ENHANCEMENT OF HABITAT HETEROGENEITY BY PLACEMENT OF BOULDERS IN STREAMS

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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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Abstract

Flow velocity and depth are important factors for the habitat requirements of many river fauna and flora. Stream channelization in the past has often homogenized the hydraulic conditions, and therefore increased the need for river rehabilitation methods that increase the heterogeneity of local velocity and depth. A study has been carried out to investigate the influence of boulder placement in a stream on the distribution of depth-averaged local velocities.

The effects of boulder size, shape, arrangement and spacing on local velocity have been assessed by simulation using RiverFLO-2D and experiments in a laboratory flume. The dimensions of the zone of influence within which the local velocity deviates within a specified amount from the undisturbed velocity were determined for single and multiple boulder arrangements. Various shapes were analysed in a wide stream and the results suggest that sharp-edged boulders have more extensive influences than rounded ones. The zone of influence was found to be increased considerably by the placement of multiple boulders in line normal to the flow direction, especially if placed close enough to induce local critical flow. The size of the zone of influence increased exponentially for the incremental addition of a boulder in a linear arrangement.

For nonlinear arrangements, the simulations indicate which boulders are most influential in modifying the flow patterns, hence enabling optimization of the placement. The width of the channel relative to boulder size, number and lateral spacing also affected the size of the zone of influence considerably, increasing it as the channel became relatively narrower. Histograms of local velocity within zones of influence were constructed for selected boulder arrangements. These showed the variance to increase considerably when the arrangement induced critical flow locally. Placing boulders close enough to cause critical flow locally therefore enhances both the size of the zone of influence of the boulder arrangement and the variance of local velocity within it, but was found to be practically effective only within a certain range of undisturbed Froude numbers.

The velocity histograms have been related to the flow class categorisation used in South Africa for defining environmental flows. The results are presented as guidelines for preliminary design, to indicate the number and arrangement of boulders required to create desired flow characteristics over a defined stream area.

KEYWORDS: Boulder placement, velocity distribution, habitat heterogeneity

We don't grow when things are easy; we grow when we face challenges

Joyce Meyer

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A	Area
b	Channel width
B	Boulder
CNC	Computer Numerical Control
d	Diameter
FD	Fast Deep
Fr	Froude number
FS	Fast Slow
g	Gravitational acceleration
H	Depth
η	Water surface elevation
L	Length
LC	Local Control
n	Manning's coefficient
ρ	Water density
q	Discharge per unit width
Q	Discharge
R	Hydraulic Radius
S	Slope
SD	Slow Deep
SS	Slow Shallow
t	Time
τ_b	Boundary shear force
V	Velocity
WUA	Weighted Usable Area
X, Y	Horizontal Co-ordinates
ZOI	Zone of influence

1 INTRODUCTION

Freshwater ecosystems, particularly rivers, play an essential role for society through the provision of food and ecological services such as waste processing. Due to an increase in human needs and activities, there is a rising demand on river resources, which have unfortunately altered the ecological conditions of the majority of rivers. The growth of the human population and the disparity between accessibility and demand of potable water resources is a big concern. It is estimated that 1.8 billion people live under a high degree of water stress, which raises the need for water supply management. The changes in land use associated with the water catchment area become a major stressor on the river's habitat. The continuous construction of dams, flood alleviation and channelization for transportation are particularly important impacts. This human involvement therefore creates a disruption in the flow of rivers, which deviates the conditions of the rivers from their natural states (Giller, 2005).

River Restoration is the action of restoring a river towards its condition prior to development, therefore its natural state. However, this is not always physically possible and often it is difficult to establish the exact historic or natural conditions. River Rehabilitation on the other hand is the aim to repair and significantly recover damaged or lost ecosystem services, which is the basis of this study (Aronson, et al., 1993). Due to an increase in concern for the environment, the topic of river rehabilitation has become a popular subject for research, as the adverse impacts on rivers due to developments has been recognised in recent years. There are many proposed schemes for the rehabilitation of rivers, which consider various physical, chemical and biological characteristics that are associated with the river channels themselves and the riparian habitats existing in them (Woolsey, et al., 2007).

Edwards et al (1984) carried out a study to evaluate the improvement of habitat diversity by means of rehabilitating rivers that have deviated from their natural state due to development. A few of the river rehabilitation projects involved geomorphic reconfiguration in the form of altering the channel, and adding in-stream structures such as the placement of boulders to create artificial pools. They found that the number of invertebrates were higher in rivers that were rehabilitated.

This study will concentrate on re-naturalising channelized streams, with particular emphasis on the physical features of river rehabilitation, particularly the flow conditions. The aim is to try and minimize the deterioration of fish habitats caused by changes in land use with respect to development. One possible strategy to solve this problem would be the strategic placement of boulders in a river bed in order to improve the heterogeneity in the flow velocity and depth. This variation in flow characteristics creates some of the habitat conditions that certain fauna and flora require and the aim is to bring the river's environment as close to its natural state as possible.

1.1 LAYOUT OF REPORT

This research report firstly introduces the importance of velocity and depth in streams and how they have an impact on habitat requirements. The significance of the research in terms of river rehabilitation is explained, making use of the relevant background information and studies previously done by researchers in this field.

Subsequent to establishing the context and importance of the research, the experimental work performed in the Hydraulics Laboratory of the School of Civil and Environmental Engineering of the University of the Witwatersrand is explained. This experimental work was used to verify that the numerical modelling computer program RiverFLO-2D, that was used, was sufficiently accurate. Having achieved verification, a large portion of the data used in this report was derived from the numerical modelling.

The report explains the procedures that were used in the experimental work, and then the procedure used for the computer modelling. The computer modelling was used to determine the effects of the Zones of Influence (ZOI) and Flow Classes around single in-stream boulders. Then the simulation of multiple in-stream boulders was analysed to determine the velocity and depth distributions that are created by the boulders in an array, in order to produce a rough guideline for placing the boulders.

The data obtained are then examined and significant observations are discussed. The conclusions of this research are drawn from the observations made from the results, and recommendations are made for placing the boulders, as well as further research that would be beneficial.

1.2 SCOPE OF WORK

Scope constraints are given to the project in order to prevent continual addition of work to an open-ended topic, as well as to avoid ambiguity in the research. It therefore gives a clear indication of the application of this research.

1.2.1 Assumption and Constraints

This research considers the following:

- The numerical computer simulations only consider undisturbed Froude numbers less than 1, therefore subcritical flow regimes. This is due to instabilities of supercritical undisturbed flow regime which are explained further in chapter 3.3.2.
- Boulders are emergent.
- Unless specified, all river channels will be considered as wide; therefore the Hydraulic Radius is approximately equal to the Flow Depth.
- River banks do not overflow.
- This research concentrates on the 10% ZOI, particularly in proposing a rough guideline.
- For all experiments the mean velocity was measured at 0.6 depth from the bottom of the flume and this is explained further in chapter 4.1.
- The longitudinal direction is the Y axis, and the transverse direction is the X axis.
- For laboratory experiments, velocity distributions are symmetrical on either side of the boulder about the Y axis.

2 BACKGROUND

This research aims to investigate the variations in flow characteristics of velocity and depth around in-stream boulders, with specific interest on how the ZOI is affected by the boulders, and to relate these effects to the flow class categorisation used in South Africa for defining environmental flows. The background for doing this research is detailed below and previous studies that are relevant are considered.

2.1 NECESSARY VARIATION IN VELOCITY AND DEPTH

Hydraulic parameters such as velocity and flow depth have direct and indirect physical influences on aquatic life. Direct influences include modifications of aquatic environment, particularly bed structure, and indirect influences include food availability and oxygen concentrations. Flow obstructions such as boulders have a significant influence on surrounding hydraulics and create important microhabitats for biota. The presence of boulders can have a complex impact on the local flow environment by modifying velocity gradients. The increase in local velocity around the sides of boulders assists various biota in obtaining food, and the decrease in local velocity in the wake zones form important refugia for invertebrates, as well as enhancing the resilience of biota communities to sudden floods. Boulders can also create turbulence and scour, providing fish with cover from visual predators. Riverine salmonid species use flow obstructions as velocity shelters to minimize exertion and therefore save as much energy as possible while migrating upstream. The heterogeneity created by boulders is considered beneficial to biota by providing habitats suitable for various life stages (Harvey & Clifford, 2009).

Jowett & Richardson (1990) carried out a study to see if invertebrate groups exhibit significant preferences to velocity, depth and substrate. They applied computer software that integrates the measurements of these variables, with statistics on the suitability of the habitat for a target species. They found that invertebrate abundance increased with depth until a maximum depth of 0.4m. A broad range of velocities was found to be suitable as this allowed invertebrates to find satisfactory habitats. The velocity preferences may however change with size of the species or life stage.

Studies of river fish assemblages have shown that abiotic factors such as temperature, current velocity, water depth and substrate can determine the distribution and abundance of various species (Rahel & Hubert, 1991). Edwards et al (1984) found that rehabilitated rivers are more effective when a wider range of substrate types and increased variance in depths and velocities are created.

Finlay et al (1999) used the variation in stable algal carbon isotopes between river habitats to study the energy flow through river food webs. They found that there was a strong relationship between carbon isotopes and water velocity. The results suggested that water velocity affects the variation in algal carbon isotopes, as the availability of CO and CO_2 affects photosynthetic rates. The velocity therefore contributes to the supply of these carbon molecules and therefore to the growth in vegetation and habitat diversity.

This study sets a scenario using boulders for river rehabilitation to create a large variation of velocities and depths and hence to satisfy as many habitat requirements as possible. A probability distribution function for velocity that has a high standard deviation needs to be achieved. Therefore there is a high probability that the velocity measurements for a random set of measurements would be spread out over a large range of values and would be disparate to the mean value. Flows with higher turbulence are expected to have a higher standard deviation in their velocity distributions (Harvey & Clifford, 2009).

2.2 ECONOMIC CONSIDERATIONS

The deterioration in river conditions has resulted in undeniably high and continually increasing costs to a country. Such costs include: loss of fisheries; bank collapse and consequent construction costs; increasing levels of water pollution and linked health costs; loss of river habitats and rare species; and loss of aesthetic & recreational value (King, et al., 2008). The South African government has however acknowledged the importance of the conservation of river ecosystems, through the legislation of the National Water Act (NWA, No. 36 of 1998), and thereby protecting our water resources (Hirschowitz, et al., 2007). The development of water supply resources and flood mitigation features are necessary and unavoidable. These changes in land use with associated impacts on the river courses should be correctly managed in order to reduce the need for river rehabilitation and the expenditure that comes with it.

Policy schemes are required in the management of rivers, which should incorporate the triple bottom line of sustainability which are recognized as: the social aspect (such as protection from floods and supply of water resources), the environmental aspect (such as the preservation of surrounding ecosystem and maintaining biodiversity), and lastly the economic aspect (such as job creation and budget). An important element to consider which is often overlooked is the participation of all stakeholders in the decision-making process. The addition of local knowledge will assist in resolving issues and mitigating conflicts as consensus among stakeholders is vital (Woolsey, et al., 2007).

The costs and benefits to implement river rehabilitation measures are difficult to quantify precisely as it is very challenging to define whether they are a success or failure, as there is no standardized approach for evaluation. The topic is strongly debatable because measurable parameters are not sufficient when there are subjective aspects to consider, such as aesthetics or recreational values, which are generally left out, although they play an important role in the perception and communication of rehabilitation success. River rehabilitation has recently become a *"billion-dollar business"*, and more resources are in place to improve river rehabilitation strategies, which is evident from rapidly increasing numbers of publications (Jähnig, et al., 2011).

2.3 HABITAT REQUIREMENT

There is a need to understand the habitat requirements of particular species, as this forms an essential starting point of a rehabilitation process. The hydraulic conditions that are most favourable for different species form part of this requirement. When these requirements are established, then a model can be produced to predict the occurrence of hydraulic conditions which create the required habitat of species in a river. The ecology of a river depends primarily on whether the flow in the river is deep or shallow, fast or slow, eutrophic or oligotrophic. For instance, the existence of a fish population in a river may be dependent on suitable sites with fast turbulent flow for spawning and the delivery of nutrients, and slow protected sites for refuge from predators and flooding (Lehtonen, 1999).

It is important to note that habitat requirements are different from one species to another and altering the flow to suit one species may be to the detriment of another. There are currently many studies which are focused on defining the habitat requirements of various freshwater fish species, such as the research undertaken by the Centre for Catchment and In-Stream Research at Griffith University, where essential data are collected (Arthington & Zalucki, 1998). In terms of habitat, the factors focused on in this study are the physical abiotic variables of water depth and velocity. Since the organisms within this ecosystem have different requirements, it is attempted to produce a diversity of conditions by manipulating these physical abiotic variables in order to create a diversity of habitats.

Various approaches have been established to assess the effects of hydraulic changes on aquatic organisms. Particular ones used in South Africa are: Habitat Suitability Criteria, Flow Classes, and Hydraulic Biotopes (Paxton, et al., 2010). This study will focus on the use of Flow Classes to define hydraulic habitat requirements.

The Habitat Suitability Criteria approach was developed for defining the hydraulic habitat most commonly used by a specific river species. It involves collecting data on depth, velocity and substratum particle size at rivers where a species of interest is found. These data are then used to describe hydraulic habitat conditions for the species. However, the disadvantages are the difficulty in using a model developed with data from one river to predict habitat quality in other rivers, and it is also time-consuming, therefore not feasible to derive them for every species in a river (Paxton, et al., 2010).

Hydraulic Biotopes are another approach to describing hydraulic habitat. A biotope has distinctive biological species associated with it. Therefore hydraulic conditions associated with a certain biotope can be used to define the living conditions of a species (Paxton, et al., 2010). Examples of hydraulic biotopes include riffles, runs, pools, glides and rapids. These are subject to change by channel morphology, substrate and flow conditions (Arthington & Zalucki, 1998).

Flow Class categorisation divides the flow in a river into different ranges of velocities and depths that can be related to various groups of organisms. Four classes, as defined by Kleynhans (1999) are shown in Table 2.1.

Table 2.1: 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

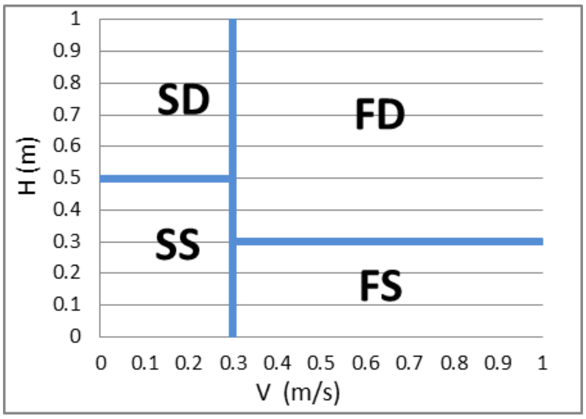


Figure 2.1: Diagram illustrating Flow Classes

Birkhead (2010) highlighted additional classes that cover further ranges of flow velocities and depths used for characterising hydraulic conditions for invertebrates. These additional flow classes also consider substrate types and inundated vegetation as indicators of flow requirements for various organisms. This study concentrates mainly on the four flow classes according to Kleynhans's (1999) which is shown in Table 2.1; however it is important to acknowledge the additional classes and it is recommended that for future work, this study should be extended to include these classes. The additional velocity classes that have been defined for macro-invertebrates include the ranges: <0.1 m/s, 0.1-0.3 m/s, 0.3-0.6 m/s and >0.6 m/s. The additional depth classes include the ranges: 0.0 - 0.1 m, 0.1 - 0.2 m, 0.2 - 0.3 m, 0.3-0.5 m and >0.5 m. Flow Classes is semi-quantitative and therefore a quicker and cheaper method to use, it is also compatible with hydraulic modelling. However, it should be noted that not all fish and invertebrate species perceive habitat in the way described by this method (Paxton, et al., 2010).

2.4 PRACTICAL USE OF BOULDERS IN RIVER REHABILITATION

During the last two decades, affected watercourses have been rehabilitated by removing barriers and replacing boulders into river channels. Boulders assist in the increase in habitat diversity by providing refuge with low velocity zones for fish to rest and feed and high velocity zones for spawning and food delivery (Engström, et al., 2009).

Schueler & Brown (2004) and Rutherfurd et al. (2000) recommended a set of approaches for placing boulders in rivers in order to improve in-stream habitat. The boulders are suggested to be placed mid channel to prevent localised bank erosion and their size should be less than roughly a fifth of the width of the river, they should be heavy enough to withstand expected current velocities and they should project slightly above the water surface. The boulders should be placed in triangular groups of three to five and they should be separated by about one boulder diameter. Large angular boulders should be used, and should not be placed in the zone of influence of the other boulders. Turbulence should be encouraged to aerate the water. This study aims to substantiate these recommendations and add to them.

Oxygen depletion often occurs in rivers that suffer from eutrophication, which arises from an excess in nutrients that have run off from the land into the river; this causes an increase in plant life and reduces the available oxygen for the fauna in the area. The reduction in oxygen reduces the space that fish can occupy, and the potential for fish deaths increases due to an increase in anoxic water. This study is not particularly concerned with the chemical requirements of oxygen in the rivers but boulders will tend to increase turbulence and assist in the mixing of oxygen into the waters, and therefore serve in rehabilitating eutrophic rivers (Muller & Stadelmann, 2004).

Engström et al. (2009) conducted a study to assess the efficiency in retention of propagules (such as a bud or spore) by river rehabilitation structures, such as boulders. They released propagule mimics (cubes, which were colour coded) and placed propagule traps (fine meshed nets) in the riparian zone. They found that retention of propagule mimics was highest in sites rehabilitated with boulders and therefore this encourages growth of vegetation and increase in diversity of habitats.

There are many current uses of boulders for rehabilitation of rivers and many studies have been carried out on the efficiencies of these in-stream structures, some of these investigations are mentioned in Table 2.2.

Table 2.2: Studies relating to the use of boulders for River Rehabilitation

Study	Location	Significance
Rutherfurd et al (2000)	Ryans Creek, Victoria, Australia	Found that the use of boulders for river rehabilitation was a low-cost alternative and effective for rehabilitation
van Zyll De Jong et al (1997)	Joe Farrell's Brook, Newfoundland, Canada, which had been negatively affected by forest harvesting activities	Found that the placement of boulder increased habitat diversity through increased variability in depths, velocity and in-stream cover
Lepori et al (2005)	Ume River, in northern Sweden, where several kilometres of streams have been rehabilitated from channelization for timber transportation	Their study suggests that the placement of the boulders had no substantial consequences for the diversity of fish and invertebrates
Huusko & Yrjänä (1997)	River Kutinjoki in northern Finland	Found that the placement of boulders increased habitat diversity and created high local gradient and fast currents.
Merz et al (2004)	Mokelumne River, California, USA, 7 large boulders were placed in a 155 meter reach	Found to enhance spawning conditions, increase velocities, and provide refuge from predators and resting zones.
Dolinsek et al (2007)	Catamaran Brook and the Little Southwest Miramichi River, in New Brunswick, Canada, 36 boulders were added	Found that the addition of boulders increased the variability in depth and velocity and improved habitat quality in that stream. However, the positive effects decreased with increasing age of juvenile Atlantic salmon, as habitat preferences changed.

2.5 2-DIMENSIONAL NUMERICAL MODELLING OF BOULDERS

Organisms in rivers respond to both water depth and velocity, therefore these factors need to be specified over space and time, this often requires sophisticated modelling techniques and measurements for calibration (Paxton & King, 2010). The advances in technology and the development in knowledge of river management have led to detailed analyses becoming a routine and therefore an increase of reliance on numerical simulation programmes in order to predict hydraulic conditions.

This study is concerned with 2-Dimensional (2D) hydrodynamic modelling, which generally uses the depth-averaged Saint-Venant equations. 2D modelling is increasingly used for aquatic biology and geomorphology. If the requirement is to model general flow characteristics of a long river reach and to acquire maximum or mean depth and velocity at a cross-section, then a 1D model should be satisfactory. However, for the investigation of variations of depth, velocities and flow intricacy around large roughness elements, then a 2D model should be used to identify the lateral velocities along the relevant section of the river (Shen & Diplas, 2008 ; Pasternack, et al., 2004). When integrated with quantitative estimates of preferred physical habitat conditions, 2D models are an influential tool for predicting fish habitat. With the use of nodal velocity vectors provided by meshing, the hydraulic conditions can be used to identify requirements for local habitats (Pasternack, et al., 2004).

There are numerous studies of 2D modelling for flows of rivers that employ various in-stream features for river rehabilitation, but the main concerns for this study are those related to the analysis of hydraulic conditions surrounding boulders. The following studies have carried out investigations on this:

Pasternack et al. (2004) studied current projects which incorporated gravel and several boulders to rehabilitate spawning habitats. They used a modelling package to design and evaluate alternative configurations in order to improve on them and compare the spawning habitat value. The results showed that 2D depth, velocity, and shear velocity predictions were sufficiently accurate to conclude that 2D modelling is adequate to assess potential alternative scenarios for habitat quality prior to construction and is therefore an effective tool for river rehabilitation design.

Shen & Diplas (2008) conducted a study to assess the ability of 2D and 3D hydrodynamic models to reproduce localized complex flow patterns that are found surrounding in-stream channel features, such as boulders. The numerical results were compared to field measurements, and the results were found to show close agreement between the two, proving the numerical models to be an important tool for aquatic habitat assessment.

Crowder & Diplas (2000) recognized that proper description of the channel and adequate mesh development is crucial to obtaining accurate numerical results. They also found that boulders significantly influence the predicted flow patterns of the river, and therefore the habitat conditions in the vicinity of the boulder. A single boulder affected flow roughly to 6-8 times the boulder's diameter downstream of the obstruction.

Lee et al (2010) analysed the hydraulic characteristics of fish habitat in an urban channel using River2D, a 2-Dimensional hydrodynamic model software, to improve the habitat of two target fish in the Daejeon Stream, Korea. They found that boulders placed at intervals in the channel bed significantly increased habitat availability and flow conditions around it. They therefore recommended that an appropriate placement of the boulders should be researched and implemented, with consideration of the characteristics of the riverbed and target fish species.

Waddle (2010) collected depth and velocity data in the vicinity of two large boulders in the South Platte River in Colorado. 2D modelling was used to simulate these flow patterns to compare with observed values. It was found that the 2D models gave generally accurate representation; however, it was suggested that errors in the simulation can be reduced by adequate quality control in data collection and calibration stages.

It is important to note that a numerical model is only as good as its input data; the quality of the output of a hydrodynamic model is reliant on the quality of the input. The collection of data is therefore a vital component in assuring accurate results (Steffler & Blackburn, 2002).

Barriers along river systems such as dams and weirs have a significant impact on the connectivity of a river system as they disrupt the flow and habitat requirements of a river. Subsequently many manmade channels such as fishways have been implemented to help fish move past these barriers and therefore restore connectivity. Many drainage channels such as those through golf courses are also important for longitudinal connectivity for fish habitats. These channels however do not adequately provide fish with the required habitat conditions and therefore it is necessary to incorporate rehabilitation measures. Migratory fish are particularly susceptible to connectivity loss as this affects their ability to reach spawning grounds (Branco, et al., 2012).

Branco et al. (2012) considered fishways in their study and used a 2D hydrodynamic model to test the effect of boulder placements on the weighted usable area (WUA). WUA is the surface area that can be utilised by a specific fish species at a particular life stage; it is dependent on depth, velocity and substrate (Payne, 2003). Branco et al. compared the results of the 2D model to experimental results using a full scale fishway. They incrementally added boulders to evaluate the effects of increasing the density of the boulders on the WUA. They found that in-stream boulder placement increases the WUA until a certain density of the boulders is reached. They suggest that high densities create strangled sections with intolerably high currents. Lower densities of the boulder configurations prove to be more successful at helping fish move through the fishway, as the flows were sufficient to orientate and stimulate the fish to progress, whilst still providing resting areas. They recommend that boulder placement must be specifically designed for each case of river rehabilitation with particular emphasis on the habitat requirement of the specific fish species involved.

As different fish species and life stages have different habitat requirements, this study will demonstrate that a general guideline for boulder placement can be achieved through the application of the “Flow Classes for fish” criteria given in Table 2.1.

2.6 OBJECTIVES

The overall project objective is to develop a guideline for the optimal placement of boulders, in order to optimise the distribution of the flow depth and velocity, and to assist rehabilitation of river habitats. The specific project objectives are as follows:

- Validate the simulation results of the numerical software against actual experimental results carried out in the flume. Then apply the software to develop a comprehensive numerical tool in order to analyse various scenarios.

- Assess how certain variables affect the distribution of flows, i.e. spacing and diameter of the boulders; slope, width and discharge of the channel. Then carry out a sensitivity analysis on the variables.

- Determine the ZOI for different boulder configurations and develop a histogram to demonstrate the variation of velocities in the considered area.

- Identify how the in-stream boulders affect the flow classes presented in Table 2.1, and to see if the boulders can manipulate the flow to give the required flow classes. Therefore to see if they produce a large variation of velocity and depths to satisfy as many habitat requirements as possible.

- Investigate the effects of a local control between boulders, on the velocity distribution histograms and flow classes in the channel.

- Investigate the effects of an array of boulders on the size of the ZOI. This will help optimise the placement of the subsequent array of boulders to the sides and downstream. The placements are such that the arrays of boulders are out of each others' zones of influences and therefore act independently. In doing so, reducing costs.

3 METHODOLOGY

3.1 PROCEDURE

The ArgusONE and RiverFLO 2D programs were primarily used to perform the analysis of the flow characteristics surrounding in stream boulders. The numerical model simulated the velocities, flow depths and Froude numbers.

In order to show that the results from the software are accurate, the simulation results were compared to the experimental results carried out in the flume of the hydraulic laboratory in the Hillman building at the University of the Witwatersrand. Depths and velocities were measured using a Nortek Vectrino I hydraulic measuring probe. The data acquired from the experiments were also used to calibrate the bed roughness of the 2D Model and to establish the boundary conditions, specifically the water surface elevation at the downstream and upstream cross sections.

Once the modelling had been validated, a model was developed to analyse the considered variables (the spacing, number and the diameter of the boulders) as well as the slope, width and discharge of the channel. In order to see how responsive the simulations are to the different variables, a sensitivity analysis was carried out. This was done by evaluating the changes in results by adjusting one variable and keeping all the other variables constant.

The aim was to present the results as a rough guideline for preliminary design of placing boulders in a channel in order to produce as high a variation of flow depths and velocities as possible. The guideline considers the significant variables mentioned above as the input, and then indicates the number and arrangement of boulders required to create desired flow characteristics over a defined stream area.

The first phase testing was to determine the ZOI of a single obstruction boulder and then multiple boulders. Therefore the first simulation was with only a single boulder placed in the centre of the virtual flume, in order to determine how much of an effect it has on the velocity in the transverse and longitudinal direction. Then boulders were added incrementally to see how the ZOI was affected. The ZOI was determined by the area of the channel containing all the measurement points with a value of velocity that falls within a certain range, different to the undisturbed flow. This ZOI is useful as it gives an indication of the distance that the next group of boulders should be placed downstream.

Tools were developed in order to assess the flow distributions, in terms of the changes in flow depths and velocities.

- The first tool was developed on Excel: a histogram. This tool represents the variation of velocities, i.e. the proportion of the total area that changes by a certain velocity. This tool can also be used to represent the various proportion of the total area that falls into the respective flow classes.
- The second tool was developed on Matlab; a method to graphically represent the ZOI in the channel. It also graphically represents the velocity distribution of the laboratory and computer results.

After the tools were developed, simulations were run in the numerical model to determine the required conditions in order to achieve a probability distribution function for velocity that has a high standard deviation. The simulations were run with undisturbed conditions and then the boulders were added, moved or removed in order to create the required changes in ZOI and Flow Classes.

The investigation eventually led to analysis of how the certain variables affect the distribution of flows and then produced a guideline for implementation of the boulder patterns in river rehabilitation. Ample measurements were taken in order to plot graphs and to establish patterns.

3.2 CONDITIONS OF THE LABORATORY EXPERIMENTS

In order to validate that the computer simulation results were accurate, the simulations were compared against laboratory experiments results. The laboratory experiments were carried out to investigate the distribution of water velocities around boulders. These boulders were represented by cylinders in the flume. The experiments were undertaken in the University of the Witwatersrand Civil Engineering Hydraulic Laboratory.

The flume used is 1.0m wide by 10m long, the water is circulated keeping the flow constant through the use of pumps and valves. The flume is installed with a Computer Numerical Control (CNC) system that controls the slope, the discharge and the position of the Vectrino I (velocity measuring probe). This system is managed through computer software that directs the instrument.

- The CNC system has a chain mechanism that adjusts the inlet valve in order to control the discharge entering the header tank. The discharge can be checked by an electronic meter located in the flume's inlet pipe or by using the v-notch weir at the outlet.
- The CNC system controls the automatic jacks at the front of the flume which are used to adjust the slope of the flume. The flume was surveyed in order to check that the slope was correct.
- The Vectrino I is mounted onto the CNC equipment, where the co-ordinate of each measuring point is inputted into the software and the probe is moved from one measuring point to the next.
- There are measuring tapes along the length of the flume to measure flow depth. The flume also has several piezometers installed along its length in order to measure the depth of the flow.
- There is a sluice gate at the outlet of the flume that can be adjusted so as to control the depth of the water flow in the flume, and create uniform conditions where necessary.
- The Manning's n of the flume was found to be 0.010. This was calculated by running several uniform flows and measuring the depths whilst the discharge was kept constant, then applying Manning's equation:

$$n = \frac{R^{2/3}.S^{1/2}}{V} \tag{3.1}$$

Where n is Manning's roughness coefficient, S is the channel Slope, V is the Velocity of the flow and R is the Hydraulic Radius. Manning's n is a vital component in the calibration of the numerical models, so that the flume measurements correctly match the numerical model.

3.2.1 Nortek Vectrino I (Side-Looking Probe)

The velocity of the flow was measured with a 3D Acoustic Doppler Velocimeter (ADV) shown in Figures 3.1 to 3.4.

Figure 3.1: Vectrino (Front)

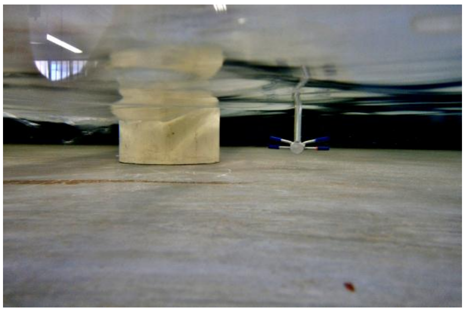


Figure 3.2: Vectrino (Back)

Figure 3.3: Vectrino (2 Boulders)

Figure 3.4: Vectrino (1 Boulder)

The Vectrino Velocimeter measures the speed of the water by using the Doppler Effect. The Vectrino transmits a sound wave to a certain sampling point and then waits for the echo back to the Vectrino. The sound wave is reflected off the suspended particles in the water such as zooplankton or suspended sediment; these particles are moving at the same average speed as the water. The sound wave is at a certain frequency, and after measuring the frequency of the return pulse, the Vectrino is then able to determine the velocity of the water from the difference in the 2 frequencies. The velocity of the sound wave is directly proportional to its frequency. The sound wave is transmitted through a central beam and is received through the four beams displaced off to the side (Nortek, 2004).

3.3 CONDITIONS OF COMPUTER SIMULATIONS

The numerical modelling was done by integrating 2 softwares; the RiverFLO-2D numerical engine by Hydronia LLC (which is capable of analysing the flow in rivers in two dimensions), with the ArgusONE software, which serves as the pre and post processor for the numerical engine. Therefore ArgusONE assists in creating the required input data files as well as visualizing the output developed by RiverFLO-2D. The software used for the 2D Modelling is described first, and then the conditions of the simulations.

3.3.1 Description of the RiverFLO-2D & ArgusONE Software

In this study ArgusONE serves as the graphical user interface for the RiverFLO-2D numerical engine, as a pre- and post- processor. Pre-processing refers to the collection of initial data and development of required input files for the numerical engine RiverFLO-2D. ArgusONE allows for the inputting of data in different layers, firstly the geometry of the channel was set-up; this was done by importing the x, y and z (elevation) co-ordinates of the flume bed as a set of nodes. In the next layer, the flume channel and the in-stream boulders were then outlined using the domain feature; here the densities of the meshes were specified. The mesh generated can be specified to have different densities in areas that require it, as the smaller the meshes, the more accurate the analysis. The area around the boulders was therefore more densely meshed (Argus-Interware, 1997).

ArgusONE then automatically translates the previous layers to a mesh geometry supported by RiverFLO-2D. It divides the flume into discrete elements. The engine can then process the mesh geometry and the required input to generate a solution for the specific mathematical equations used by the engine. The automatic mesh generation in Argus ONE is carried out using the Delaunay triangulation algorithm, which is essential to avoid instability and it allows for a more efficient method of creating the model (Argus-Interware, 1997).
The flume's Manning's n parameter and the boundary conditions were then assigned in additional layers. The boundary conditions of the inflow discharge and the outflow water elevation are crucial in the simulation carried out in RiverFLO-2D for evaluating the flow characteristics, and therefore these parameters, including Manning's n are required to be

calibrated. After RiverFLO-2D runs its calculations and outputs the solution as data, this data is then post-processed in ArgusONE, which allows manipulation of the data in a way to display it in an understandable manner for presentations, such as graphical representations of the flow characteristics (Argus-Interware, 1997).

RiverFLO-2D specializes in riverine and sediment transport applications. The governing equation in the RiverFLO-2D numerical engine software is the shallow water or Saint Venant equations, for depth-averaged flow and it makes use of finite element methods. It computes the outputs that we require such as velocity and water surface elevation (Hydronia LLC, 2009a).

$$\frac{\partial \eta}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0 \tag{3.2}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + g\frac{\partial \eta}{\partial x} + \frac{\tau_{bx}}{\rho H} = 0 \tag{3.3}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + g\frac{\partial \eta}{\partial y} + \frac{\tau_{by}}{\rho H} = 0 \tag{3.4}$$

Where: x and y are the horizontal coordinates, t is the time, η is the water surface elevation, H is the water depth, U and V are the vertically averaged velocities in x and y directions respectively, ρ is the water density, g is the gravitational acceleration. The boundary shear variables τ_{bx} and τ_{by} are defined as follows;

$$\tau_{bx} = \frac{gn^2 U\sqrt{U^2+V^2}}{H^{4/3}} \tag{3.5}$$

$$\tau_{by} = \frac{gn^2 V\sqrt{U^2+V^2}}{H^{4/3}} \tag{3.6}$$

And n is the Manning's roughness coefficient (Hydronia LLC, 2009a).

This software makes use of inputs, such as the geometry of the channel, the surface roughness and the boundary conditions. The area considered, was divided up into mesh elements which are all connected and act in response to each other. In this study, the meshes were all three-node triangular elements. The software applies the Galerkin weighted residual method to the governing shallow water equation, as well as all relevant continuity equations. This broke the analysis of the flow into smaller more manageable discrete units. This method therefore permitted the problem to be solved discretely with numerical method techniques (Hydronia LLC, 2009a).

3.3.2 Computer Modelling Conditions

Various models were created for runs in RiverFLO-2D for the investigation into flow velocity distributions. All the models represent a rectangular virtual channel with varying slopes and discharges.

- The boulders are represented by cylinders and are placed in the centre of the channel, where possible the placements are symmetrical about the x or y axis or both, i.e. placed evenly in the middle of the length and evenly in the middle of the width of the channel. Refer to Figure 3.5.
- The boulders are aligned normal to the flow direction.

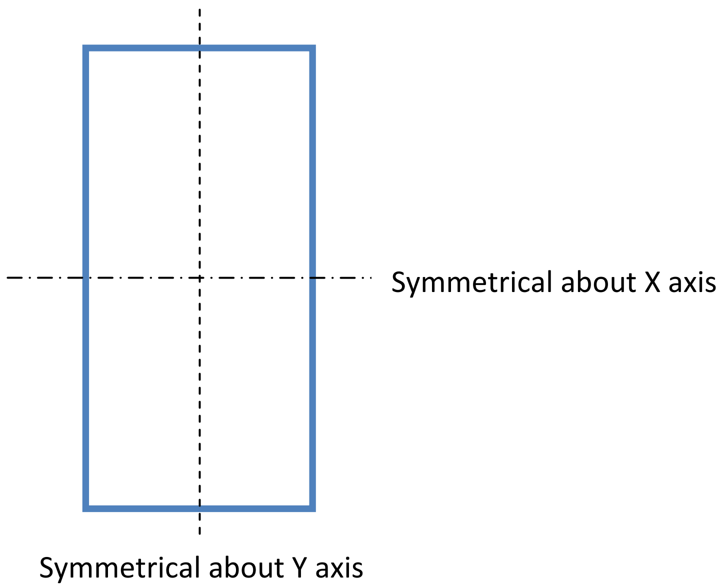


Figure 3.5: Illustration of X & Y axis

For the varying discharges, the corresponding outlet water surface elevations were calculated for each slope using the Manning's equation for uniform conditions and then the flow depth with its corresponding discharge was used as input for the boundary conditions. All models used the boundary conditions of an inlet discharge in m^3/s and an outlet water surface elevation in m. The first models created were to replicate the Laboratory experiments for comparing results and to verify the software. The models were calibrated using the Manning's roughness coefficient calculated in the flume of the Laboratory. Manning's n for all channels were calibrated to 0.010.

Further models created are discussed in detail in Chapter 5 and they include:

- Assessing the Generalised Zone of Influence created by placement of in-stream Boulders
    - Section 5.1: Linear Arrangements; 1, 2, 3 and 4 Boulders placed in the centre of the channel - varying the Slope, Width & Discharge of the channel, and the Diameter & the Spacing of the boulders in the *X* Direction
    - Section 5.2: Placement of Boulders Downstream; 2, 3 and 4 Boulders - varying the Spacing of the boulders in the *Y* Direction
    - Section 5.3: Non-Linear Arrangements; 3 and 4 Boulders - varying the Spacing of the boulders in the *X* and *Y* Directions
- Assessing the effects that different shapes of boulders have on the flow
    - Section 5.4: Square, Circle, Triangle, Inverted Triangle and Diamond Shapes
- Assessing the Flow Classes created by placements of in-stream Boulders
    - Section 5.5: Evaluating how the placement of boulders affects the proportions of Flow Classes of the channel, compared to the undisturbed flow - 0, 1 and 2 Boulders.

The density of the meshes will determine how accurately the model represents reality, the finer the meshes the closer it will characterize the physical bathymetry. Therefore if the meshes are too coarse then it could lead to inaccuracies, however it must be considered that if the meshes are too fine then it could lead to instabilities (Argus-Interware, 1997). The density also affects the simulation run time and requires a greater processing capacity. For this study, greater detail is required around the boulders; therefore larger densities of mesh elements were used along the channel boundaries and finer densities of mesh elements around the boulders. The length of the mesh elements were at a maximum of 0.18m and at a minimum of 0.018m.

The flow characteristics for the mesh nodes at the starting time of the simulation are input as the initial conditions, which are required for the running of the model, and therefore are assigned in RiverFLO-2D if they are known. If no suitable information is available as in our case, RiverFLO-2D allows the user to assume either a dry channel bed or wet bed with the water at rest, therefore a flat horizontal water surface elevation. This study assumed a wet bed as the initial condition; this assigned initial condition reduces instabilities (Hydronia LLC, 2009a).

The modelling carried out in this study was concerned with an undisturbed (i.e. without boulders in place) Froude number of less than 1, therefore subcritical flow regimes. The scope did not include conditions that create supercritical flow regimes of undisturbed flows, as the hydrodynamic modelling has associated instabilities (Beffa, 2008). Gravitational forces are dominant in subcritical flow which is characterized by low velocities, and inertial forces are dominant in supercritical flow which is characterized by high velocities (Chow, 1959). The St. Venant equations are therefore influenced differently by the 2 flow regimes.

It is possible to overcome model instabilities by refining the initial conditions and the boundary conditions. RiverFLO-2D requires proper use of the boundary conditions for a successful simulation. For subcritical flows, it is required to provide a condition at the inflow boundary (discharge or velocity) and one for the outflow boundary (water surface elevation). However, for supercritical flow all conditions must be imposed on the inflow boundary (discharge or water surface elevation) and no condition on the outflow boundary (free). It must be noted that having only discharge and no water surface elevation may result in instabilities due to violation in the theoretical boundary condition requirement of the shallow water equation (Hydronia LLC, 2009b).

Instabilities may also be caused due to all the mesh elements being dependent on the neighbouring elements to determine flow characteristics, and when fluxing occurs, there is unsuccessful convergence and flow characteristics may fall out of the tolerance limitation of the software (Beffa, 2008). These instabilities can be dealt with by adjusting the initial conditions. Due to time constraints of this master’s research and to avoid errors, this study will only be applicable to undisturbed Froude number less than one. Therefore a recommendation for future work is to carry out investigations of zones of influences and flow classes created by boulder placements in undisturbed supercritical flow.

4 LABORATORY EXPERIMENTS AND MODEL VALIDATION

4.1 EXPERIMENTS CONDUCTED

To test the accuracy of the numerical model software, it was essential to gauge how the outputs compare to the laboratory experiments. Therefore it was important to strategically decide which experiments would be necessary to ensure that the software would be validated.

Assessments were carried out on how the software reacts to changes in the slope, as well as the discharge. The first five experiments shown in Table 4.1 have the discharge and slope adjusted, whilst having 1 boulder in the centre of the flume. It was then decided to compare how the numerical model compares to flow around 2 boulders, one scenario produces a local control between the boulders and the other does not, this is depicted in the last two experiments in Table 4.1.

Table 4.1: Conditions of Laboratory Experiments

Experiment No.	*No. of Boulders*	*Discharge (m^3/s)*	*Slope*	*Measured Depth*
1	1	0.0278	0.0008	0.6
2	1	0.0347	0.0008	0.6
3	1	0.0417	0.0008	0.6
4	1	0.0278	0.0005	0.6
5	1	0.0278	0.001	0.6
6	2 (Local Control)	0.0417	0.0008	0.6
7	2 (No Local Control)	0.0417	0.0008	0.6

The experiments measured the velocities at deliberate positions in the flume. Velocity distributions were assumed to be symmetrical about the Y axis of the channel. Therefore measurements were only taken at points on one side of the centreline, the measuring points for experiments 7 are shown in plan in Figure 4.1. The measuring points in plan for experiments 1 to 6 are shown in Appendix 1. The co-ordinates for the measuring points of all the experiments are in Appendix 1. The Probe was stopped at each measuring point for 40 seconds to take readings, the velocities measured during this time period were then averaged.

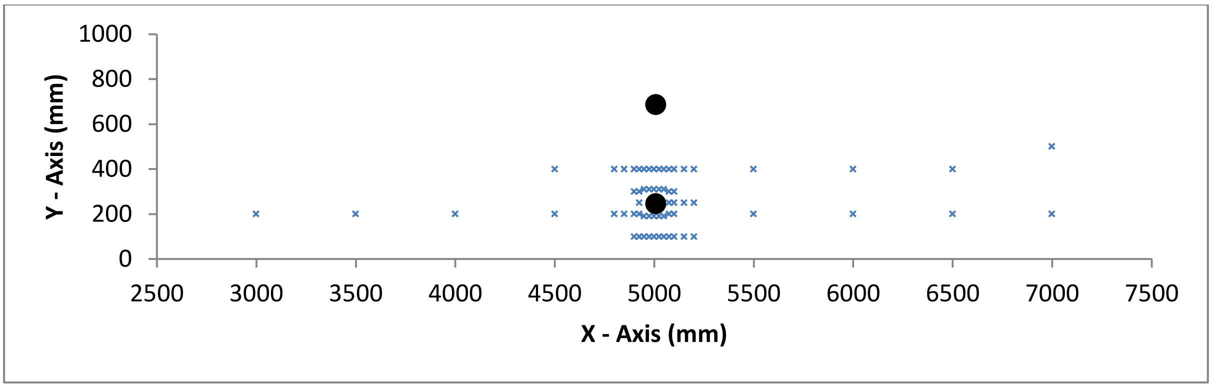


Figure 4.1: Measuring Points for Experiment 7

The velocities measured in this study were taken at 0.6 of depth, this is due to the assumption that the “mean” velocity will be acquired by measurements at this depth. Extensive experiments have shown that the mean velocity occurs between 0.5 and 0.7 of the total depth, this is determined by assessing the vertical velocity distribution curve (Horton, et al., 1906). In general practice the mean velocity is considered to be at 0.6 of the depth (Pierce, et al., 1941). This is known as the six-tenths-depth method and is generally used for shallow flows (United States Department of the Interior Bureau of Reclamation, 2001).

4.2 COMPARISON OF EXPERIMENTAL RESULTS AND SIMULATION

The measured results were then compared to the predicted software results. This was done by plotting the velocities of the two samples on Excel and then the measurements were analysed statistically to see if they correlate. Subsequent to that, the velocities were presented graphically by generating the contours on Matlab, and then the velocity frequencies were presented in histograms.

4.2.1 Comparison of Measured Velocity with Predicted Velocity

Figure 4.2 represents the measured velocity plotted against the predicted software velocity for one of the experiments (Experiment 6). The figures for the rest of the experiments (Experiments 1-5 & 7) are available in Appendix 1. The statistics to calculate the P-value and the R square value were found using the software GraphPad Prism 5 and are shown in Table 4.2 below.

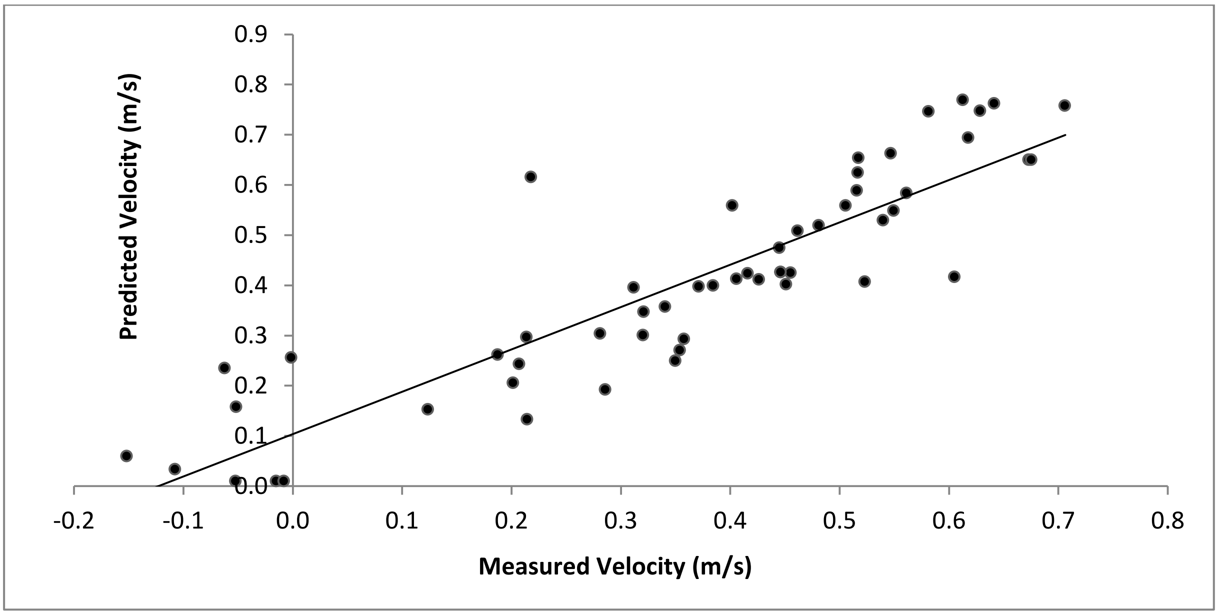


Figure 4.2: Measured vs. Predicted Velocities for Experiment 6

Table 4.2: P value and R-square Value for the measured and predicted samples

Experiment	***P - Value (Mann Whitney test) Unpaired, α = 0.05***	***R-Square***
1	0.119	0.871
2	0.063	0.860
3	0.290	0.838
4	0.576	0.846
5	0.109	0.863
7	0.169	0.821
	P - Value, Normal Distribution (t- test) Unpaired, α = 0.05	***R-Square***
6	0.260	0.783

Only experiment 6 represents a normal distribution and therefore the t-test was used for it, the others were assessed using the Mann Whitney test. All the P-values were calculated assuming that the samples are unpaired, i.e. one sample is not dependent on the other. For alpha = 0.05, the p values for all the experiments show that the null hypothesis can be rejected and that there is no significant difference between the measured and the predicted samples. Therefore the correlation between observed and expected was assessed by looking at the R^2 value.

R-square is a useful measure of how well the model fits a set of observations. The R-square value was however evaluated in conjunction with another statistics application to see that the results were not just by chance; therefore the p-value was calculated. R^2 is the fraction of the total squared error by the model and thus values closer to one are desirable. Often data contain clear errors as in this case, which can be explained by the random variability in the material response that the model may not be able to account for (Annis, 2008). This variability is uncontrollable, it is portrayed as deviations in material characteristics such as temperature and turbulence, and therefore the model will not predict every point.

The variability is demonstrated by the outliers and the negative velocities from the readings, shown in the Measured vs. Predicted Velocities figures; these can be explained by the fact that the conditions of one experiment will never be identical to that of another due to the turbulence around the boulder. The velocity fluctuations can be attributed to eddies, which is the swirling of a fluid and the reverse current created when the fluid flows past an obstacle, the eddies were not reproduced in the modelling as no negative velocities were produced. The flow creates a void on the downstream side of the object and when fluid flows into the void, it creates a swirl on each edge of the obstacle, followed by a short reverse flow of fluid upstream (EncyclopædiaBritannica, 2013).

The difference in the R^2 value can also be explained, by the fact that when creating the model, the meshes are automatically generated using the Delaunay triangulation algorithm, and the vertices of the elements do not exactly coincide with the positions of the measured laboratory points. Therefore triangulation was used with the closest vertices to acquire the velocities of the simulations, in order to compare the 2 samples. The vertices may be manually edited; however this may produce bugs in the model and lead to instabilities.

For this study, the R^2 value is acceptable as the investigation merely aimed at giving a generalised rough guide for the placement of boulders.

4.2.2 Matlab Graphical Comparison of Velocities

Figures 4.3 and 4.4 show that the distributions of velocities are very similar for the two samples of the laboratory and the simulated results. However, the velocity patterns are not identical, which can be accounted for by there being a lot more points used to grid the simulation than the laboratory experiments, the measuring probe could not measure closer than 0.05m to the cylinder wall, and RiverFLO-2D does not represent the negative velocities in the flume, which is seen as the lowest velocity of 0.0m/s.

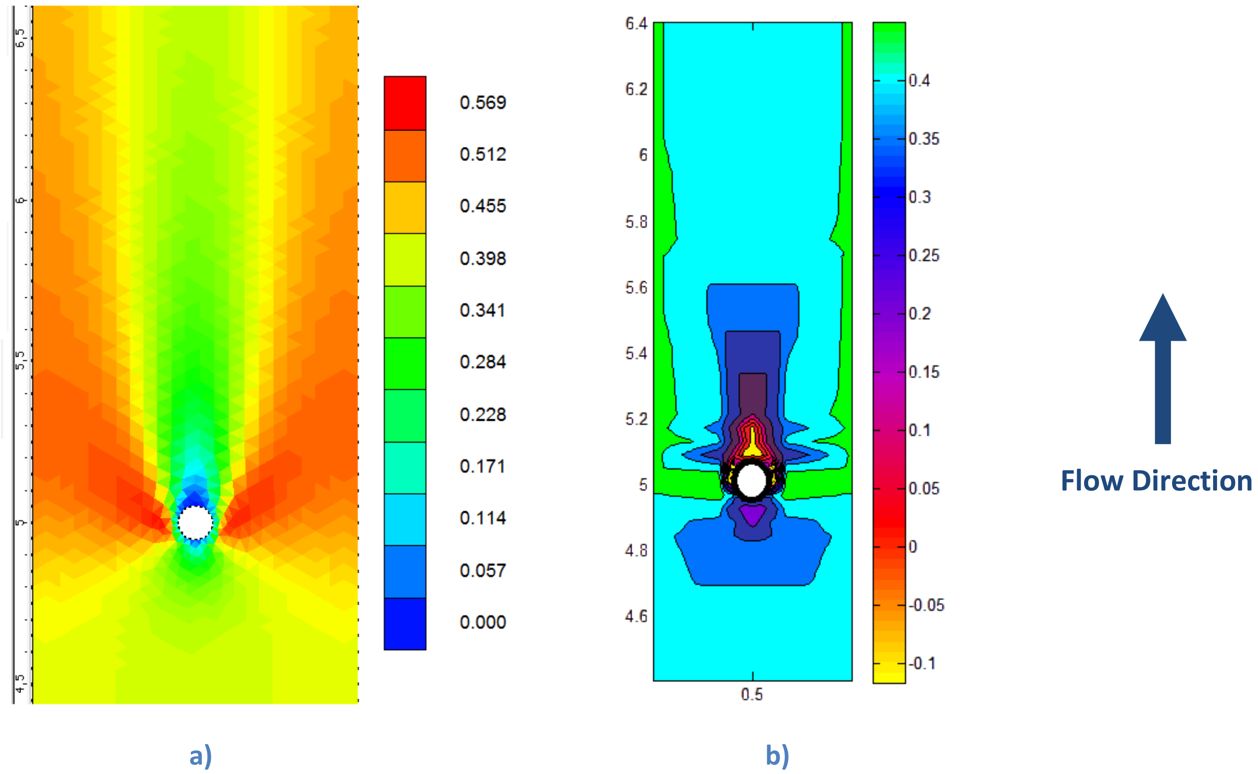
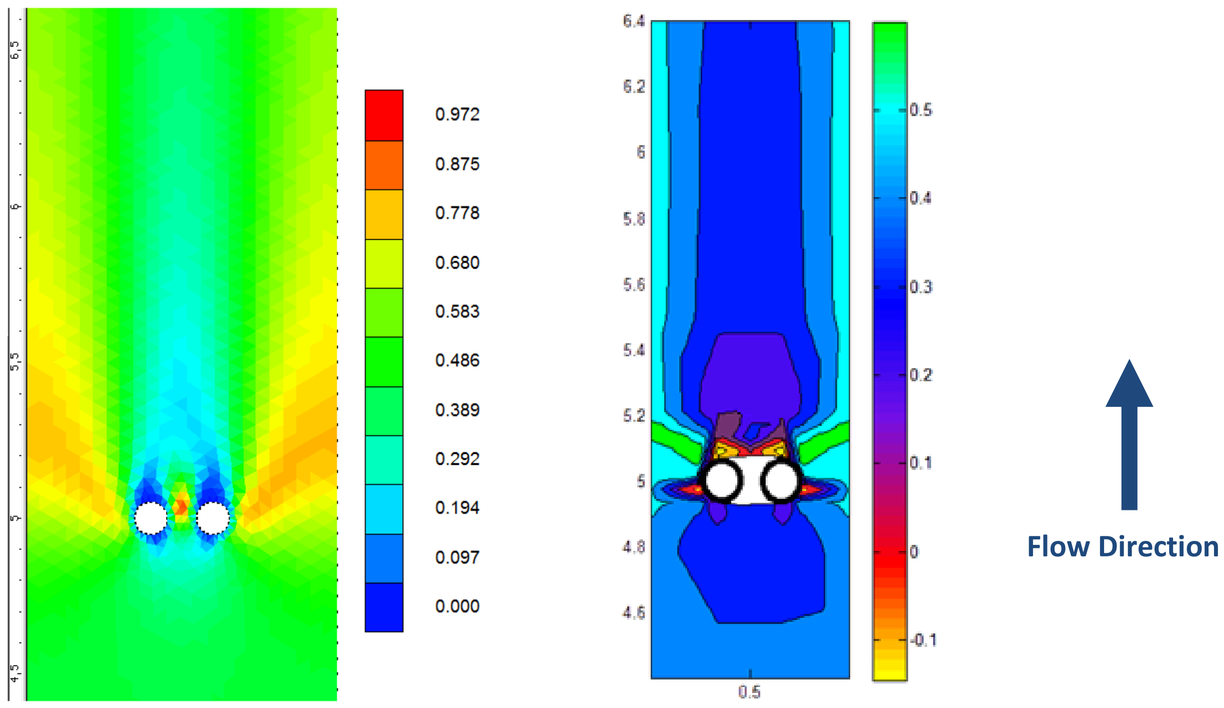


Figure 4.3: Matlab Graphical Comparison of Velocities for 1 Boulder, a) Simulated results & b) Laboratory results (the numbers on the colour scale are velocities in m/s; dimensions are in m)



a) b)

Figure 4.4: Matlab Graphical Comparison of Velocities for 2 Boulders, a) Simulated results & b) Laboratory results (the numbers on the colour scale are velocities in m/s; dimensions are in m)

The model still represents the velocity distribution adequately for the purposes of this study in terms of the spatial variation of the velocity. Even though the model does not represent the real-life situation exactly, the disparity was accepted as discussed in the statistical evaluation. RiverFLO-2D was considered to give a reasonable representation of the velocity distributions in the flume for our purposes and it can be used reliably to generate more models for further investigation.

4.3 VELOCITY FREQUENCY HISTOGRAMS

The Velocity Frequency Histograms were constructed by considering a grid covering an area of the channel and calculating the velocities at the centre of each grid section. All sections that have a velocity that fall in the same range have their corresponding areas added up and divided by the total area in order to give a proportion and get a frequency histogram.

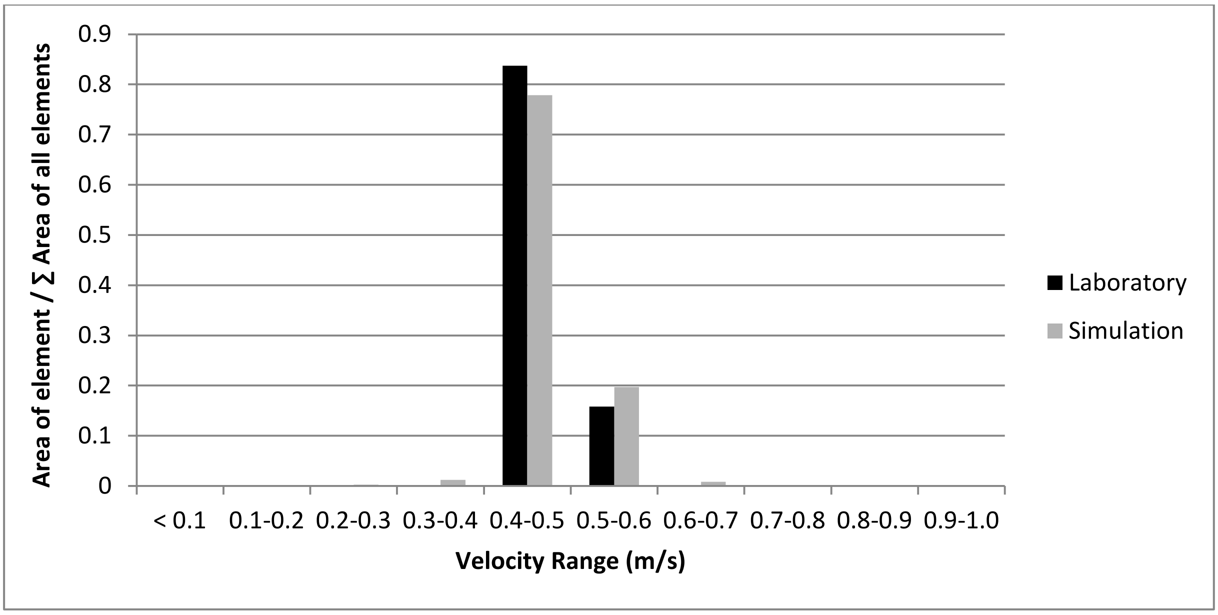


Figure 4.5: Comparison of Experiment 3 of Laboratory and Simulation Velocity Frequency Histogram

The comparison in Figure 4.5 of the experimental with simulated histograms indicates that the model adequately represents the variation of the velocity distribution when a boulder is placed; there was similar agreement in the comparisons of the histograms for the laboratory and simulation results with 2 boulders, shown in Appendix1. The histograms of velocity frequency for experiments 1, 2, 4 & 5 are in Appendix 1

The effects of placing boulders in the flow and how it changes the velocity distribution were then analysed. Experiment 3, 6 and 7 have the same discharge and slope and are therefore evaluated together in the histogram presented in Figure 4.6. The variance was calculated for the 3 experiments; experiment 3 (1 boulder) had a variance of 0.0399, experiment 7 (2 boulders without local control) had a variance 0.0368, and experiment 6 (2 boulders in local control) had a variance of 0.49. The larger the variance the more spread out the velocity distribution is, and therefore the values are further from the mean. Therefore it is clear that placement of the boulders is more desirable when a local control is induced between them as a normal probability distribution is considered in this case, this will be emphasised further in a later section (5.2.1).

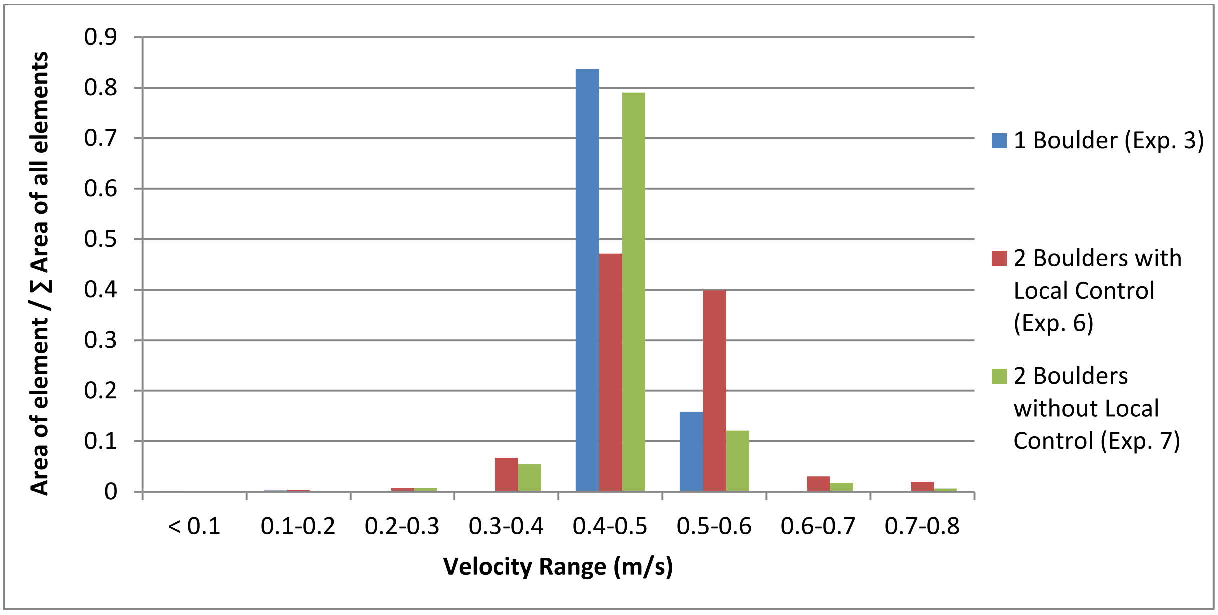


Figure 4.6: Histogram of Velocity Frequency for Experiments 3, 6 & 7

4.4 FLOW CLASS FOR MEASURED VELOCITY

All flow depths for the laboratory experiments are below 0.3m, and therefore represent only two possible flow classes, Slow Shallow & Fast Shallow, according to Kleynhans's (1999) classification of flow classes in Table 2.1. In this instance it should be acknowledged that the additional flow classes indicated by Birkhead (2010) are also applicable and should be considered in future work. The proportional change from the undisturbed flow class is not significant in the case of the laboratory experiments; however it was sufficient enough that the boulders have the ability to vary the velocity to cover both sides of the 0.3m/s boundary. However, the depths are not adequately altered, unless the undisturbed flow depths are close to the boundaries, of 0.3m and 0.5m depths. This will be discussed in more detail in Section 5.6.

5 APPLICATION OF RIVERFLO-2D

The work in Chapter 4 confirmed that the simulations are sufficiently reliable; and all the data in this study from now on will be acquired from the use of the ArgusONE and RiverFLO-2D software. As explained in the simulation conditions section (Section 3.3), the boulders were placed in the centre of the virtual flume symmetrically about the X axis, the Y axis or both. Simulations with only a single boulder were run first in order to determine how much of an effect it has on the velocity in the transverse and longitudinal directions. Then boulders were added incrementally to see how the Zone of Influence was affected. Many simulations were carried out but only the relevant 80 simulation models will be mentioned and discussed in this chapter.

5.1 LINEAR ARRANGEMENTS

5.1.1 1-Boulder

Initially, one boulder was placed in the centre of the channel, and the zones of influence were evaluated and their extents described by generalised dimensionless equations. This served as the base from which to compare the effects of placing any additional boulders.

5.1.1.1 Generalised Zone of influence

In this section the disturbance created by a boulder placed in a channel is determined and quantified. The disturbance is quantified by determining the area that is influenced, known as the Zone of Influence (ZOI), which is the extent over which the boulder considerably disturbs the flow around it, i.e. the area where the velocities are substantially different from the uniform velocity.

This study focuses on a greater than 10% change to the undisturbed flow. Figure 5.1 below demonstrates a graphical distribution of velocities simulated using Matlab. A greater than 10% increase in velocity is shown in blue, and greater than 10% decrease in velocity is shown in red, for 1 boulder of 0.20m diameter, placed in a channel with slope of 0.00080, width of 5m and discharge per unit width of 0.25 $m^3/s/m$. The flow is moving towards the top of the page.

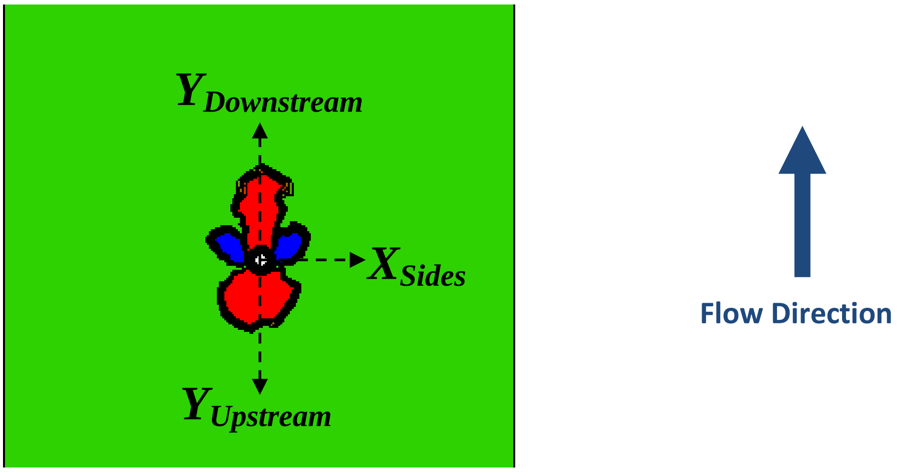


Figure 5.1: ZOI Area for 1 Boulder (Green is <10% change in velocity from undisturbed flow, Red is >10% decrease in velocity from undisturbed flow, Blue is >10% increase in velocity from undisturbed flow)

It is hypothesised that the ZOI will be affected by the following variables: discharge, channel slope, channel width and boulder diameter. Therefore the experiment used to assess the effects of these variables was a sensitivity analysis carried out in RiverFlo-2D. The initial simulation runs included changes in these variables by a certain percentage from a selected standard run; these runs are shown in Table 5.1.

Table 5.1: Simulations used to assess effects of single in-stream boulders

1 Boulder				
Model No.	***Discharge, q ($m^3/s/m$)***	***Slope***	***Width, b (m)***	***Boulder Diameter (m)***
1	0.25	0.0008	5	0.2
2	0.025	0.0008	5	0.2
3	2.5	0.0008	5	0.2
4	0.25	0.0005	5	0.2
5	0.25	0.001	5	0.2
6	0.25	0.0008	2.6	0.2
7	0.25	0.0008	3	0.2
8	0.25	0.0008	4	0.2
9	0.25	0.0008	6	0.2
10	0.25	0.0008	10	0.2
11	0.25	0.0008	5	0.1
12	0.25	0.0008	5	0.4

The first significant observation was that the zones were different upstream, downstream and to the sides of the boulder. Therefore it was decided that a ZOI description should be found for these three directions. The ZOI will be approximated by the area (A) calculated by multiplying the length of the disturbance in the Y direction (upstream plus downstream of the boulder) to that in the X direction (sides of the boulder).

For simulations where the width of the channel was large enough that it does not affect the ZOI it was found that the discharge per unit width (q), the channel slope (S), the boulder diameter (d) and the channel width (b) were directly proportional to A, i.e. an increase in the q, S, d and b caused an increase in A. The converse was found for the surface roughness (n), and it was therefore inversely proportional to A. The channel width and the boulder diameter seemed to have the biggest impact on the magnitude of A.

With these observations, all of these variables are incorporated in the proposed equations to predict the ZOI. The dimensionless Froude number (Fr) was considered, as it contains all of these variables excluding the boulder diameter. This is shown in the equations below:

$$Fr = \frac{V}{\sqrt{gH}} \tag{5.1}$$

$$V = \frac{1}{n}\ R^{2/3}\, S^{1/2} \tag{5.2}$$

$$V = \frac{1}{n}\left(\frac{A}{P}\right)^{2/3} S^{1/2}; \tag{5.3}$$

$$A = bH \tag{5.4}$$

$$P = 2H + b \tag{5.5}$$

$$Fr = \frac{1}{n}\left(\frac{bH}{2H+b}\right)^{2/3} S^{1/2} \cdot \frac{1}{\sqrt{gH}} \tag{5.6}$$

Since b and d had the biggest impact on A, the equation for the influence in the X and Y direction can therefore be the multiple of Fr, b and d. However, - Fr, b and d - will have different effects in the upstream, downstream and side directions; therefore they will all be to the power of an appropriate value that conveys the necessary relative scale. They will also need to be multiplied by a constant (c) to express the necessary magnitude. In order to represent the ZOI by a dimensionless equation for practical applications, the influence in the

X and Y direction were divided by d as it has a significant effect on the ZOI. Therefore the boulder influences the flow patterns up to a distance approximately $\frac{X,Y}{d}$ times the boulder's diameter in the direction concerned. As an increase in d produces a decrease in $\frac{X,Y}{d}$, d is included in the denominator on the right-hand-side of the prediction equations.

$$\frac{X,Y}{d} = c\ \frac{Fr^e\, b^f}{d^g} \quad (5.7)$$

It was found that f and g are equal and therefore b and d were combined to give a dimensionless ratio.

$$\frac{X,Y}{d} = c\ Fr^e \left(\frac{b}{d}\right)^h \quad (5.8)$$

A general equation was found to specify the ZOI; it proposes a length of the portion of flow that has a velocity that deviates from the undisturbed channel velocity. On the upstream and downstream sections a 10%, 20% & 50% deviation from uniform flow was defined, shown in Figures 5.2 and 5.3. On the side sections a 10%, 20% & 30% deviation from uniform flow was defined, shown in Figure 5.4. After identifying the ZOI lengths from the results in the X and Y directions for the models 1 to 12, and by plotting a best fit curve of these values, the following equations were derived:

Table 5. 2: Equations to predict ZOI around a single in-stream boulder

Downstream	$\frac{Y_{Di}}{d} = K_{Di}\ \ Fr^{0.25} \left(\frac{b}{d}\right)^{0.25}$ (5.9)		
	$K_{D10} = 2.19$	$K_{D20} = 1.38$	$K_{D50} = 0.79$
Upstream	$\frac{Y_{Ui}}{d} = K_{Ui}\ \ Fr^{1} \left(\frac{b}{d}\right)^{0.1}$ (5.10)		
	$K_{U10} = 3.48$	$K_{U20} = 2.12$	$K_{U50} = 1.06$
Sides	$\frac{X_{Si}}{d} = c_{Si}\ \ Fr^{0.25} \left(\frac{b}{d}\right)^{0.25}$ (5.11)		
	$C_{S10} = 1.02$	$C_{S20} = 0.69$	$C_{S30} = 0.55$

In all the above equations, Fr is the Froude number of the undisturbed channel. Y is the length of the ZOI in the upstream and downstream direction, and X is the length of the ZOI on the sides of the boulder. The equations are demonstrated using model 1, where Fr=0.67, d=0.20m and b=5.00m. If the length of the ZOI for 20% deviation from uniform flow in the upstream direction is required, then equation 5.10 is used with the constant K_{U20}.

$$\frac{Y_{U20}}{d} = 2.12 \quad 0.67^{1} \left(\frac{5}{0.2}\right)^{0.1} = 1.96 \tag{5.12}$$

The simulated Y/d for 20% ZOI in the upstream direction is 2.05; this is shown in Table 5.3 along with the comparisons of Y/d for the ZOI in the other directions. These equations were applied to the models 1 to 12 (shown in Appendix 2) which gave a good comparison as indicated by the percentage differences.

Table 5.3: Comparison of Predicted ZOI to Simulated ZOI for Model 1

	Model 1							
	Fr	0.67	d		0.20		b	5.00
	Downstream				Upstream			
	Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.80	4.00	4.44	10.91	0.65	3.25	3.22	-0.90
20%	0.59	2.95	2.81	-4.76	0.41	2.05	1.96	-4.19
50%	0.33	1.65	1.61	-2.67	0.21	1.05	0.98	-7.05
	Sides							
	Simulated		Predicted					
	X	X/d	X/d	% Diff				
10%	0.42	2.10	2.02	-3.62				
20%	0.29	1.45	1.42	-1.89				
30%	0.20	1.00	1.08	8.02				

All equations are only applicable when the width of the channel does not affect the ZOI. These widths are discussed further in Section 5.2.2. These equations are also applicable to 2, 3 and 4 boulders and are demonstrated in subsequent sections of this chapter. Crowder & Diplas (2000) observed in their study conditions that a single obstruction influenced the downstream flow patterns up to a distance approximately 6–8 times the obstruction's diameter. Applying the 10% ZOI prediction equation to their study conditions gives a Y/d of roughly 5 times the boulders diameter, which is an underestimation; however this will vary depending on the % ZOI that is chosen, a 5% ZOI would likely give similar patterns.

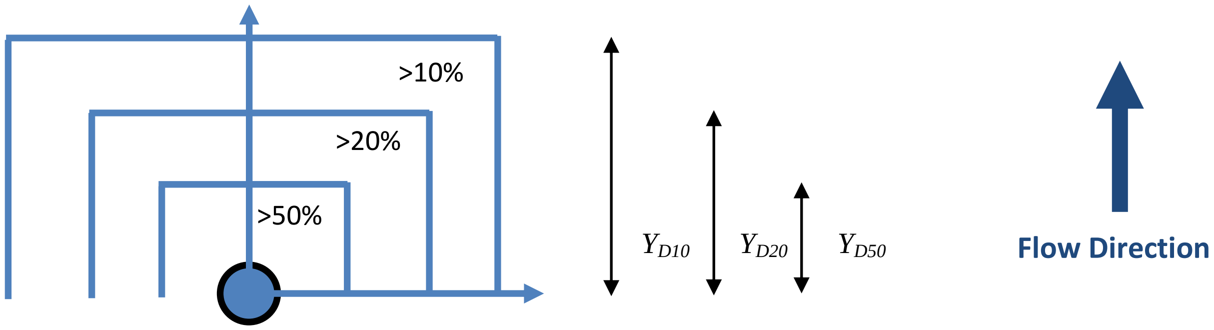


Figure 5.2: ZOI Areas for the Downstream Section of the Boulder

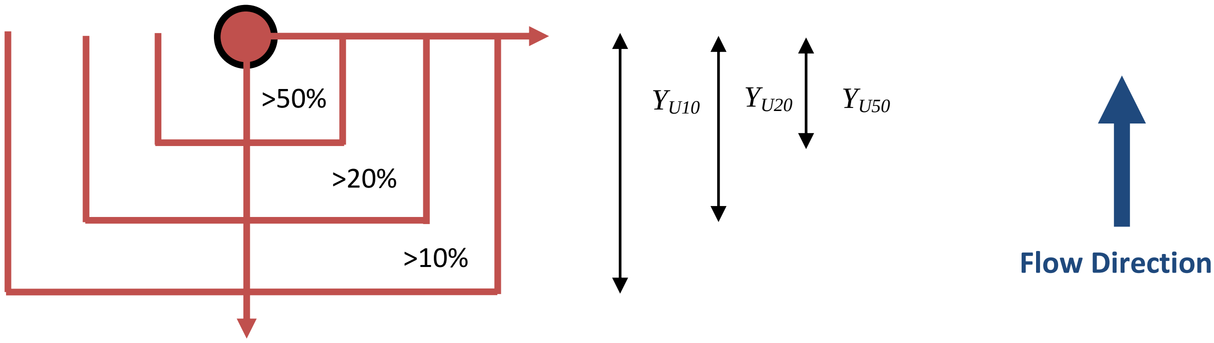


Figure 5.3: ZOI Areas for the Upstream Section of the Boulder

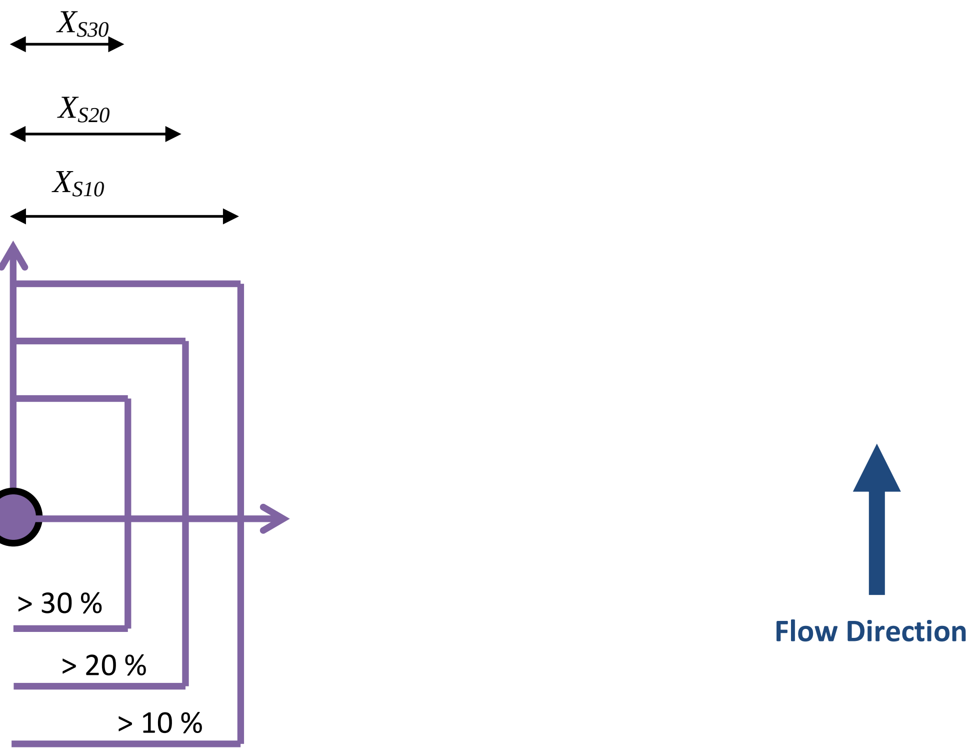


Figure 5.4: ZOI Areas for the Side Section of the Boulder

5.1.1.2 Generalised Histograms

As was mentioned in the laboratory experiments (Chapter 4), the Velocity Frequency Histograms consider a grid covering an area of the channel and then the velocity at the centre of each grid section is identified. All sections that have a velocity that falls in the same range will have their corresponding areas added up and divided by the total area in order to give a proportion and produce a frequency histogram. Figure 5.5 presents the histograms for the area of the whole flume in black, and the velocities in the 10% ZOI area in grey.

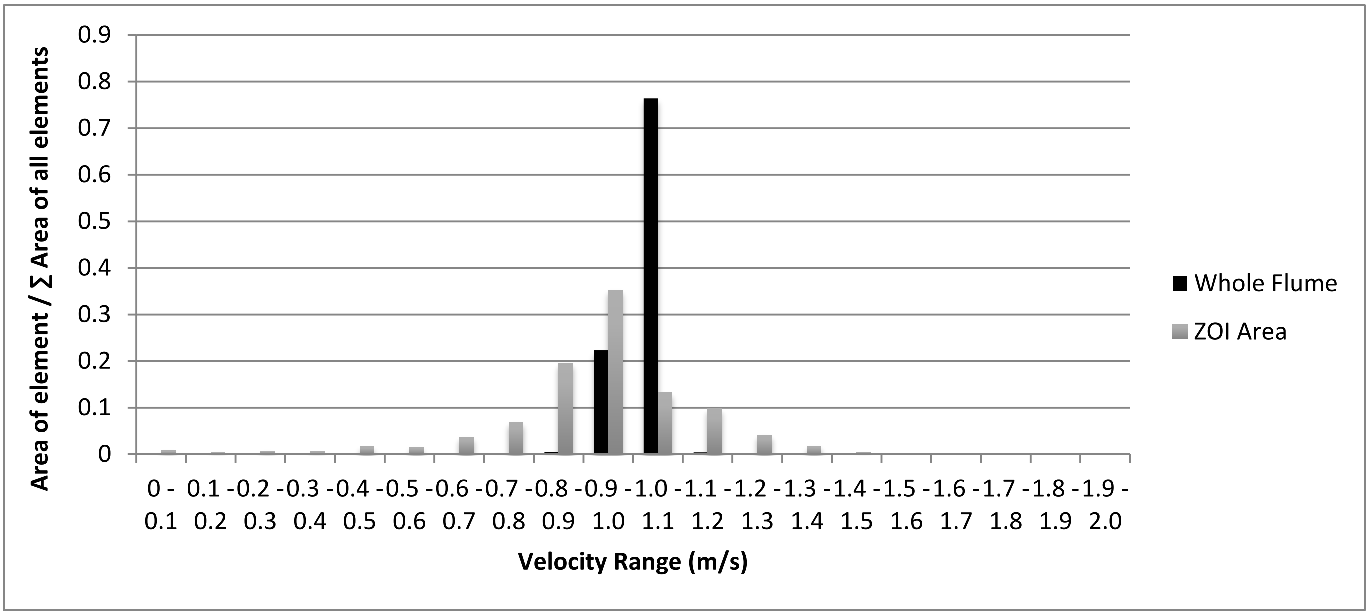


Figure 5.5: Histogram for the Whole Flume Area and the ZOI Area

It can be seen from the above histograms that majority of the flume falls within the uniform velocity. Since the area of the flume is relatively large compared to the size of the boulder, the effects they create are not adequately demonstrated, therefore we consider the 10% ZOI area in order to give a more satisfactory representation of the variance in the flows around the boulders. All of the histograms in this report will be Velocity Frequency Histograms for the velocities inside the 10% ZOI in order to assess the impacts of the boulders. It must be noted however that when models are being compared, the histograms of all the cases need to be over the same area. Therefore the largest ZOI area of the models considered must be chosen and applied to all models for fair comparison.

In order to make the histograms easier to read, only the velocity range that is most influenced is considered. As can be seen (Figure 5.5), the uniform velocity is in the centre of the histogram and the ranges on the outer sides cover an insignificant portion of the Influenced area. Therefore, with an example of the above histogram, we only consider the velocity range from 0.5 m/s to 1.5 m/s, which is demonstrated in the histogram in Figure 5.6. This allows for the columns to be enlarged and made more apparent for inspection.

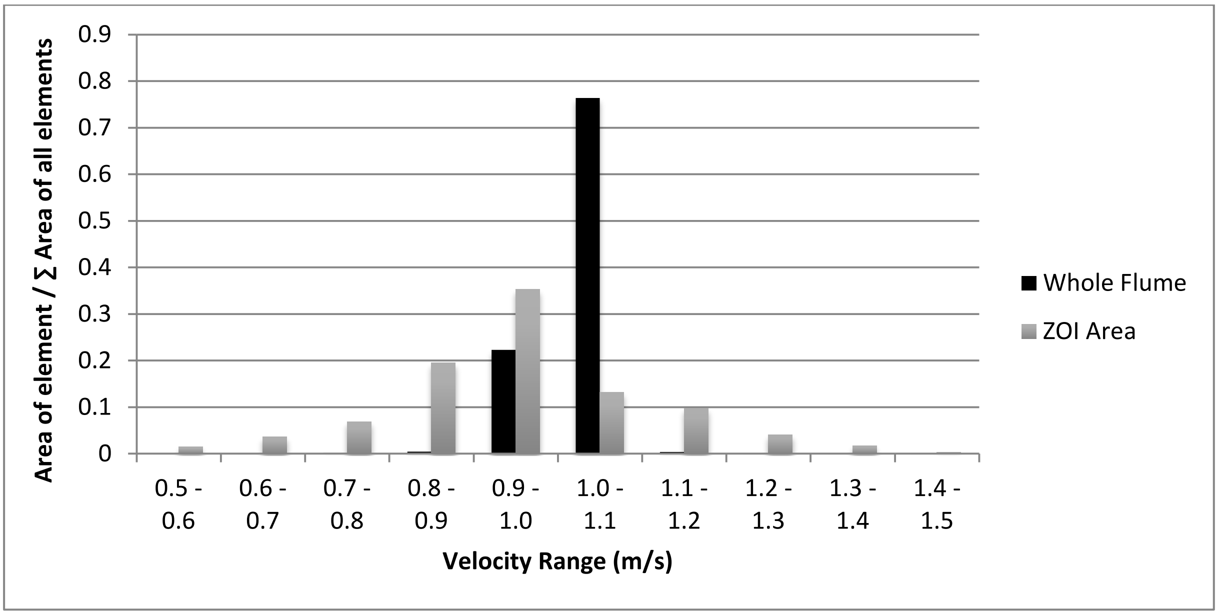


Figure 5.6: Histogram for the Relevant Velocity Ranges

The effects on the velocity distribution after changing the discharge (q), slope (S), width (b), and diameter (d) were analysed using the velocity frequency histograms. As expected the q and the S altered the uniform velocity and therefore the centres of the histograms, whereas the changes in d and b did not significantly change the histograms. The q and the b histograms are shown below with a table of the variances and standard deviations for the changes in all the variables, the S and d histograms can be found in Appendix 2.

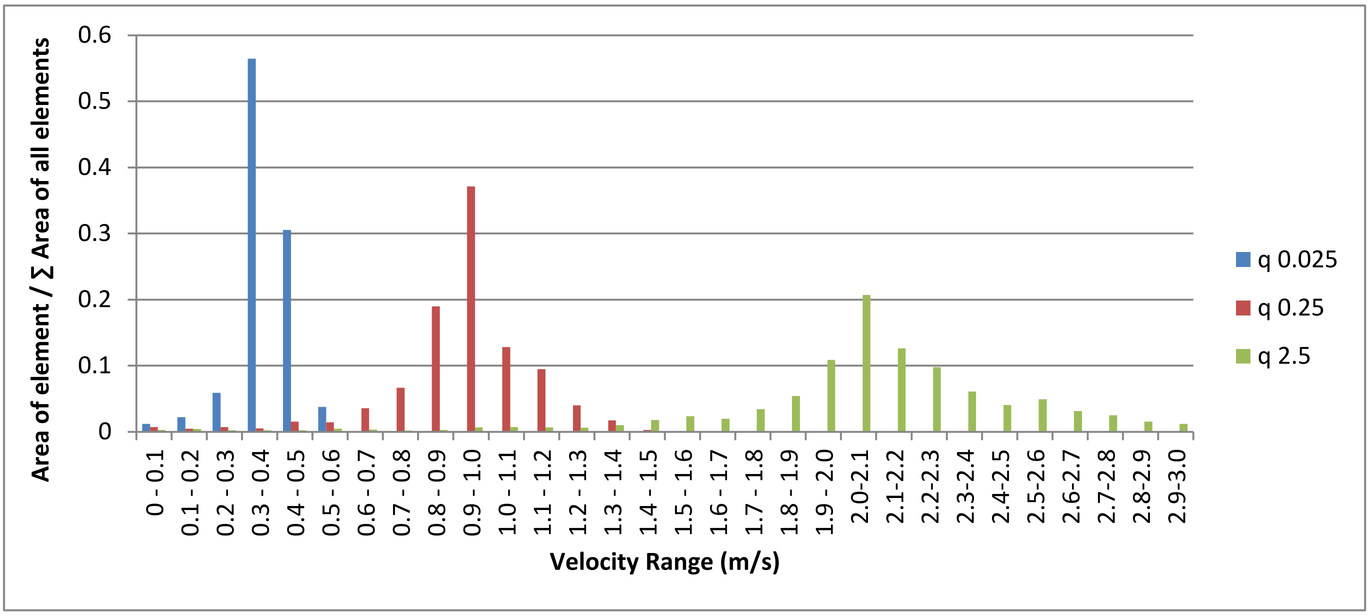


Figure 5.7: Histogram for varying discharges

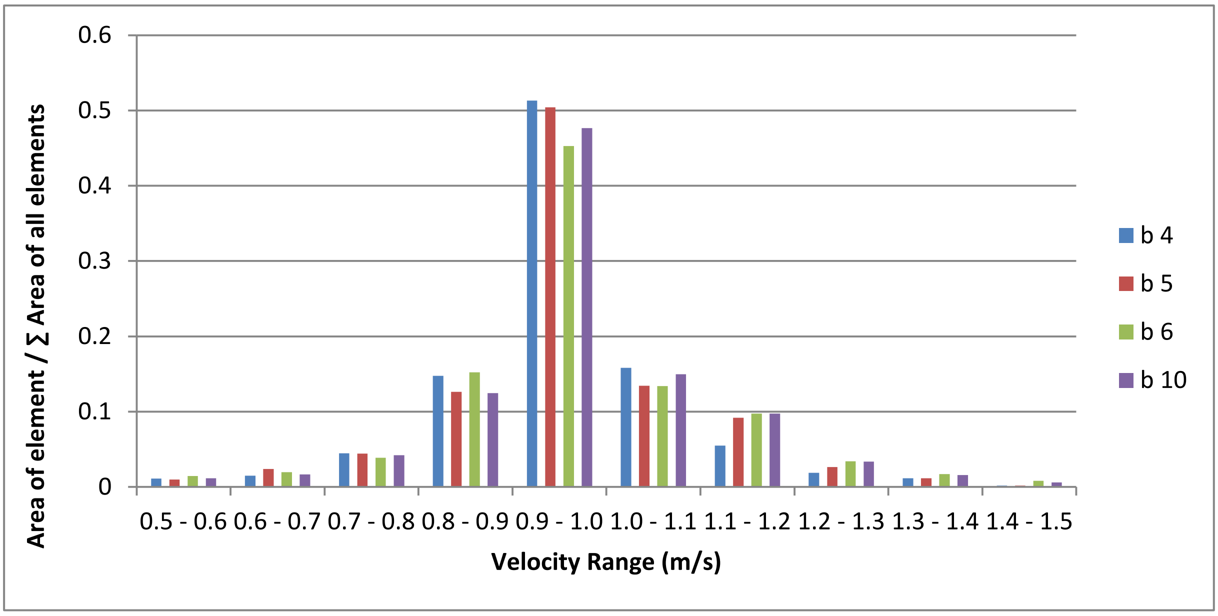


Figure 5.8: Histogram for varying Widths

All the variances and standard deviations for velocities in this study considered the largest ZOI area of all models that were compared, therefore matching the histogram areas.

Table 5.4: Variances of single in-stream boulders for varying conditions

	Discharge ($m^3/s/m$)			Slope			Width (m)				Diameter (m)		
	0.025	0.25	2.5	0.0005	0.0008	0.001	4	5	6	10	0.1	0.2	0.4
Model No.	2	1	3	4	1	5	8	1	9	10	11	1	12
Variance	0.02	0.128	0.66	0.0895	0.1278	0.149	0.117	0.12	0.146	0.128	0.057	0.102	0.163
Standard Deviation	0.142	0.358	0.812	0.2991	0.3575	0.386	0.342	0.346	0.382	0.358	0.239	0.319	0.404

It was found that the change in discharge had the most impact on the velocity distributions, not only were the centres altered but the peaks too. The peaks decreased as the discharge increased, this was expressed in the variances; the greater the discharge the greater the variance in the velocity distribution. The other variables had a less significant but noticeable influence on the peaks of the histograms, particularly the slope and the diameter which had obvious differences in the variance, again the greater the slope and diameter, the greater the variance.

5.1.2 Local Control

It is hypothesised that if boulders are placed close enough to induce local critical flow, the ZOI around the boulder will be increased and improve the distribution of velocities in the channel. This section describes the effect of setting two boulders normal to the flow and varying the spacing between them until a Local Control (LC) is created. The effects of having the boulders in local control are analysed and a method is derived to produce it.

Table 5.5: Models to induce LC

2 Boulders								
Discharge, q ($m^3/s/m$)			***Slope***			***Boulder Diameter (m)***		
0.25			0.0008			0.2		
						***Transverse Spacing***		
Model No.	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***
Spacing (m)	X = 0.6	X = 0.7	X = 0.8	X = 2.0	X = 0.7	X = 0.8	X = 0.9	X = 1.0
Width, B (m)	5	5	5	5	10	10	10	10

To check that a LC has been induced, the graphical representation (Figure 5.9) of the Froude numbers that are produced by ArgusONE are examined. In order for there to be a LC, it must be observed that the Froude number is greater than 1 across the section in between the boulders.

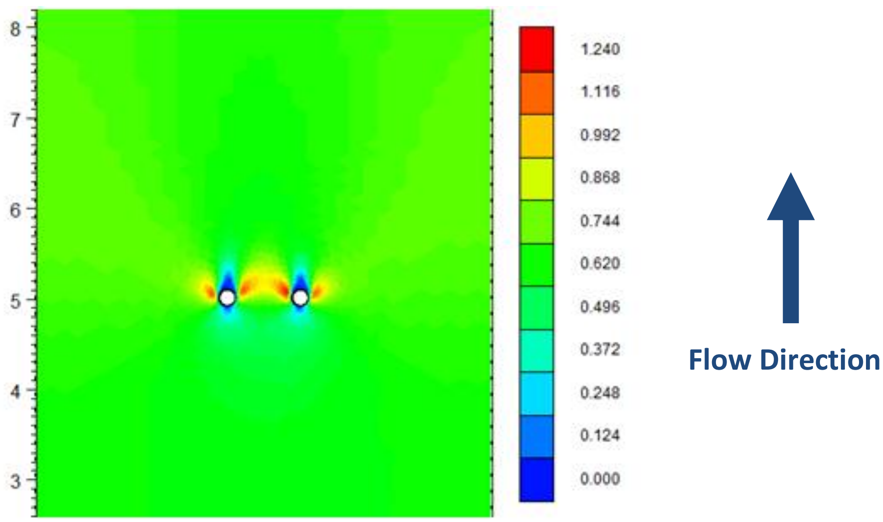


Figure 5.9: Graphical representation of the flow Froude numbers in the channel

The desirability of creating a LC is assessed by inspecting the velocity distributions and their variances by generating velocity frequency histograms. The influence that boulders normal to the flow have is then compared when there is one boulder, 2 boulders not in LC, and 2 boulders that are in LC. The largest ZOI area of the three scenarios is selected and applied to all of the histograms. A 5m width is considered, and histograms with their variances for the above 3 scenarios are shown in Figure 5.10 and Table 5.6.

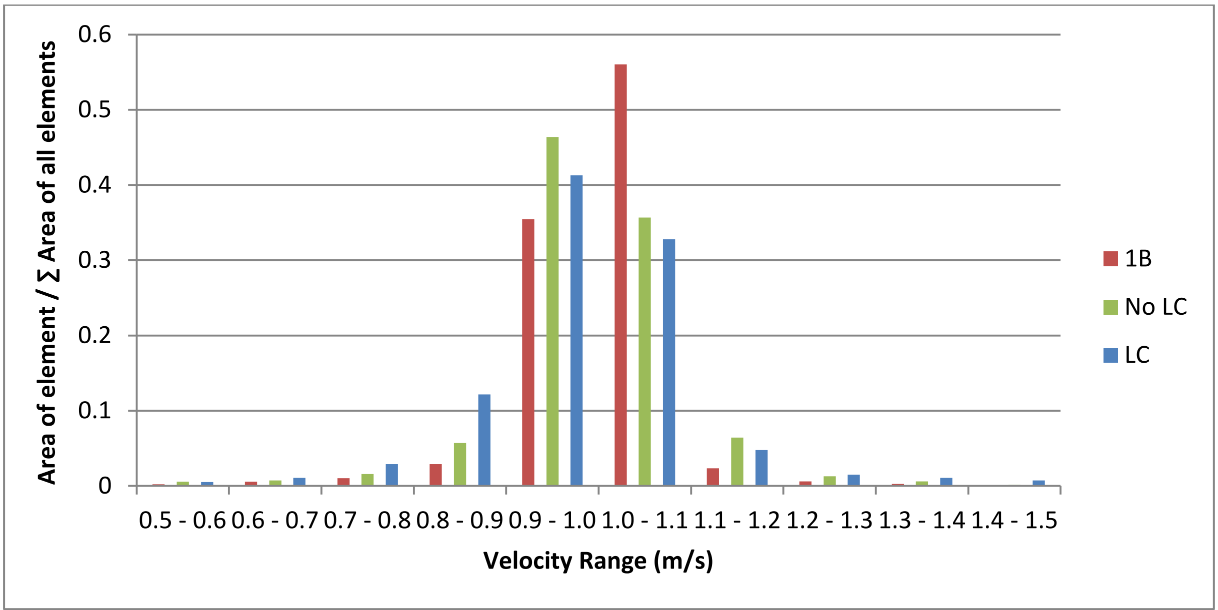


Figure 5.10: Histogram for single and double in-stream boulders with and without LC

Table 5.6: Variances of single and double in-stream boulders with and without LC

	1B	No LC	LC
Variance	0.081	0.099	0.118
Standard Deviation	0.285	0.316	0.344

It is clear that increasing the number of boulders increases the variance of the velocity distribution, which can be further increased by inducing a LC. Therefore a LC is in fact desirable to enhance the variance in the velocities.

A designer may however not necessarily want to create a LC, we therefore compare model 14 (LC) and model 16 (No LC). It was observed that not having a LC resulted in similar ZOI lengths to a single boulder in the downstream and upstream sections for the 10% ZOI, and the ZOI lengths approximately doubled for these sections when a LC was created. The side sections of the boulders had similar ZOI lengths despite having a LC. We then looked at the variances in Table5.6 and observed that the mere fact of having multiple boulders increases the variance from a single boulder; therefore not having a LC is still an attractive option to increase the variance. It is however recommended that a LC should be induced where possible because of the larger ZOI that it produces.

It was found that for a width of 5m, a LC can be induced when the spacing is less than 0.8m for the mentioned conditions. For a width of 10m, it was found that a LC can be induced when the spacing is less than 0.9m for the mentioned conditions.

Schueler & Brown (2004) proposed that for the placement of boulder clusters, the boulders should be separated by 1 boulder diameter. It is desirable to have the largest spacing that is possible between boulders in order to reduce the number of boulders required and therefore the construction costs. It is suggested that the spacing between boulders should be just close enough to induce LC. It must be noted that an increase in the q, b, S, d and ZOI lengths increased the transverse spacing required between boulders to induce LC.

There is no particular correlation between the transverse spacing and the ZOI length prediction equation 5.11 (which include the variables q, b, S and d), therefore further analysis is required, and it is proposed for this study that the transverse spacing between boulders should be roughly less than 4 times the boulder's diameter.

5.1.3 2-, 3- & 4-Boulders Normal to the Flow direction

Knowing that a LC is advantageous, a transverse spacing that induced a LC was chosen and applied between 2, 3 and 4 boulders. A spacing of 0.7m was selected and the conditions of the models are shown in Table 5.7. Therefore the impact on the ZOI of placing additional boulders in a channel was assessed. A histogram was produced to assess the velocity distribution of 1, 2, 3 and 4 boulders in a 10m wide channel. This section also sets out to find out how small the width of the channel needs to be for it to start affecting the size of the ZOI.

Table 5.7: Models to assess multiple in-stream boulders for varying widths

<table>
<tr><th colspan="5">Discharge, q (m³/s/m)</th><th colspan="4">Slope</th><th colspan="5">Boulder Diameter (m)</th></tr>
<tr><td colspan="5">0.25</td><td colspan="4">0.0008</td><td colspan="5">0.2</td></tr>
<tr><td rowspan="2">Flow Direction</td><td colspan="4">2 Boulders</td><td colspan="4">3 Boulders</td><td colspan="5">4 Boulders</td></tr>
<tr><td colspan="4">X</td><td colspan="4">X X</td><td colspan="5">X X X</td></tr>
<tr><td colspan="14">Transverse Spacing, X = 0.7m</td></tr>
<tr><td>Model No.</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td></tr>
<tr><td>Width, B (m)</td><td>3</td><td>4</td><td>5</td><td>10</td><td>5</td><td>6</td><td>8</td><td>10</td><td>5</td><td>6</td><td>7</td><td>8</td><td>10</td></tr>
</table>

After assessing the models for 1 boulder and the models in Table 5.7, it was found that when the boulders were close enough to the banks, then the width of the channel relative to boulder size had a considerable effect on the size of the ZOI, increasing it as the channel became relatively narrower. The limit from when the width of the channel started affecting the size of the ZOI for the conditions mentioned in Table 5.7 is shown in Table 5.8. It was found that when the widths were incrementally reduced to the limits in Table 5.8 then the ZOI were affected, when the widths were reduced even further, then a point was reached where a back-up effect started occurring in the upstream section which considerably increased the ZOI in this direction. It is recommended for future studies to determine the width that produces this back-up effect as it would be desirable for practical purposes.

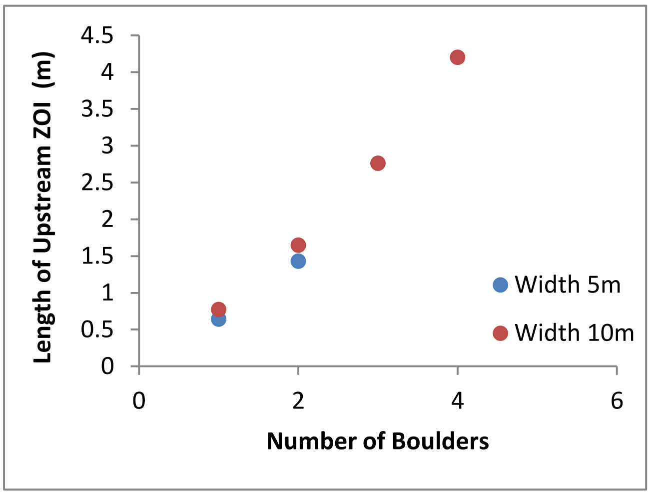
Table 5.8: Width of the channel to affect ZOI

No. of Boulders	Width (m)
1	< 2.6
2	< 5
3	< 8
4	< 10

It was then observed what the effects of incrementally adding boulders had on the ZOI, and it was found to increase considerably by the placement of multiple boulders in line normal to the flow direction, particularly if placed close enough to induce LC. The ZOI increased in size by factors of approximately 2 for additional boulders, demonstrated in Table 5.9 and Figure 5.11 for widths of 5 and 10m. This pattern was observed for wide channels.

Table 5.9: Lengths of the 10 % ZOI in the up/downstream sections

No. of Boulders	Model No.	Width, b = 5m		Model No.	Width, b = 10m	
		Y_U	Y_D		Y_U	Y_D
1	1	0.64021	0.79129	10	0.76848	1.368
2	23	1.42767	1.57659	24	1.64555	2.7149
3	Width affects ZOI			28	2.75819	5.5032
4				33	4.19818	9.2692



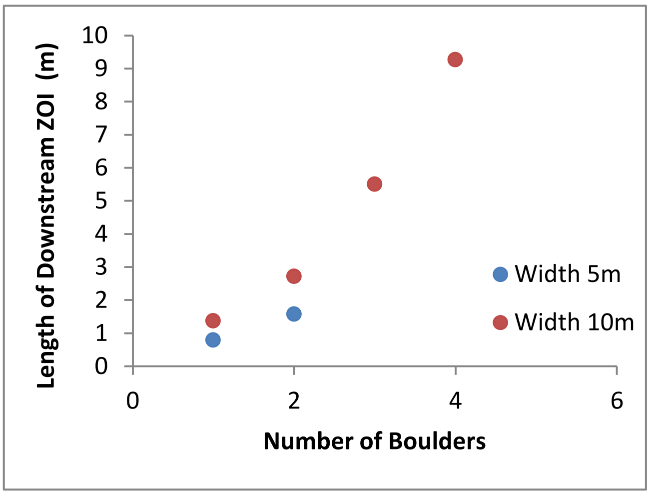


Figure 5.11: Lengths of the 10 % ZOI in the up/downstream sections

The ZOI approximately doubles upstream and downstream every time an additional boulder is placed in LC. Therefore if 1 boulder has ZOI "Z", 2 boulders with LC between them has ZOI 2 x "Z", 3 boulders with LC between them has ZOI 4 x "Z" and 4 boulders with LC between them has ZOI 8 x "Z". Therefore the ZOI for more than 1 boulder is equal to 2 to the power of (No. of Boulders -1) multiplied by the length of ZOI of 1 Boulder in the upstream or downstream section whichever is required.

$$\text{ZOI for multiple boulders} = 2^{(\text{No. of Boulders - 1})} \times (\text{ZOI for 1 boulder}) \qquad (5.13)$$

Figures 5.12 to 5.15 graphically represent this scenario for a 10% ZOI in a 10m wide channel for the conditions mentioned in Table 5.7, and the velocity distribution histograms (Figure 5.16) generated, with Table 5.10 showing their variances.

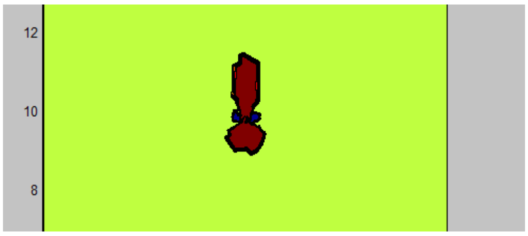


Figure 5.12: 10% ZOI for 1 Boulder

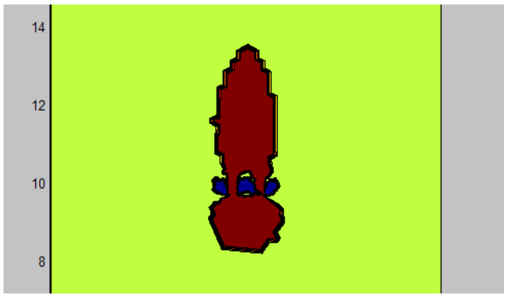


Figure 5.13: 10% ZOI for 2 Boulders

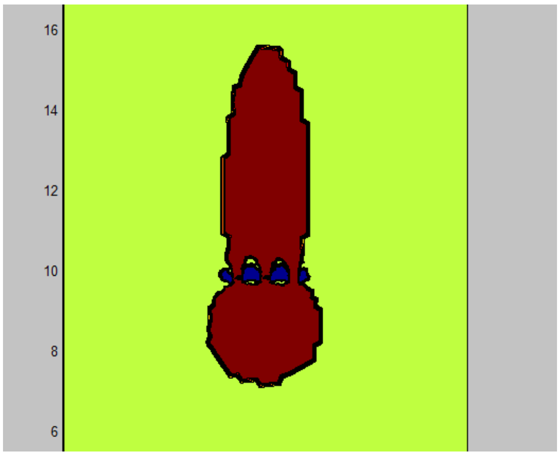


Figure 5.14: 10% ZOI for 3 Boulders

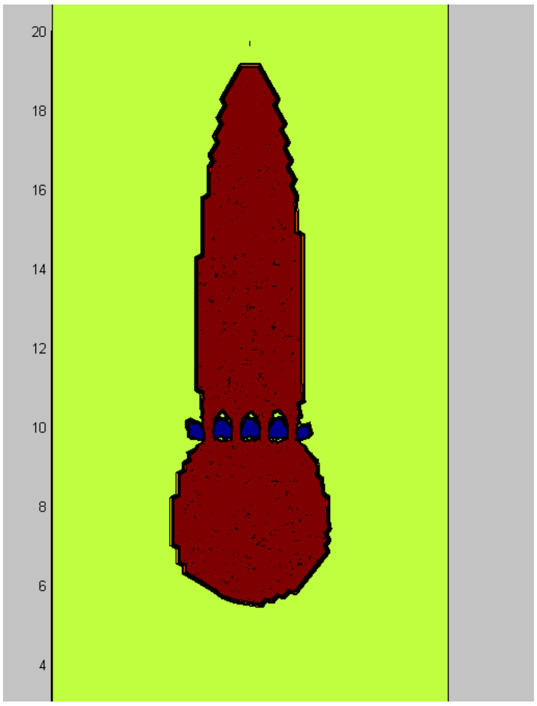


Figure 5.15: 10% ZOI for 4 Boulders

Flow Direction

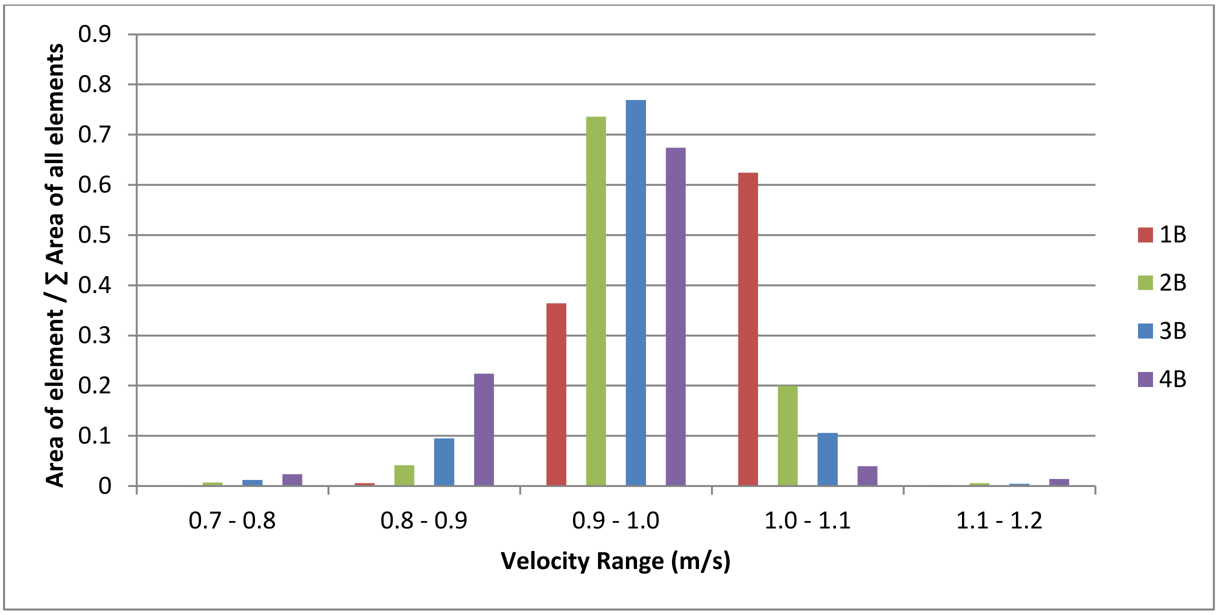


Figure 5.16: Histogram for multiple in-stream boulders in same conditions

Table 5.10: Variances of multiple in-stream boulders in same conditions

	1B	2B	3B	4B
Variance	0.023	0.049	0.056	0.085
Standard Deviation	0.151	0.223	0.237	0.291

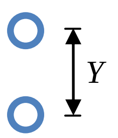
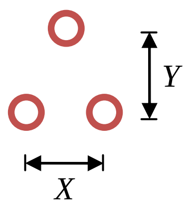
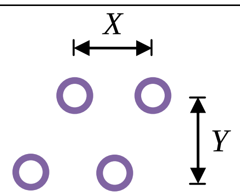
As expected, it was found that increasing the number of boulders along the width of the channel increased the variance in the velocity distribution and is therefore more desirable. The more boulders adjacent to each other, the further the ZOI reaches. Therefore in terms of structural expenditure, a balance needs to be found in the design between the placement of boulders next to each other and the distance of placing the next set of boulders downstream, which will be investigated in Section5.3.

5.2 PLACEMENT OF SUBSEQUENT BOULDERS DOWNSTREAM

In order to minimise the use of boulders and construction costs, each array of boulders should act independently, as in the ZOI that one array creates should be separate from the ZOI that the subsequent downstream array creates. Schueler & Brown (2004) proposed that boulders should not lie in the wake of an upstream boulder and that the downstream boulders should be placed at the edge of the turbulent flow created by the next upstream boulder.

To give a rough estimation of placing the next set of boulders at a sufficient distance downstream so that they do not fall in each other's ZOI, the longitudinal distance between boulders is varied until a separation is evident in the graphical representations of the ZOI. The models used are shown in Table 5.11. Two graphical illustrations are also shown in Figure 5.17, where in one scenario the downstream boulder is not placed at sufficient distance and another scenario where it is.

Table 5.11: Models to assess the ZOI for arrangements with varied longitudinal spacing

Discharge, q (m^3/s/m)						***Slope***					***Boulder Diameter (m)***				
0.25						0.0008					0.2				
	2 Boulders					**3 Boulders**					**4 Boulders**				
	Width = 5m					***Width = 10m***					***Width = 10m***				
						X Spacing = 0.7m					***X Spacing = 0.7m***				
 **Flow Direction**															
Arrangement	*Linear*					*Triangular*					*Parallelogram*				
Model No.	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Y Spacing (m)	1	2	3	3.5	4	6	7	8	9	10	8	9	10	11	12

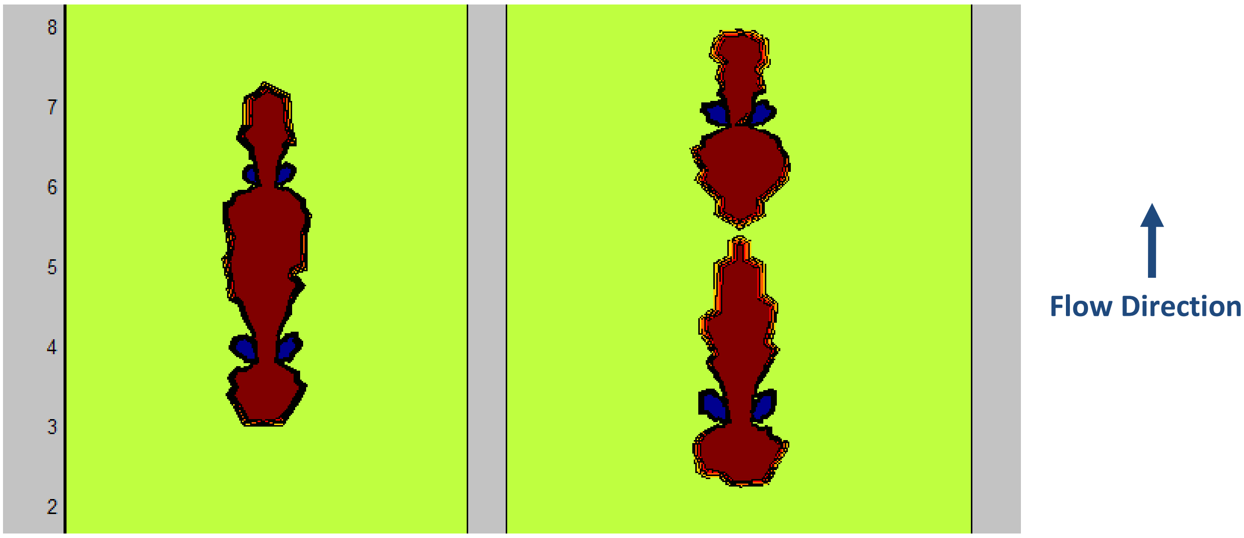


Figure 5.17: Illustration of separation in ZOI from boulder downstream

It was found that for the linear arrangement, where there is 1 boulder upstream and 1 boulder downstream in a 5 m wide channel, that the distance required for the boulders to act independently of each other, i.e. the separation distance (Y_S) was equal to 3.5m. In the triangular arrangement, where there are 2 boulders upstream and 1 boulder downstream in a 10 m wide channel, Y_S was 9m. In the Parallelogram arrangement, where there are 2 boulders upstream and 2 boulders downstream in a 10 m wide channel, Y_S is 11m. These distances are considerably longer than expected from the ZOI dimensions for isolated arrangements with no subsequent boulders.

Table 5.12: Analysis of Distance for boulders to act independently

	Model	Y_U(m)	Y_D(m)	Length, L (m)		Distance for boulders to act independently, Y_S (m)		Y_S / L
Width , b = 5m								
1Boulder	1	0.64	0.80	$Y_{U1} + Y_{D1}$	1.44	*Linear*	3.5	2.43
Width , b = 10m								
1Boulder	10	0.78	1.37	$Y_{U1} + Y_{D2}$	3.50	*Triangular*	9	2.57
2Boulders	24	1.65	2.72					
2Boulders	24	1.65	2.72	$Y_{U2} + Y_{D2}$	4.37	*Parallelogram*	11	2.52

In order to give a rough estimate of the distance to place the next set of boulders downstream the lengths of the ZOI of 1 and 2 boulders in the upstream (Y_U) and downstream (Y_D) sections are considered. For the linear arrangement, simulated in a 5m wide channel, the ZOI for 1 boulder can be calculated from equations (5.9) and (5.10) to give Y_U = 0.64m plus Y_D = 0.8m, i.e. a total ZOI distance (L) of 1.44m as shown in Table 5.12. Dividing Y_S by L gives 2.43. The triangular arrangement is simulated in a 10m wide channel, 2 boulders are upstream and 1 downstream, and therefore the ZOI distance (L) is Y_D of 2 boulders added it to the Y_U of 1 boulder, to give L equal to 3.5. Dividing Y_S by L we get 2.57. The same method is applied to the Parallelogram arrangement giving Y_S divided by L as 2.52.

It was observed that Y_S/L = ~2.5. Therefore the distance between the set of boulders should be approximated to a distance equal to (the length of the ZOI considered) multiplied by 2.5.

$$Y_S = L \,.\, 2.5 \tag{5.14}$$

It is recommended for future studies to investigate if Y_S/L = ~2.5 changes for different boulder sizes and flow conditions.

5.3 NON-LINEAR ARRANGEMENTS

In terms of aesthetics, it is often more appealing to have boulders that are not just placed in straight lines. In order to give a natural appearance, arrangements that are not linear are investigated to see whether they give similar effects as the linear arrangements. Linear boulder arrangements are rearranged so that they are no longer in straight lines, by moving selected boulders downstream, while keeping the rest in the same position. For example, Figure 5.18 demonstrates that if we have 3 boulders in line, it is hypothesized that if the centre boulder is moved a certain distance away it will still have a similar influence on the flow characteristics.

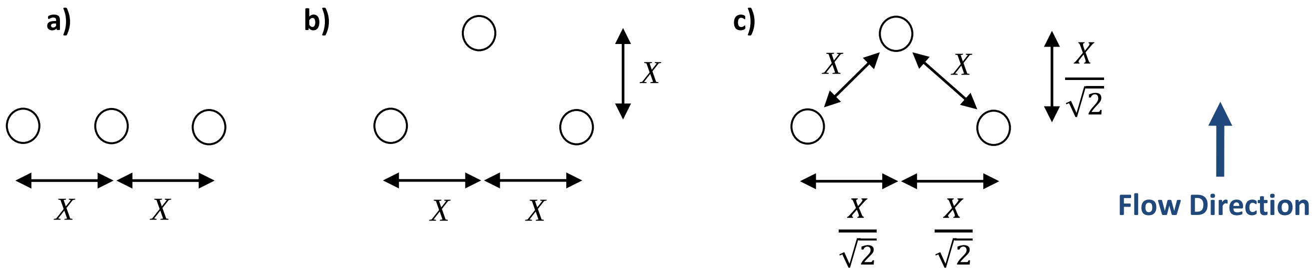
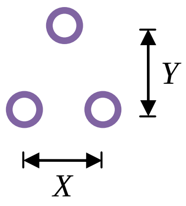
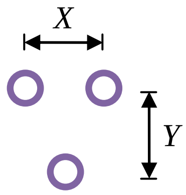


Figure 5.18: Depiction of the movement of the boulders to create non-linear arrangements

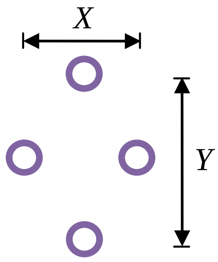
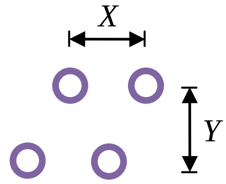
The longitudinal spacing in the Y direction and the transverse spacing in the X direction were adjusted. The different models that were used to assess these non-linear arrangements are shown in Table 5.13 for 3 and 4 boulders in wide channels. The impacts are analysed by finding the lengths of the ZOI and generating histograms with their velocity variances. As before, the largest ZOI area was selected from all the models being compared and applied to each of them to get their histograms. Schueler & Brown (2004) suggest that triangular groups of three to five boulders are the most effective design.

Table 5.13: Models for Non-Linear Arrangements

Discharge, q ($m^3/s/m$)	Slope	Boulder Diameter (m)	Width, b (m)
0.25	0.0008	0.2	10

<table>
<tr><th colspan="7">3 Boulders</th></tr>
<tr><td>Flow Direction</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Arrangement</td><td colspan="3">Triangular</td><td colspan="3">Inverted Triangular</td></tr>
<tr><td>Model No.</td><td>49</td><td>50</td><td>51</td><td>52</td><td>53</td><td>54</td></tr>
<tr><td>X, Trans. Spacing (m)</td><td>0.7</td><td>$2(0.7/\sqrt{2})=1$</td><td>1.4</td><td>0.7</td><td>$2(0.7/\sqrt{2})=1$</td><td>1.4</td></tr>
<tr><td>Y, Long. Spacing (m)</td><td>0.7</td><td>$(0.7/\sqrt{2})=0.5$</td><td>0.7</td><td>0.7</td><td>$(0.7/\sqrt{2})=0.5$</td><td>0.7</td></tr>
</table>

Discharge, q ($m^3/s/m$)	Slope	Boulder Diameter (m)	Width, b (m)
0.25	0.0008	0.2	10

<table>
<tr><th colspan="11">4 Boulders</th></tr>
<tr><td>Flow Direction</td><td colspan="5"></td><td colspan="5"></td></tr>
<tr><td>Arrangement</td><td colspan="5">Diamond</td><td colspan="5">Rhombus / Parallelogram</td></tr>
<tr><td>Model No.</td><td>55</td><td>56</td><td>57</td><td>58</td><td>59</td><td>60</td><td>61</td><td>62</td><td>63</td><td>64</td><td>65</td></tr>
<tr><td>X, Trans. Spacing (m)</td><td>0.7</td><td>0.7</td><td>1.4</td><td>1.4</td><td>$2(0.7/\sqrt{2})=1$</td><td>1.4</td><td>1.4</td><td>0.7</td><td>0.7</td><td>$2(0.7/\sqrt{2})=1$</td><td>1.4</td></tr>
<tr><td>Y, Long. Spacing (m)</td><td>0.7</td><td>1.4</td><td>0.7</td><td>1.4</td><td>$2(0.7/\sqrt{2})=1$</td><td>0.5</td><td>0.7</td><td>0.7</td><td>1.4</td><td>$(0.7/\sqrt{2})=0.5$</td><td>1.4</td></tr>
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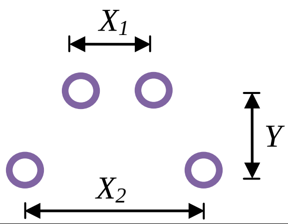
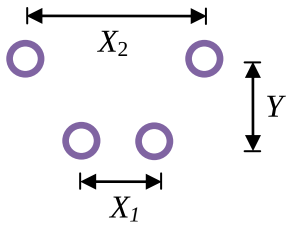
<table>
<tr><td>Flow Direction</td><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td>Arrangement</td><td colspan="3">Trapezoidal</td><td colspan="3">Inverted Trapezoidal</td></tr>
<tr><td>Model No.</td><td>66</td><td>67</td><td>68</td><td>69</td><td>70</td><td>71</td></tr>
<tr><td>X_1, Trans. Spacing (m)</td><td>0.7</td><td>0.7</td><td>$0.7/\sqrt{2}=0.5$</td><td>0.7</td><td>0.7</td><td>$0.7/\sqrt{2}=0.5$</td></tr>
<tr><td>X_2, Trans. Spacing (m)</td><td>2.1</td><td>2.1</td><td>$3(0.7/\sqrt{2})=1.5$</td><td>2.1</td><td>2.1</td><td>$3(0.7/\sqrt{2})=1.5$</td></tr>
<tr><td>Y, Long. Spacing (m)</td><td>0.7</td><td>1.4</td><td>$(0.7/\sqrt{2})=0.5$</td><td>0.7</td><td>1.4</td><td>$(0.7/\sqrt{2})=0.5$</td></tr>
</table>

5.3.1 Non-Linear Arrangements with Three Boulders

The ZOI lengths in the upstream and downstream directions created by the non-linear arrangements with 3 boulders are shown in Table 5.14, with the percentage difference between the linear and the non-linear arrangements in order to give a comparison. It was observed that for 3 boulders, the triangular arrangement has more of an influence than the inverted triangular arrangement. The triangular arrangement that resulted in the closest ZOI lengths to that of the linear arrangement was when the spacing between the boulders of the linear arrangement was made equal to X, and the centre boulder was moved X downstream, as depicted in Figure 5.18 b.

The histograms for the triangular arrangements are shown in Figure 5.19, the histograms for the inverted triangular arrangements can be found in Appendix 2. Table 5.15 gives the variances and standard deviations of the velocity distributions; it was observed for 3 boulders that even though the triangular arrangement had a longer ZOI length, the inverted triangular arrangement had a larger variance in velocity. Since the ZOI lengths for the two non-linear arrangements were similar, the inverted triangular arrangement was more desirable.

Table 5.14: Size of ZOI areas created by Non-Linear Arrangements with 3 Boulders

No. Of Boulders	Model No.	Y_B, Long. Spacing (m), Distance between Up/Downstream Boulders	Length of ZOI			
			Y_U	Y_D	$L = Y_U + Y_D + Y_B$	% Diff. b/w Linear and Non-Linear
3	28	0 (3 Boulder in line)	2.758	5.503	8.261	0
Triangular Arrangement						
3	49	0.7	1.834	5.708	8.242	-0.230
3	50	0.5	1.876	5.668	8.044	-2.627
3	51	0.7	1.803	5.159	7.662	-7.251
Inverted Triangular Arrangement						
3	52	0.7	1.360	6.082	8.142	-1.441
3	53	0.5	1.659	5.709	7.869	-4.745
3	54	0.7	1.518	5.388	7.606	-7.929

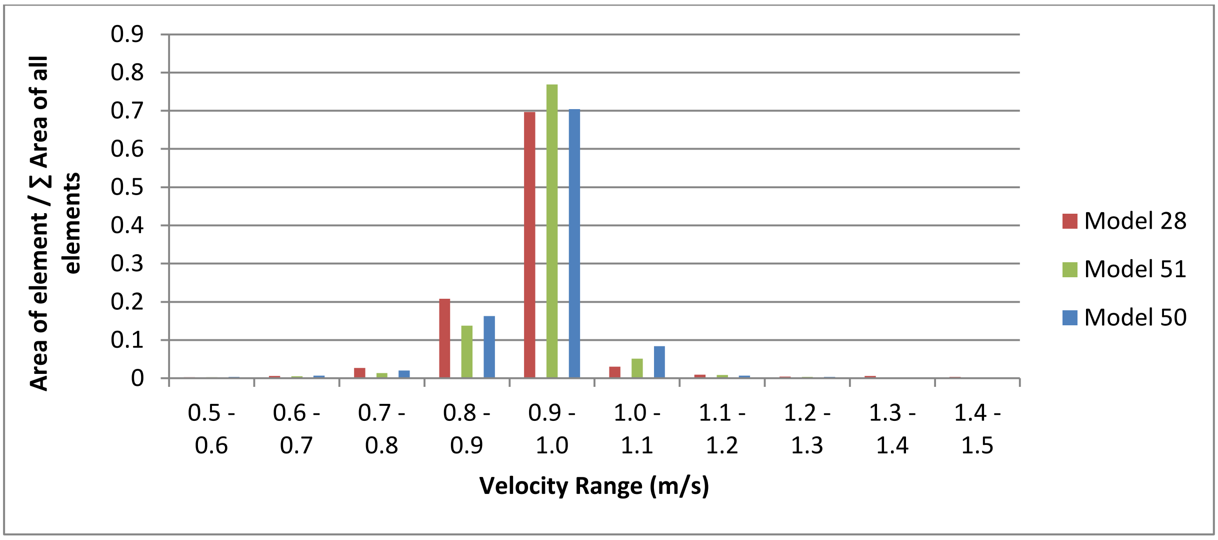


Figure 5.19: Histograms for Triangular Non-Linear Arrangements

Table 5.15: Variances of Non-Linear Arrangements with 3 Boulders

Arrangement	Triangular (3 B)			Inverted Triangular (3 B)		
Model No.	28	51	50	28	54	53
Variance	0.083	0.073	0.078	0.084	0.088	0.076
Standard Deviation	0.288	0.27	0.28	0.29	0.296	0.277

5.3.2 Non-Linear Arrangements with Four Boulders

For 4 boulders, the ZOI lengths are shown in Table 5.16 with the percentage difference between the linear and the non-linear arrangements. A lower percentage difference indicates that the flow impacts of the non-linear arrangements are closer to that of the linear arrangement. It was found that the arrangements, from the most influence to the least were the Trapezoidal followed by the Inverted Trapezoidal, then the Parallelogram and lastly the Diamond. The arrangement that had the closest ZOI Length to that of the linear arrangement was the Trapezoidal, when the spacing between the boulders of the linear was made equal to X, then for the Trapezoidal arrangement the spacing was reduced to $X/\sqrt{2}$ and the two centre boulders were moved $X/\sqrt{2}$ downstream.

The histograms for the trapezoidal arrangements are shown in Figure 5.20, the histograms for the rest of the 4 boulder non-linear arrangements can be found in Appendix 2. Table 5.17 gives the variances and standard deviations of the velocity distributions; it was observed for 4 boulders that the trapezoidal arrangement had the largest variance in velocity distribution. Therefore also having the longest ZOI length, the trapezoidal arrangement was clearly the most attractive out of all the non-linear arrangements. The other 4 boulder arrangements besides the Diamond had similar variances in velocity. Therefore all of the non-linear arrangements for 3 and 4 boulders, excluding the Diamond arrangement could be considered as alternatives to linear arrangement if it is required.

Table 5.16: Size of ZOI areas created by Non-Linear Arrangements with 4 Boulders

No. Of Boulders	Model No.	Y_B, Long. Spacing (m), Distance between Up/Downstream Boulders	Length of ZOI			
			Y_U	Y_D	$L = Y_U + Y_D + Y_B$	% Diff. b/w Linear and Non-Linear
4	33	0 (4 Boulder in line)	4.198	9.269	13.467	0
Diamond Arrangement						
4	55	0.7	1.939	6.855	9.495	-29.494
4	56	1.4	1.622	6.075	9.097	-32.450
4	57	0.7	2.259	6.706	9.664	-28.239
4	58	1.4	1.879	6.559	9.838	-26.947
4	59	1	1.977	6.449	9.426	-30.007
Rhombus / Parallelogram Arrangement						
4	60	0.5	3.057	7.061	10.618	-21.155
4	61	0.7	2.462	8.256	11.418	-15.215
4	62	0.7	2.425	7.171	10.296	-23.546
4	63	1.4	2.326	6.499	10.225	-24.074
4	64	0.5	2.613	7.525	10.638	-21.007
4	65	1.4	2.204	6.974	10.579	-21.445
Trapezoidal Arrangement						
4	66	0.7	2.533	8.870	12.103	-10.128
4	67	1.4	2.269	6.974	10.643	-20.970
4	68	0.5	2.784	9.079	12.363	-8.198
Inverted Trapezoidal Arrangement						
4	69	0.7	2.675	8.456	11.830	-12.156
4	70	1.4	2.318	8.211	11.929	-11.421
4	71	0.5	2.799	7.711	11.009	-18.252

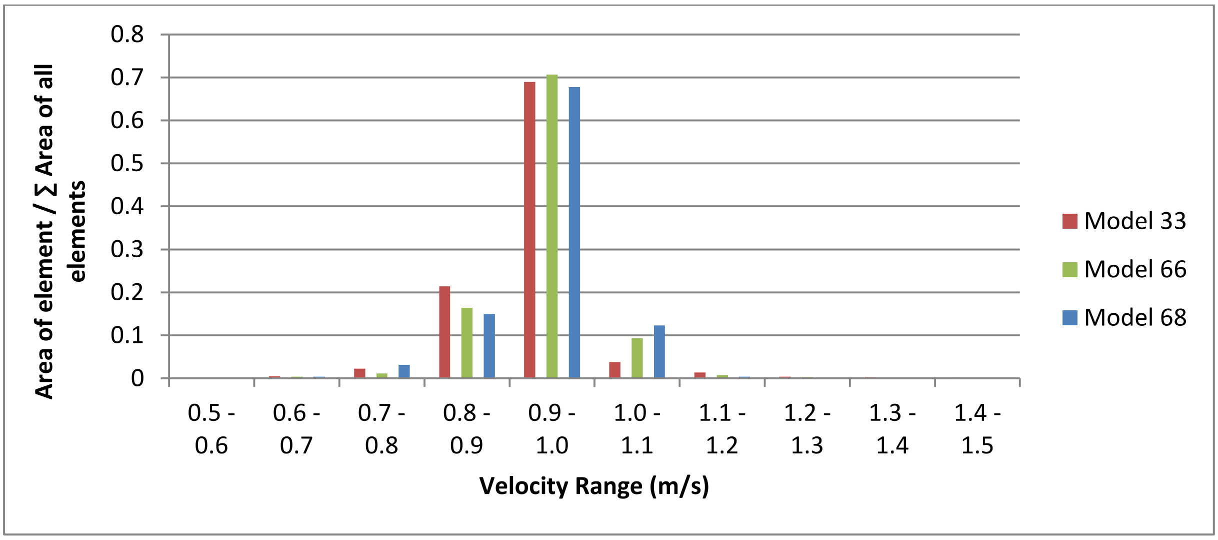


Figure 5.20: Histograms for Trapezoidal Non-Linear Arrangement

Table 5.17: Variances of Non-Linear Arrangements with 4 Boulders

Arrangement	Diamond (4 B)			Parallelogram (4 B)		
Model No.	33	58	59	33	61	64
Variance	0.085	0.061	0.06	0.085	0.068	0.066
Standard Deviation	0.291	0.248	0.245	0.291	0.261	0.257
Arrangement	Trapezoidal (4 B)			Inverted Trapezoidal (4 B)		
Model No.	33	66	68	33	69	71
Variance	0.082	0.071	0.076	0.085	0.072	0.067
Standard Deviation	0.287	0.267	0.275	0.291	0.268	0.259

5.4 VARIED SHAPES

In this chapter, the effect of the shape of a boulder on the flow characteristics around it is examined. As in the previous chapter the ZOI Lengths, the velocity distribution histograms and variances are used to compare the different models. Table 5.18 gives the shapes and the conditions used.

Table 5.18: Models for assessing various shapes

Discharge, q (m^3/s/m)		***Slope***		***Width, b (m)***	
0.25		0.0008		5	
Model No.	72	73	74	75	76
Shape	*Circle*	*Square*	*Diamond*	*Triangle*	*Inverted Triangle*
Size	○ ↔ *0.2 m*	□ ↔ *0.2 m*	◇ ↔ *0.2 m*	△ ↔ *0.2 m*	▽ ↔ *0.2 m*

Flow Direction

Table 5.19: ZOI sizes for the Various Shapes

Model No.	***Shape***	***Length of ZOI***		
		Upstream	Downstream	L = Up + Down
72	*Circle*	0.640	0.791	1.432
73	*Square*	0.745	0.944	1.689
74	*Diamond*	0.574	0.935	1.509
75	*Triangle*	0.738	1.091	1.828
76	*Inverted Triangle*	0.537	1.115	1.652

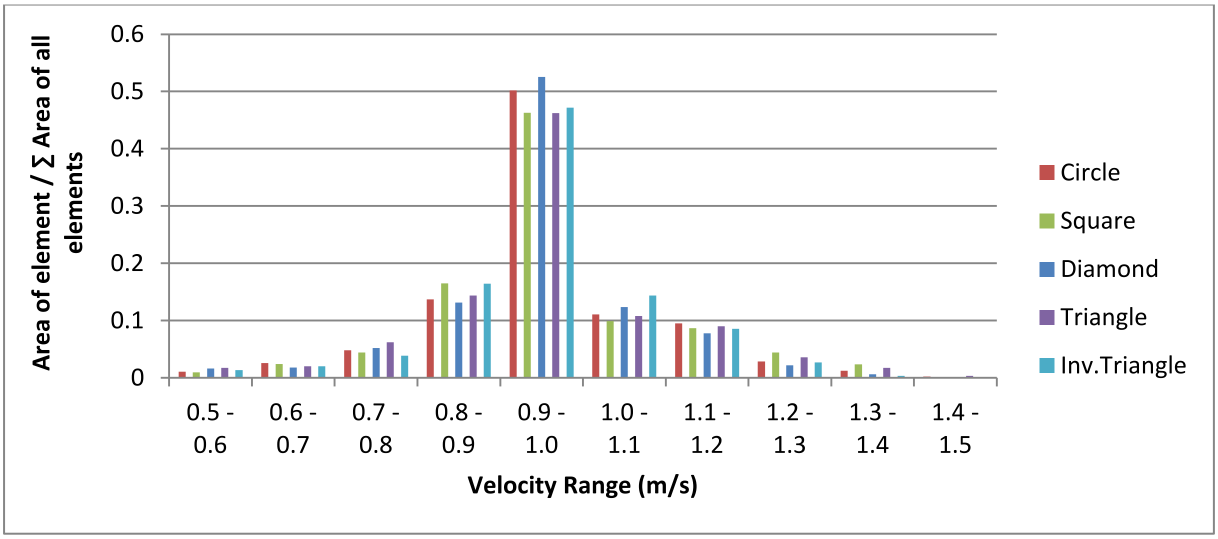


Figure 5.21: Histograms for the Various Shapes

Table 5. 20: Variances for the Various Shapes

Shape	Circle	Square	Diamond	Triangle	Inverted Triangle
Variance	0.121	0.157	0.109	0.158	0.112
Standard Deviation	0.348	0.396	0.331	0.397	0.335

It was observed that the circle shape had the least effect on the ZOI created around it, and therefore it is assumed that the more angular the shape the more influence the boulders have on the ZOI lengths. This is in accordance with Rutherfurd et al. (2000) who have suggested that large angular boulders should be used in boulder placements in order to encourage as much hydraulic disturbance as possible, therefore improve the heterogeneity of the flow characteristics.

The deflection of the flow by the upstream face of the boulder induces a region of locally increased pressure, whilst on the downstream a region of locally low pressure is created, the pressure difference exerts a force on the boulder, and the component of this force in the direction of the flow is known as drag. The drag force is dependent on the cross sectional area perpendicular to the direction of flow, the shape of the boulder and also the flow characteristics (Chadwick, et al., 2004). The triangle and the square shapes had the most effect on the ZOI lengths, which can be attributed to the angle of the boulder face in the direction of the flow. The circle may have had the lowest ZOI length; however in terms of the variance in velocity, it was not the worst. This may be accounted for by the hydrodynamics around the diamond and the inverted triangle shapes as their pointed upstream face reduces the drag and therefore the variance in the velocity around it. The square and the triangle shapes had the largest variance and are therefore considered to be the most advantageous shape to incorporate in the design of the boulders.

5.5 FLOW CLASSES

Boulders have a complex influence on the local flow environment as they modify the velocity and depth distributions. Until now, attention has been concentrated mainly on the ZOI that the boulders create; this chapter will address the Flow Class criteria that are used in South Africa for habitat requirements. The Flow Class criterion is a very broad method that divides the flow in a river into categories of velocity and depth that can be related to various groups of organisms. Boulders have a significant influence on surrounding hydraulics and create important microhabitats for plants and animals. The velocity and depth frequency histograms in Figures 5.22 and 5.23 respectively demonstrate how the placement of boulders causes a variance in the flow around it. The histograms represent model 1 for the ZOI area around a single boulder in the centre of the channel.

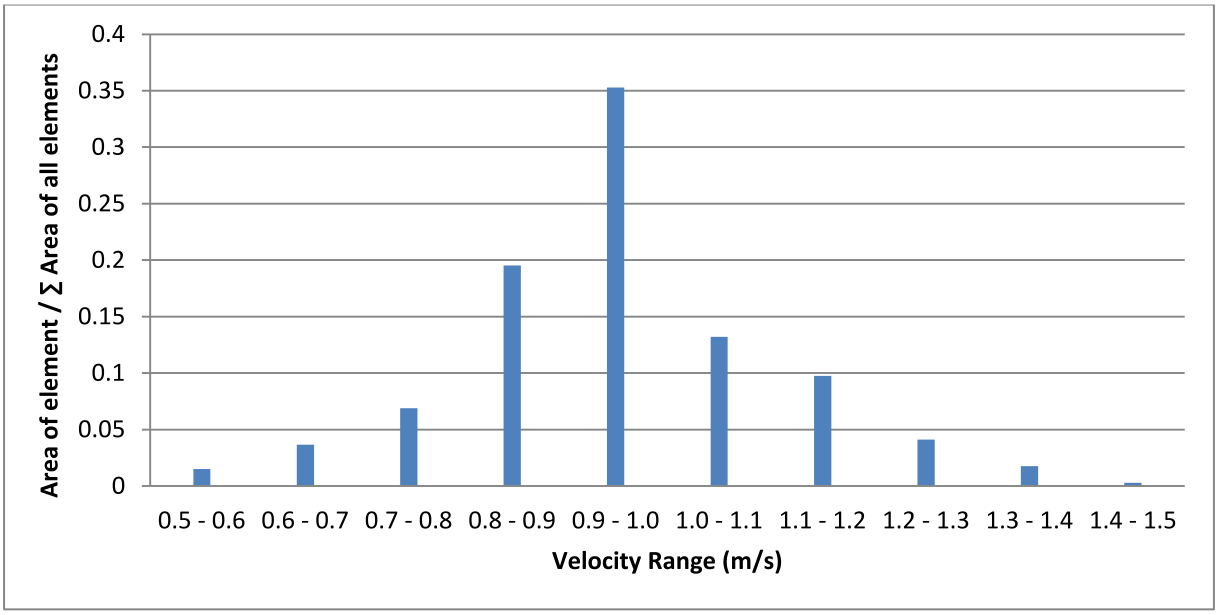


Figure 5.22: Histogram of Velocity Distribution for model 1

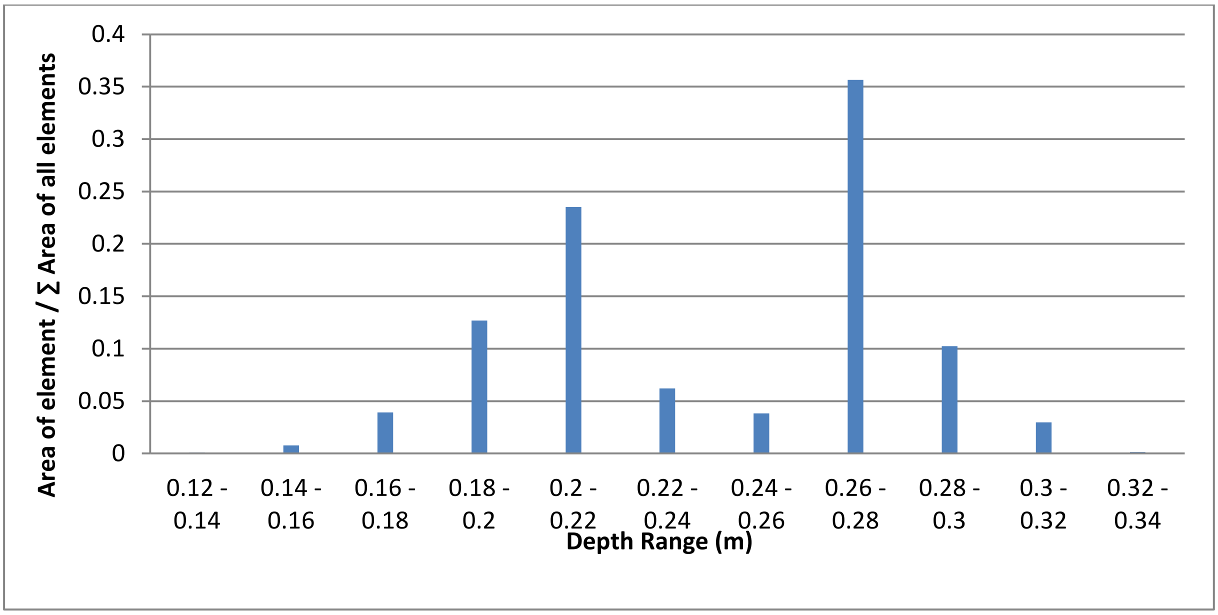


Figure 5.23: Histogram of Depth Distribution for model 1

Considering the channel in its entirety and not just the ZOI area, it must be pointed out that the placement of boulders may not be enough to change the majority of the channel's flow characteristics so that it shifts from one class to another (even when there are sufficient boulders laterally along the cross section so that the width of the channel affects the ZOI). For example, if the undisturbed flow depth is 0.1 m, even if the boulder doubles the flow depths locally, the flow classes will still remain in the shallow flow class boundaries. Having said that, the sub-categories of flow depths for fish and velocities for macroinvertebrates which are defined by Birkhead (2010) give additional ranges to consider than just the 4 classes defined by Kleynhans (1999) in Table 2.1. Therefore if the undisturbed flow depth is 0.1 m, and the boulders double the flow depths locally, the flow classes will move from the very shallow flow class boundary to the shallow flow class boundary. This study however, still highlights the importance of undisturbed flow characteristics to be close to flow class boundaries, to allow a shift of a large portion of the flow classes from one class to another.

Two scenarios were investigated; firstly it was observed how the flow classes compare for a model that had conditions close to the flow class boundaries and another which did not. Secondly, it was investigated how incrementally adding boulders influenced the flow classes, particularly when there were enough boulders set out laterally so that the width of the channel started to affect the ZOI. In order to compare, a flow class histogram was used which incorporates the same concept as the velocity histograms to find which portion of the total area has a certain flow class. The histograms for this section, Figures 5.24 and 5.25, considered the area of the entire channel. Table 5.21 shows the models that were used to assess the two conditions above.

Table 5.21: Models to assess Flow Classes

Model No.	***Discharge, q ($m^3/s/m$)***	***Slope***	***Width, b (m)***	***No. of Boulders***	***Diameter (m)***
77	0.2875	0.0008	2	0	-
78	0.2875	0.0008	2	1	0.2
79	0.2875	0.0008	2	2	0.2
80	0.25	0.0008	2	2	0.2

The histogram in Figure 5.24 demonstrates two separate models, each has 2 boulders in LC, the discharges are however different, where the one is close to the flow class boundary for deep and shallow (model 79) and the other is not (model 80). The advantage of having conditions close to the flow class boundaries is quite apparent as it is possible to shift a large portion of the area from one class to another, whereas when the conditions are not close then it is more difficult to shift a large portion of the area to a different flow class. Since the discharge is the only difference between the two models, there is also an indication that the classes are sensitive to discharge as there is a significant class change between the fairly close discharges for these two models.

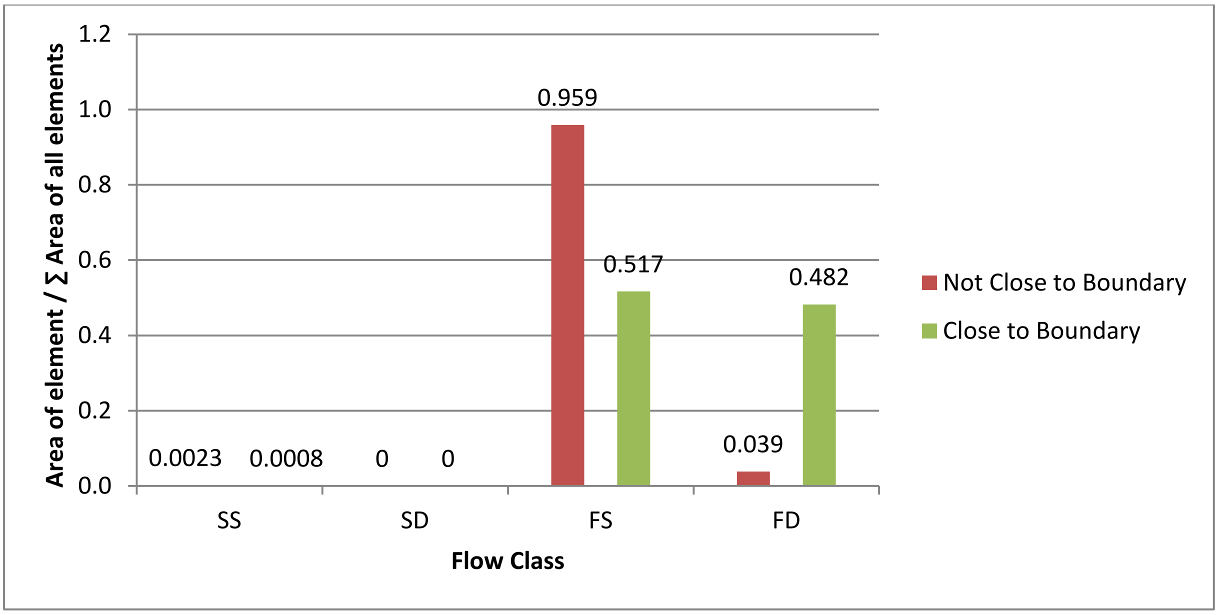


Figure 5.24: Histogram of Flow Classes for models 79 (green) & 80 (red)

The second scenario of incrementally adding boulders is shown in the histogram below and it was observed that in order to shift a large portion of the flow classes from one class to another, there need to be enough boulders in the channel for the width to affect the ZOI. This is demonstrated by the model with 2 boulders in the histogram below, as the model with 1 boulder is similar to that with none.

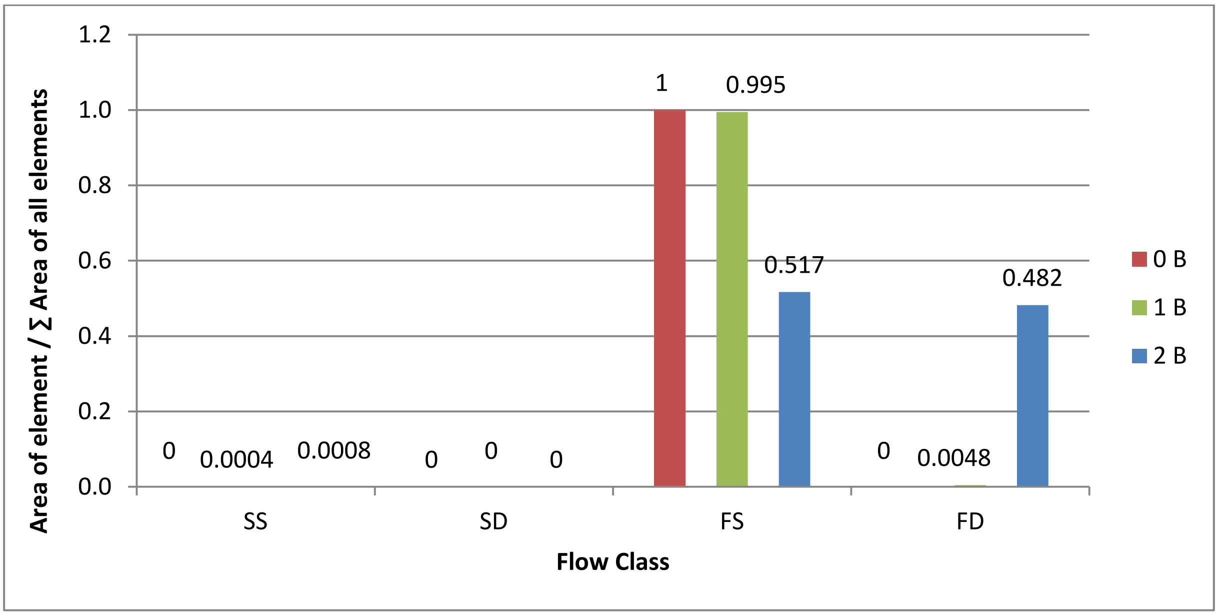


Figure 5.25: Histogram of Flow Classes for models 77 (red), 78 (green) & 79 (blue)

The above suggests that the undisturbed uniform conditions need to be investigated, and where possible to see what circumstances place them close to the flow class boundaries.

5.5.1 Conditions for Flow Classes in Undisturbed Flow

If the undisturbed conditions are near the flow class boundaries (i.e. close to 0.3m depth, 0.5m depth, or 0.3m/s velocity, as shown in Table 2.1, which is repeated below as Table 5.22) then the placement of boulders can cause a shift of a large portion of the area into another flow class. If not then it is more difficult to shift a large area of the channel into another flow class. This detail should be considered when constructing artificial channels such as fishways or drainage channels through golf courses. This chapter suggests a set of gradients, discharges and Froude numbers for the undisturbed channel that can be used to determine whether a certain flow class will occur in a particular channel, and recommends conditions that should be incorporated in channel construction where possible.

Table 5.22: Kleynhans's (1999) hydraulic habitat descriptions

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

The limits of the flow class quadrants, when Velocity (V) is 0.3 m/s and when the Depth (H) is 0.3m and 0.5m were carefully examined. The limits were then input into Manning's equation, which was rearranged to get the slope term by itself. For V = 0.3m/s and H = 0.3m the slope is "j". For V = 0.3m/s and H = 0.5m the slope is "k".

$$\boldsymbol{j} = \left(\frac{\mathbf{0.3}\,\boldsymbol{n}}{\left(\frac{\mathbf{0.3}\,\boldsymbol{b}}{\boldsymbol{b}+\mathbf{0.6}}\right)^{2/3}}\right)^{\mathbf{2}} \qquad (5.15)$$

$$\boldsymbol{k} = \left(\frac{\mathbf{0.3}\ \boldsymbol{n}}{\left(\frac{\mathbf{0.5}\ \boldsymbol{b}}{\boldsymbol{b}+\mathbf{1}}\right)^{\mathbf{2/3}}}\right)^{\mathbf{2}} \tag{5.16}$$

For V = 0.3m/s and the depth is very large (so that R becomes b/2), rearranging Manning's gives slope "l".

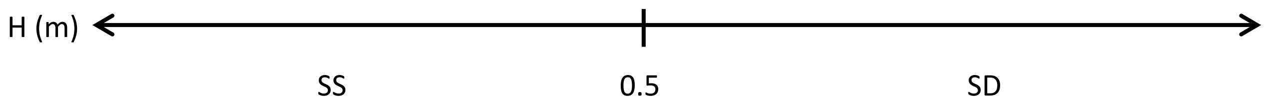
$$\boldsymbol{l} = \left(\frac{\mathbf{0.3}\ \boldsymbol{n}}{\left(\frac{\boldsymbol{b}}{\mathbf{2}}\right)^{\mathbf{2/3}}}\right)^{\mathbf{2}} \tag{5.17}$$

For the last equation, depth "m" is obtained by inputting V = 0.3m/s into Manning's equation and rearranging it while leaving the width as a variable.

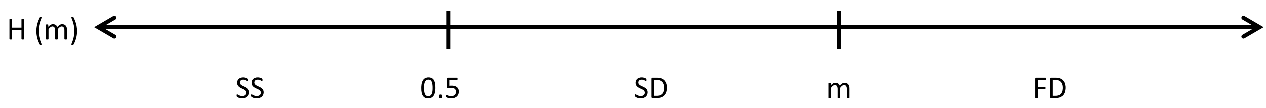
$$\boldsymbol{m} = \frac{\left(\frac{\mathbf{0.3}\ \boldsymbol{n}}{\boldsymbol{S}^{\mathbf{1/2}}}\right)^{\mathbf{3/2}}.\boldsymbol{b}}{\boldsymbol{b}-\mathbf{2}\left(\frac{\mathbf{0.3}\ \boldsymbol{n}}{\boldsymbol{S}^{\mathbf{1/2}}}\right)^{\mathbf{3/2}}} \tag{5.18}$$

The above equations are useful and their functions are explained below. Refer to Figure 5.26 on the next page to get a graphical representation of what is explained below in terms of the relationship between slope, depth and velocity.

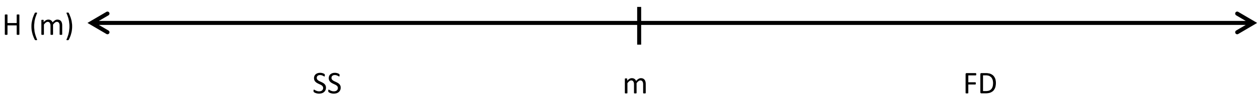
- When the channel slope is less than "l" then the undisturbed flow classes will either be SS or SD depending on the discharge. It will be SS if H is less than 0.5m or SD if it is greater than 0.5m.



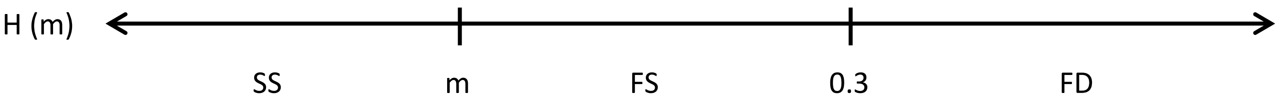
- When the channel slope is between "l" and "k", then the undisturbed flow classes will either be SS, SD or FD depending on the discharge. It will be SS if H is less than 0.5m, SD if H is between 0.5m and "m".
  - If the flow depth is greater than "m", the velocity category moves into "Fast", and the flow becomes FD.



- When the channel slope is between "k" and "j", then the undisturbed flow classes will either be SS or FD depending on the discharge. It will be SS if H is less than "m". If H is greater than "m", the velocity category moves into "Fast" and the flow class will be FD when H is greater than "m".



- When the channel slope is greater than "j" then the undisturbed flow classes will either be SS, FS or FD depending on the discharge. It will be SS if H is less than "m". If H is greater than "m" then the velocity category moves into "Fast". The flow class is FS when H is between "m" and 0.3m and the flow class is FD when H is greater than 0.3m.



This is then represented graphically, and the lines placed above on to a flow depth against velocity diagram with the flow classes overlain. Each contour demonstrates one of the three slopes described above.

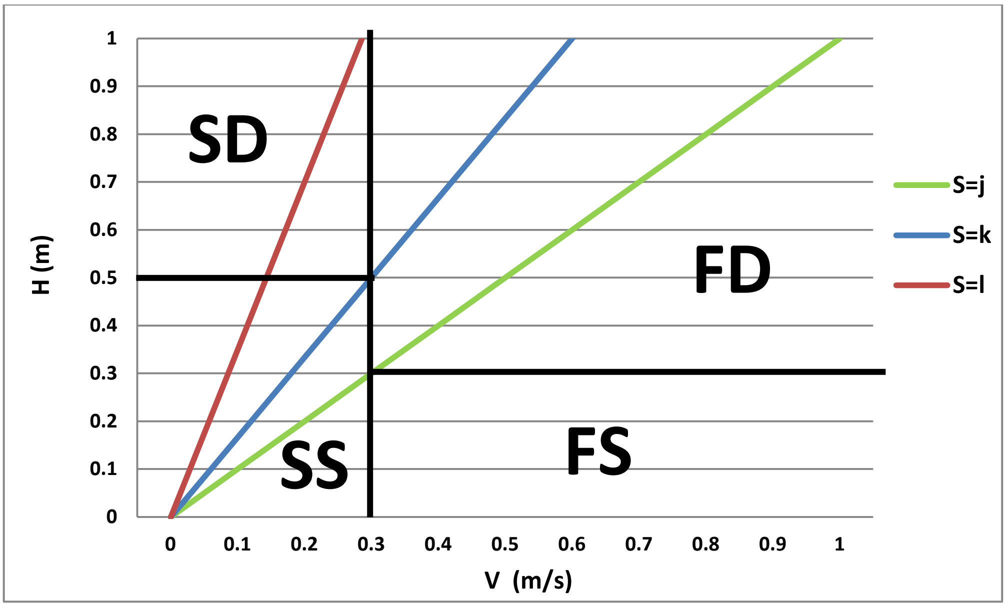


Figure 5.26: Flow depth vs. velocity for slope contours, with flow classes overlain

Figure5.26 shows that certain slopes may cover several flow classes; it was found that slopes greater than “l” were desirable as undisturbed flow classes in all the quadrants were possible. Similar graphical representations were done for discharge per unit width (q) and Froude number (Fr) and have been placed onto a flow depth against velocity diagram with the flow classes overlain.

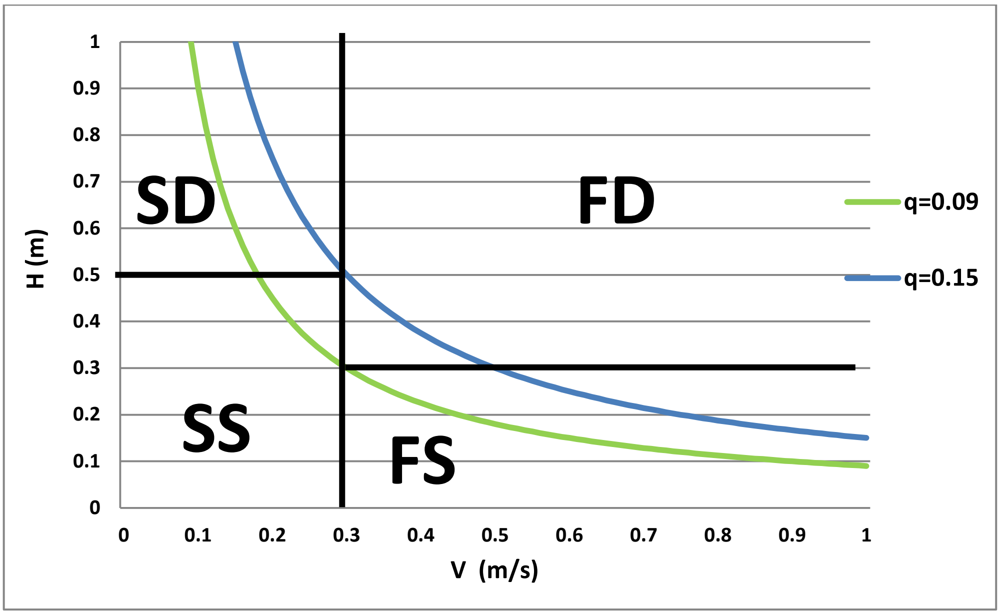


Figure 5.27: Flow depth vs. velocity for discharge per unit width contours, with flow classes overlain

The discharges per unit width that are significant were found to be $0.09m^3/s/m$ and $0.15m^3/s/m$, as they intersect the corners of the quadrants.

- When the discharge is less than $0.09m^3/s/m$, then the undisturbed flow classes may either be SS, SD or FS.
- When the discharge is between $0.09m^3/s/m$ and $0.15m^3/s/m$, then the undisturbed flow classes may either be SS, SD, FS or FD.
- When the discharge is greater than $0.15m^3/s/m$, then the undisturbed flow classes may either be SD, FS or FD.

Figure5.27 shows that it is desirable for the discharge per unit width to be between $0.09m^3/s/m$ and $0.15m^3/s/m$ as undisturbed flow classes in all the quadrants were possible.

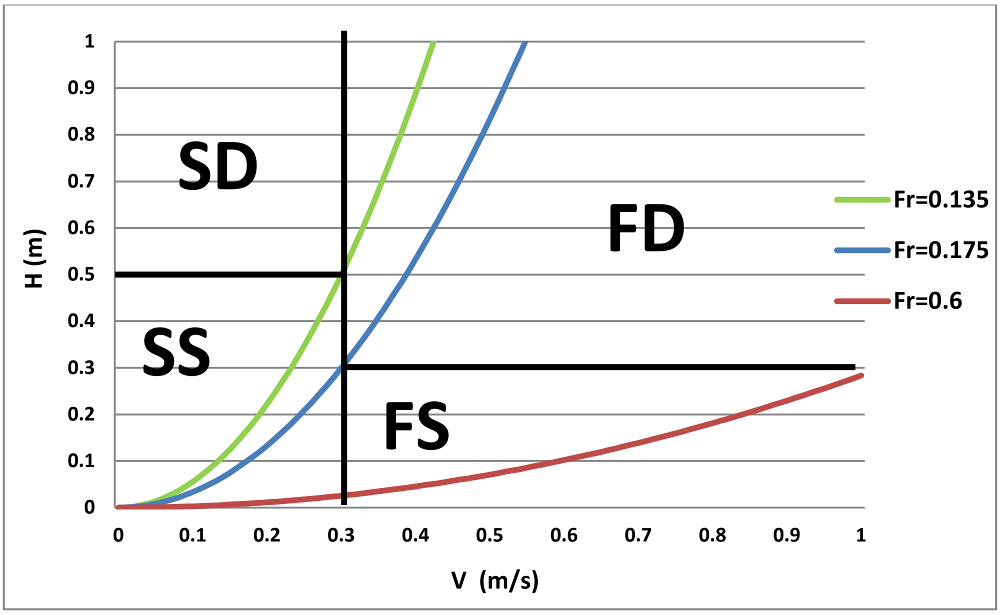


Figure 5.28: Flow depth vs. velocity for Froude Number contours, with flow classes overlain

The maximum Froude number of an undisturbed channel was found to occur when the flow depth is equal to the width of the channel divided by six (H = b/6). This was calculated by substituting Manning's equation into the Froude equation, then equating the derivative of the Froude equation to 0 in order to get a maximum (Fr' = 0).

$$Fr = \frac{V}{\sqrt{gH}} \tag{5.19}$$

$$Fr = \frac{\frac{1}{n} R^{2/3} \; S^{1/2}}{\sqrt{gH}} \tag{5.20}$$

$$Fr = \frac{b^{2/3}H^{1/6}}{(2H+b)^{2/3}} \cdot \frac{S^{1/2}}{n\sqrt{g}} \tag{5.21}$$

$$Fr' = b^{2/3} \frac{S^{1/2}}{n\sqrt{g}} \frac{d}{dH} \left(\frac{H^{1/6}}{(2H+b)^{2/3}}\right) \tag{5.22}$$

Fr' = 0 gives:

$$H = \frac{b}{6} \tag{5.23}$$

Substituting equation 5.23 into equation 5.21 and simplifying gives:

$$Fr = \frac{b^{1/6}}{1.633} \cdot \frac{S^{1/2}}{n\sqrt{g}} \tag{5.24}$$

The maximum undisturbed Froude number can then be calculated. The Froude numbers that were found to be significant are 0.135 and 0.175, as they intersect the corners of the quadrants. Figure5.28 shows that it is desirable for the maximum undisturbed Froude number to be greater than 0.175 as undisturbed flow classes in all the quadrants were possible.

Riddet (2012) also suggested that a Froude number of 0.6 is significant. She found that the undisturbed Froude number needs to be greater than 0.6 to allow for a LC to occur between 2 boulders. The Froude numbers of the undisturbed channel in the simulated models which had LC were investigated, and it was found that LC does occur below 0.6 but not by much and therefore this value of 0.6 may be conservative but a good indication of the limit of Froude number for the undisturbed channel to create a LC. Riddet (2012) also found that the standard deviation in velocity increases as the maximum and undisturbed Froude number increases.

5.6 ROUGH GUIDELINE FOR THE PLACEMENT OF BOULDERS

This rough guideline concentrates on placement of cylindrical boulders to maximise the 10% ZOI. The ZOI was dependent on the spacing, number and the diameter of the boulders; as well as the slope, width and discharge of the channel. It was found that for the placement of an in-stream boulder in the centre of the channel, increasing the discharge, slope and boulder diameter, would produce an increase in the variance of the flow in the channel and therefore improve the heterogeneity for organisms in the surrounding habitat.

5.6.1 Undisturbed Channel Characteristics

It is often not possible to alter the slope and the discharge but where construction of artificial channels are undertaken; they should be designed for a predetermined flow condition that is close to the flow class boundary limits, so that the placement of boulders can cause a considerable change in the flow classes around it. The Flow Classes defined by Kleynhans (1999) were used for this study but these flow class categories should be extended to include additional flow classes defined by Birkhead (2010).

- In terms of the slope of the channel, it should be greater than "l", as this range of slopes allows for the potential for the undisturbed flow to fall into all the flow classes.

$$\boldsymbol{l} = \left(\frac{\mathbf{0.3}\,\boldsymbol{n}}{\left(\frac{\boldsymbol{b}}{\mathbf{2}}\right)^{\mathbf{2/3}}}\right)^{\mathbf{2}} \qquad (5.17)$$

Where n is Manning's coefficient and b is the channel width.

- The undisturbed Froude number (Fr) should be greater than 0.6 so as to allow for inducing LC. However, if LC is not required, then the undisturbed Fr should be greater than 0.175, as this range covers all the flow classes

- The discharge per unit width should be between $0.09 m^3/s/m$ and $0.15 m^3/s/m$ as this range allows for the potential for the undisturbed flow to fall into all the flow classes.

5.6.2 Boulder Characteristics

This rough guideline recommends that angular boulders be incorporated into the boulder placement designs as this increases the variance, the ZOI and the aesthetics, this is in accordance with Rutherfurd et al. (2000).

The results in this study have been found and therefore only applicable to emergent boulders. Rutherfurd et al. (2000) has however also suggested that the boulders be emergent, placed in the centre of the channel (to reduce erosion) and the boulders should be large enough to prevent the flow from moving the boulders, therefore the forces between the boulders, the bed material and flow need to be evaluated, and should be calculated with relevant guidelines. It was also recommended that the boulders should be less than 1/5 of the channel width or between 0.6 and 1.5m in diameter.

5.6.3 Placement of Boulders in the Transverse Direction

It was found to be advantageous to induce local critical flow as this would increase the variance in the velocity distribution, the ZOI and therefore the heterogeneity of the flow in the channel. The spacing and the diameter of the boulders; as well as the slope, width and discharge of the channel affect the transition from non-locally controlled to locally controlled flow.

- For Wide Channels:

It was found that the placement of multiple boulders increased the ZOI by a factor of two, for every incrementally added boulder.

ZOI for multiple boulders = $2^{(\text{No. of Boulders - 1})}$ x (ZOI for 1 boulder, Y_D+Y_U) (5.13)

The ZOI length of 1 boulder relative to its diameter in the downstream section (Y_D) is:

$$\frac{Y_D}{d} = 2.2\,\frac{Fr^{0.25}\,b^{0.25}}{d^{0.25}} \qquad (5.9)$$

The ZOI length of 1 boulder relative to its diameter in the upstream section (Y_U) is:

$$\frac{Y_U}{d} = 3.5\,\frac{Fr^{1}\,b^{0.1}}{d^{0.1}} \qquad (5.10)$$

Where Fr is the Froude number of the undisturbed channel, b is the channel width and d is the boulder diameter.

- For channel width narrow enough that it affects the ZOI:

The limits for the width to start affecting the ZOI is summarised in Table 5.8 for 0.2m diameter boulders. When the widths of the channels were incrementally reduced past these limits, a back-up effect started occurring in the upstream section which considerably increased the ZOI in this direction. It is recommended, that where possible this back-up effect should be induced to increase the ZOI area, increase the variances in the flow and increase the portion of the channel area that shifts from one flow class to another.

It is proposed for this rough guideline that the transverse spacing between boulders should be roughly less than 4 times the boulder's diameter, to allow for the maximum spacing yet induce a LC.

Since the width of the channel relative to boulder size also affects the size of the ZOI considerably, where possible there should be enough boulders placed laterally to allow the side embankments to have an effect on the ZOI. Over-constricting the flow in the channel should however be avoided as to prevent bank erosion.

5.6.4 Placement of Boulders in the Longitudinal Direction

In order to minimise the use of boulders and construction costs, each array of boulders should act independently, as in the ZOI that one array creates should be separate from the ZOI that the subsequent downstream array creates. Schueler & Brown (2004) proposed that boulders should not lie in the wake of an upstream boulder.

In terms of placing the next set of boulders downstream, equation 5.14 is implemented:

$$Y_S = L \,.\, 2.5 \qquad (5.14)$$

Where Y_S is the distance between a set of boulder and L is the length of the ZOI that is created by each set of boulders in the upstream and downstream directions respectively, these ZOI lengths are calculated using equation 5.13 and 5.9 or 5.10 accordingly (as shown on the previous page). I.e. if we have 1 boulder downstream and 2 boulders upstream, we find the downstream ZOI for 2 boulders using equations 5.13 and 5.9, which is $2^{(2-1)}$ x

$2.2\ \frac{Fr^{0.25}\ b^{0.25}}{d^{0.25}}$ x d, then we find the upstream ZOI for 1 boulder using equations 5.13 and 5.10, which is $2^{(1\text{-}1)}$ x $3.5\ \frac{Fr^{1}\ b^{0.1}}{d^{0.1}}$ x d. Then we add these two to get L and multiply it by 2.5 to get the distance that is required between the two sets of boulders.

5.6.5 Non-Linear Placement of Boulders

In terms of aesthetics, instead of just placing boulders in lines, they may be rearranged for more of a natural appearance, while still giving similar effects on the flow characteristics. For 3 boulders in line, an inverted triangular arrangement is recommended, however a triangular arrangement can also be used. If we have 3 boulders in line with the spacing between the boulders equal to X, then the centre boulder can be moved upstream or downstream by a distance of X.

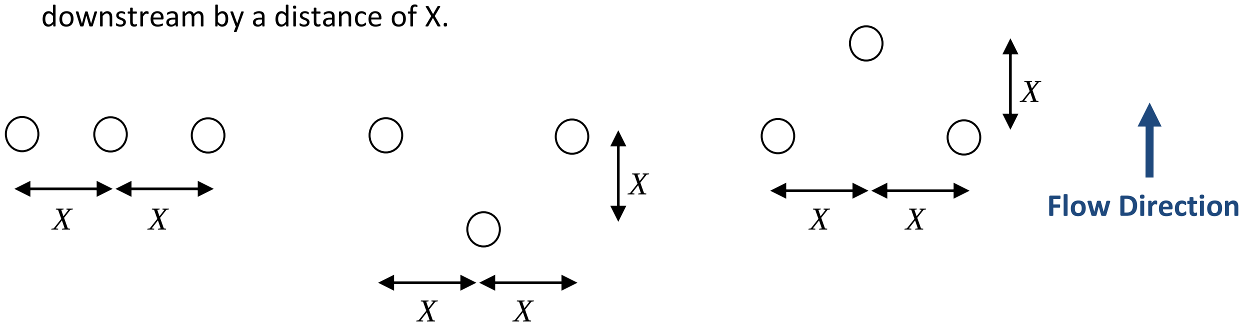


Figure 5.29: Depiction of the movement of boulders to create non-linear 3 boulder arrangements

For 4 boulders placed in line, a Trapezoidal arrangement is recommended; if we have 4 boulders in line with the spacing between the boulders equal to *X,* then the spacing can be reduced to $X/\sqrt{2}$ and the two centre boulders can be moved a distance of $X/\sqrt{2}$ downstream. The inverted Trapezoidal arrangement may also be used however, the spacing should remain *X*, and the two centre boulders should be moved a distance of *X* upstream. Lastly, a Parallelogram arrangement may be used, and the spacing should remain *X*, while the 2nd and 4th boulders should be moved a distance of *X* downstream.

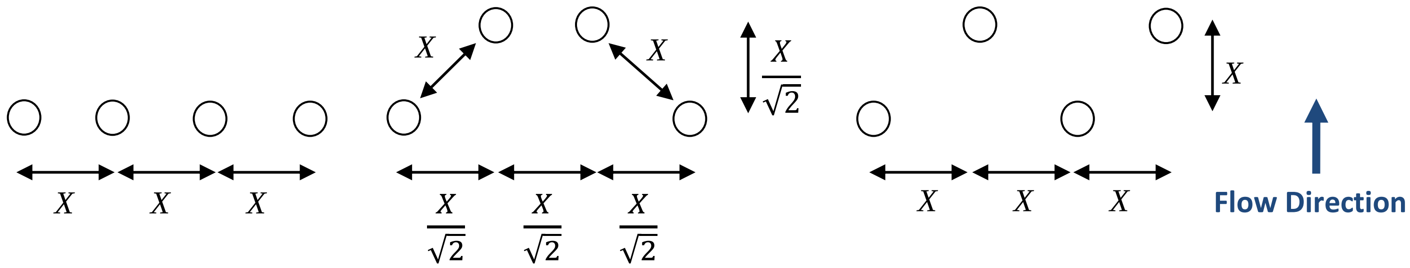


Figure 5.30: Depiction of the movement of boulders to create non-linear 4 boulder arrangements

5.6.6 Rough Guideline Example

Table 5.23: Conditions of Rough Guideline Example

Discharge, Q (m^3/s)	*Slope*	*Manning's n*	*Width, b (m)*
10	0.015	0.05	15

For the above conditions, the undisturbed depth is equal to 0.47m and the undisturbed Froude number is equal to 0.66.

- The size of the boulder should be evaluated on the basis of its tractive force (Rutherfurd, et al., 2000). The diameter will be taken to be 1m in diameter for this example. The boulder should also be emergent and angular.
- The spacing between the boulders should be approximately 4 times the boulder's diameter to allow for the maximum spacing yet induce a LC, as recommended on page 44 using results of section 5.1.2. 4 x 1m (boulder diameter) = 4m; therefore 4 boulders should be placed laterally along the width of the channel.
- For aesthetic appeal, the Trapezoidal arrangement is used for 4 boulder placements. Since the spacing is equal to 4m, this spacing can be reduced to $\frac{4}{\sqrt{2}}$ = 2.83m and the two centre boulders should be moved a distance of 2.83m downstream
- The next set of boulders downstream should be placed Y_S away from each other.

$$Y_S = L \,.\, 2.5 \qquad (5.14)$$

Equation 5.13, 5.9 and 5.10 were then used to determine L and give equation 5.25:

$$L = (2^{(\text{No. of Boulders -1})} \times 2.2\ \frac{Fr^{0.25}\, b^{0.25}}{d^{0.25}} \times d) + (2^{(\text{No. of Boulders -1})} \times\ 3.5\ \frac{Fr^{1}\, b^{0.1}}{d^{0.1}} \times d) \qquad (5.25)$$

$$L = (2^{(4\ -1)} \times 2.2\ \frac{0.66^{0.25}\ 15^{0.25}}{1^{0.25}} \times 1) + (2^{(4\ -1)} \times\ 3.5\ \frac{0.66^{1}\ 15^{0.1}}{1^{0.1}} \times 1) \qquad (5.26)$$

$$L = 31.22 + 24.23 \qquad (5.27)$$

$$L = 55.45\text{m} \qquad (5.28)$$

$$Y_S = 55.45 \,.\, 2.5 \qquad (5.29)$$

$$Y_S = 138.63\text{m} \qquad (5.30)$$

Therefore the next set of boulders should be placed 138.63m downstream.

6 CONCLUSION AND RECOMMENDATIONS

The main focus of this study was to investigate ways to improve habitat conditions for organisms in channelized streams. Various conclusions were drawn from the results of the laboratory experiments and computer simulations. It was found that the placement of boulders does create a variance in velocity and an increase in ZOI, particularly for multiple boulders in line normal to the flow direction. When the boulders are placed close enough to create a LC then the ZOI is increased exponentially with the incremental addition of boulders to the arrangements. LC produces a greater distribution of velocities and a larger standard deviation, which is a desirable characteristic. It encourages natural habitat in river rehabilitation as various river fauna and flora require different flow conditions at different life stages. For LC the flow will transition from being relatively slow to relatively fast in a short space.

The effects of boulder spacing, size and shape on local velocity were assessed by observing the changes in the size of the ZOI within which the local velocity deviates by a predetermined ratio from the undisturbed velocity. It was found that angular boulders had more of an influence than circular boulders, particularly when having a large face on the upstream side so as to increase the drag. It was also found that the larger the boulders, the more affect it had on the ZOI. The spacing should be close enough to induce LC.

The effects of the arrangement of the boulders, the slope, the width and the discharge of the channel, on the velocity distribution were also assessed. Due to numerical instabilities the simulations in this study were only conducted for a subcritical range of undisturbed Froude numbers. For LC to be induced, the Froude number should be greater than 0.6. It was found that the width of the channel relative to boulder size also affected the size of the ZOI, the ZOI increased as the channel became narrower, and this was defined relative to the number of boulders placed laterally along the cross sections and their diameters. The undisturbed flow conditions should be altered, where possible, to bring them close to the flow class boundaries, so that the placement of boulders may cause a substantial change and a wider range in the flow classes. It was also found that the greater the discharge, the larger the variance in the velocity distribution in the area around the boulders.

Lastly, in terms of improving the aesthetics of boulder placements, it was found that certain nonlinear arrangements may be used to give a more natural appearance yet give similar effects as linear arrangements for the flow characteristics. The results are presented as guidelines for preliminary design, to indicate the number, spacing and arrangement of boulders required to create desired flow characteristics over a defined stream area.

6.1 Recommendations for Further Research

As this topic is very open-ended, there are a few specific suggestions that can be investigated in order to further this research. These recommendations can help with the validation of the findings made and are as follows:

- In terms of Laboratory experiments;
    - More sampling points should be taken with longer measurement time periods; this will give a more accurate representation and possibly reduce the occurrence of outliers.
- In terms of hydrodynamic modelling simulations;
    - Investigations should be carried out for the range of undisturbed Froude numbers that fall in supercritical flow regimes.
    - Investigations should be undertaken for the optimum placement of angular boulders (not just cylindrical), in terms of their arrangements and placement downstream of each other.
    - Analysis of arrangements with more than four boulders should be carried out.
    - A wider range of flow conditions, channel dimensions and boulder properties need to be analysed to expand the application of the proposed rough guideline.
    - Extend this study to include additional flow classes defined by Birkhead (2010).
    - To determine the widths of channels that produce a back-up effect as it would be desirable for practical purposes.
    - Investigate if equation 5.14 (Y_S/L = ~2.5) changes for different boulder sizes and flow conditions.

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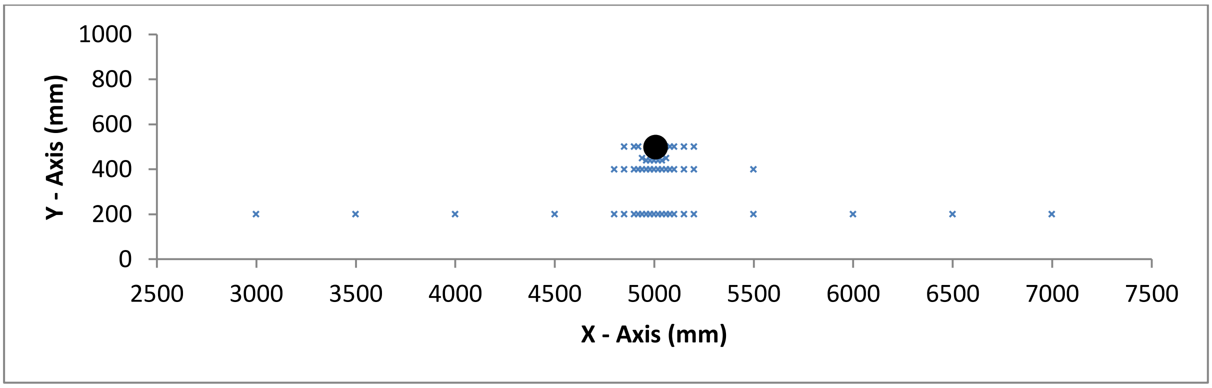
APPENDIX 1: LABORATORY EXPERIMENTS

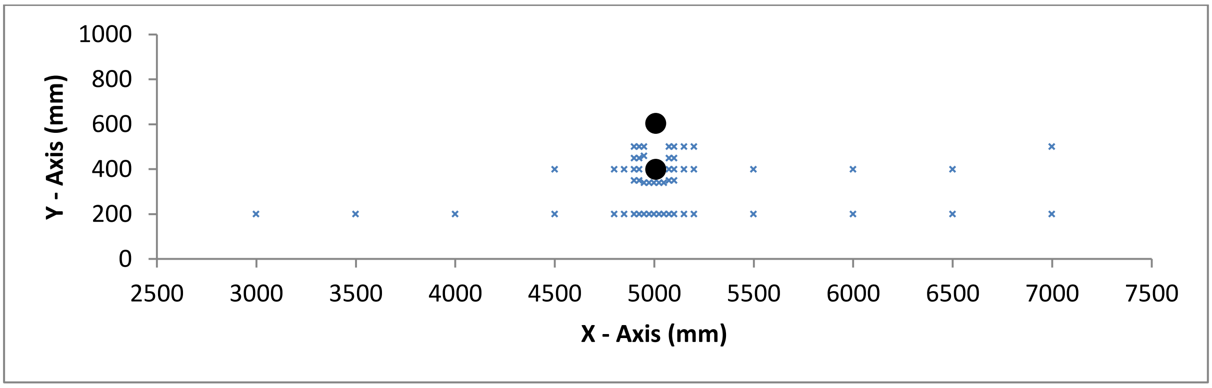
Co- ordinates of Laboratory Experiments Measuring Points

Experiments 1 to 5			Experiment 6			Experiment 7		
Point	X (mm)	Y (mm)	Point	X (mm)	Y (mm)	Point	X (mm)	Y (mm)
1	3000	200	1	3000	200	1	3000	200
2	3500	200	2	3500	200	2	3500	200
3	4000	200	3	4000	200	3	4000	200
4	4500	200	4	4500	200	4	4500	200
5	4800	200	5	4500	400	5	4500	400
6	4800	400	6	4800	200	6	4800	200
7	4850	200	7	4800	400	7	4800	400
8	4850	400	8	4850	200	8	4850	200
9	4850	500	9	4850	400	9	4850	400
10	4900	200	10	4900	200	10	4900	100
11	4900	400	11	4900	350	11	4900	200
12	4900	500	12	4900	400	12	4900	300
13	4920	200	13	4900	450	13	4900	400
14	4920	400	14	4900	500	14	4925	100
15	4920	500	15	4925	200	15	4925	200
16	4940	200	16	4925	350	16	4925	250
17	4940	400	17	4925	400	17	4925	300
18	4940	450	18	4925	450	18	4925	400
19	4960	200	19	4925	500	19	4950	100
20	4960	400	20	4950	200	20	4950	190
21	4960	440	21	4950	340	21	4950	310
22	4980	200	22	4950	460	22	4950	400
23	4980	400	23	4950	500	23	4975	100
24	4980	440	24	4975	200	24	4975	190
25	5000	200	25	4975	340	25	4975	310
26	5000	400	26	5000	200	26	4975	400
27	5000	440	27	5000	340	27	5000	100
28	5020	200	28	5025	200	28	5000	190
29	5020	400	29	5025	340	29	5000	310
30	5020	440	30	5050	200	30	5000	400
31	5040	200	31	5050	340	31	5025	100
32	5040	400	32	5075	200	32	5025	190
33	5040	440	33	5075	350	33	5025	310
34	5060	200	34	5075	400	34	5025	400
35	5060	400	35	5075	450	35	5050	100
36	5060	450	36	5075	500	36	5050	190
37	5080	200	37	5100	200	37	5050	310
38	5080	400	38	5100	350	38	5050	400

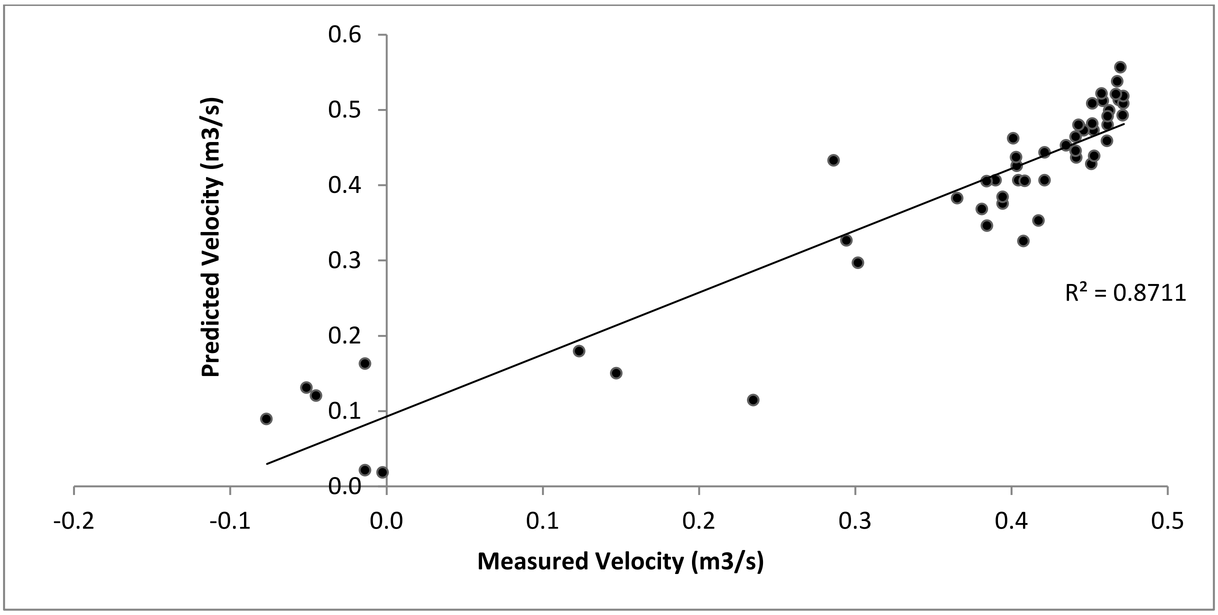
39	5080	500	39	5100	400	39	5075	100
40	5100	200	40	5100	450	40	5075	200
41	5100	400	41	5100	500	41	5075	250
42	5100	500	42	5150	200	42	5075	300
43	5150	200	43	5150	400	43	5075	400
44	5150	400	44	5150	500	44	5100	100
45	5150	500	45	5200	200	45	5100	200
46	5200	200	46	5200	400	46	5100	250
47	5200	400	47	5200	500	47	5100	300
48	5200	500	48	5500	200	48	5100	400
49	5500	200	49	5500	400	49	5150	100
50	5500	400	50	6000	200	50	5150	250
51	6000	200	51	6000	400	51	5150	400
52	6500	200	52	6500	200	52	5200	100
53	7000	200	53	6500	400	53	5200	250
			54	7000	200	54	5200	400
			55	7000	500	55	5500	200
						56	5500	400
						57	6000	200
						58	6000	400
						59	6500	200
						60	6500	400
						61	7000	200
						62	7000	500



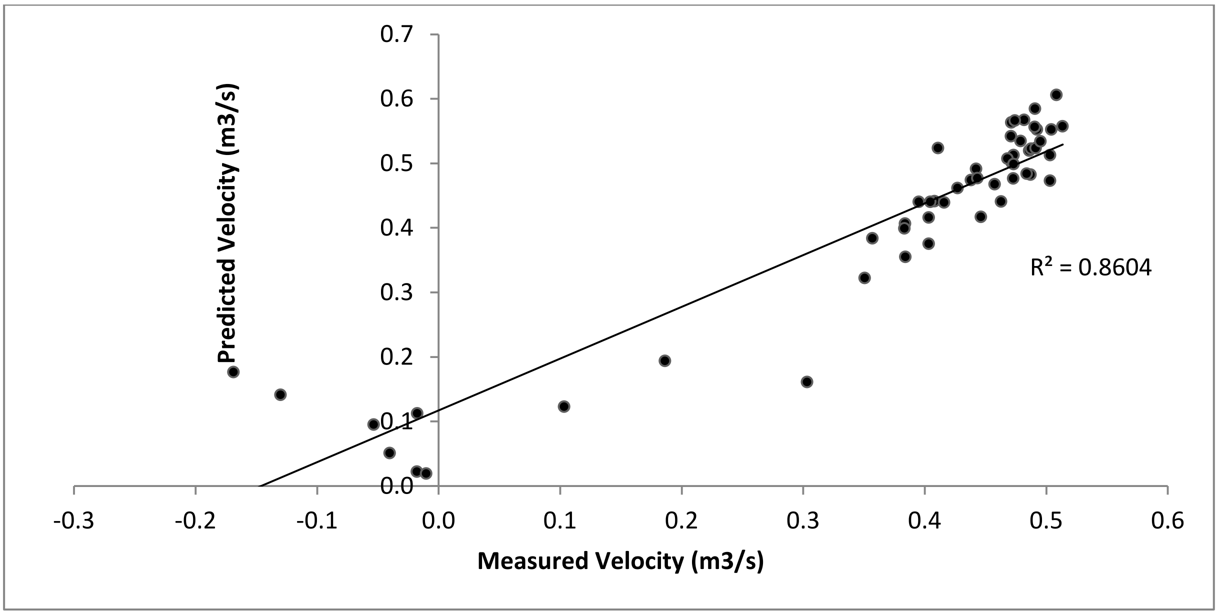
Measuring Points in Plan for Experiment 1 to 5



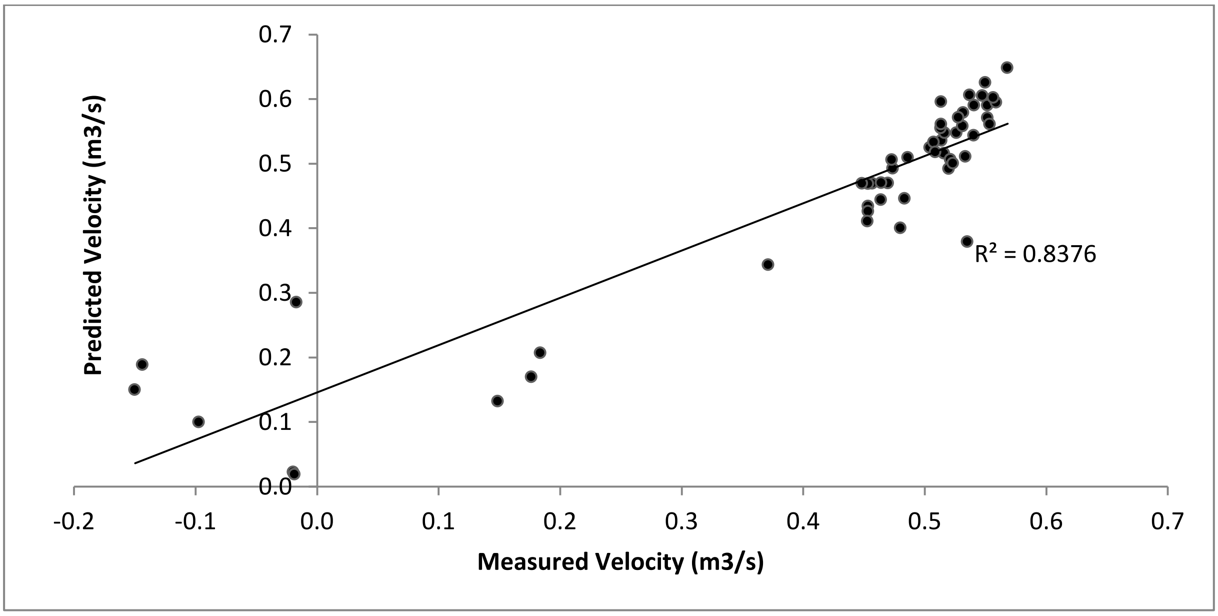
Measuring Points in Plan for Experiment 6



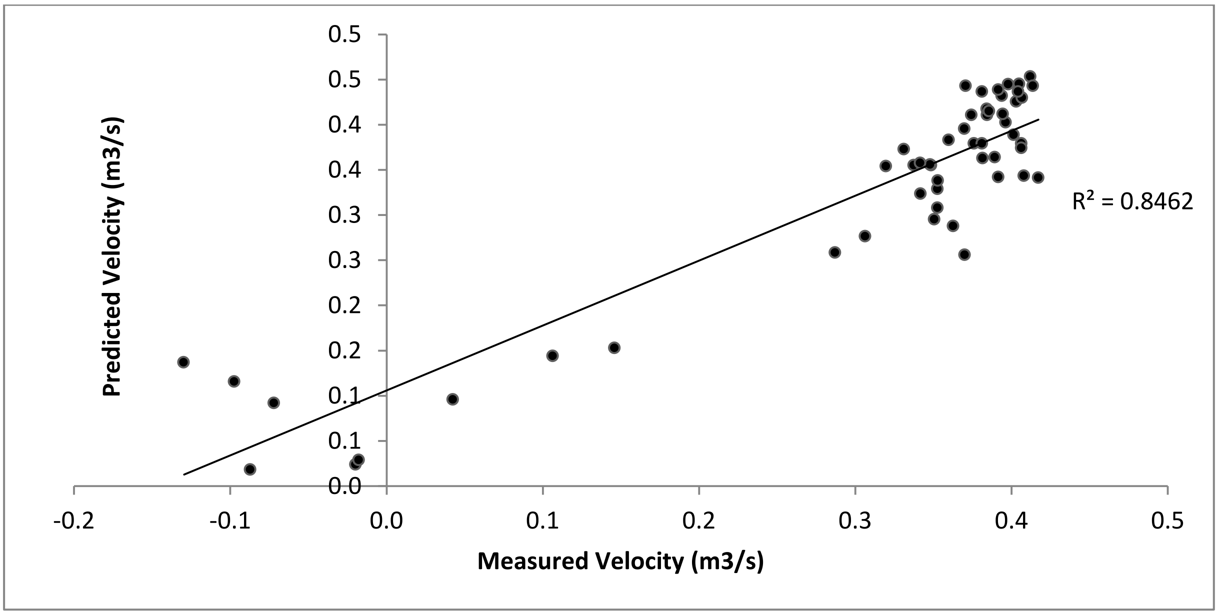
Measured vs. Predicted Velocities for Experiment 1



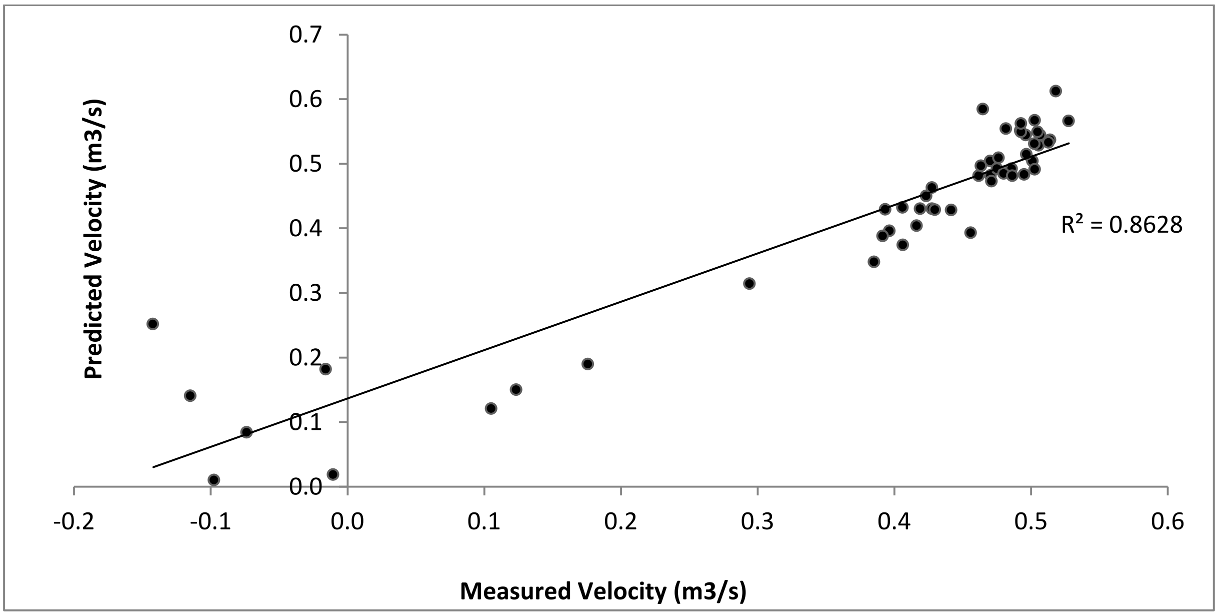
Measured vs. Predicted Velocities for Experiment 2



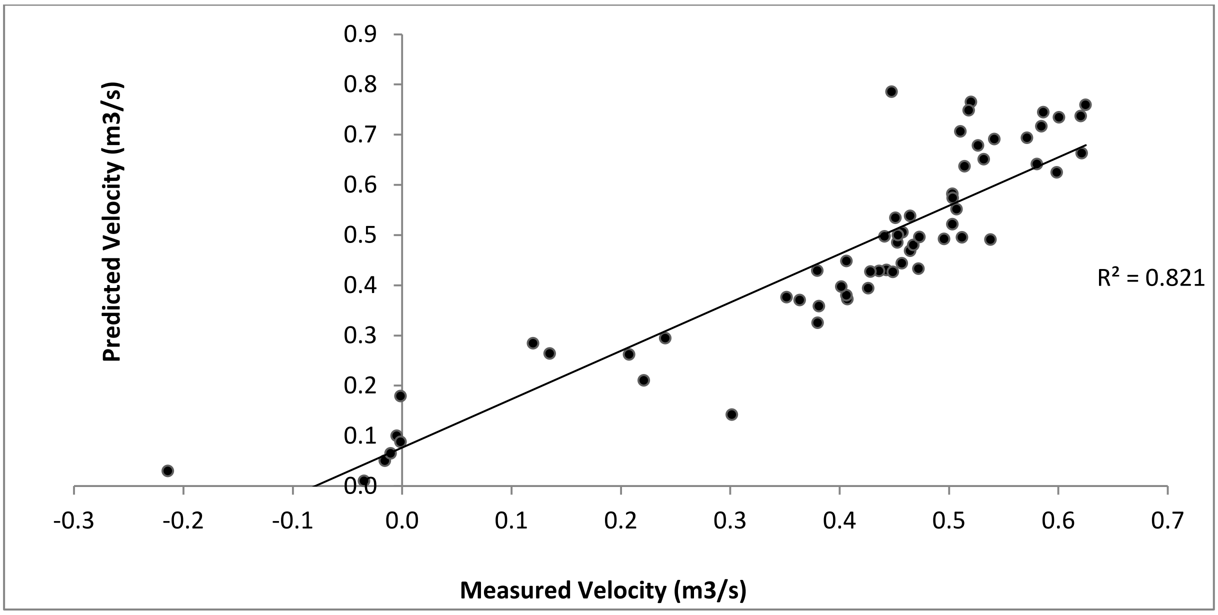
Measured vs. Predicted Velocities for Experiment 3



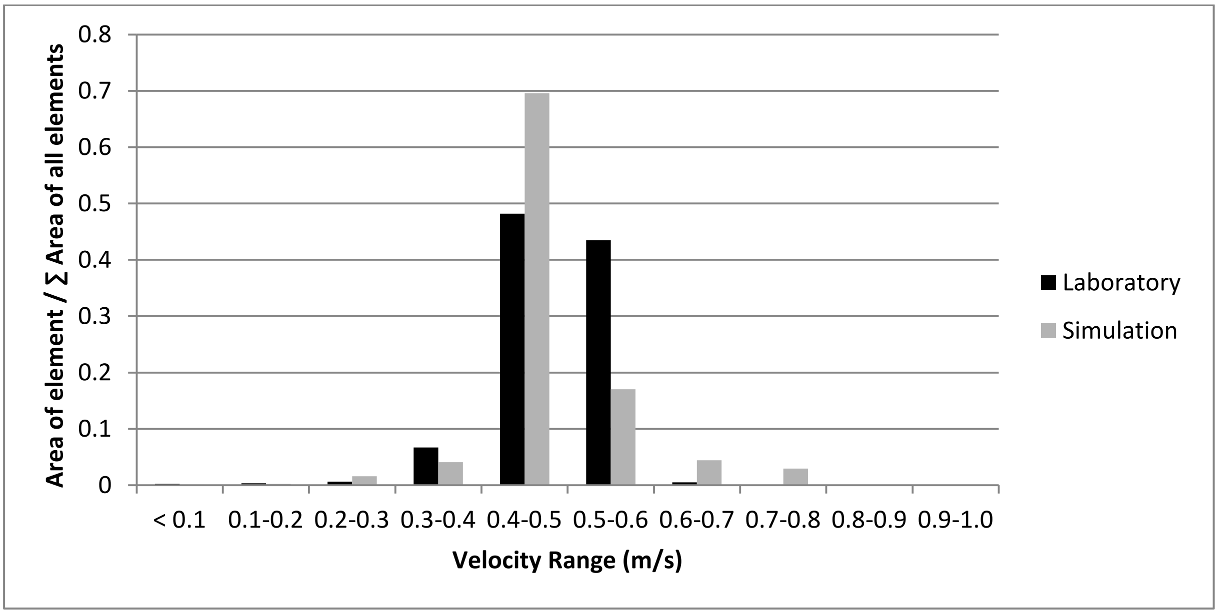
Measured vs. Predicted Velocities for Experiment 4



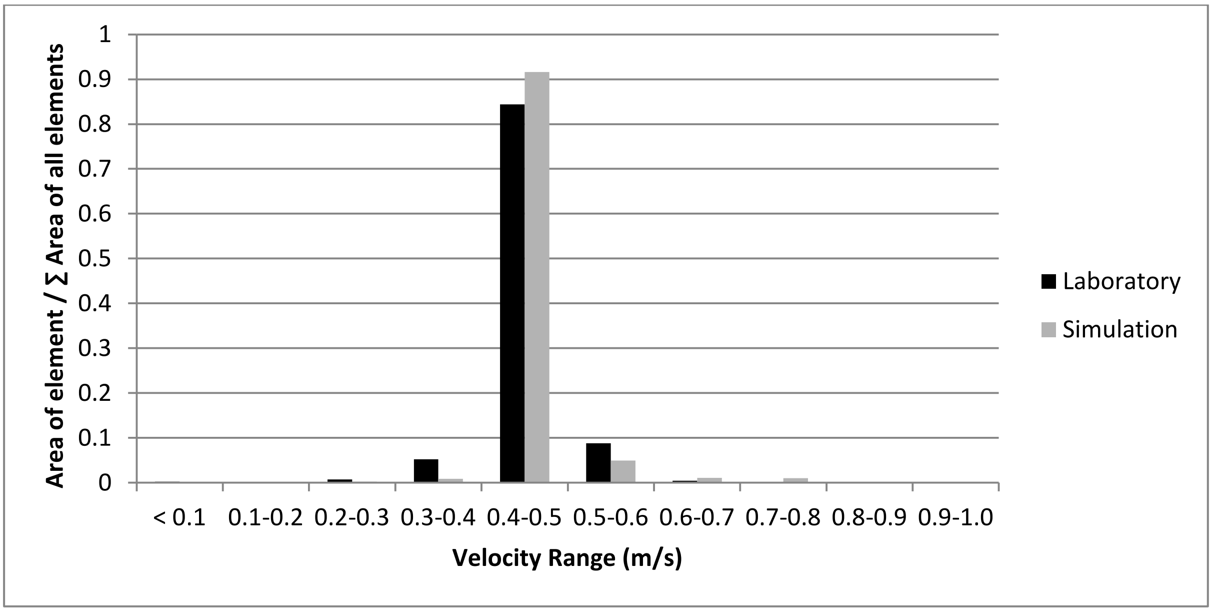
Measured vs. Predicted Velocities for Experiment 5



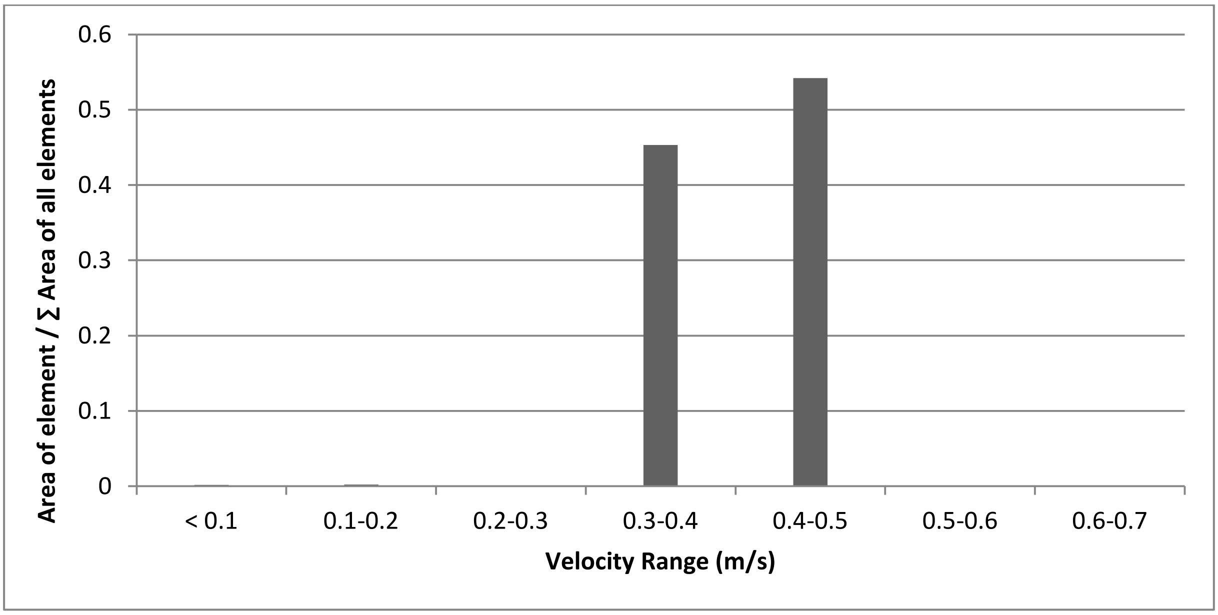
Measured vs. Predicted Velocities for Experiment 7



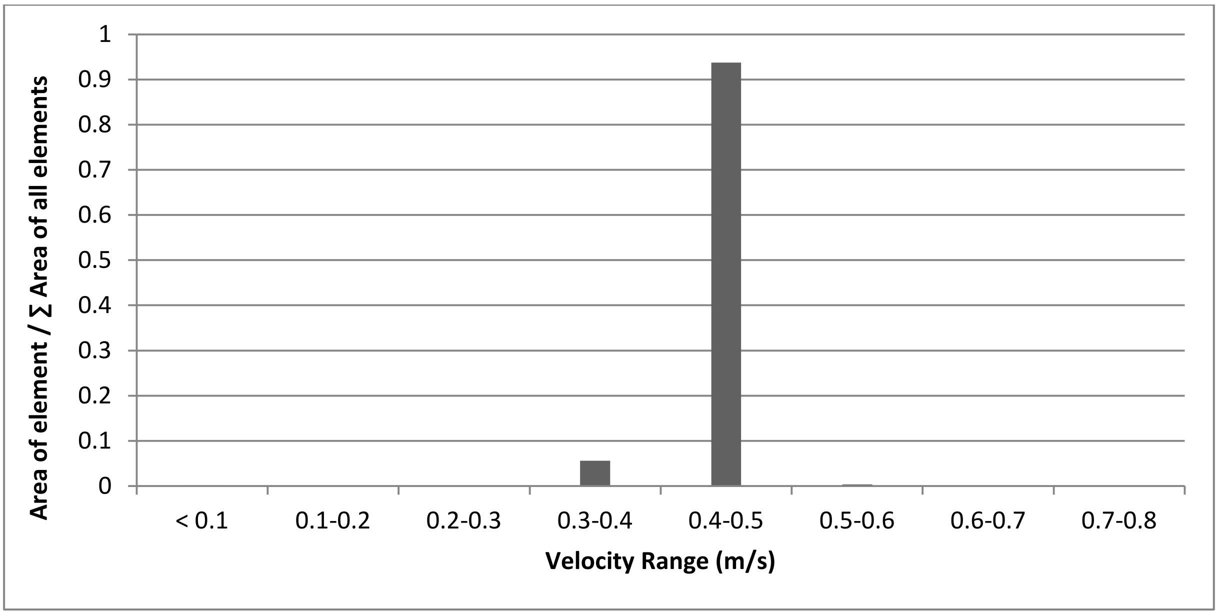
Comparison of Experiment 6 of Laboratory and Simulation Velocity Frequency Histogram



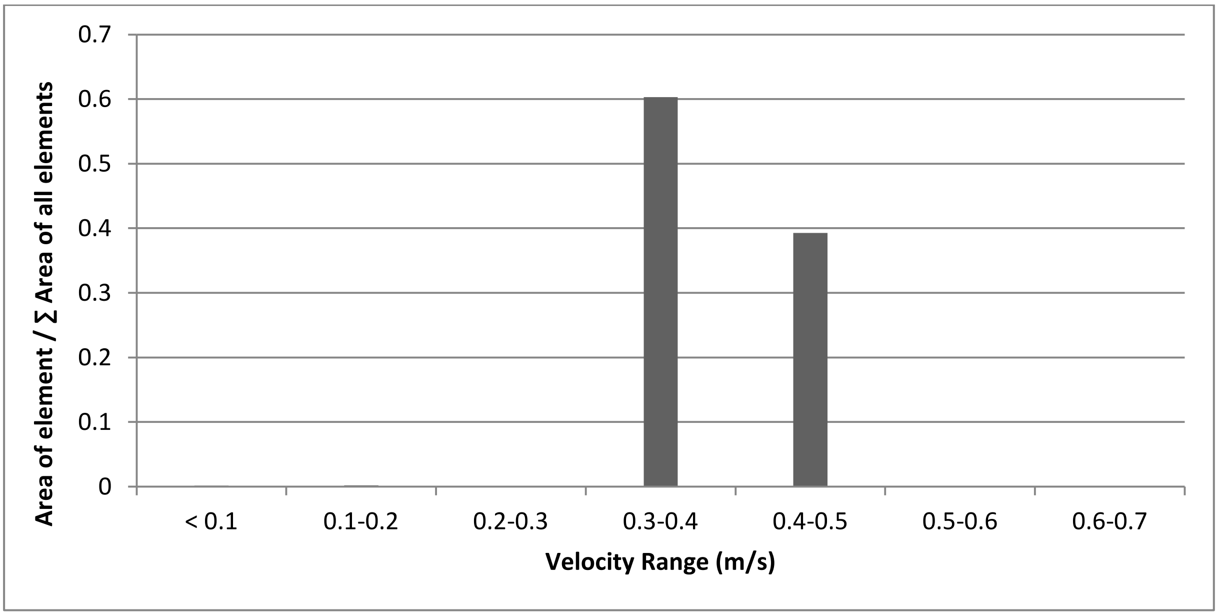
Comparison of Experiment 7 of Laboratory and Simulation Velocity Frequency Histogram



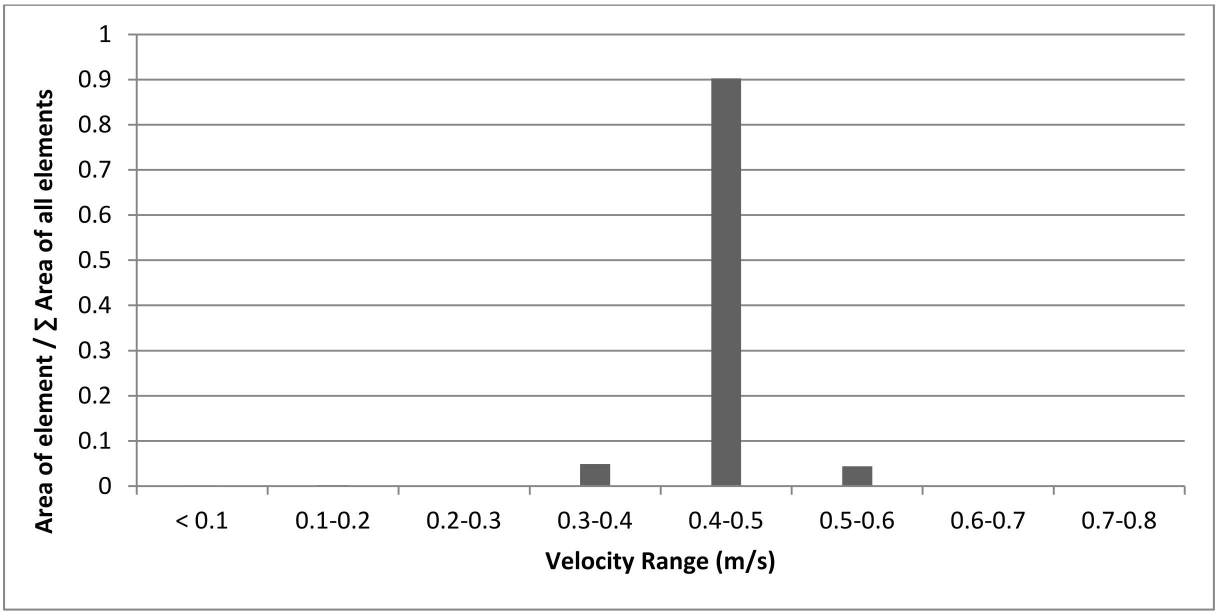
Histograms of Velocity Frequency for Experiment 1



Histograms of Velocity Frequency for Experiment 2



Histograms of Velocity Frequency for Experiment 4



Histograms of Velocity Frequency for Experiment 5

APPENDIX 2: COMPUTER SIMULATIONS

Comparison of Predicted ZOI to Simulated ZOI in the downstream direction for models 1 to 12

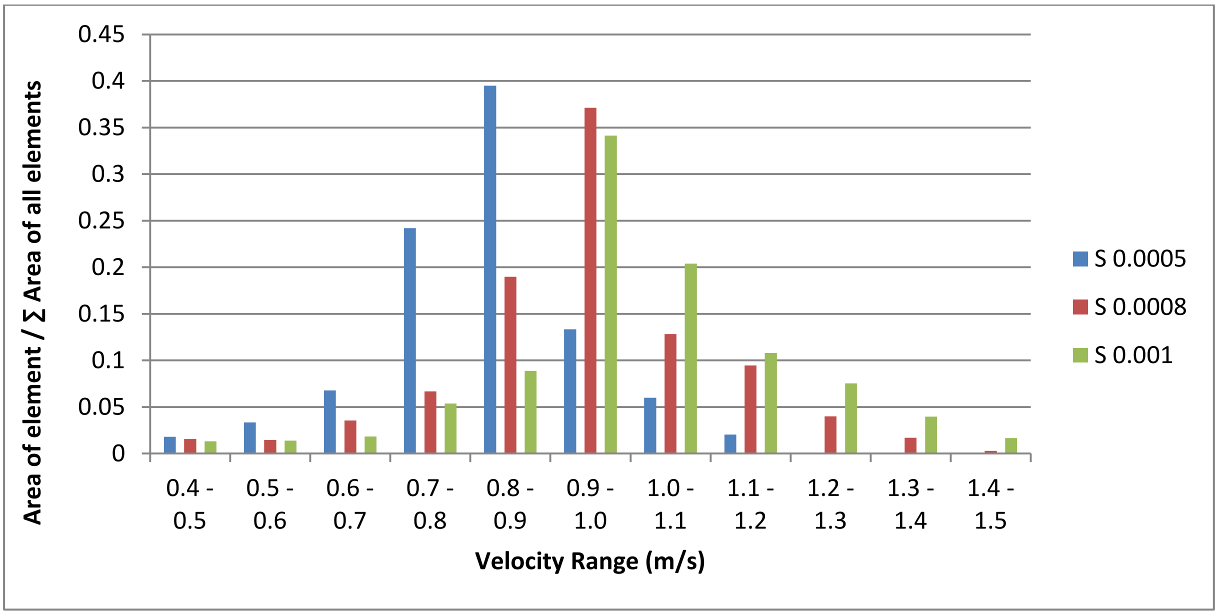
	Downstream											
	Model 1				Model 2				Model 3			
	Fr	0.67	d	0.20	Fr	0.55	d	0.20	Fr	0.72	d	0.20
			b	5.00			b	5.00			b	5.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.80	4.00	4.44	10.91	0.80	4.00	4.23	5.79	0.85	4.25	4.52	6.27
20%	0.59	2.95	2.81	4.76	0.53	2.65	2.68	1.14	0.59	2.95	2.86	3.03
50%	0.33	1.65	1.61	2.67	0.33	1.65	1.53	7.16	0.33	1.65	1.63	0.91
	Model 4				Model 5				Model 7			
	Fr	0.54	d	0.20	Fr	0.74	d	0.20	Fr	0.65	d	0.20
			b	5.00			b	5.00			b	3.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.80	4.00	4.20	4.98	0.85	4.25	4.55	7.13	0.77	3.85	3.87	0.49
20%	0.53	2.65	2.66	0.36	0.59	2.95	2.88	2.25	0.53	2.65	2.45	7.53
50%	0.33	1.65	1.52	7.88	0.33	1.65	1.65	0.11	0.29	1.45	1.40	3.41
	Model 8				Model 9				Model 10			
	Fr	0.66	d	0.20	Fr	0.68	d	0.20	Fr	0.69	d	0.20
			b	4.00			b	6.00			b	10.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.83	4.15	4.18	0.75	1.20	6.00	4.65	22.44	1.00	5.00	5.31	6.24
20%	0.47	2.35	2.65	12.69	0.65	3.25	2.95	9.31	0.57	2.85	3.36	18.05
50%	0.29	1.45	1.51	4.38	0.31	1.55	1.68	8.68	0.32	1.60	1.92	20.18
	Model 11				Model 12							
	Fr	0.67	d	0.10	Fr	0.67	d	0.40				
			b	5.00			b	5.00				
	Simulated		Predicted		Simulated		Predicted					
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff				
10%	0.57	5.70	5.28	7.45	1.61	4.03	3.73	7.32				
20%	0.36	3.60	3.34	7.19	0.85	2.13	2.36	11.18				
50%	0.21	2.10	1.91	9.06	0.50	1.25	1.35	8.03				

Comparison of Predicted ZOI to Simulated ZOI in the upstream direction for models 1 to 12

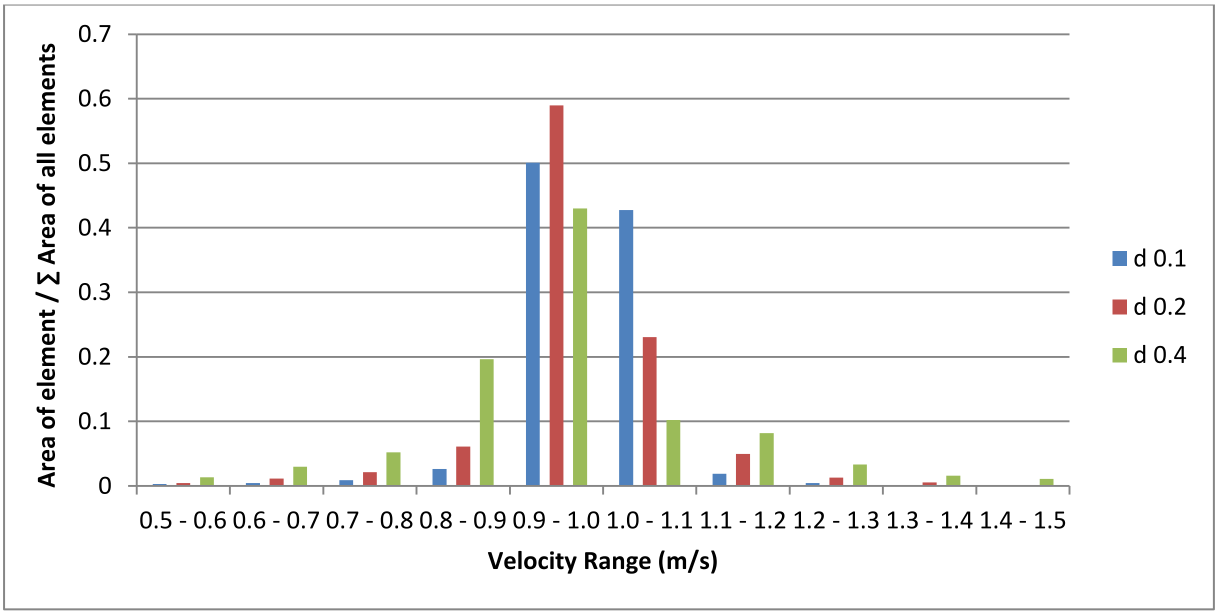
	Upstream											
	Model 1				Model 2				Model 3			
	Fr	0.67	d	0.20	Fr	0.55	d	0.20	Fr	0.72	d	0.20
			b	5.00			b	5.00			b	5.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.65	3.25	3.22	0.90	0.58	2.90	2.67	8.05	0.69	3.45	3.46	0.30
20%	0.41	2.05	1.96	4.19	0.36	1.80	1.63	9.66	0.41	2.05	2.11	2.94
50%	0.21	1.05	0.98	7.05	0.18	0.90	0.81	10.22	0.21	1.05	1.05	0.13
	Model 4				Model 5				Model 7			
	Fr	0.54	d	0.20	Fr	0.74	d	0.20	Fr	0.65	d	0.20
			b	5.00			b	5.00			b	3.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.58	2.90	2.59	10.86	0.69	3.45	3.57	3.58	0.62	3.10	2.95	4.81
20%	0.36	1.80	1.58	12.41	0.43	2.15	2.18	1.37	0.38	1.90	1.80	5.28
50%	0.18	0.90	0.78	12.96	0.21	1.05	1.08	3.13	0.20	1.00	0.89	10.57
	Model 8				Model 9				Model 10			
	Fr	0.66	d	0.20	Fr	0.68	d	0.20	Fr	0.69	d	0.20
			b	4.00			b	6.00			b	10.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff
10%	0.61	3.05	3.11	1.86	0.65	3.25	3.31	1.85	0.61	3.05	3.55	16.34
20%	0.39	1.95	1.89	2.84	0.39	1.95	2.02	3.52	0.40	2.00	2.16	8.20
50%	0.18	0.90	0.94	4.61	0.19	0.95	1.00	5.59	0.19	0.95	1.08	13.19
	Model 11				Model 12							
	Fr	0.67	d	0.10	Fr	0.67	d	0.40				
			b	5.00			b	5.00				
	Simulated		Predicted		Simulated		Predicted					
	Y	Y/d	Y/d	% Diff	Y	Y/d	Y/d	% Diff				
10%	0.38	3.80	3.45	9.16	1.15	2.88	3.00	4.52				
20%	0.23	2.30	2.11	8.47	0.72	1.80	1.83	1.81				
50%	0.12	1.20	1.05	12.83	0.38	0.95	0.91	4.15				

Comparison of Predicted ZOI to Simulated ZOI to the sides of the boulders for models 1 to 12

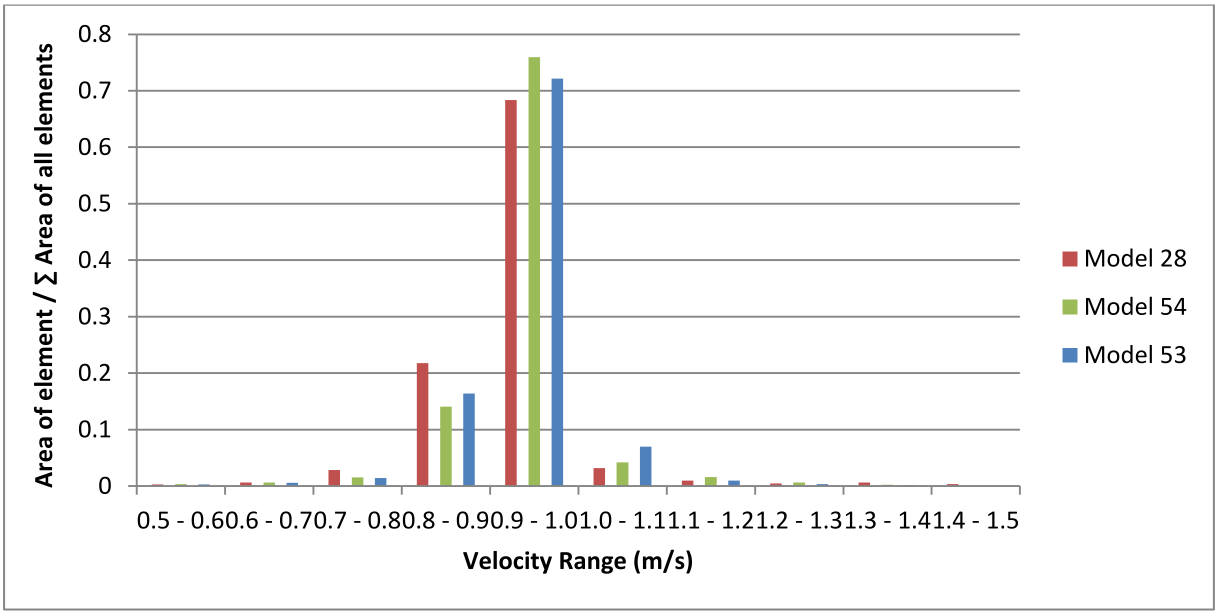
	Sides											
	Model 1				Model 2				Model 3			
	Fr	0.67	d	0.20	Fr	0.55	d	0.20	Fr	0.72	d	0.20
			b	5.00			b	5.00			b	5.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff
10%	0.42	2.10	2.02	3.62	0.39	1.95	1.93	0.99	0.42	2.10	2.06	1.87
20%	0.29	1.45	1.42	1.89	0.28	1.40	1.36	3.07	0.29	1.45	1.45	0.12
30%	0.20	1.00	1.08	8.02	0.19	0.95	1.03	8.46	0.22	1.10	1.10	0.02
	Model 4				Model 5				Model 7			
	Fr	0.54	d	0.20	Fr	0.74	d	0.20	Fr	0.65	d	0.20
			b	5.00			b	5.00			b	3.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff
10%	0.39	1.95	1.92	1.75	0.42	2.10	2.08	1.08	0.42	2.10	1.77	15.94
20%	0.28	1.40	1.35	3.82	0.29	1.45	1.46	0.69	0.29	1.45	1.24	14.44
30%	0.19	0.95	1.02	7.63	0.22	1.10	1.11	0.79	0.20	1.00	0.94	5.79
	Model 8				Model 9				Model 10			
	Fr	0.66	d	0.20	Fr	0.68	d	0.20	Fr	0.69	d	0.20
			b	4.00			b	6.00			b	10.00
	Simulated		Predicted		Simulated		Predicted		Simulated		Predicted	
	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff
10%	0.38	1.90	1.91	0.41	0.43	2.15	2.12	1.24	0.42	2.10	2.42	15.41
20%	0.29	1.45	1.34	7.53	0.28	1.40	1.49	6.59	0.31	1.55	1.70	9.90
30%	0.24	1.20	1.02	15.16	0.25	1.25	1.13	9.34	0.23	1.15	1.29	12.48
	Model 11				Model 12							
	Fr	0.67	d	0.10	Fr	0.67	d	0.40				
			b	5.00			b	5.00				
	Simulated		Predicted		Simulated		Predicted					
	X	X/d	X/d	% Diff	X	X/d	X/d	% Diff				
10%	0.23	2.30	2.41	4.65	0.70	1.75	1.70	2.74				
20%	0.16	1.60	1.69	5.73	0.51	1.28	1.20	6.18				
30%					0.42	1.05	0.91	13.49				



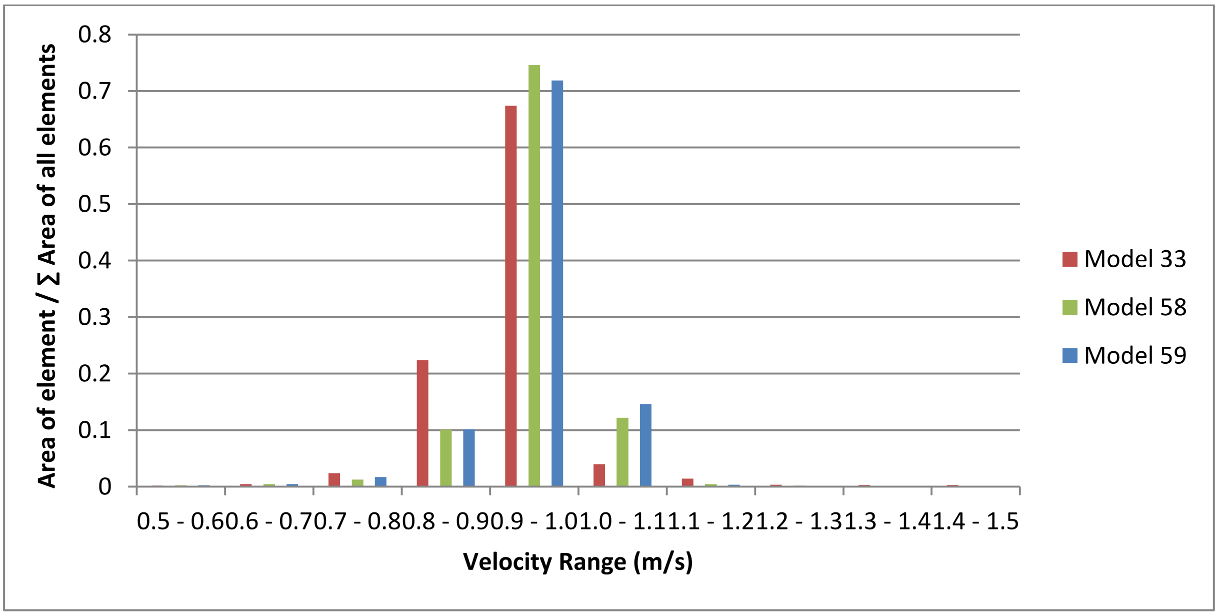
Histogram of velocity distribution around single boulder with varying Slopes



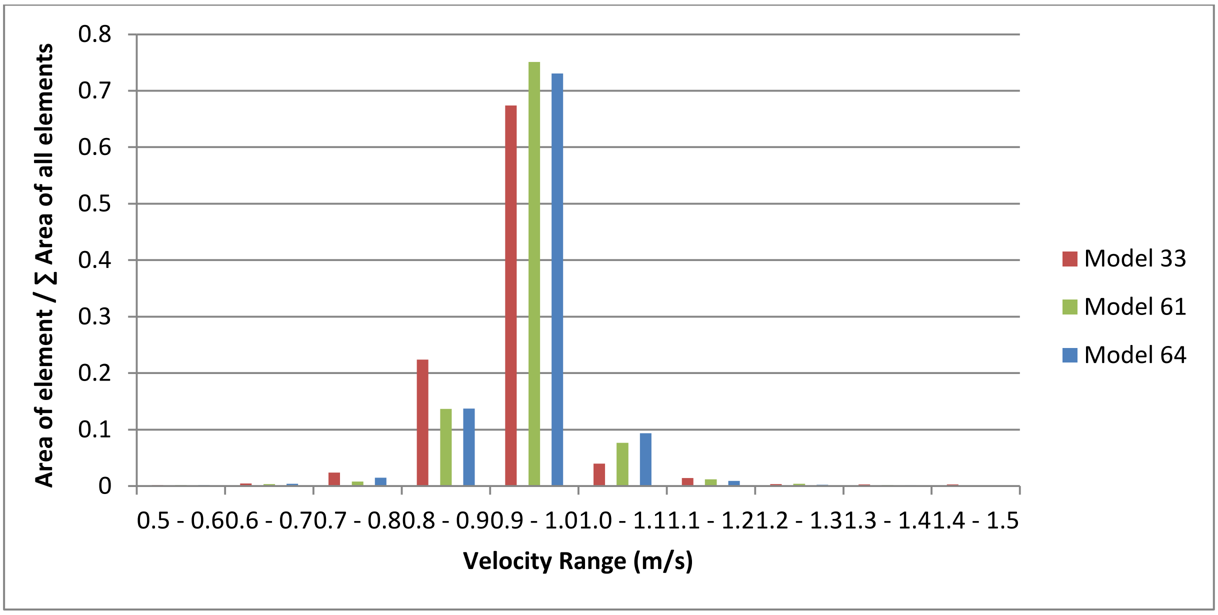
Histogram of velocity distribution around single boulder with varying Boulder Diameters



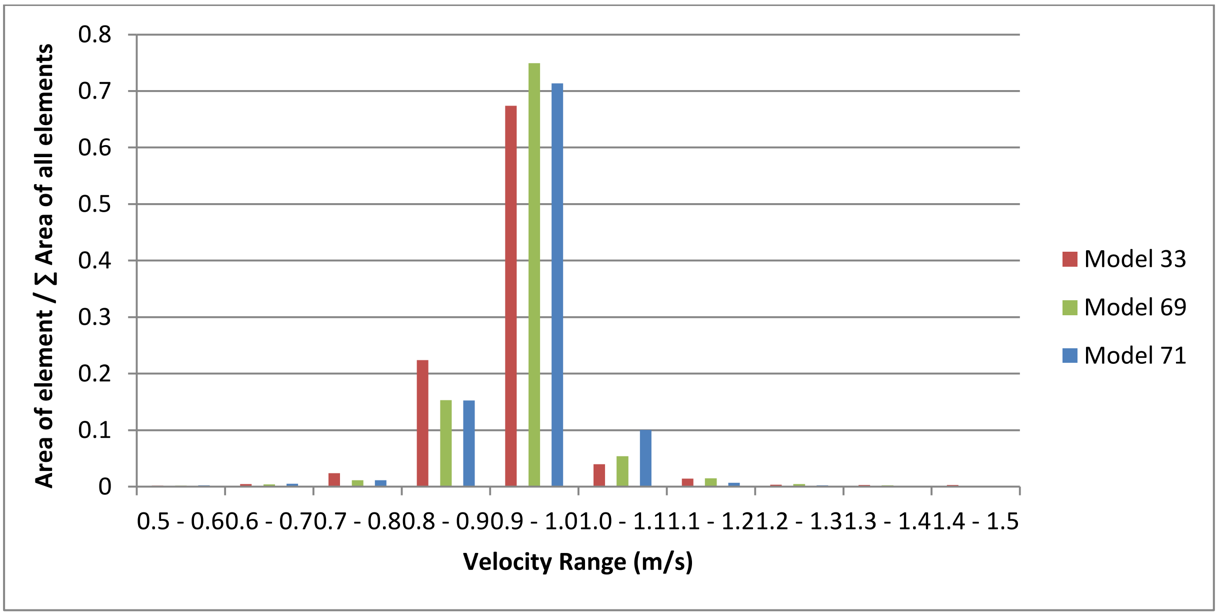
Histograms for Inverted Triangular Non-Linear Arrangements



Histograms for Diamond Non-Linear Arrangements



Histograms for Parallelogram Non-Linear Arrangements



Histograms for Inverted Trapezoidal Non-Linear Arrangements