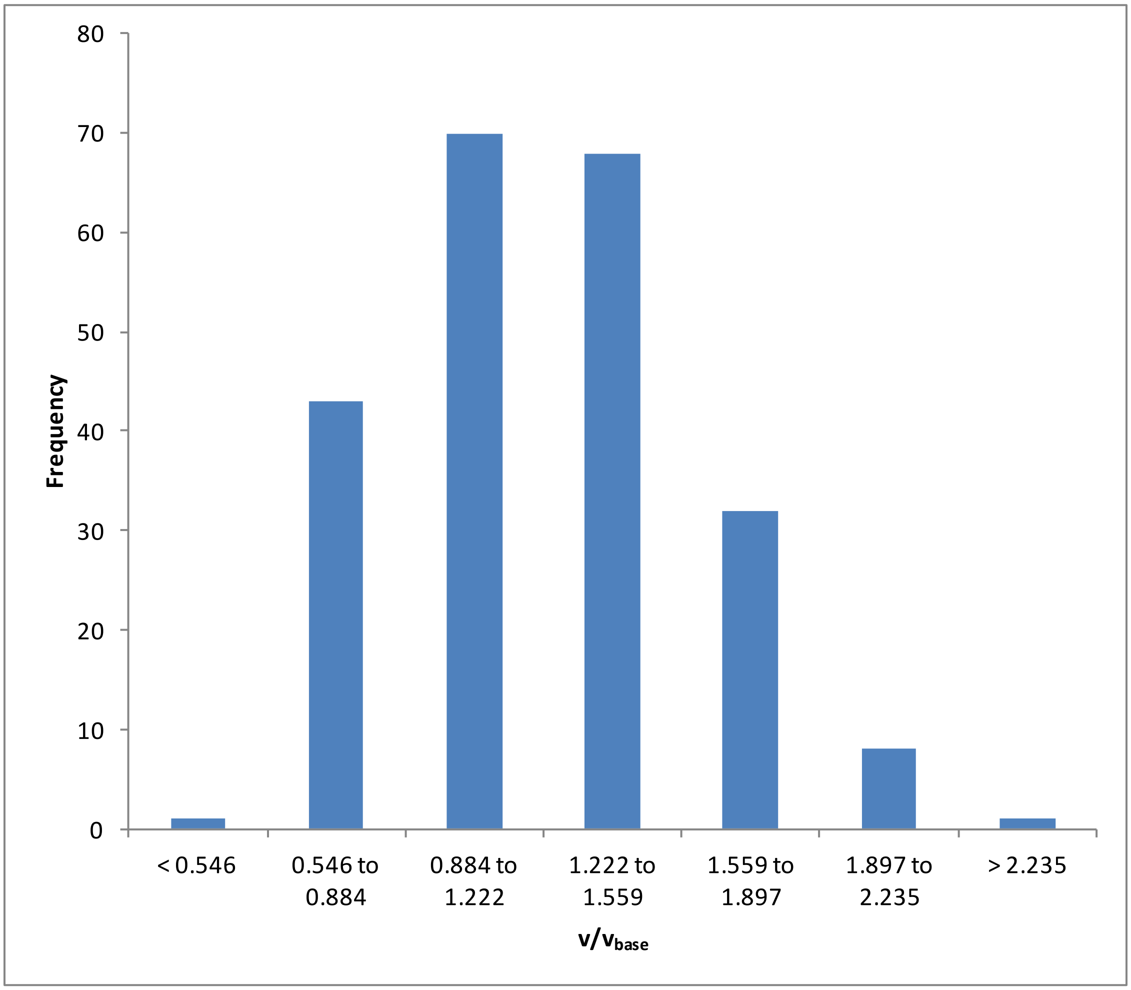

Figure 7: Histogram describing velocity distribution for experiment 3

Experiment 3 is another locally controlled case, with the measured velocities exceeding the critical velocity of 0.550m/s (v/v_{base} = 1.50). Here various similarities can be seen to experiment 2. Again, the histogram of this experiment is not a centrally peaked distribution (Figure 7), but is skewed towards the lower velocities and has many velocities around the uniform velocity for the slope and discharge in the flume, which is 0.367m/s. This histogram does, however display a more central peak than experiment 2's. This may be because experiment 3's flow is slightly more uniform in nature than experiment 2's flow. Another reason why this may be is because in this case there is only one local control, between the cylinders, and not two local controls as was the case in experiment 2.

The zone of influence of the cylinders, which can be seen in Figure 8, is roughly 12 times the diameter of the cylinder, indicating that there may not be a significant difference in the size of the zone of influence between more uniform flows and more locally controlled flows. However, this will be further investigated in later chapters. Interestingly, the range of velocities for this experiment upstream and downstream of the cylinders is about the same as that for experiment 2.

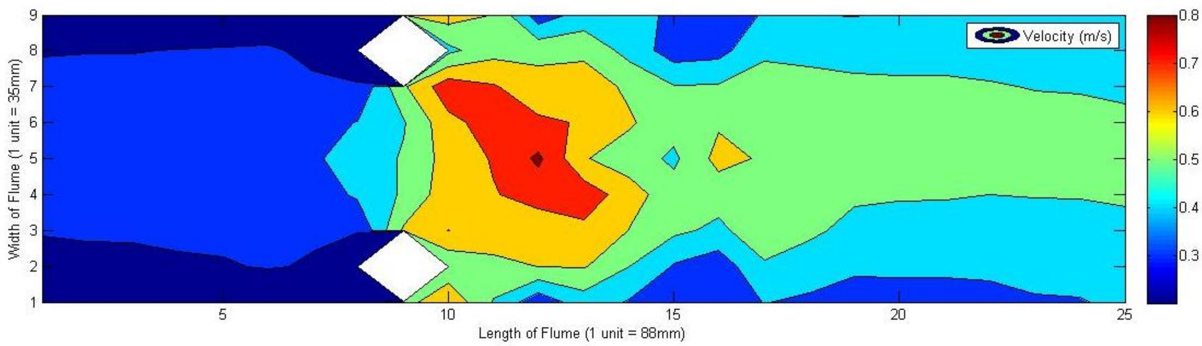

Figure 8: Two-dimensional velocity distribution for experiment 3

3.1.3.4 Discussion of experiments

From the above histograms and velocity plots, it can be seen that each histogram and velocity distribution is different, which implies that changing the geometry or discharge of a system changes the velocity distribution in that system and that a local control and pseudouniform flow each have a noticeably different effect on the velocity distribution. The differences in the histogram peaks may also indicate that there is more variation in velocity when a local control is present than when there is pseudouniform flow. This forms the basis of further investigation as there is sufficient difference in the histograms and velocity plots to justify further effort in investigating these differences.

Further laboratory experiments are described below and further investigation using numerical modelling is described in a later chapter.

3.2 Laboratory Experiments – Flume C

3.2.1 Description of flume

Flume C is a 2.0m wide by 10m long rectangular recirculating flume. The discharge in the flume can be adjusted using a valve that is connected to a header tank at the flume inlet. The discharge is measured using either the electronic meters connected in the flume's inlet pipe or by using the v-notch weir downstream of the flume. The flume has several piezometers installed to measure the depth of flow along its length. There are also measuring tapes along the length of the flume to measure depth.

There is a variable height tail gate at the outlet of the flume that can be used to control the depth and velocity of the flow in the flume.

The slope of the flume is changed using a manual jack. The flume then has to be surveyed in order to ensure that it is level across its width. The slope of the flume was set to 0.00050.

The Manning's n of the flume was found to be 0.010. This was calculated by running several uniform flows through the flume and then calibrating a computer model so that the flume measurements matched the numerical computer model. The model used for calibration of the Manning's n for this flume will be explained in greater detail in the Computer Modelling chapter.

3.2.2 Velocity measurement

The velocity of the flow in Flume C is measured with one of two velocimeters – either a 2D or a 3D Acoustic Doppler Velocimeter (ADV). In this research, the 3D ADV was used, which is shown in Figure 9. The ADV works by using the Doppler Effect to measure the velocity of the water flowing past it. The ADV sends out an acoustic signal at a certain frequency, using the arms shown in Figure 10, which is reflected off particles in the water back to the ADV. Depending on the frequency of the return signal, the ADV then determines the velocity of the water from the change in the sent and received frequencies. The 3D ADV measures the velocity in three directions – longitudinally, transverse and vertically. Only the longitudinal and transverse velocities were measured in this investigation in order to examine the difference in velocity distribution between the pseudouniform case and the locally controlled case. The velocities were measured at mid-depth in the flow (for the same reason as is given in the Flume B experiments).

The ADV takes velocity measurements instantaneously, and these measurements need to be averaged over a time in order to even out local fluctuations that the ADV may pick up in its velocity measurements, such as eddies in the flow. In this research, the velocities were averaged over one minute.

Figure 9: 3D ADV in Flume C

Figure 10: Head of the 3D ADV showing the arms that send and receive the frequency signals

The ADV is mounted on a railing that allows it to move across the width of the flume as well as up and down the length. The amount that the velocimeter moves can be monitored by a measuring tape along the length of the flume as well as a measuring tape that measures how far across the width of the flume the ADV is.

The ADV measures several values that help to ensure that the results obtained are valid. These values include the Signal to Noise Ratio (SNR), measured in decibels, and the correlation factor. It is recommended that the SNR be kept above 5dB for mean data collection and that the correlation factor be above 70 (Nortek 2004). In this research, the SNR was generally in the range of 13 to 20dB and the correlation factor was usually between 70 and 90.

The velocity of the flow was also verified by using the numerical model constructed of the flume. More detail on this verification can be found in the Computer Modelling chapter.

3.2.3 Experiments conducted

Three uniform flows with different discharges and no obstructions in the flume, and two different non-uniform flows with two cylinders, of 0.11m diameter, obstructing the flow were investigated in Flume C. One non-uniform flow was used to investigate the pseudouniform flow condition and the other was used to investigate a local control. These experiments are described below.

3.2.3.1 Uniform flow experiments

Three different uniform flows were measured in a clear flume. The velocity of the uniform flows was measured in a regular grid, with readings taken every 20cm across the entire width of the flume and every 30cm along the length for 1.5m. The characteristics of the three different flows are summarised in Table 3 below.

Table 3: Characteristics of uniform flows measured in Flume C

Experiment Number	Slope	Discharge (m^3/s)	Depth (m)
1	0.00050	0.0256	0.044
2	0.00050	0.0311	0.049
3	0.00050	0.0431	0.080

The uniform flow readings were used to calibrate the numerical model of the flume and determine the Manning's n of the flume, which was found to be 0.010±0.0015. The method of determining the Manning's n in this manner will be discussed in the Computer Modelling chapter.

A typical histogram (the histogram of experiment one from Table 3) is included in Figure 11 to show the distribution of velocities for a uniform flow case.

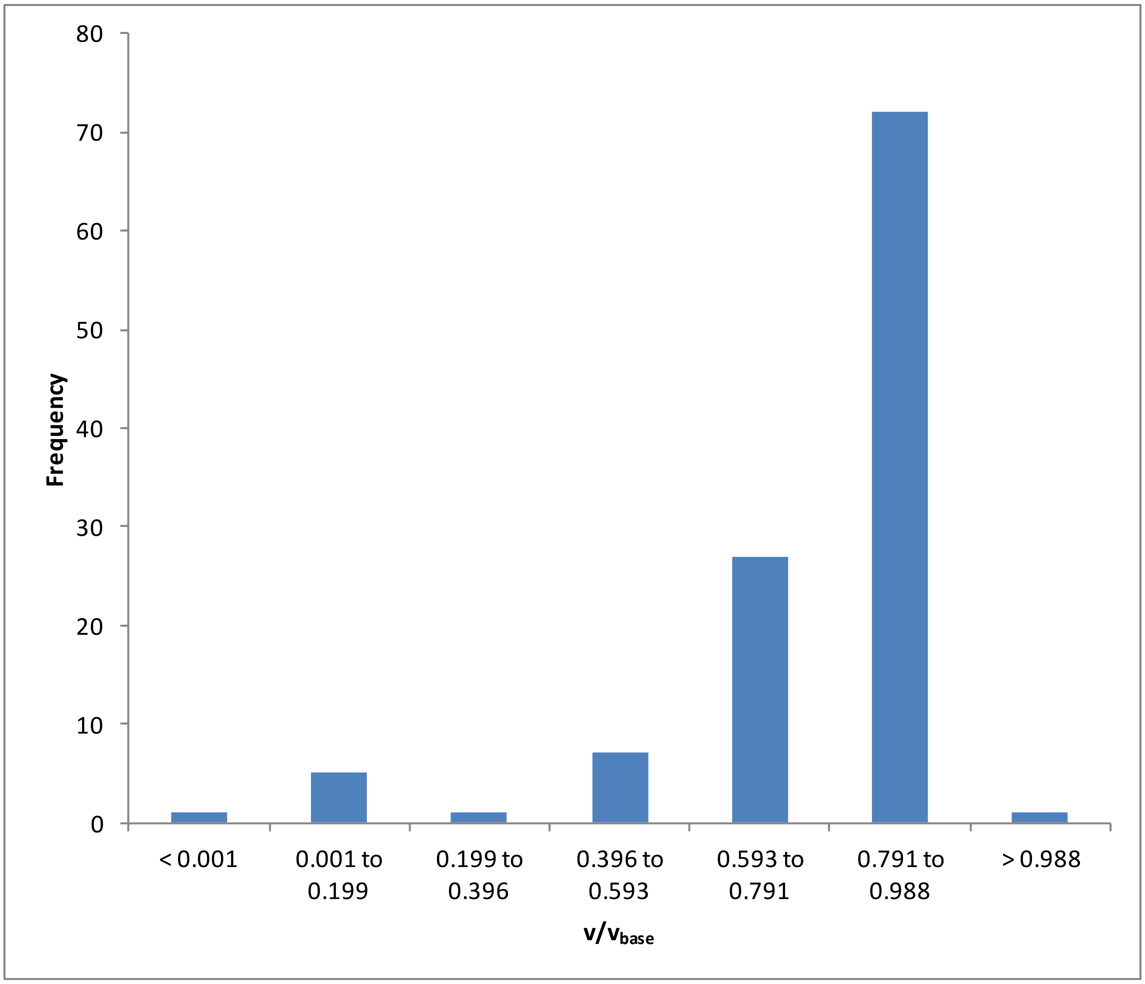

Figure 11: Histogram showing velocity distribution of uniform flow experiment one in Flume C

3.2.3.2 Non-uniform flow experiments

Two different non-uniform flow geometries were investigated – a pseudouniform case and a locally controlled case. These cases involved investigating the velocities of flows around two cylinders placed in the flow. The velocity for the non-uniform flows was measured in a regular 2.0cmx2.0cm grid for 1.0m along the length of the flume and across 1.0m of the width. The geometries investigated are summarised in Table 4.

Table 4: Characteristics of non-uniform flows measured in Flume C

Experiment Number	Slope	Discharge (m^3/s)	Spacing between cylinders (m)
1	0.00050	0.0247	0.232
2	0.00050	0.0490	0.020

The velocity readings from the ADV were collected by the companion software and the results were then converted into an Excel file for further processing. Each velocity measurement was taken as an average of instantaneous velocity measurements for at least 30 seconds. The data were then plotted using Excel and Matlab to produce histograms and two-dimensional velocity plots. These are shown below.

3.2.3.2.1 Pseudouniform case

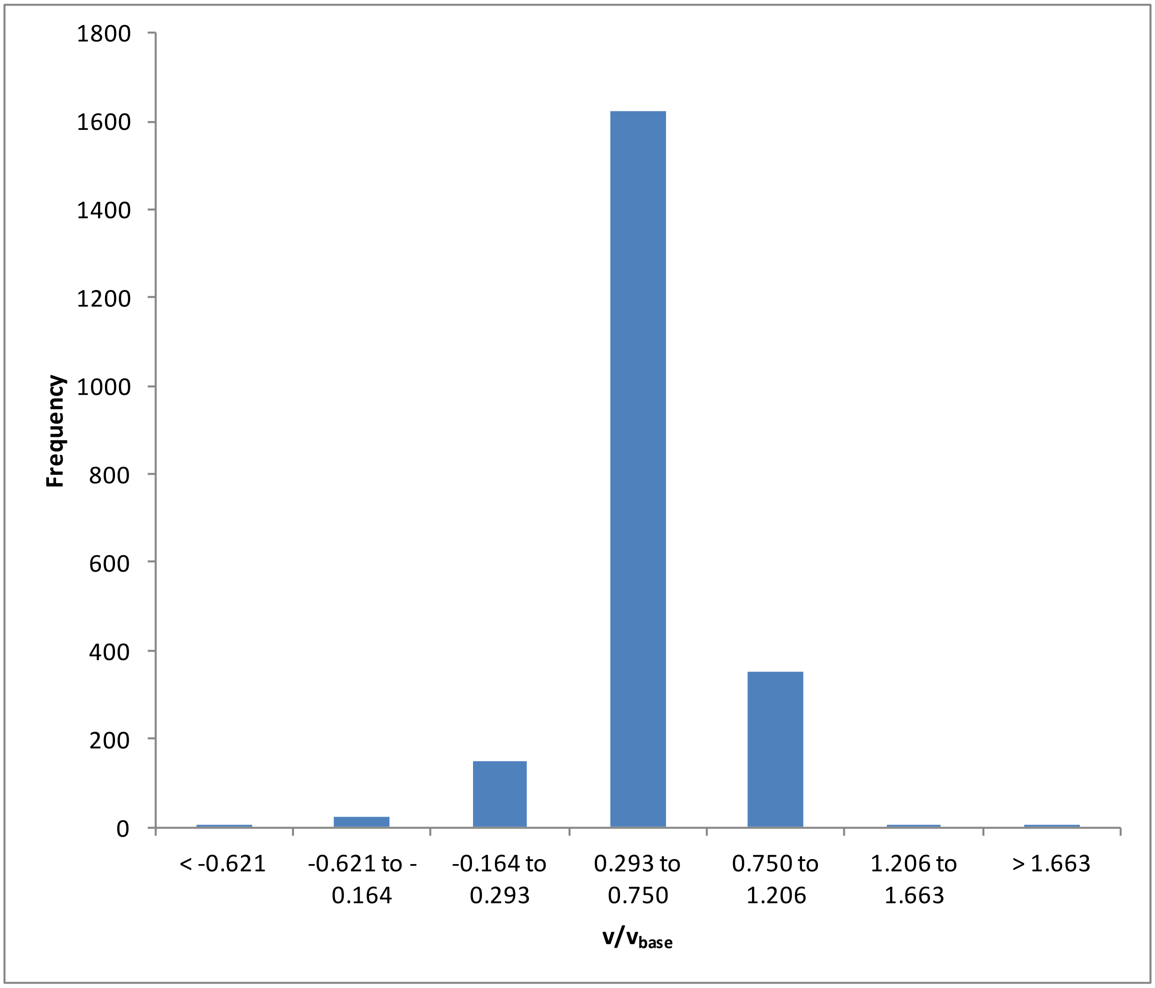

Figure 12: Histogram showing distribution of velocities in pseudouniform flow

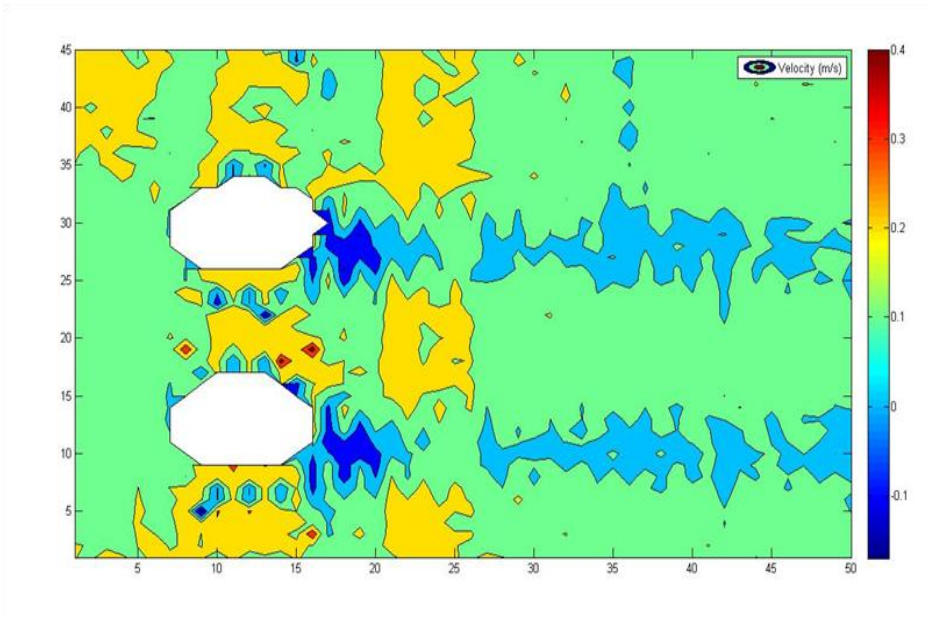

Figure 13: Velocity distribution of flows around cylinders for pseudouniform flow case (over an area of 1m wide by 1m long)

The histogram for the pseudouniform flow case in Figure 12 shows a very peaked distribution of velocities and the two-dimensional velocity plot in Figure 13 shows the distribution of velocities around the cylinders. The zone of influence for this case is roughly twice the cylinder diameter, with residual effects extending down the length of the flume. This will be discussed in further detail in later chapters.

The range of velocity from just upstream of the cylinder to just downstream is roughly 0.10m/s. The negative velocities just downstream of the cylinders are caused by the turbulence that is generated by the cylinders.

The variance of the velocity for this case is 0.00349 and the standard deviation of the velocity is 0.059.

3.2.3.2.2 Locally controlled case

This flow case is locally controlled and there is a noticeable variation in the depth of the flow around the cylinders.

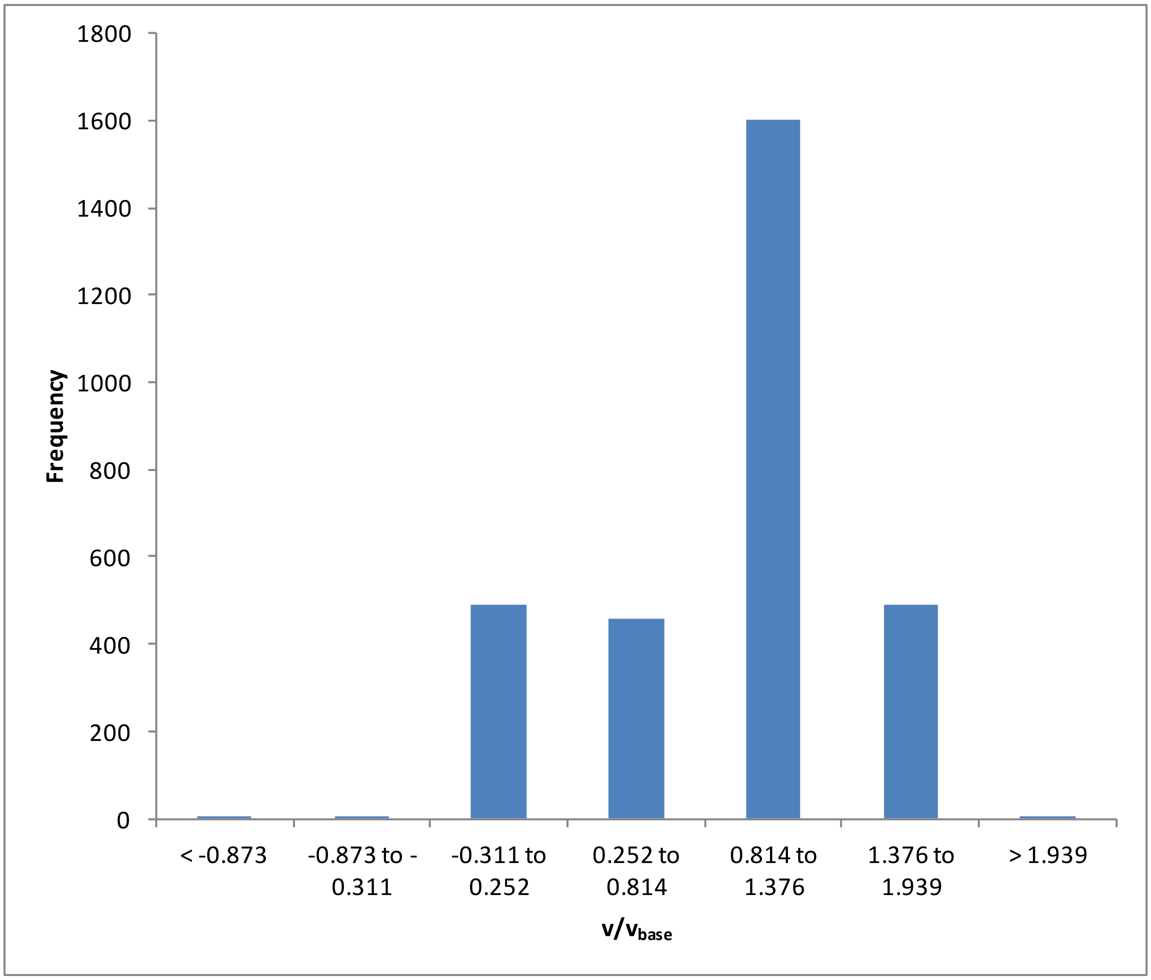

Figure 14: Histogram showing the velocity distribution for the locally controlled case

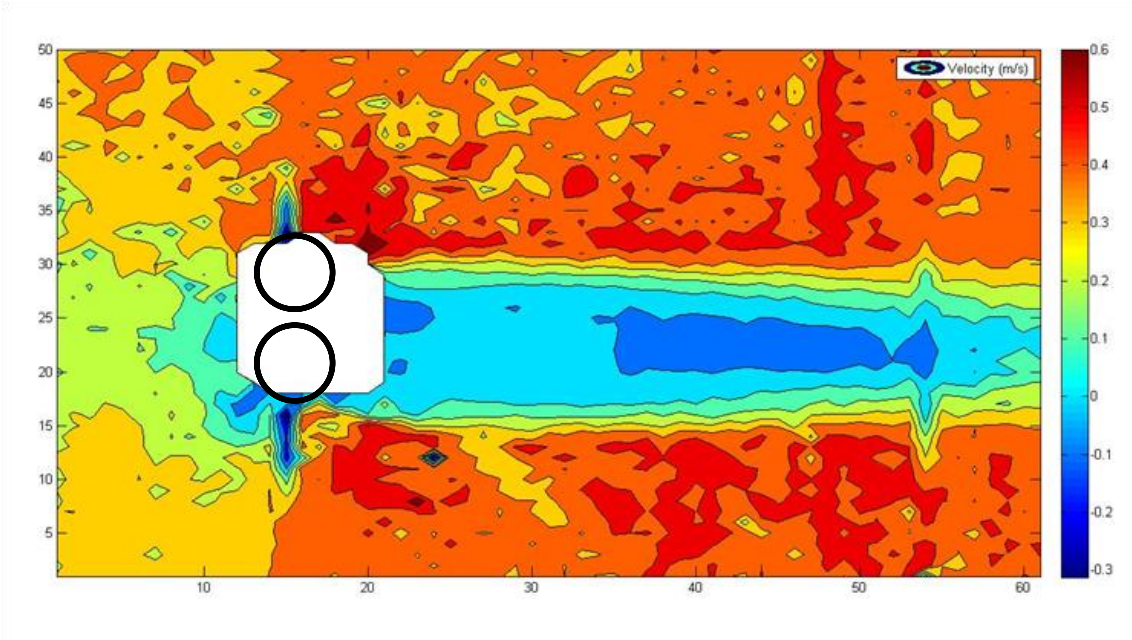

Figure 15: Velocity distribution for the locally controlled case (two cylinders show in black in above figure)

The histogram for this case (Figure 14) is much less centrally peaked than the histogram shown for the pseudouniform case. It has a skew towards the higher velocities that were recorded. The two-dimensional velocity distribution plot in Figure 15 shows that the effect of the cylinders extends further than it does for the pseudouniform case. It should be noted that there are still two cylinders that were used in this experiment, but because of their proximity they are plotted as one by Matlab (the cylinders have been represented as black rings in the white region of the Matlab plot). The critical velocity for this case is 0.622m/s (v/v_{base} = 1.737).

The zone of influence of the cylinders in this case is roughly five times the diameter of the cylinders and is much more pronounced than that of the pseudouniform flow. The range of velocities upstream and downstream of the cylinders (the extent as shown in Figure 15) is roughly 0.30m/s. There is a fair amount of turbulence just next to the cylinders as this is where the flow appears to transition from subcritical to supercritical, which induces some turbulence.

The standard deviation of velocity of this case is 0.167, while the variance of the velocity is 0.0280, which is 8 times more than the variance for the pseudouniform case. This indicates that there is a much greater variation in velocity when there is a local control present. This will be explored in greater detail in the next chapter.

3.2.3.3 Effect of grid size change on resolution of results

As part of the experimental investigation in this research, the effect of the measurement grid size on the resolution of the velocity result plots was looked into. The size of the grid used to take velocity measurements in the flume, as mentioned previously, was a 2.0cm by 2.0cm grid. The results were also investigated using a 4.0cm by 4.0cm grid and an 8.0cm by 8.0cm grid. The results of these investigations are shown in Figure 16 and Figure 17.

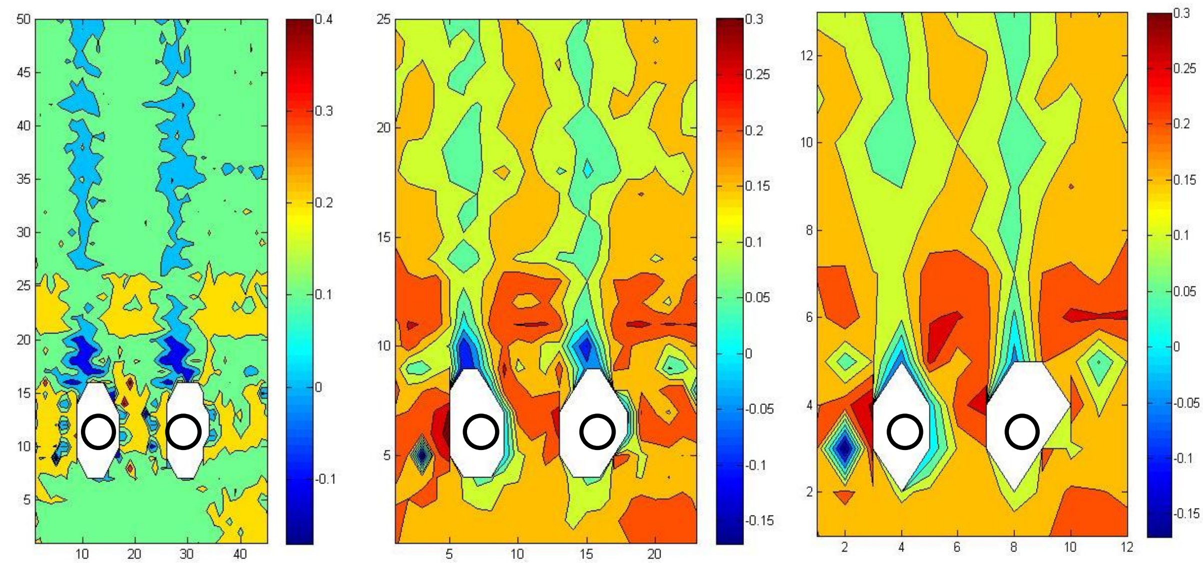

Figure 16: Velocity contours for pseudouniform case showing 2.0cmx2.0cm grid on the left, 4.0cmx4.0cm grid in the middle and 8.0cmx8.0cm grid on the right

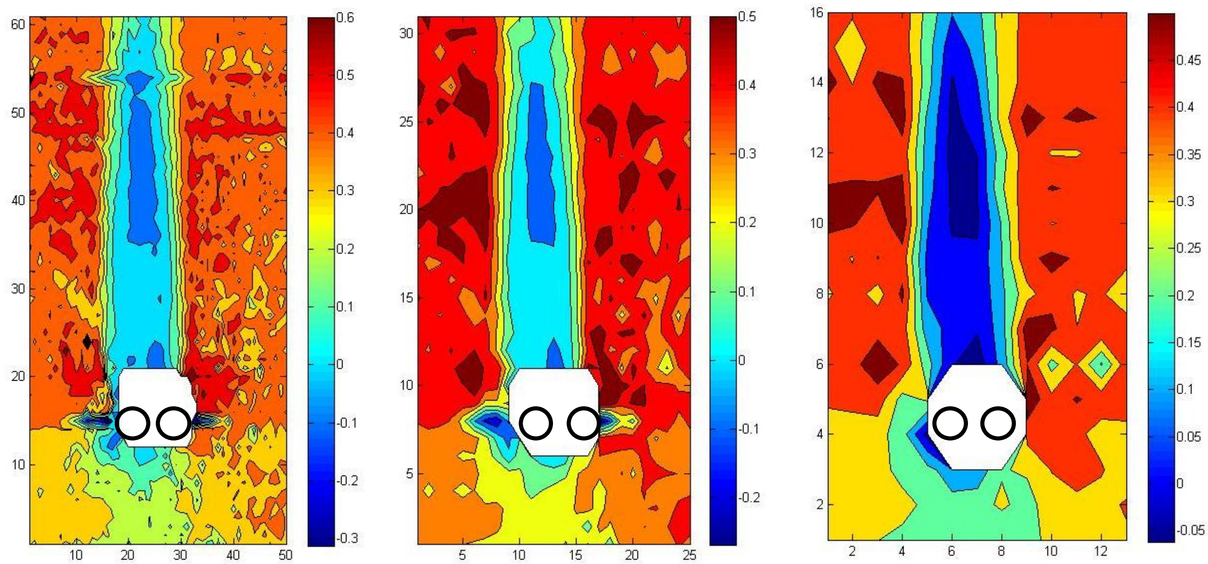

Figure 17: Velocity contours for the partially locally controlled case, showing 2.0cmx2.0cm grid on the left, 4.0cmx4.0cm grid in the middle and 8.0cmx8.0cm grid on the right

As can be seen from these figures, the 2.0cm by 2.0cm measurement grid shows much greater detail in the velocity variation, especially around the area of the cylinders. In the pseudouniform case, the highest velocities are captured by this grid between the two cylinders and these are shown on the velocity contour plot. These high velocities are not captured in the 4.0cm by 4.0cm grid, although the variation of the velocities is still shown downstream of the cylinders, which is shown less by the 8.0cm by 8.0cm grid of measurements. The more uniform velocities at the upstream extent of the measurements and the downstream end of the measurements are still the same, as the flow is much more uniform at these sections.

In the locally controlled case, the same pattern emerges even more markedly. The detail in the variation of velocity around the cylinders is shown well with the 2.0cm by 2.0cm grid, but some of this detail is lost with the 4.0cm by 4.0cm grid and much of it is lost when the 8.0cm by 8.0cm grid is used. The more uniform sections of flow (at the upstream and downstream extents of the measurement) are still represented fairly well by all three grid sizes.

It is also interesting to note that as the grid size gets larger, the extreme velocities are not represented on the velocity contour plots for both the pseudouniform case and the locally controlled case. This may be explained by the fact that these extreme low and high velocities will be found in the area surrounding the cylinders, which is not well represented by the larger grid sizes and thus these values of velocity are missing from the 4.0cm by 4.0cm grid and the 8.0cm by 8.0cm grid plots.

From the above discussion, it can be seen that the size of grid that is used for measurement of velocity depends on the detail necessary in the subsequent evaluation of the velocities measured and what the purpose of measuring the velocities is. It may be advisable to use a smaller grid size when measuring in the area directly affected by the cylinders (or obstructions, more generally) – i.e. an area of roughly one or two obstruction-diameters away from the obstructions and then use a coarser grid for measurements that are further from the obstacles or area of interest.

3.2.3.4 Discussion of geometry cases

The locally controlled case investigated above has a greater effect on the flow than the pseudouniform flow case. This makes sense as the local control will force a greater variation in the velocities and therefore will have a greater influence on the flow. The histogram shows a non-uniform distribution and a visibly different distribution to that of the pseudouniform case. The conclusion that can be drawn from this is that because the histogram of the locally controlled case has velocities spread more evenly over the entire range of velocities than the pseudouniform case does, there is a greater variation in the velocities in the locally controlled case than there is in the pseudouniform case.

Further investigation into the variation of velocity with flow case will be conducted in a computer program called RiverFLO-2D in order to numerically model the flume and thereby investigate many more cases than would be possible in the laboratory. These investigations will be discussed in the Computer Modelling chapter and the Results and Discussion chapters that follow. It is hypothesised that the greater variation of velocity will become more noticeable when a local control is formed. This will be investigated specifically.

4 COMPUTER MODELLING

Once the laboratory work was completed, the numerical computer modelling was started. The computer modelling was done in a program called RiverFLO-2D, which is capable of analysing the flow in rivers in two dimensions, and Argus ONE, which is a pre- and post-processing program for RiverFLO-2D (Argus-Interware 1997; FLO-2D 2009).

4.1 RiverFLO-2D and Argus ONE

RiverFLO-2D is a computer program that is specifically developed for the analysis of rivers. It uses the shallow water equations (or Saint Venant equations) for depth-averaged flow to compute various output variables, such as velocity, water surface elevation and Froude number, from input including the geometry of the system, and boundary conditions such as discharge and water depth.

The shallow water equations are solved by dividing the solution domain up into finite elements by applying the Galerkin weighted residual method, which breaks a continuous problem up into discrete units. This method takes a continuous problem, such as the geometry of a river or the flume, and divides it into discrete elements, in this case 3-noded triangular finite elements. This allows a continuous problem to be solved discretely with numerical methods.

Argus ONE is the pre- and post-processing software that RiverFLO-2D uses. This software makes the generation of geometry and other input parameters for RiverFLO-2D simple as well as easy to check.

The geometry input into Argus ONE is usually a domain that can be imported as a set of nodes with x, y and z values (a position on a two-dimensional Cartesian plane with a corresponding elevation). The node positions can be imported directly into Argus ONE from a text file, which is easily generated using Excel. These points can then be meshed automatically by Argus ONE to create a solution domain that can then be assigned input parameters for RiverFLO-2D such as discharge or water surface elevations. The automatic mesh generation in Argus ONE is performed by using a Delaunay triangulation algorithm, which generates a triangular mesh while avoiding skinny triangles, which can compromise the validity of the triangular mesh.

The mesh generated by Argus ONE can be specified to have different densities in different portions of the solution domain and therefore a higher solution resolution can be obtained and therefore greater confidence in the results.

The velocity results that will be compared to experimentation for model validation are the longitudinal and transverse velocities, not the total magnitude of the velocity.

For the purposes of this research, the Student Version of Argus ONE was used, which is limited to 2000 elements. This was adequate for the purposes of this report; however any finer mesh would require a greater number of elements.

4.2 Models Created

Various models were created for runs in RiverFLO-2D, including models for verification of the model itself, verification of the laboratory work and investigation into flow velocity distributions. These will be described below.

All models that were created used the boundary conditions of an inlet discharge in m^3/s and an outlet water surface elevation in m. A first check performed for all models was that the input and output discharges were equal. This was the case for all models run. The discharge and fixed water surface elevation at the outlet were input into the model as text files and the Manning's n for each case is input using graphical methods.

All models created were of Flume C in the civil engineering laboratory and are therefore 10m long by 2.0m wide.

4.2.1 Model verification

Various different sizes of finite element mesh were investigated in order to ensure that the model run in RiverFLO-2D would produce reliable results. Two geometry cases were tested – a clear flume and a flume with two cylinders in the middle of the flume, 0.50m apart. Several different mesh sizes were run for each of the two geometries, while all other variables (such as discharge and water surface elevation at the outlet) were kept constant for the runs.

For the clear flume, the mesh densities tested ranged from 1.0 to 0.2. This means that the average element size of the mesh ranged from 1.0m to 0.2m. An example of these meshes is shown in Figure 18, which shows the finest mesh investigated (0.2m) and the coarsest mesh investigated (1.0m). Other meshes investigated ranged between these two values.

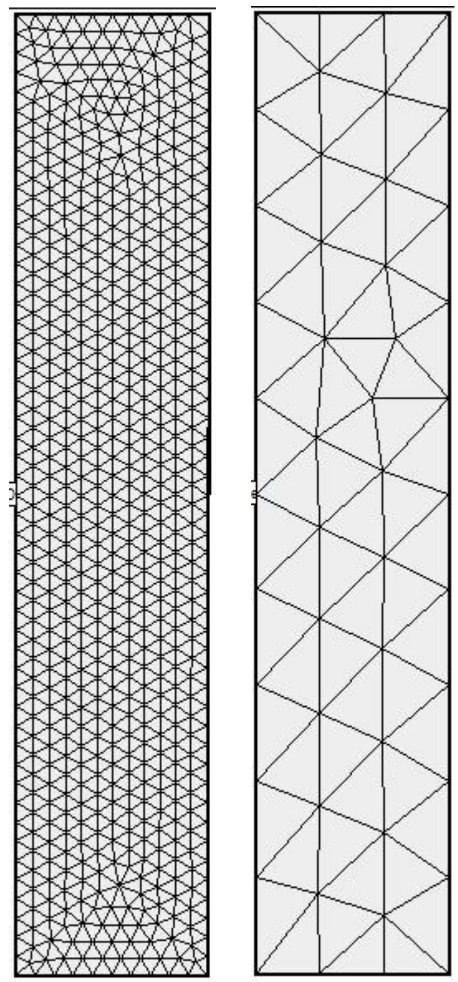

Figure 18: Two different meshes used for mesh convergence study in clear flume

The values of velocity were compared for the different resolutions of mesh and it was found that the difference between the highest velocity and the lowest velocity was 0.8% (this is velocity at the same point with the different meshes). Therefore the model was shown to be very robust, as the velocities obtained compared very favourably with theory (as is shown in the following section).

Because the different meshes in the clear flume gave such similar results, another geometry configuration was investigated for mesh sensitivity. This geometry was the same as would be used for further velocity distribution investigation – i.e. the flume with two cylinders positioned halfway along the flume. The cylinders in this case were chosen to have a spacing of 0.50m between them.

In this case, a coarse mesh was used to model most of the flume bed and a finer mesh was used around the cylinders, as a small grid is required around flow obstructions to obtain meaningful results from a model (Shields and Rigby 2005). To study the sensitivity, several different densities were used for both the fine and coarser meshes. The densities used for the fine mesh ranged from 0.030 to 0.50, while the densities for the coarse mesh ranged from 0.20 to 1.0. The finest mesh and the coarsest mesh tested are shown in Figure 19.

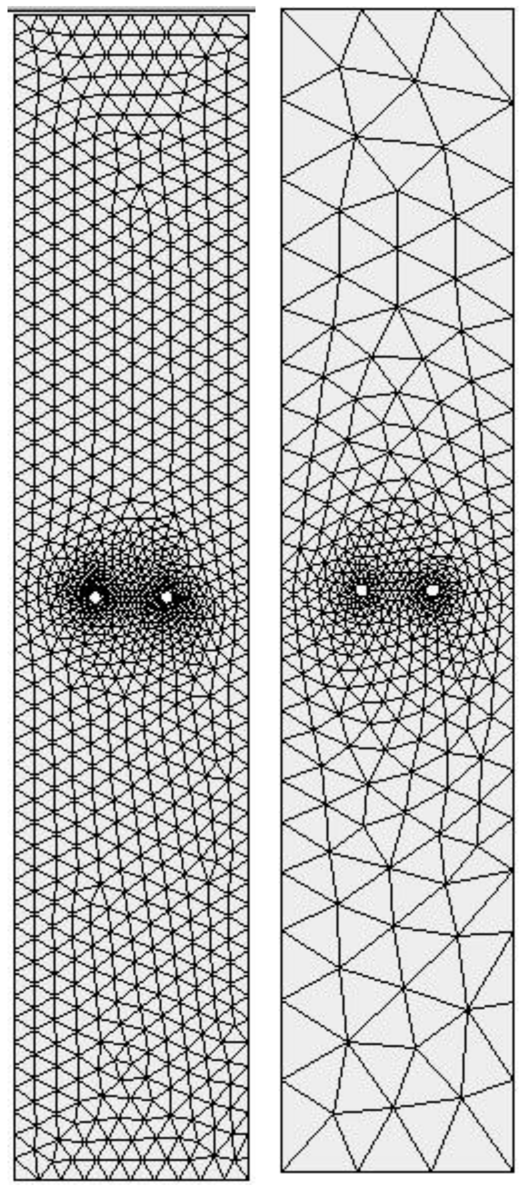

Figure 19: Two different meshes used for convergence study in flume with two cylinders

The maximum velocity values were compared from these two models and the difference between the highest velocity and the lowest velocity was found to be 5.0% (this is the velocity at the same point in the flume with different mesh densities). Because this difference is very low and the velocities obtained from these models is very close to the theoretical values (as is shown in the next section), these models may be used reliably to represent the flows in the flume.

Because no particular mesh size was shown to be more reliable than another mesh size, the mesh density was chosen based on a mesh that was able to represent the desired geometry (i.e. the pair of cylinders in the flume) visually satisfactorily – i.e. so that the cylinders appear to be round – and so that the model run time was reasonable (a finer mesh will take longer to run than a courser mesh).

4.2.2 Verification of laboratory work

Three uniform flows and two non-uniform flows were analysed in Flume C in order to verify that the computer model generated by RiverFLO-2D would dependably represent the flow conditions in this flume and therefore give reliable results for further investigations.

4.2.2.1 Uniform flows

The measured characteristics of the three uniform flows in Flume C are shown in Table 3. These three flows were modelled using Argus ONE and RiverFLO-2D. The velocities obtained from these models were compared with simple hydraulic theory (i.e. obtaining velocity using the relationship between discharge, the area of the flow and the velocity of the flow) and with laboratory work to ensure that the velocities obtained were sufficiently close to each other to be confident that the computer model's results were reliably representing theory and the laboratory situations for the purposes of this research.

The models of the uniform flows in RiverFLO-2D were calibrated by running each flow with various different Manning's n values until a value was found that simulated the flume conditions satisfactorily. This was checked by changing the Manning's n until a uniform depth and velocity were achieved throughout the model. From this calibration procedure, the Manning's n for the flume was found to be 0.010 ± 0.0015.

The velocity results from the laboratory work, theory and RiverFLO-2D are summarised in Table 5.

Table 5: Velocity results for model verification

Experiment Number	Discharge (m^3/s)	Velocity - Laboratory Work (m/s)	Velocity - Theory (m/s)	Velocity - RiverFLO-2D (m/s)
1	0.0256	0.286	0.291	0.290
2	0.0311	0.273	0.317	0.315
3	0.0431	0.288	0.269	0.275

These results were then compared against each other, the results of which are shown in Table 6.

Table 6: Comparison of different velocity results

Experiment Number	% Difference between Laboratory and Theory Results	% Difference between Laboratory and RiverFLO-2D Results	% Difference between Theory and RiverFLO-2D Results
1	-1.72	-1.38	0.34
2	-13.88	-13.33	0.63
3	7.06	4.73	-2.18

As can be seen from Table 5 and Table 6, the largest difference in velocities is between the measured velocity in the flume for uniform flow case 2, which is a difference of just under 14%. There is less difference between the theory and the RiverFLO-2D results than between those results and the laboratory results. This may be because the theory and RiverFLO-2D results were calculated in similar ways, whereas the laboratory results may have been influenced by laboratory conditions or slight variations in the flow of the flume, which would not affect the theoretical results.

The depth and discharge results may be slightly more accurate than the velocity measurements, which would explain why the theoretical results agree more fully with each other than the laboratory results do.

However, these differences are still acceptable, especially considering that all other results are within 10% of each other and the largest difference between RiverFLO-2D and the theoretical results was under 3%. Therefore we can be confident that the velocity fields will be represented reliably by RiverFLO-2D.

4.2.2.2 Non-uniform flows

In order to ensure that the two-dimensional velocity distribution around large roughness elements was sufficiently well represented by RiverFLO-2D, two non-uniform flows were run in Flume C and their longitudinal velocities measured in detail. The characteristics of these flows are shown in Table 4. A comparison of the two-dimensional longitudinal velocity distribution obtained from both the flume and RiverFLO-2D for both the pseudouniform and the locally controlled flows are shown in Figure 20 and Figure 21.

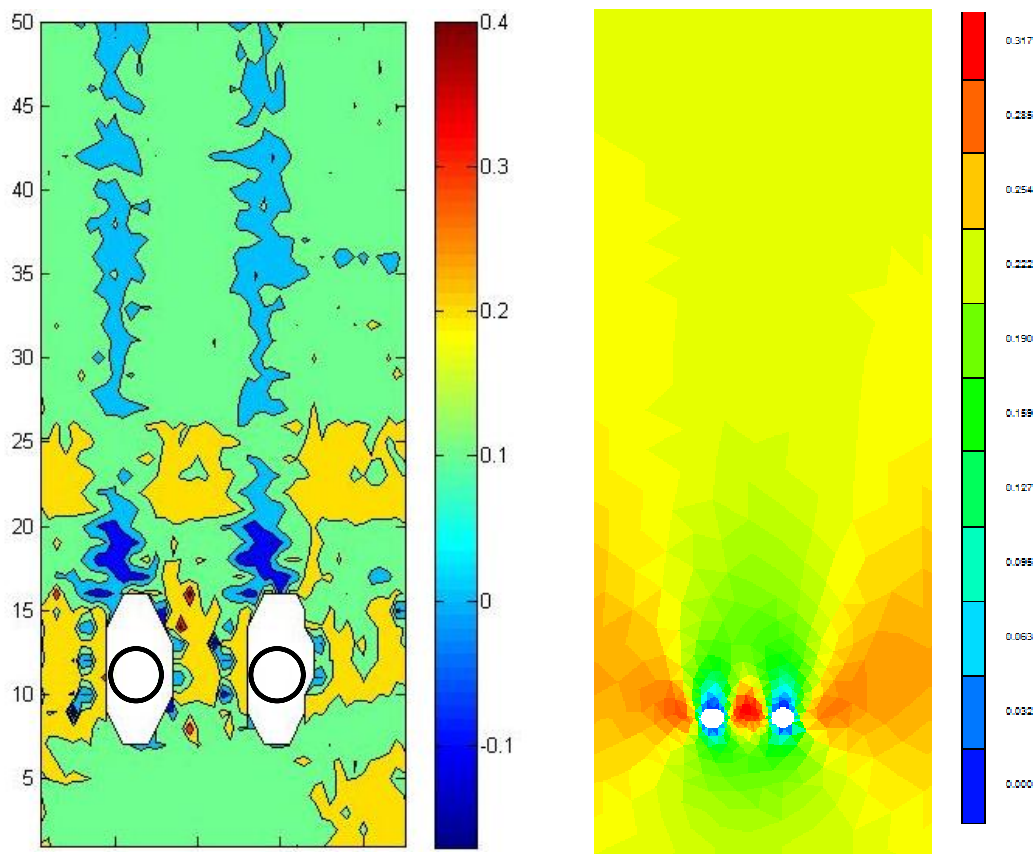

Figure 20: Two-dimensional longitudinal velocity contour plots showing pseudouniform velocity distribution from Flume C (on the left) and results from RiverFLO-2D (on the right)

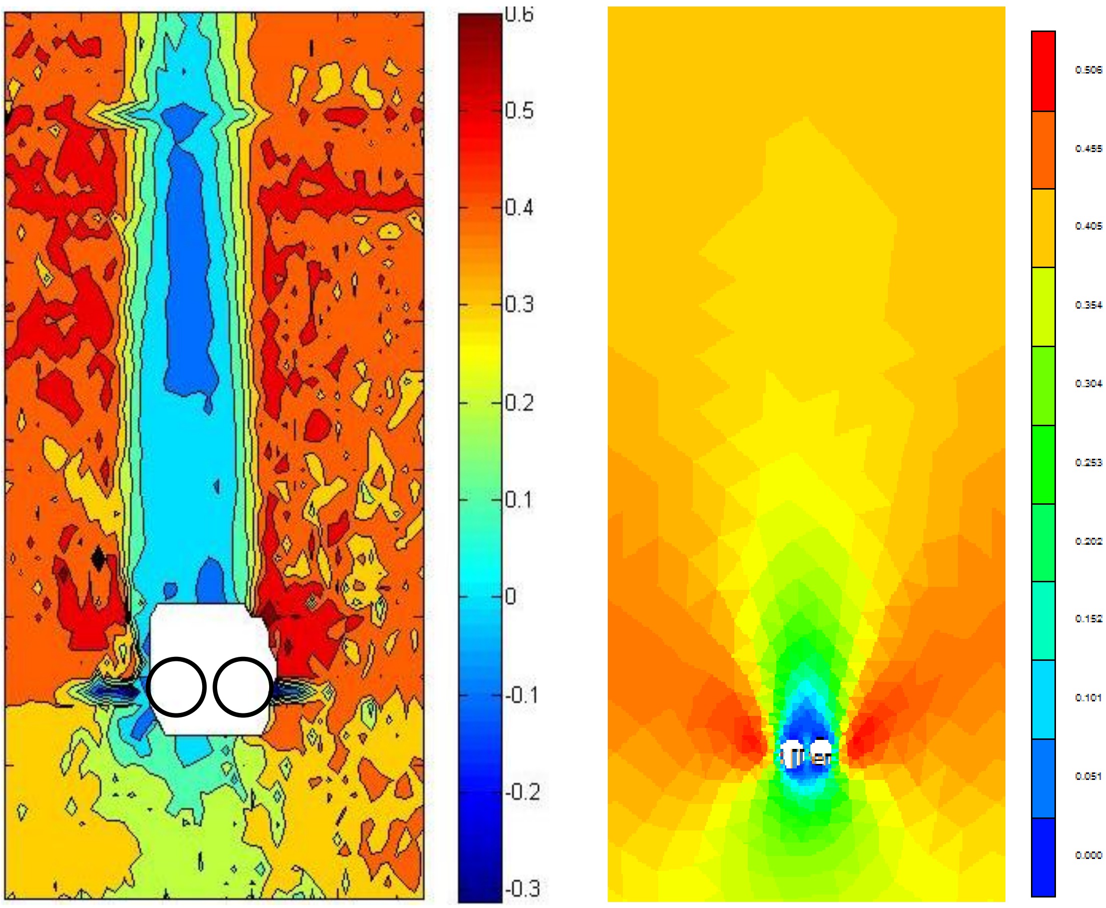

Figure 21: Two-dimensional longitudinal velocity contour plots showing local control velocity distribution from Flume C (on the left) and from RiverFLO-2D (on the right)

As can be seen from inspection of the above figures, the distributions of velocities are very similar for the laboratory case and the case simulated by RiverFLO-2D. The velocity patterns look slightly different because the laboratory plots are shown on a larger scale than the modelled plots, but the general patterns and forms of the velocity distributions are the same. As well as this, the maximum velocity through the centre of the cylinders is very similar for the pseudouniform case (roughly 0.32m/s in both cases) and the maximum velocity next to the cylinders for the local control case is roughly 0.55m/s for both the laboratory case and the modelled case. Also, the general velocity for both geometry cases is similar for the laboratory case and the computer modelled case.

It should be noted that the cylinders for the laboratory cases plot as larger than their actual size because the ADV could measure no closer than 2.0cm to the cylinder wall. This means that the cylinders plot as though they are 2.0cm larger than they actually are. This also accounts for the two cylinders in the partial local control case plotting as one cylinder.

It should be noted that RiverFLO-2D does not represent the negative velocities in the flume well. This is seen as the lowest velocity present in the model of the flume is 0.0m/s. Therefore the velocity distribution of the model and the flume are not exactly the same (this could be in part due to the fact that measurement between the cylinders in experimentation was not possible); however, the model still represents the velocity distribution adequately for the purposes of this report in terms of the variation of the velocity and how that affects the purposes of the research. That is, the model represents the actual velocity well in a qualitative manner, which is what is necessary for this report.

For instance, while the model does not represent the real-life situation exactly, the same trend is still followed in the statistical variation of the model and the flume studies.

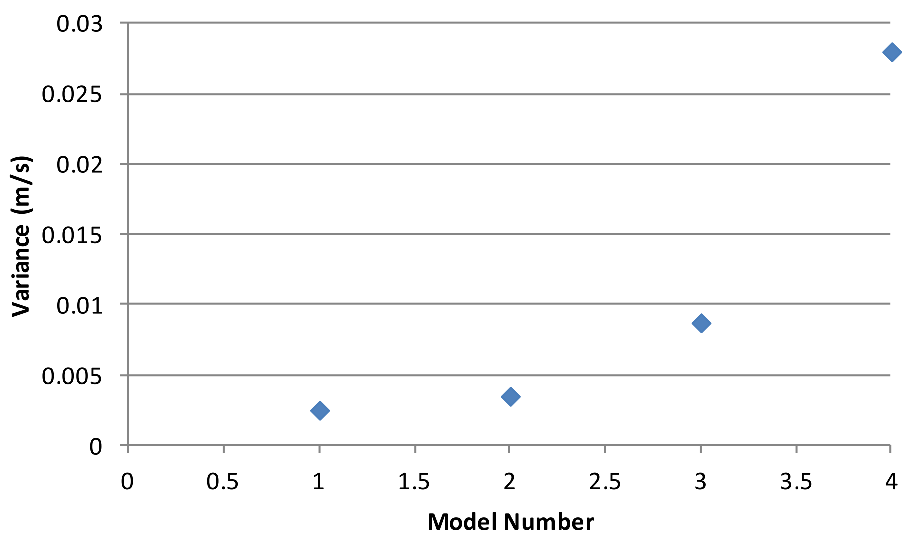

Figure 22: Graph showing trend in variance of computer models and flume studies

In Figure 22, the x-axis label ‘Model Number’ refers to the following:

1. Computer model of the pseudouniform situation created in the flume
2. Velocity data from the pseudouniform situation in the flume
3. Computer model of the local control situation created in the flume
4. Velocity data from the local control situation in the flume

It can be seen, in Figure 22, that the first two points and the second two points are following the same trend. From this it can be inferred that the variance (and therefore standard deviation as variance is the square of the standard deviation) is similar for the pseudouniform case and for the local case for the model and for the flume study. Thus the statistics can be qualitatively compared, but not completely quantitatively. It is possible that there is more variance in results obtained from laboratory studies than from the computer models because of the greater uncertainty in the laboratory results, as explained in 4.2.2.1.

Another way in which it is possible to check that the model is representing the flume case sufficiently well for our purposes is to check that the different flow classes are represented adequately. To check this, two contour plots were created – one from the flume data and one from the RiverFLO-2D model. For these contour plots, only velocities that are greater than 0.30m/s were plotted, i.e. those velocities that would show the flow class of Fast-Shallow according to Kleynhans's classification of flow (James and King (Eds) 2010), as all the depths on these models are well below 0.30m. The comparison of the flume data and the RiverFLO-2D model is show in Figure 23.

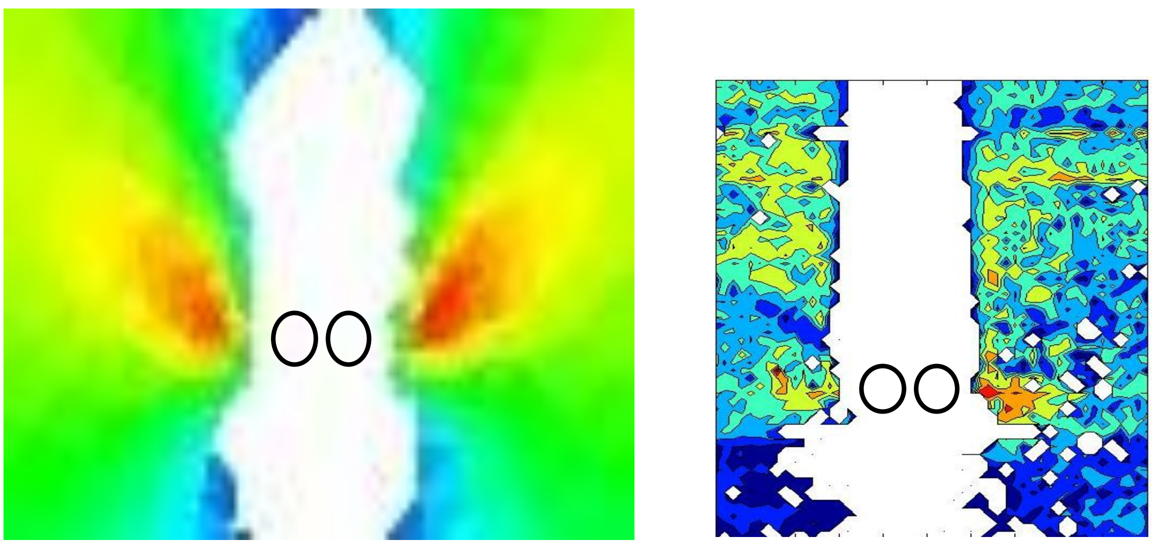

Figure 23: Comparison of RiverFLO-2D model (on the left) and flume data (on the right) showing the velocities in the flow class 'Fast-Shallow' ('Fast Shallow' is represented by the white on the figure)

It can be seen from these contour plots that the flow classes are very similar. This is important for this research, as the difference in flow class, or zone of influence, are both represented by the percentage of variation in velocities, which will be used to reinforce the idea that there is a larger variation in the velocities when a local control is present than when there is more uniform flow around the cylinders.

Thus it can be seen that RiverFLO-2D gives a good representation of the velocity distributions in the flume for our purposes. Therefore it can be used reliably to generate more plots for further investigation.

4.2.3 Models created for velocity distribution investigation

Various models were created in order to investigate further the velocity of flow around large roughness elements. The basic geometry used was two cylinders aligned transverse to the flow direction (Figure 19) with varying spacing in between them and varying slopes. The two cylinders were placed in the middle of the flume – i.e. 5.0m along its 10m length – and in the middle of the width of the flume – i.e. 1.0m into its 2.0m width. At least 5 different spacings were used between the cylinders, which were modelled on 4 different slopes. Each of these geometries was modelled with 3 different discharges through the system.

The different slopes used for the investigation were:

- Slope = 0.00050
- Slope = 0.00090
- Slope = 0.0012
- Slope = 0.0015

On each slope, the following spacing between cylinders was investigated:

- Spacing = 0.10m
- Spacing = 0.20m
- Spacing = 0.50m
- Spacing = 0.75m
- Spacing = 1.0m

These spacings were chosen to create a range of velocity conditions, as the 1.0m spacing would provide the least interference between cylinders and the 0.10m spacing is the smallest spacing that could be reliably modelled with the Student Version of Argus ONE.

3 different discharges and corresponding outlet water surface elevations were used for each slope. The water surface elevations were calculated to be the uniform flow depth for the corresponding discharge. The discharges and water surface elevations used were:

For a slope of 0.00050:

- Discharge = 0.0256m^3/s and depth at outlet = 0.046m
- Discharge = 0.0311m^3/s and depth at outlet = 0.052m
- Discharge = 0.0490m^3/s and depth at outlet = 0.068m

For a slope of 0.00090:

- Discharge = 0.0170m^3/s and depth at outlet = 0.030m
- Discharge = 0.0394m^3/s and depth at outlet = 0.050m
- Discharge = 0.0682m^3/s and depth at outlet = 0.070m

For a slope of 0.0012:

- Discharge = 0.0220m^3/s and depth at outlet = 0.032m
- Discharge = 0.0509m^3/s and depth at outlet = 0.054m
- Discharge = 0.0880m^3/s and depth at outlet = 0.075m

For a slope of 0.0015:

- Discharge = 0.0220m^3/s and depth at outlet = 0.030m
- Discharge = 0.0509m^3/s and depth at outlet = 0.050m
- Discharge = 0.0880m^3/s and depth at outlet = 0.070m

These different conditions were run in RiverFLO-2D for each different spacing to produce various contour plots, including velocity contour plots, depth contour plots and contour plots of the Froude number.

The finite element meshes produced by Argus ONE's automatic meshing algorithm are shown in Figure 24 for the 1.0m and 0.050m spacings of the cylinders.

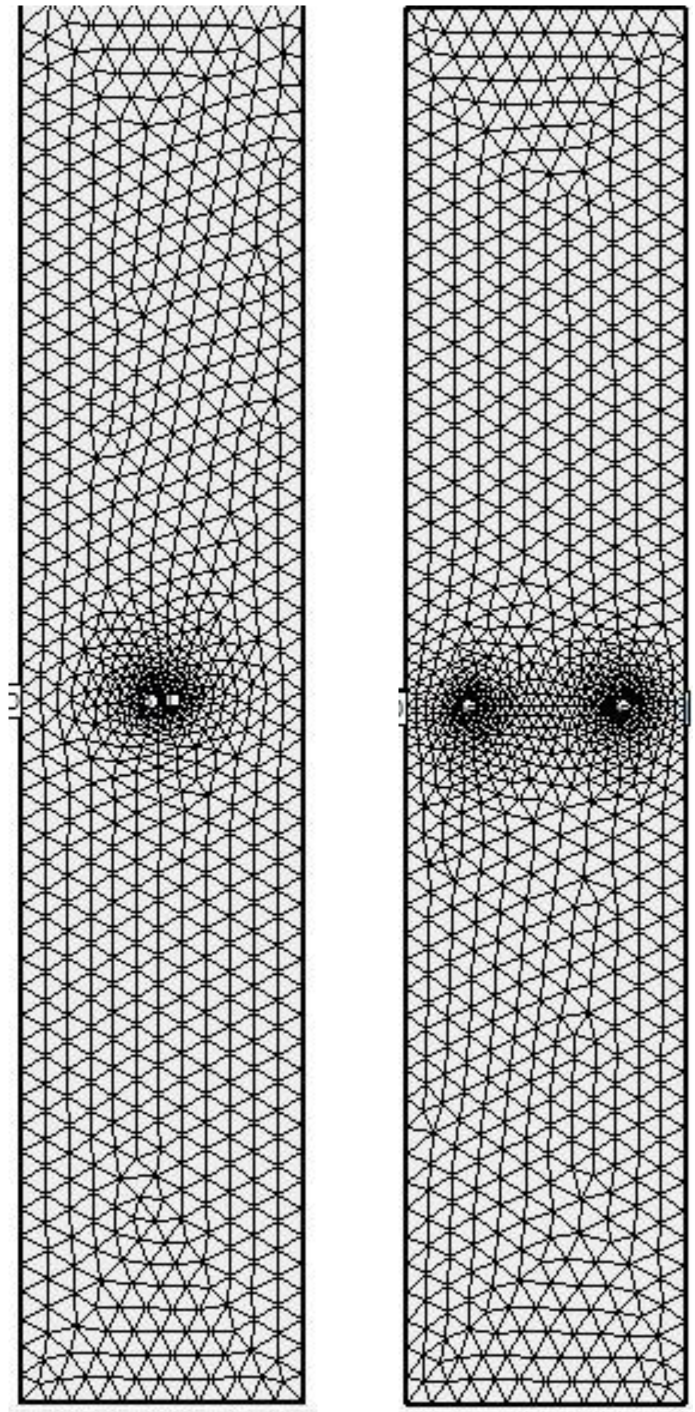

Figure 24: Finite element meshes showing two different spacings of the cylinders

As can be seen from Figure 24, the finite element mesh becomes much denser closer to the cylinders. This ensures that the flow is suitably modelled close to these cylinders, as a finer mesh generally produces better results from a finite element model. The fine mesh used around the cylinders can be seen in Figure 25.

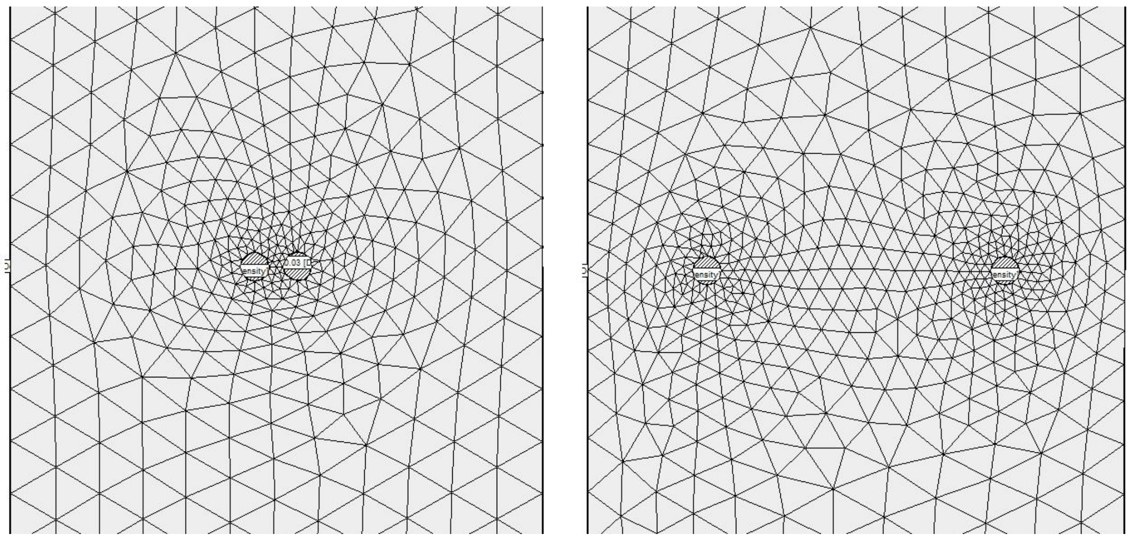

Figure 25: The fine mesh around the cylinders for the 0.050m spacing (on the left) and the 1.0m spacing (on the right)

The boundary conditions used were the input discharge and the outlet fixed water surface elevation and the Manning's n assigned to the entire flume was 0.010, the value determined from the calibration studies.

Various results were obtained by running these models in RiverFLO-2D, including velocities in the transverse and longitudinal directions (transverse velocities being along the width of the flume and longitudinal velocities along its length), depths along the length of the flume and Froude numbers of the flow in the flume. Examples of these results are shown in Figure 26 to Figure 29. Other pertinent results will be shown and discussed in later chapters.

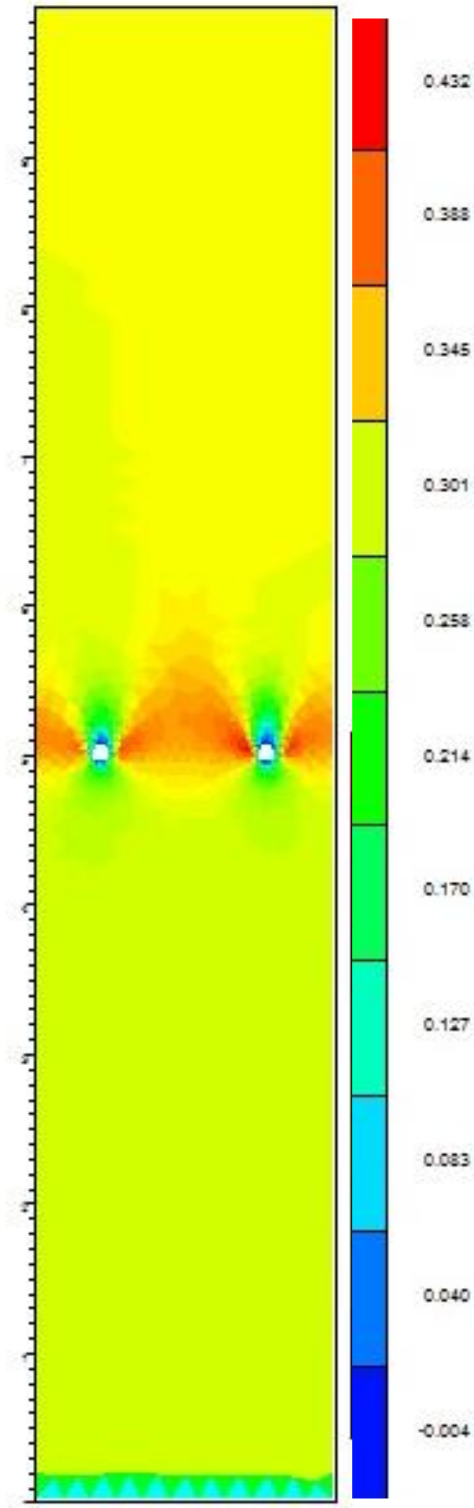

Figure 26: Example of longitudinal velocity results plot (m/s)

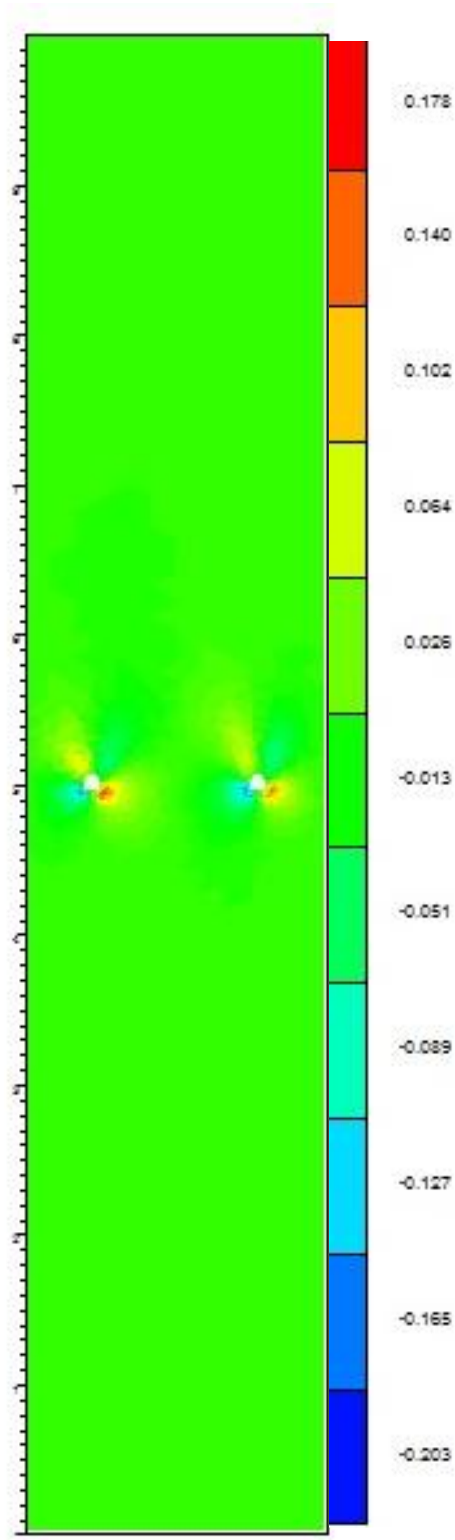

Figure 27: Example of transverse velocity contour plot (m/s)

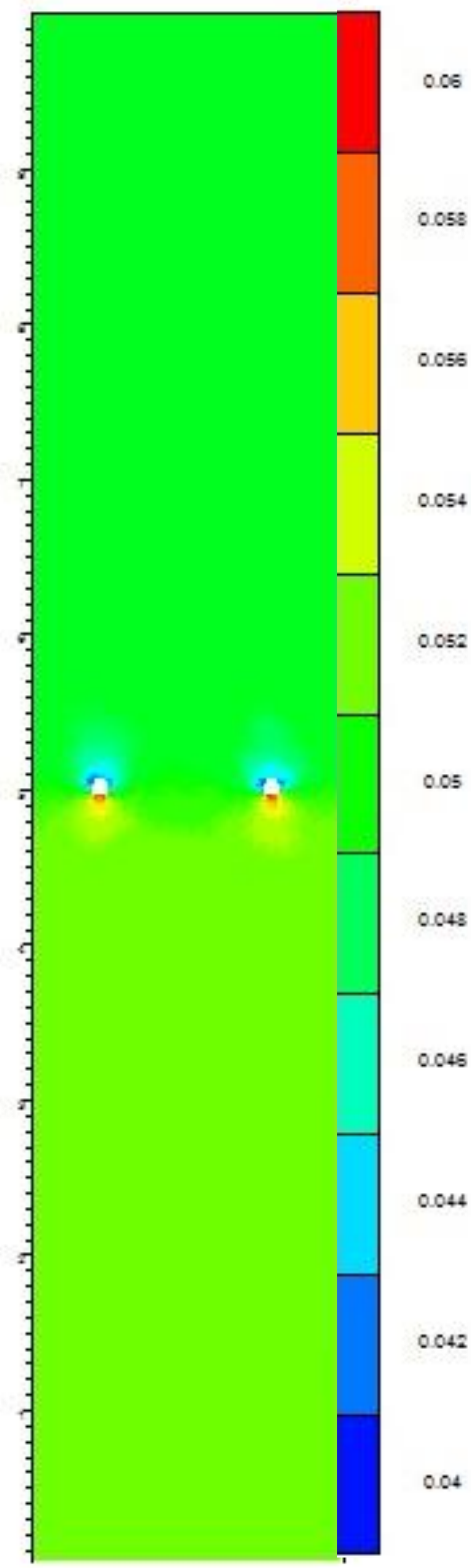

Figure 28: Example of depth contour plot (m)

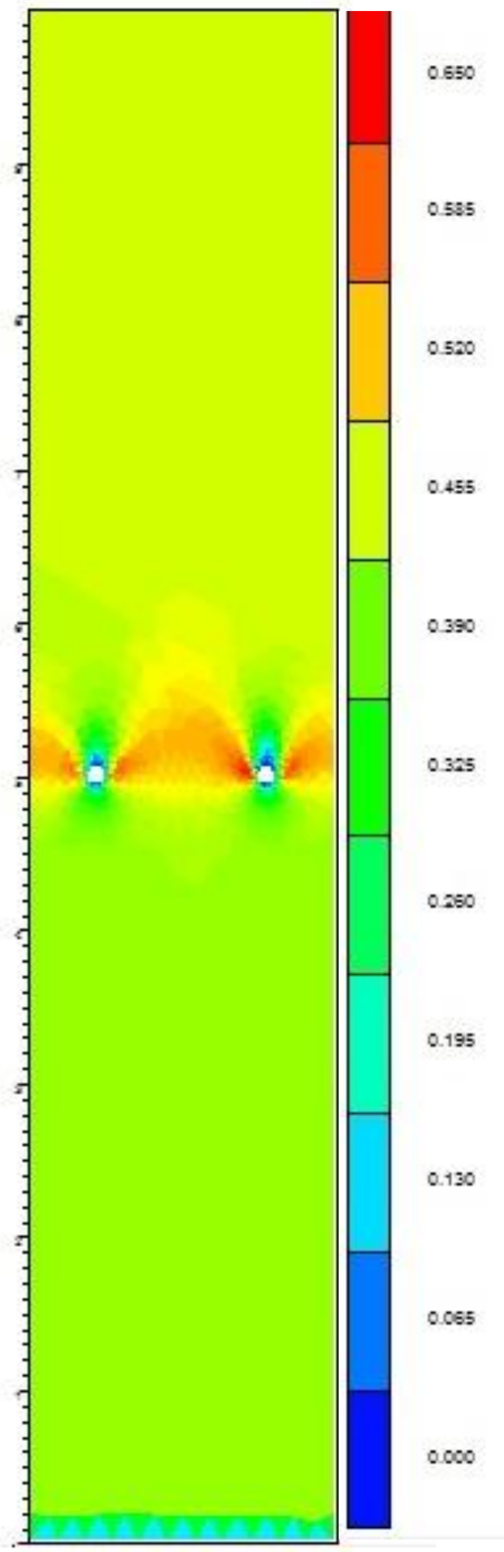

Figure 29: Example of Froude number contour plot

Thus it is seen that the results from RiverFLO-2D are reliable and can be used to further investigate the velocity distributions and other characteristics of flows around large roughness elements in the flume. Further results from RiverFLO-2D can be found in the following chapter and these results and their significance will be discussed in that chapter.

5 RESULTS AND DISCUSSION

Various different conclusions can be drawn from the data that was obtained by running computer models as described in the previous chapter. These results can be used to show various conclusions from this data relating to different flow quantifiers. These will be discussed below.

The results used are those from the different geometry cases run in RiverFLO-2D that are described in the previous chapter. Further data was then created by doing more runs in RiverFLO-2D with different slopes to obtain a local control for each discharge and each different spacing of cylinders that was investigated.

The results that will be investigated specifically are those which show the differences between situations where there is a local control in the flow and situations where there is no local control. It is hypothesised that the situations that include a local control will show more statistical variation in the velocities present and will therefore also display a variation in zone of influence, which may not be present in those cases where a local control does not exist.

Having shown that a greater variation in velocities is present when a local control is formed, a case study will then be discussed where guidelines are suggested on how to create the local control, as it may be desirable in certain situations to have variation in velocities in some areas of the flow.

5.1 Variation with Different Flow Conditions

Various types of variations are observed with the two different flow conditions (i.e. a local control present and no local control present) around the cylinders in the flow. These variations include the statistical variation in the values of the velocities surrounding the area of the cylinders (this includes a variation in the range of velocities and therefore in the statistical variance seen in the velocity values around the cylinders), a variation in the effect that the cylinders have on the flow, which can be seen in a variation in the size of the zone of influence of the cylinders.

5.1.1 Statistical variations

Descriptive statistics were analysed for various different cases with a local control and without a local control to determine whether there was any significant difference in these statistics. The statistics for each of the various cases analysed in the model were investigated using different areas around the cylinders, varying from an area around the cylinders including the entire flume to an area around the cylinders that is 1.0m long by 1.5m wide. The statistics varied slightly from the largest to the smallest areas, with less variance in the statistics occurring in the larger areas and more in the smaller areas. This can be explained by the fact that the disturbance caused by the cylinders will become smaller as the flow moves further away from the cylinders and therefore the greater the area around the cylinders included, the smaller the variance will be as the flow characteristics will be closer to the base flow characteristics further from the cylinders. For the purpose of investigating the statistics in this report, the area used will be the 1.0m long (centred around the cylinders) by 1.5m wide area with the cylinders placed centrally across the width of the flume. This will represent the greatest variation in statistics for both the non-locally controlled cases and the locally controlled cases. The descriptive statistics that best describe the variation in velocity results (i.e. the standard deviation and the variance of the data points) are shown in Table 7 and Table 8. Statistics from all flow cases investigated can be found in Appendix 1.

Table 7: Comparison of average variance in non-locally controlled and locally controlled cases

Average variance in non-locally controlled cases	0.00837
Average variance in locally controlled cases	0.0182
Percentage difference between non-locally controlled and locally controlled cases	**54.0**

Table 8: Comparison of average standard deviation in non-locally controlled and locally controlled cases

Average standard deviation of non-locally controlled cases	0.0900
Average standard deviation of locally controlled cases	0.126
Percentage difference between non-locally controlled and locally controlled cases	**28.3**

From these tables it can be seen that the variation in velocities is greater when there is a local control present in the flow compared to when there is no local control present in the flow. Thus, from the descriptive statistics, it would be considered beneficial in terms of habitat hydraulics to have a local control present in the flow, as greater variation in velocities will encourage a more natural habitat (as was indicated in the Background chapter of this report).

5.1.2 Zone of Influence Variations

The zone of influence is the area of flow that is affected by the cylinders. In this case, the zone of influence will be defined as the area around the cylinders that has a velocity that is more than either 10% higher or 10% lower than the base flow velocity. From the computer models, it can be seen that as the Froude number increases and the flow becomes critical, the zone of influence of the cylinders increases. This is seen in Figure 30.

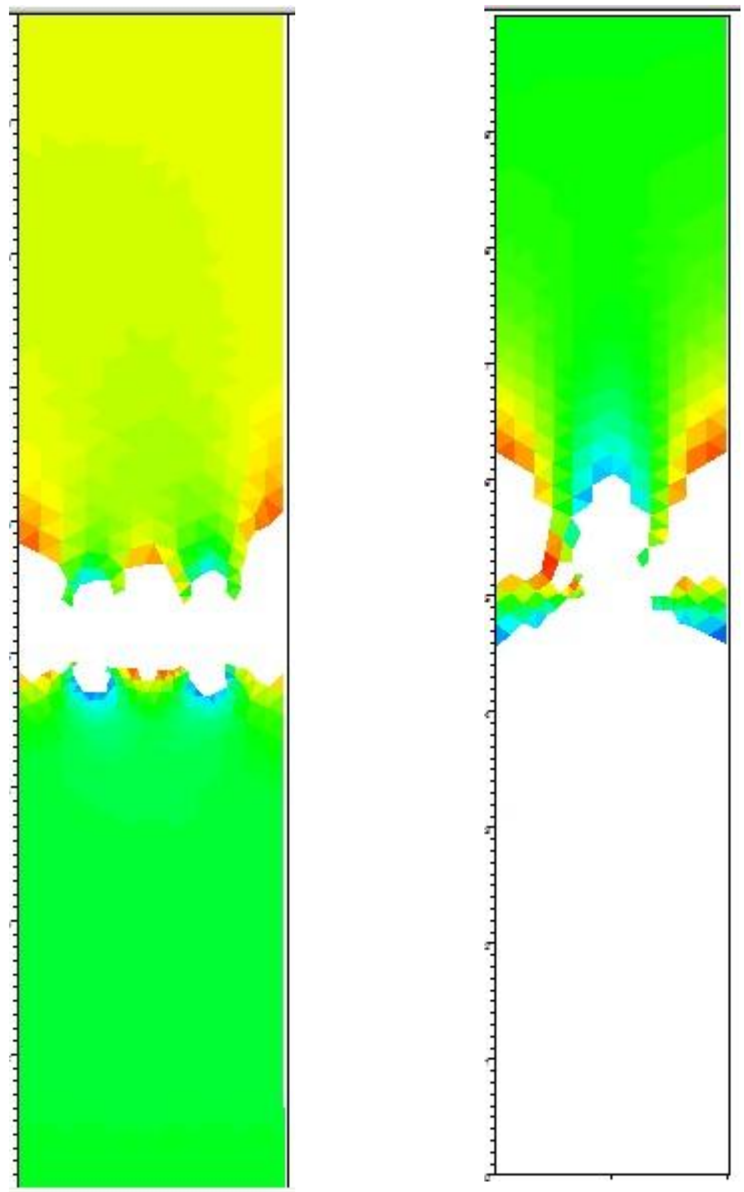

Figure 30: Zone of influence for non-locally controlled flow (on the left) and zone of influence for locally controlled flow (on the right)

Figure 30 shows a typical representation of the zone of influence for the non-locally controlled case and the zone of influence for the locally controlled case (figures from all investigated flow conditions can be found in Appendix 2). The zone of influence, or area where the velocity varies by more than 10% from the base flow, is shown as the white zones in Figure 30. As can be seen from this figure, the zone of influence when the flow is locally controlled is much greater than when the flow is not locally controlled – when the flow is not locally controlled, the zone of influence is roughly 4 to 5 times the diameter of the cylinder, whereas when the flow is locally controlled the zone of influence can be between 45 to 50 times the diameter of the cylinder. This is of interest as it again implies that there is a greater variation in flow conditions when the flow is locally controlled compared to when there is no local control present, which will encourage more natural conditions in a river, as has previously been mentioned. This change appears to be gradual to some extent – i.e. as the spacing between the cylinders changes, the zone of influence of the cylinders changes, although the zone of influence generally increases quite substantially as a local control is formed. The gradual change is not always the case (as can be seen from all the results shown in Appendix 2) and further research would be necessary to draw any real conclusions from this postulation.

It is interesting to note that when the flow is locally controlled, there is a much greater deviation from the base flow velocity directly upstream of the cylinders than when there is no local control. This is because, when a local control is present in the flow, the flow reaches greater velocities as it passes the cylinders, but it also backs up considerably upstream of the cylinders, which gives rise to the large zone of influence that is seen on the right hand side of Figure 30. This slowing down of the flow can lead to the creation of pools behind obstructions in the flow, which creates an important part of the natural habitat in some cases.

In cases where the base flow velocities (or depths) are around the transition points for Kleynhans's flow classes (James and King (Eds) 2010), the flow in a stream or river may represent two different flow classes, such as slow shallow and fast shallow if the velocity changes from below 0.30m/s to greater than 0.30m/s within the area of interest. The two different flow classes would be represented more strongly as the flow tends towards a local control, as they will follow a similar trend to the zone of influence that has been shown above.

The zone of influence is also of interest for cases where rivers are being rehabilitated as it may be desirable to have pairs of obstacles that affect the flow but whose effects on the flow do not interact with each other to try and increase the variation in flow conditions – i.e. the flow reverts to its base flow characteristics before encountering the next set of obstacles downstream. Thus, when a local control is created and it is desirable for the flow characteristics to return to the base characteristics before the next set of obstacles, the pairs of obstacles should be placed roughly 50 obstacle diameters from each other in the flow direction. This is assuming that the undisturbed flow is that flow that is within 10% of the base flow.

5.2 Guidelines for Creating a Local Control for a Specific Case

In this research, various circumstances were investigated for a specific layout of cylinders, as has been described in the Computer Modelling chapter. The layout of cylinders was specifically a pair of cylinders side-by-side and perpendicular to the direction of flow. The cases described in the Computer Modelling chapter were all investigated in order to attempt to determine what conditions were needed in order to create a local control in the flow, as modelled by RiverFLO-2D. These investigations are detailed below, followed by rough guidelines that may assist in creating a local control when pairs of cylinders are used perpendicular to the direction of flow.

The first step in this investigation was to determine whether or not a local control was created in the flow. This was determined by checking the maximum Froude number calculated by RiverFLO-2D against the critical Froude number, i.e. the Froude number when the flow changes from subcritical to supercritical flow. The critical Froude number is equal to 1.0. Thus any Froude number greater than 1.0 indicates that a local control is formed in the flow and the flow transitions from subcritical to supercritical at the point where the Froude number changes from below 1.0 to above 1.0.

In order to find out where the point of transition lay for each discharge, all the cases described in the Computer Modelling chapter were run and compared against each other. From these it was seen that there was a transition from non-locally controlled to locally controlled that was dependent on slope and discharge more than the spacing between the cylinders (the spacing between the cylinders was thought to perhaps have some effect on whether the flow was locally controlled or not). Therefore, it was decided to investigate each discharge to attempt to find the point of transition from locally controlled to non-locally controlled for each different spacing between the cylinders. This was done by varying the slope for a specific discharge and spacing until a transition point was found. This was done for 5 different discharges, namely:

- $Q = 0.00900m^3/s$
- $Q = 0.0220m^3/s$
- $Q = 0.0509m^3/s$
- $Q = 0.0880m^3/s$
- $Q = 0.500m^3/s$

For each of these discharges, 7 different geometries were investigated by changing the spacing between the cylinders. This involved choosing a specific spacing and changing the slope for that spacing and discharge until the transition point was reached. Thus many more cases were investigated than are detailed in the Computer Modelling chapter; however RiverFLO-2D was used in the same manner as was used in the Computer Modelling chapter and therefore these extra cases will not be detailed here. The raw data and Argus ONE files from all of the cases investigated to produce Figure 31 may be found in the Digital Appendix. The transition points for each of the different geometry cases were found. This created a graph, as shown in Figure 31.

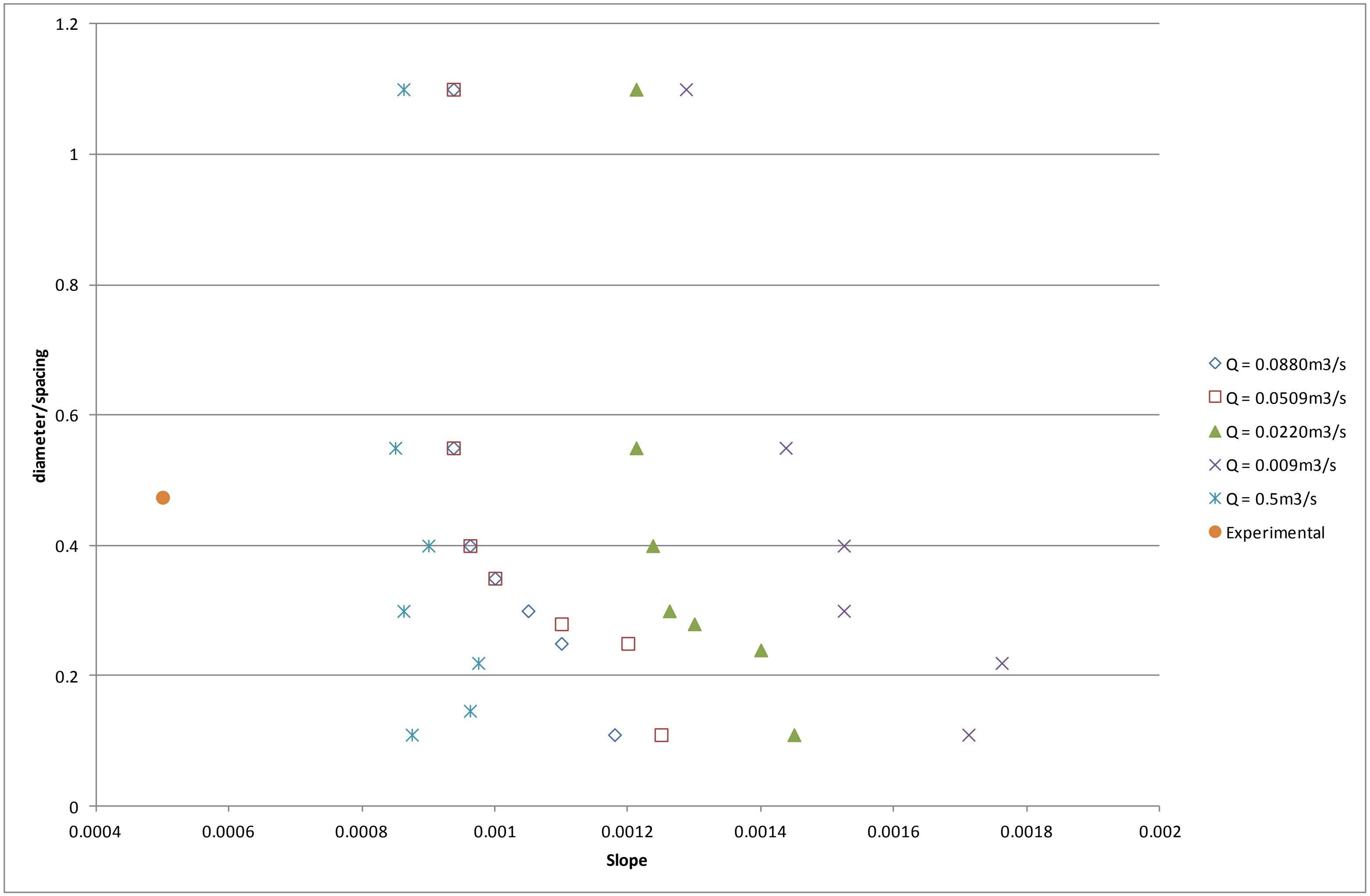

Figure 31: Slope required to create a local control versus the ratio of diameter/spacing between the cylinders

In Figure 31, each point represents the point at which flow transitions from non-locally controlled to locally controlled flow, i.e. the point on the graph represents the point where critical flow occurs for the first time. The round orange point on the graph is the data point that is generated from the 'pseudouniform' experimental case that was investigated in the laboratory flume. The other data point obtained from the laboratory investigation cannot be plotted on this graph as the spacing between the cylinders is much smaller than was used for the computer generated cases and therefore that point would not fall on the graph.

This is the data from the analyses carried out in RiverFLO-2D, which explains the slight variation in the pattern of the graphs – i.e. why each graph does not have exactly the same shape. This is explained by the fact that the point of critical control is an unstable point in the computer analysis and therefore the exact point at which the flow transitions from subcritical to supercritical flow may vary slightly each time the program is run. The accuracy of this data depends on the quality of input data as well as the quality and fineness of the mesh at the critical point. While the mesh in this research was as fine as was possible to create, a more stable shape to the above curves may be obtained with a finer mesh around the cylinders. However, the graphs in the above figure do show that a general pattern is developing from this data.

The pattern developing can be clearly seen in the graphs of the discharges between 0.0880m^3/s and 0.0220m^3/s. These three graphs show the pattern that the data points tend to follow. As the discharge gets smaller, i.e. as can be seen on the 0.00900m^3/s discharge graph, the bottom of the graph seems to lengthen slightly, while with the higher discharge graph (i.e. the 0.0500m^3/s discharge), the points tend more towards a straight vertical line.

It can be seen from Figure 31 that both slope and discharge have a significant impact on whether or not a local control is formed in the flow. Also, it can be noted that the spacing between the cylinders in the flow does not have as large an effect on the formation of a local control as the slope and discharge do and thus, while the spacing may still be important in the formation of a local control, it seems that it is more important to have the correct slope and discharge (and most likely a pair of obstructions will be better for creating a local control rather than a single obstruction).

As well as this, it is noted that there is an increase the slope required to create a local control as the diameter over spacing ratio decreases – the change happens around diameter/spacing = 0.2. Thus as the cylinders get further away from each other a steeper slope is required to create a local control.

These graphs form a manner of guideline for each discharge in that if the flume modelled has a certain discharge and slope, it is possible to determine what spacing of two cylinders placed perpendicular to the flow would be necessary to create a local control at the cylinders. While Figure 31 can only be used in this manner for the specific flume case that was modelled in RiverFLO-2D it is hypothesised that similar graphs may exist for other geometry cases and if enough of these graphs are generated, then they may then be of general value.

Another interesting observation that can be made from this graph, having calculated the base flow characteristics for each case (which can be seen in full in Appendix 3), is that the base flow Froude number for each point on the graph is always close to or just above 0.60. This can be seen in the summarised base flow characteristics in Table 9.

Table 9: Summary base flow characteristics for points in Figure 31

Discharge	Average depth	Average velocity	Average Froude number
m^3/s	**m**	**m**	
0.0090	0.017	0.260	0.630
0.0220	0.031	0.351	0.632
0.0509	0.056	0.456	0.617
0.0880	0.079	0.558	0.635
0.5000	0.246	1.016	0.654

From this information it can be inferred that a local control is only possible, at least in this case, when the base Froude number is over 0.60. This may be important information for determining when it is possible to create a local control in a river; however, further research will be necessary to confirm that this result may be generalised and is not specific only to this case.

This conclusion can be seen more clearly in Figure 32, which shows diameter over spacing against the base Froude number for the transition cases (i.e. where the flow transitions from being completely subcritical to having a local control for a particular geometry). The base flow characteristics of the points in Figure 32 are listed in Table 9, while the rest of the characteristics may be found in Appendix 1.

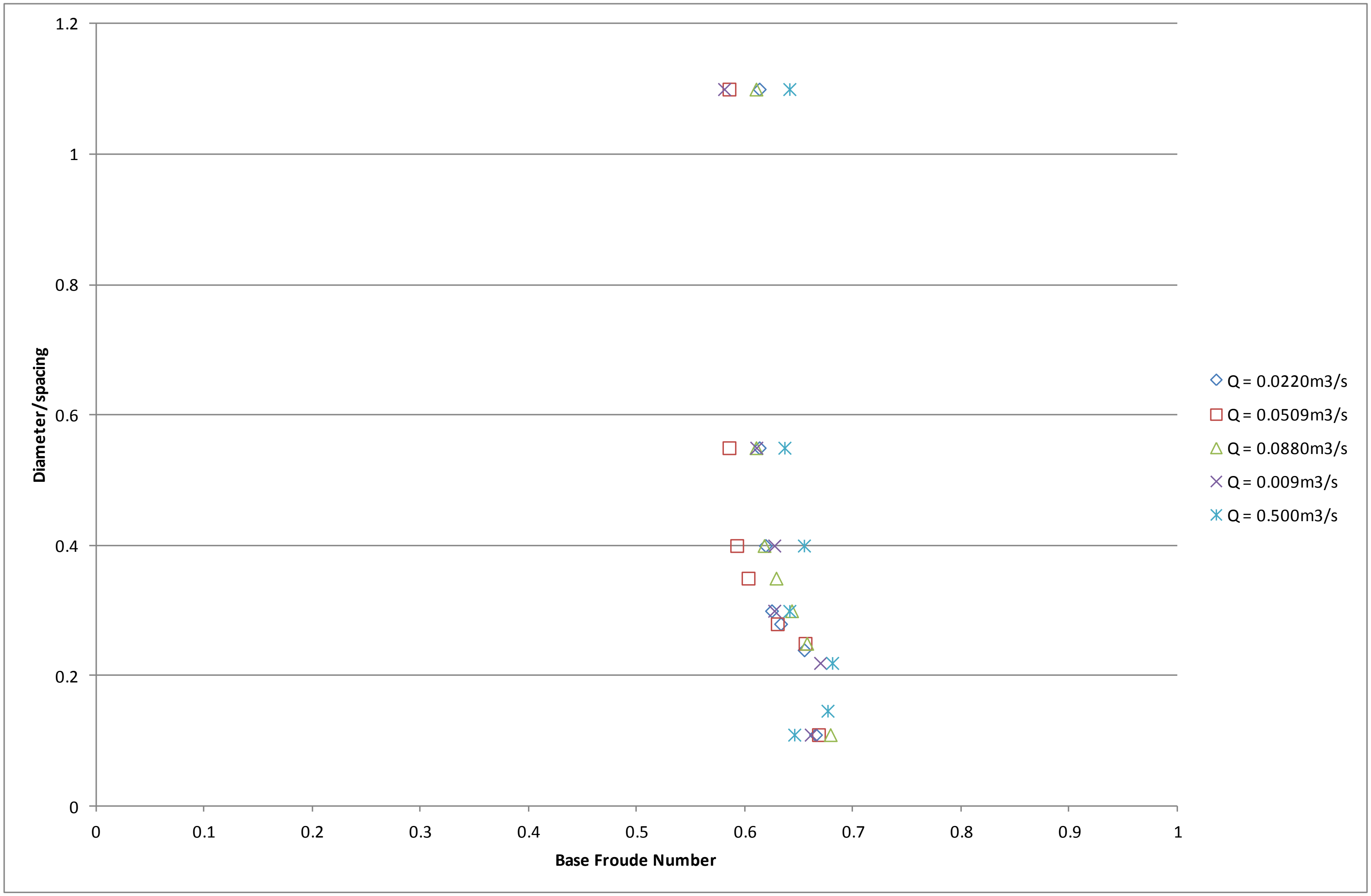

Figure 32: Froude number versus diameter over spacing for the transition cases

In Figure 32, the flow that would be represented by the area on the left of the points plotted has no local control, while the flow that would be represented by the area to the right of the points has a local control present. From this figure, it can be seen that whatever the slope or discharge for a particular case is, the transition to locally controlled flow will only happen when the base Froude number is above 0.60.

Thus if greater variance is desired in a stream, a local control may be created by ensuring that the base Froude number is above at least 0.60. This can be achieved by changing various geometry conditions that will change the flow, such as slope and width, and also by varying the discharge in a river, if this is possible.

Once a local control is created in the flow, the variance or standard deviation may be increased by increasing the Froude number. This is shown in Figure 33.

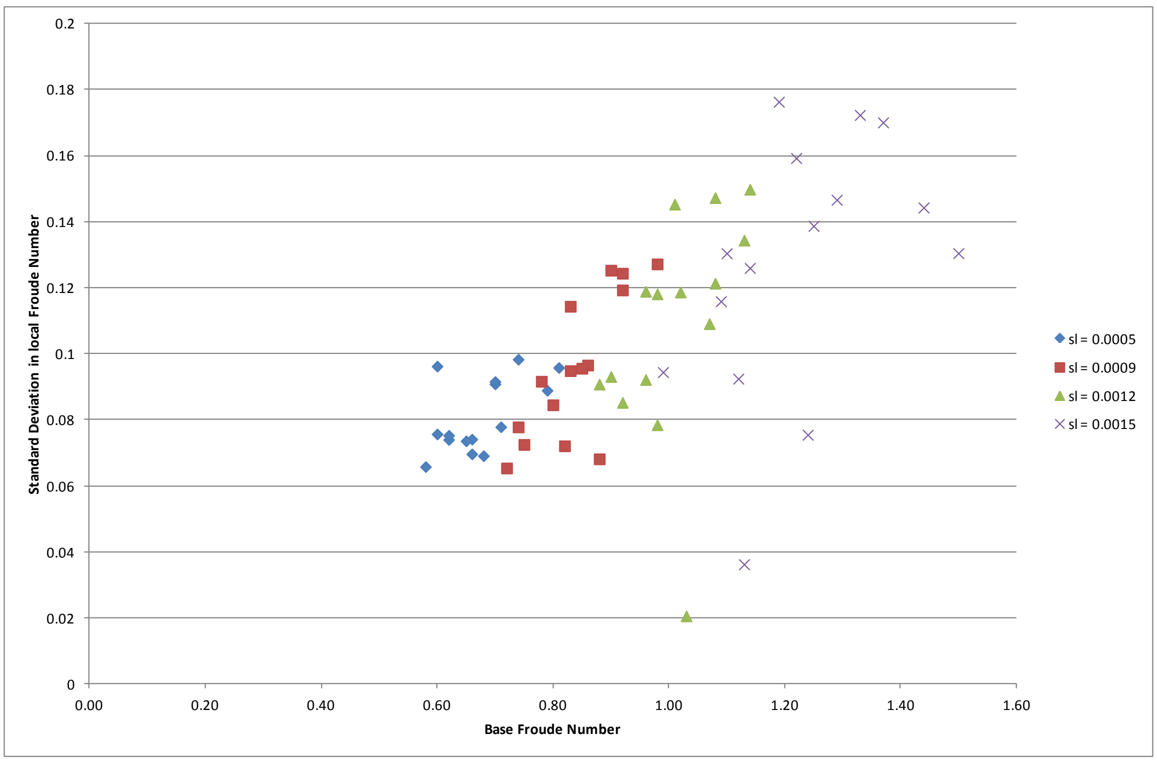

Figure 33: Froude number versus standard deviation, showing the increase in variance with increase in Froude number (sl = slope of flume)

Figure 33 shows that as the Froude number increases, the standard deviation in velocity (or variation in the velocity values) also increases. The Froude number shown above is the maximum Froude number for a specific case, which increases as the base Froude number for each case increases. Thus, if more variation in velocity is required, a larger base Froude number would be useful in achieving this goal.

In connection with the above conclusion, it can be shown that as the spacing between the two cylinders decreases (i.e. as they get closer together), the maximum Froude number also increases. This is shown in Figure 34.

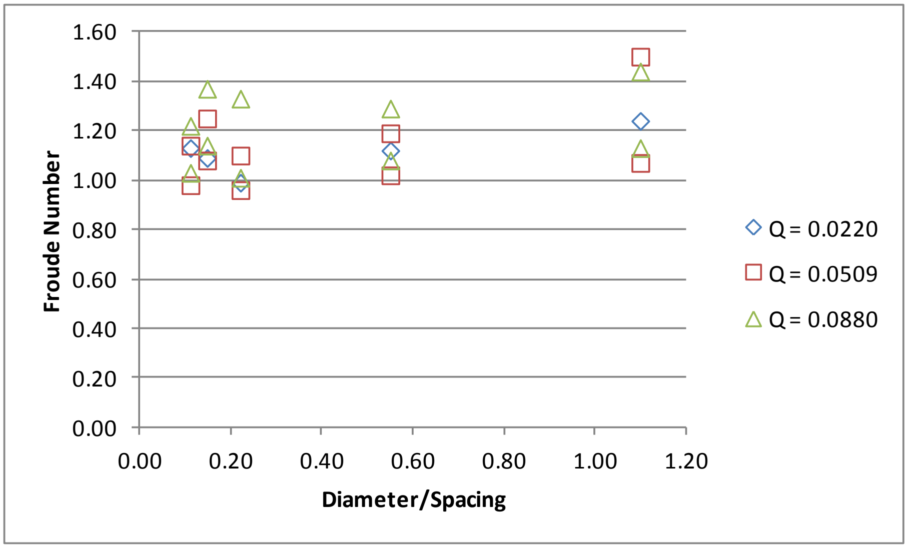

Figure 34: Diameter over spacing versus maximum Froude number when flow is locally controlled

In Figure 34, an upward trend is seen for each different discharge. Thus, as the cylinders get closer together, the maximum Froude number of the flow increases, which in turn will mean that the standard deviation of the flow increases. Thus once a local control has been created in the flow by inserting two large roughness elements, moving the elements closer together will have the effect of increasing the variation in the velocity. Moving the cylinders closer together will not increase the variance as much as creating a local control will (in the cases investigated, the standard deviation only increased by an average of 20% from the largest spacing to the smallest), but it is still useful to know that variation can be increased, however slightly, by moving the cylinders.

Also, the effect of increasing variation with decreasing the spacing between the cylinders may not have been very prevalent in this study because of the effects of the wall of the flume on the flow. Further research is suggested using a wider flume as a model.

6 CONCLUSIONS AND FURTHER RESEARCH

Having conducted laboratory studies and numerous numerical studies in the computer programs Argus ONE and RiverFLO-2D, there are various conclusions that can be drawn from the research. Firstly, it should be noted that because variance in velocity is a desirable characteristic in encouraging a natural habitat to form in a rehabilitated river, it is useful to know how to produce this variance in velocity when trying to rehabilitate rivers.

It has been shown that the variation in velocity in a situation, specifically the case of the model of Flume C investigated in this report, can be increased when a local control is present in the flow. This is because the flow will transition from subcritical flow to supercritical flow and therefore the velocity will transition from being relatively slow to relatively fast in a short space. This is useful for fish and other river fauna and flora as many of them require different flow conditions for different life stages and purposes.

Having established that the local control may be a desirable condition to have in a river system for velocity variation, it was attempted to ascertain the conditions that would be conducive to the formation of a local control so that if a situation arose where a local control would be desirable, an engineer may be able to set up the geometry of a river so that a local control would form. These conditions are as follows for a situation where a pair of obstructions, in this case cylinders protruding from the flow, are placed transverse to the flow:

- In terms of the graph in Figure 31, or the appropriate similar graph for the situation being considered, the spacing over diameter ratio and slope should be such that they fall to the right of the relevant graph of discharge
- The base Froude number of the flow should be above at least 0.60 as this seems to create the correct conditions for the formation of a local control, as shown in Figure 32.
- This variance in velocity can then be further increased by decreasing the spacing between the obstructions in the flow, as shown by Figure 33 and Figure 34.

These are the conditions for creating a local control in the flow. If a local control is created and it is desired that several pairs of cylinders be inserted in the flow along the length of the stream or river and the effects of the various pairs of cylinders (and the flow transition) do not interfere with each other (i.e. that the cylinder pair placed upstream of another cylinder pair is placed outside of the zone of influence of the downstream pair), the upstream pair of cylinders should be placed at least 50 diameters upstream of the first pair (the diameter here indicates the diameter of the downstream pair of cylinders, depending on the flow condition – if there is a local control then roughly 50 diameters upstream

These guideline conditions are specific (especially Figure 31) to the case considered in this report – i.e. two cylinders protruding from the flow in a 2m wide rectangular flume. However, it is thought that some results, especially those shown by Figure 32 to Figure 34, may be generalised fairly easily.

6.1 Recommendations for Further Research

There are various avenues that can be explored in order to further the research detailed in this report and to either verify or debunk the findings made. Some suggestions and recommendations are as follows:

- Broaden the study to include different geometric situations other than only two protruding cylinders placed transverse to the flow, and also without the constraints of the side walls of the flume that were in place in this study
- Broaden the numerical study by running models in RiverFLO-2D or other similar programs that do not have the limitations on mesh size that were encountered in this study – i.e. run the same geometry case with a finer mesh (especially around the cylinders) and with a larger width, for instance
- Investigate the current geometry with more discharge cases in order to make Figure 31 more general for this geometry case
- Make Figure 31 of more general applicability – i.e. find a way in which to minimise the dependence on slope and make the graph dimensionless, for instance
- Confirm that the Froude number should be greater than 0.60 in order for a local control to be formed in the flume for other geometries than the one investigated in this research and also confirm how much variance in velocity will increase with the decrease in spacing between the cylinders.

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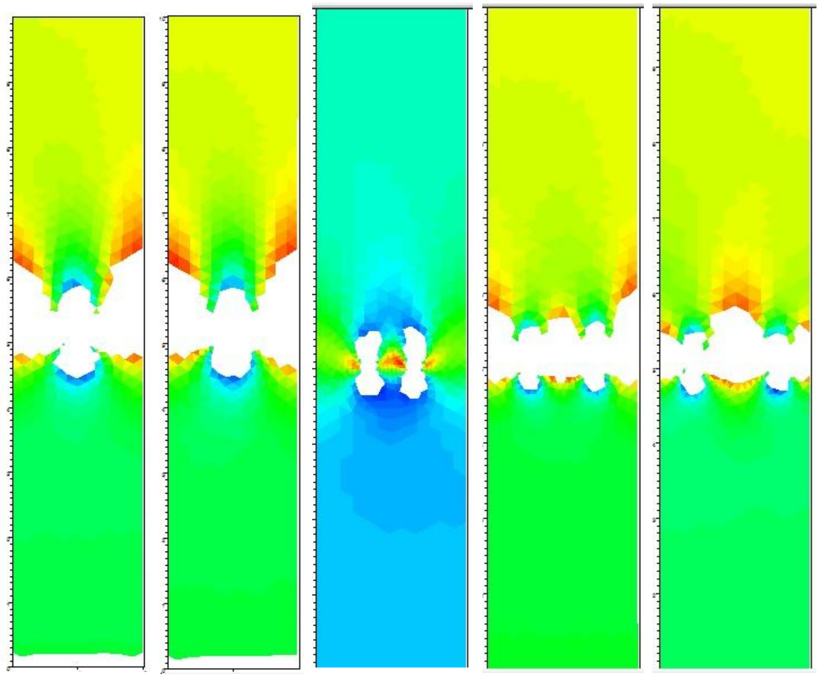
8 Appendix 1: Statistics from RiverFLO-2D Runs

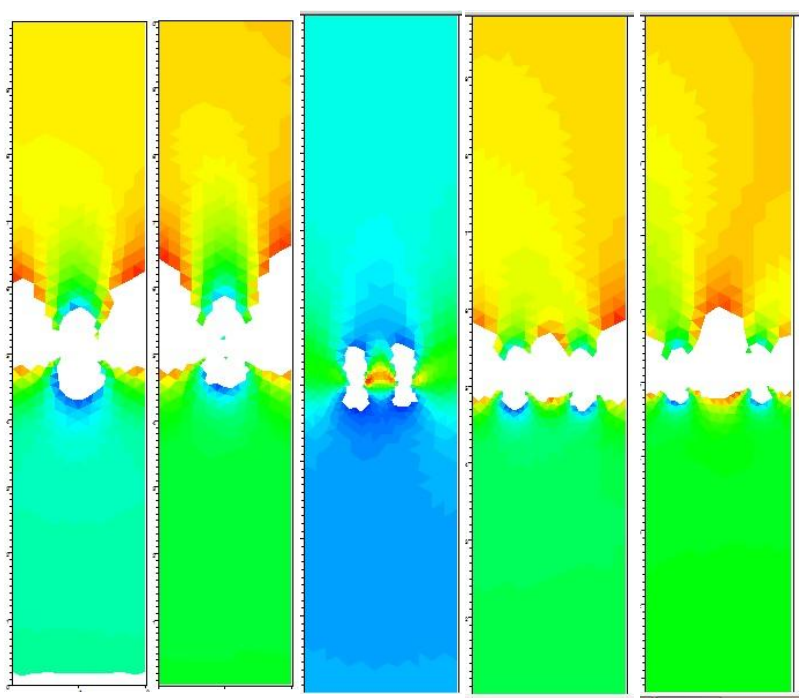
Slope	Spacing	Discharge	Maximum Froude Number	Variance	Standard Deviation
	m	m^3/s			
0.00050	0.10	0.0256	0.66	0.00485	0.070
0.00050	0.10	0.0311	0.60	0.00573	0.076
0.00050	0.10	0.0490	0.79	0.00791	0.089
0.00050	0.20	0.0256	0.68	0.00477	0.069
0.00050	0.20	0.0311	0.71	0.00606	0.078
0.00050	0.20	0.0490	0.81	0.00918	0.096
0.00050	0.50	0.0256	0.58	0.00433	0.066
0.00050	0.50	0.0311	0.66	0.00549	0.074
0.00050	0.50	0.0490	0.70	0.00826	0.091
0.00050	0.75	0.0256	0.62	0.00548	0.074
0.00050	0.75	0.0311	0.62	0.00567	0.075
0.00050	0.75	0.0490	0.74	0.00967	0.098
0.00050	1.00	0.0256	0.60	0.00926	0.096
0.00050	1.00	0.0311	0.65	0.00542	0.074
0.00050	1.00	0.0490	0.70	0.00684	0.092
0.00090	0.10	0.0170	0.88	0.00465	0.068
0.00090	0.10	0.0394	0.80	0.00715	0.085
0.00090	0.10	0.0682	0.83	0.01308	0.114
0.00090	0.20	0.0170	0.82	0.00520	0.072
0.00090	0.20	0.0394	0.86	0.00933	0.097
0.00090	0.20	0.0682	0.92	0.01424	0.119
0.00090	0.50	0.0170	0.72	0.00427	0.065
0.00090	0.50	0.0394	0.83	0.00900	0.095
0.00090	0.50	0.0682	0.90	0.01570	0.125
0.00090	0.75	0.0170	0.74	0.00606	0.078
0.00090	0.75	0.0394	0.85	0.00914	0.096
0.00090	0.75	0.0682	0.98	0.01618	0.127
0.00090	1.00	0.0170	0.75	0.00526	0.073
0.00090	1.00	0.0394	0.78	0.00840	0.092
0.00090	1.00	0.0682	0.92	0.01548	0.124

Slope	Spacing	Discharge	Maximum Froude Number	Variance	Standard Deviation
	m	m^3/s			
0.00120	0.10	0.0220	0.98	0.00616	0.078
0.00120	0.10	0.0509	1.07	0.01191	0.109
0.00120	0.10	0.0880	1.13	0.01807	0.134
0.00120	0.20	0.0220	0.92	0.00727	0.085
0.00120	0.20	0.0509	1.02	0.01409	0.119
0.00120	0.20	0.0880	1.08	0.02170	0.147
0.00120	0.50	0.0220	0.88	0.00825	0.091
0.00120	0.50	0.0509	0.96	0.01414	0.119
0.00120	0.50	0.0880	1.01	0.02112	0.145
0.00120	0.75	0.0220	0.96	0.00850	0.092
0.00120	0.75	0.0509	1.08	0.01473	0.121
0.00120	0.75	0.0880	1.14	0.02245	0.150
0.00120	1.00	0.0220	0.90	0.00867	0.093
0.00120	1.00	0.0509	0.98	0.01396	0.118
0.00120	1.00	0.0880	1.03	0.02056	0.021
0.00150	0.10	0.0220	1.24	0.00570	0.075
0.00150	0.10	0.0509	1.50	0.01703	0.130
0.00150	0.10	0.0880	1.44	0.02083	0.144
0.00150	0.20	0.0220	1.12	0.00855	0.092
0.00150	0.20	0.0509	1.19	0.03110	0.176
0.00150	0.20	0.0880	1.29	0.02151	0.147
0.00150	0.50	0.0220	0.99	0.00892	0.094
0.00150	0.50	0.0509	1.10	0.01702	0.130
0.00150	0.50	0.0880	1.33	0.02971	0.172
0.00150	0.75	0.0220	1.09	0.01343	0.116
0.00150	0.75	0.0509	1.25	0.01925	0.139
0.00150	0.75	0.0880	1.37	0.02894	0.170
0.00150	1.00	0.0220	1.13	0.00131	0.036
0.00150	1.00	0.0509	1.14	0.01588	0.126
0.00150	1.00	0.0880	1.22	0.02537	0.159

9 Appendix 2: Zone of Influence Figures for RiverFLO-2D Cases



Slope = 0.00050, Q = 0.0256m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



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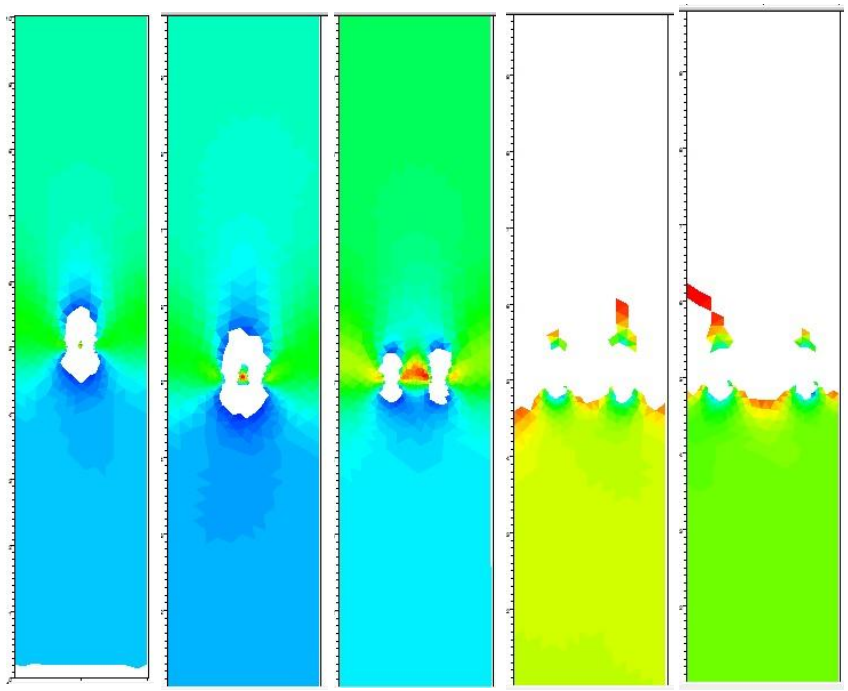
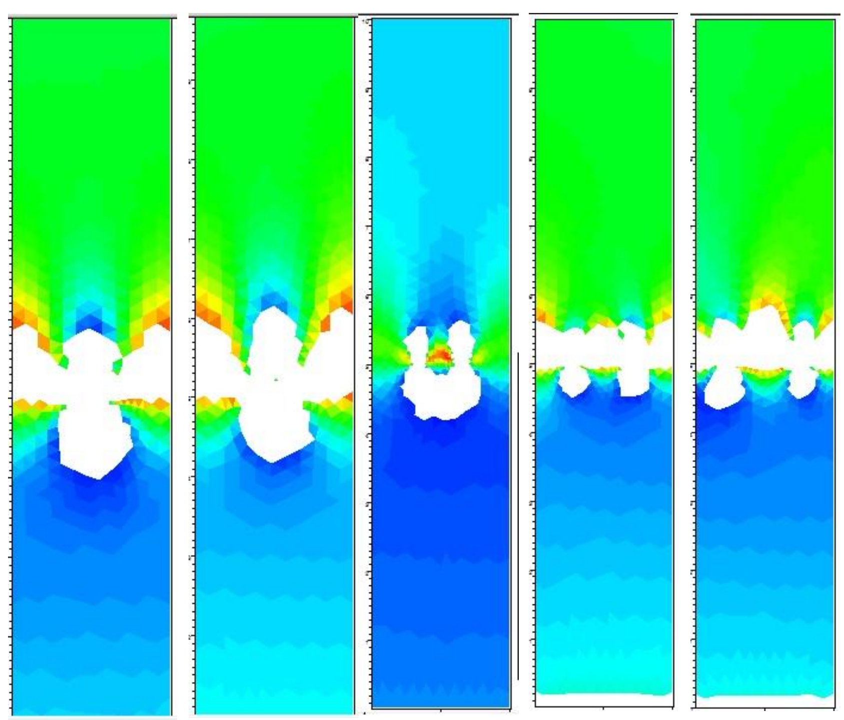
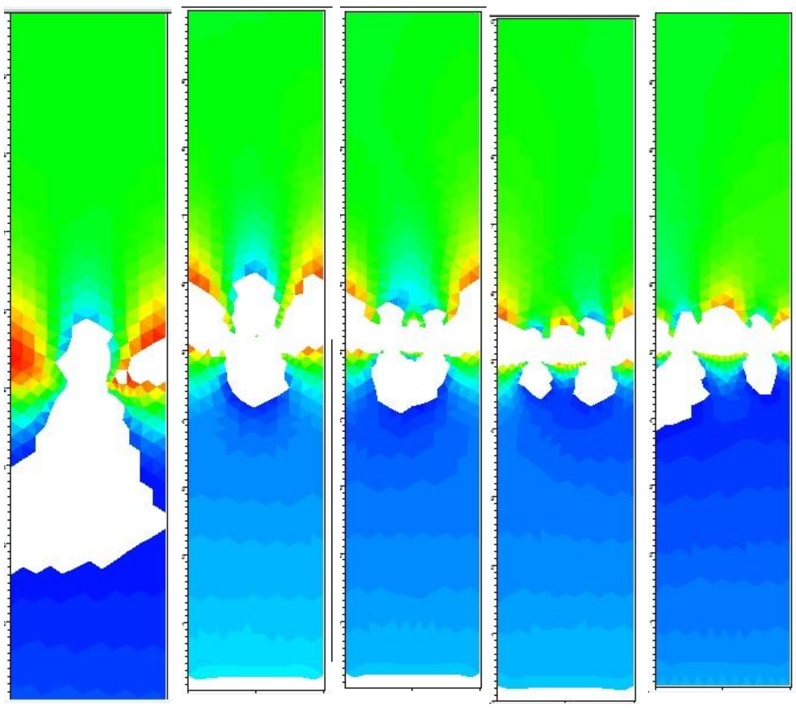


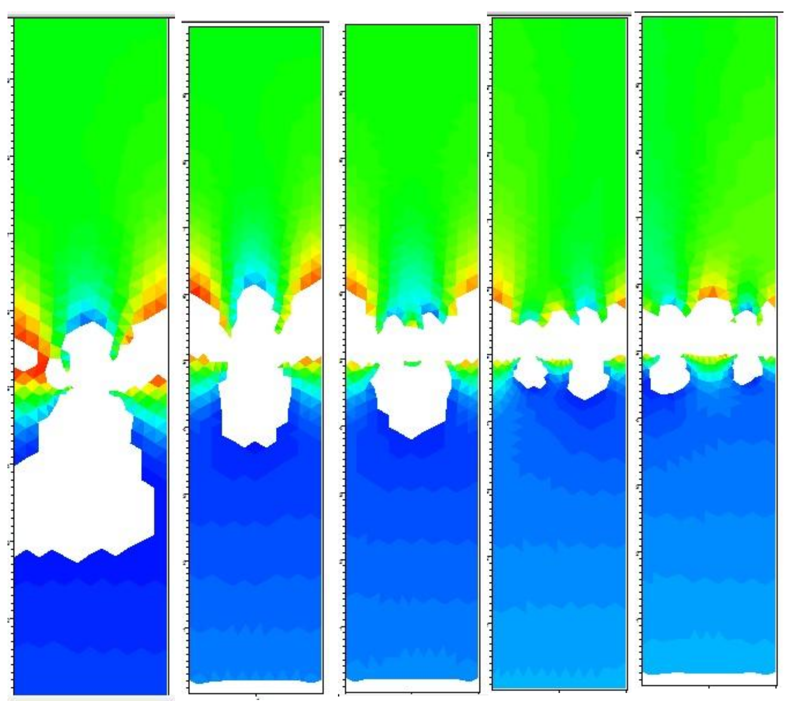
Slope = 0.00050, Q = 0.0490m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



Slope = 0.00090, Q = 0.0170m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



Slope = 0.00090, Q = 0.0394m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



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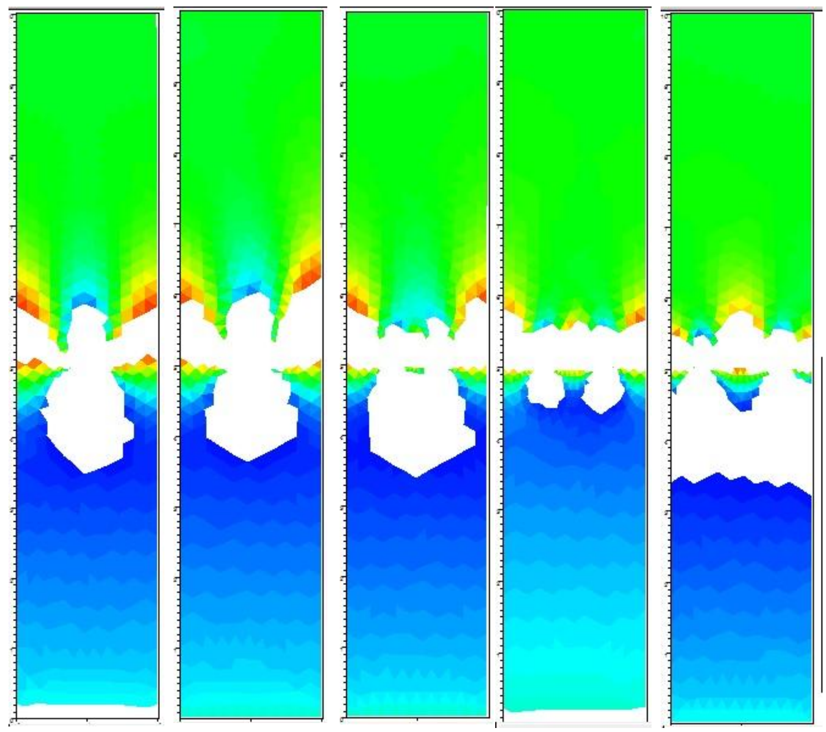
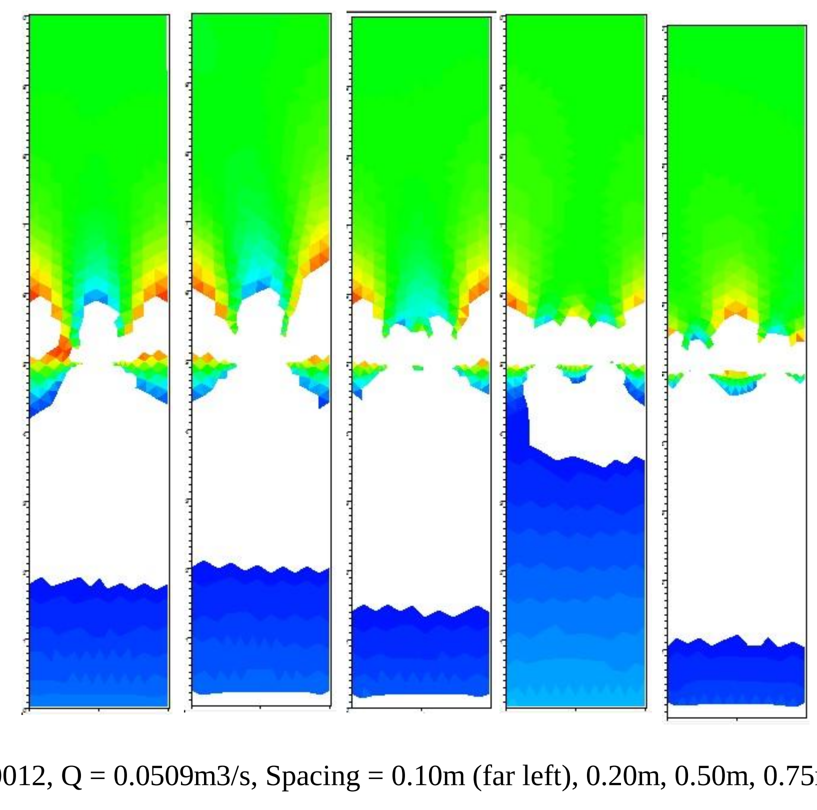
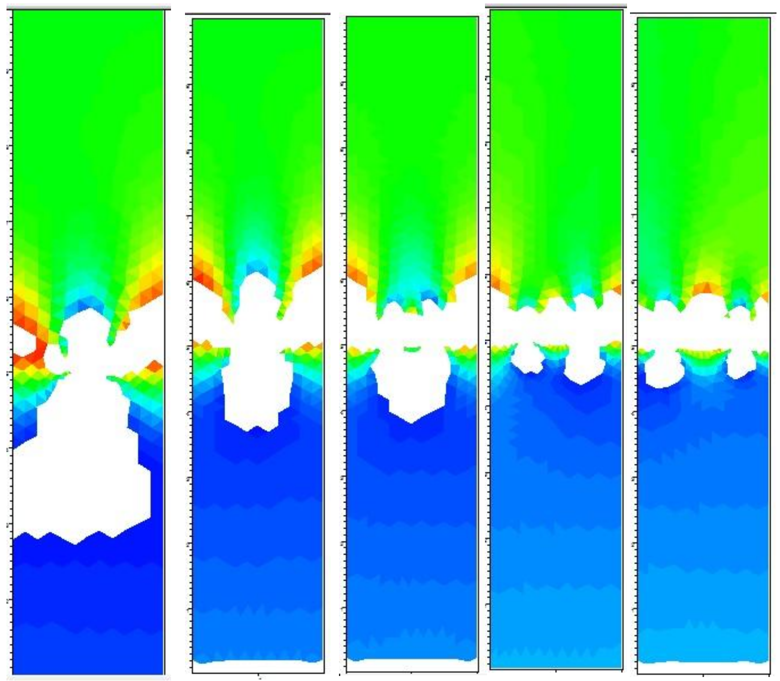


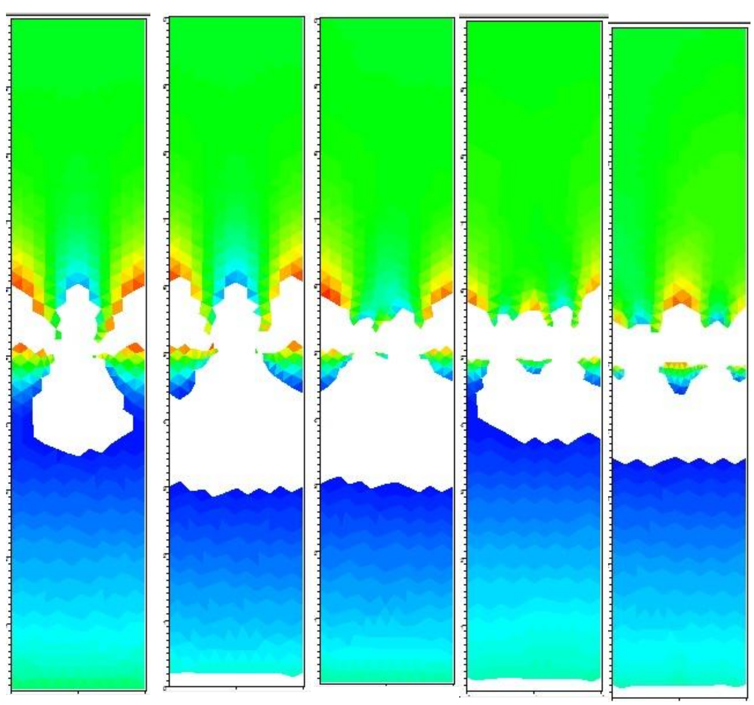
Slope = 0.0012, Q = 0.0220m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



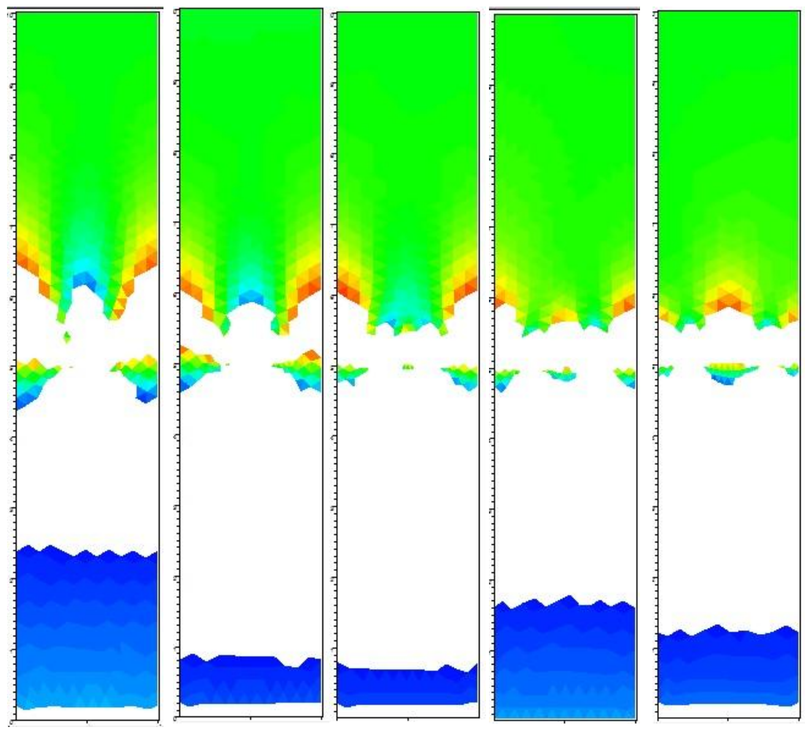
Slope = 0.0012, Q = 0.0509m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



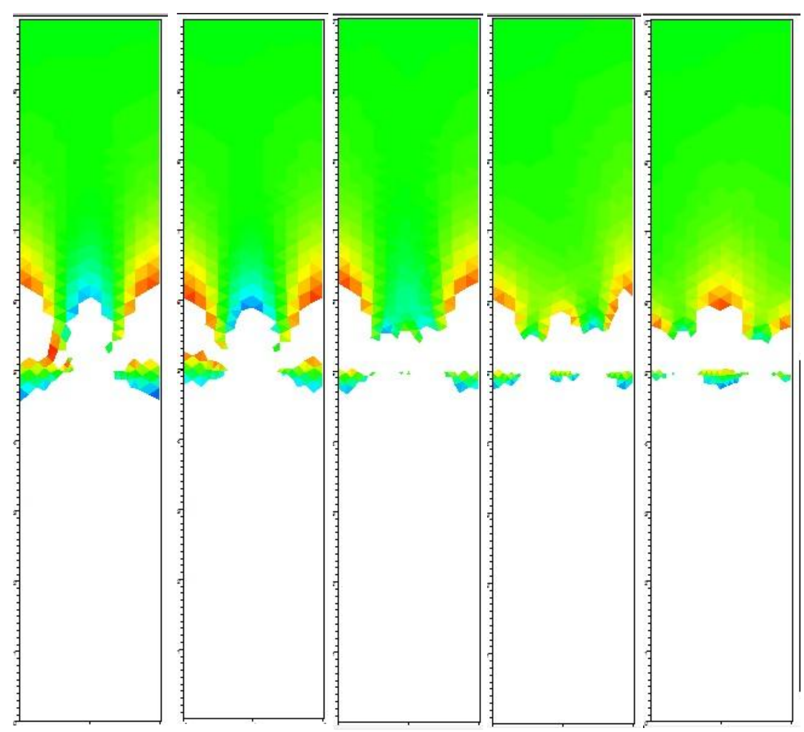
Slope = 0.0012, Q = 0.0880m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



Slope = 0.0015, Q = 0.0220m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



Slope = 0.0015, Q = 0.0509m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)



Slope = 0.0015, Q = 0.0880m3/s, Spacing = 0.10m (far left), 0.20m, 0.50m, 0.75m, 1.0m (far right)

10 Appendix 3: Base Flow Characteristics for Graph Points

Discharge	Slope	Flow Depth	Velocity	Froude Number
m^3/s		m	m/s	
0.00900	0.00	0.0183	0.25	0.57800
0.00900	0.00	0.0177	0.25	0.60800
0.00900	0.00	0.0173	0.26	0.63200
0.00900	0.00	0.0168	0.27	0.65900
0.00900	0.00	0.0167	0.27	0.66800
0.02200	0.00	0.0319	0.35	0.61600
0.02200	0.00	0.0313	0.35	0.63300
0.02200	0.00	0.0306	0.36	0.65500
0.05090	0.00	0.0580	0.44	0.58200
0.05090	0.00	0.0575	0.44	0.58900
0.05090	0.00	0.0566	0.45	0.60300
0.05090	0.00	0.0550	0.46	0.63000
0.05090	0.00	0.0535	0.48	0.65600
0.08800	0.00	0.0812	0.54	0.60700
0.08800	0.00	0.0506	0.55	0.61400
0.08800	0.00	0.0793	0.56	0.62900
0.08800	0.00	0.0770	0.57	0.65700
0.08800	0.00	0.0750	0.59	0.68400
0.5	0.00085	0.25	0.99800	0.637
0.5	0.0009	0.249	1.0030	0.641
0.50000	0.00	0.2480	1.01	0.64600
0.50000	0.00	0.2460	1.02	0.65500
0.50000	0.00	0.2410	1.04	0.67700
0.50000	0.00	0.2400	1.04	0.68100

11 Digital Appendix: Data from all RiverFLO-2D Runs