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Culvert Roughness Elements for Native Utah Fish Passage: Phase I

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Culvert Roughness Elements for Native

Utah Fish Passage: Phase I

Lindsay D. Esplin

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Culvert Roughness Elements for Native Utah Fish Passage: Phase I

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Culverts can increase stream velocities as a result of reduced waterway areas and prevent upstream passage of small non-salmonid fish such as the Native Utah Leatherside chub (*Gila copei*) and Longnose dace (*Rhinichthyscataractae*). To mitigate this problem, current culvert design standards for fish passage match sustained fish swim speeds with average cross sectional velocity through the culvert. Such policies dictate relatively large barrels and do not recognize the role of reduced velocity zones near culvert boundaries. Obstacles and streambed substrate create turbulent regions with lower velocity zones that can increase upstream fish passage. A comparison of upstream passage success using native Utah fish in an experimental flume was conducted with three different conditions: (1) a smooth boundary, (2) a smooth boundary with strategically placed cylinders, and (3) a boundary consisting of natural substrate.

The refuge provided by the cylinders and substrate allowed fish to expend less energy as they swam upstream. Energy expenditure was compared between the conditions by mapping the velocity field near the boundary and tracing fish swim paths. Substrate provided sufficient refuge for the fish to behave in a manner similar to their behavior in a natural environment and with significantly reduced energy expenditure. Cylinders provided limited refuge that allowed fish to rest periodically as they navigated the flume. The smooth boundary case required the highest energy expenditure as there was no refuge provided. Fish swimming capabilities in the form of prolonged and burst velocities have been recorded for most species. Streamwise velocity near the boundary can be compared to the prolonged and burst swim speeds to predict passage rates.

Further field testing is necessary to fully substantiate the effectiveness of utilizing reduced velocity zones in non-salmonid fish passage prediction. If such a design approach can be used instead of using the conservative but overly simplistic average velocity to evaluate the retrofit of existing culverts and to design new culverts it will help minimize costs and result in fewer culvert replacements and smaller and simpler new designs. Other implications such as downstream effects on stream bed stability and scour remain an issue.

Keywords: fish passage, culvert hydraulics, native Utah fishes

ACKNOWLEDGMENTS

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1 INTRODUCTION

Barriers to upstream movement of non-salmonid fish can negatively affect the fitness of the population. Culverts often increase river and stream velocities to a point that the culverts become impassable to small non-salmonids such as the Native Utah Leatherside chub (*Gila copei*) and Longnose dace (*Rhinichthyscataractae*). Current culvert design standards for fish passage require the average cross sectional velocity through the culvert match sustained fish swim speeds. The barrel sizes dictated by such policies do not recognize the role of reduced velocity zones near boundaries in the culvert. Obstacles and streambed substrate create turbulent regions and lower velocity zones that can increase upstream fish passage through culverts. Research has been conducted to determine how fish use the region near the boundary for passage to allow for retrofitting of existing culverts with roughness elements where appropriate.

1.1 Scope

The scope of this study is restricted to native Utah fish, particularly non-salmonid species, for use in the retrofitting and replacement of Utah Department of Transportation (UDOT) managed culverts. The results may have implications for other regions and fish species which would necessitate further research. Only the passage of fish is considered.

1.2 Objectives

This study focuses on the excessive velocity barrier issue for native non-game fishes of Utah. We hope to further understand the swimming patterns of non-salmonids and account for their utilization of reduced velocity zones in hydraulic design. It is hoped that this research can start to address some of the unknowns when it comes to how fish utilize turbulence and boundary layers to improve engineering design of fish passage culverts. The results provide initial data and information to be used in subsequent field testing. Following field testing, design standards for retrofitting and new fish passage culverts can be proposed.

1.3 Document Organization

This study focuses on the excessive velocity barrier issue for native non-game fishes of Utah. We hope to further understand the swimming patterns of non-salmonids and account for their utilization of reduced velocity zones in hydraulic design. It is hoped that this research can start to address some of the unknowns when it comes to how fish utilize turbulence and boundary layers to improve engineering design of fish passage culverts. The results provide initial data and information to be used in subsequent field testing. Following field testing, design standards for retrofitting and new fish passage culverts can be proposed.

1.4 Literature Review

Culverts can negatively affect fish populations by reducing abundance and diversity, altering runoff patterns, increasing sedimentation, reducing natural dispersal rates, preventing spawning migrations, inhibiting recolonization after disturbances, and by genetic isolation (Coffman 2005). Over a short time smaller populations are more likely to die of chance events, but over the long term, genetic homogeneity and natural disturbances are also likely to extirpate larger populations (Hotchkiss and Frei 2007). The primary physical factors that impede fish passage are fairly well documented and include outlet drop, excessive velocity, and insufficient water depth (Blank et al. 2005). Some important biological considerations include fish species, size and condition of fish, life history requirements, and movement timing (Blank et al. 2005). This study addresses the obstacle of excessive velocity, which consequently will influence the water depth obstacle. The focus is reducing negative effects of culvert crossings for the least native Utah species. *Least species* is the term used by Brigham Young University (BYU) researchers to indicate the weakest swimmer/leaper species in the watershed (Beavers et al. 2008).

Fish passage culvert design strategies in the Federal Highway Administration (FHWA) *Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report* include no impedance, geomorphic simulation, hydraulic simulation, and hydraulic design options (Hotchkiss and Frei 2007). A stream crossing using the no impedance option spans both the channel and floodplain, usually accomplished by a bridge. Geomorphic simulation is based on recreating the geomorphic elements of the stream including slope, channel-bed width, bed materials, and bedforms. Hydraulic simulation provides hydraulic conditions conducive to fish passage by providing hydraulic diversity that is similar but not identical to the natural channel. Hydraulic design creates water velocities and depths that meet the abilities of target fish species during their periods of movement. Geomorphic and hydraulic simulation are intended to pass all fish species, which may prove difficult or costly using the hydraulic design option. But in many situations where conventional culverts are barriers to fish movement the cost of replacement is prohibitively high due to deep fill or location and hydraulic design techniques are favored. (Hotchkiss and Frei 2007)

Historically the focal point of most fish passage research has been anadromous fish like salmon and little attention has been given to native fish and the effects of barriers on their movement (Coffman 2005). It is generally desirable to provide passage for native migratory fish that are or were historically present (Hotchkiss and Frei 2007). It has also been shown that these non-game fish can be very mobile, demonstrating both exploratory and seasonal movements that can be important for repopulation of stream reaches after local disturbances (Coffman 2005).

The FHWA states that little is understood about the utilization and development of boundary layers within a culvert, and that little is understood about turbulence effects as well (Hotchkiss and Frei 2007). Turbulence is defined as chaotic vortical flows of multiple strengths and sizes superimposed onto a mean flow velocity (Liao 2007). Recent studies have shown that fish prefer to hold in zones of low turbulence. It is thought by some that variability in flow patterns and fish utilization are likely too great for boundary layer velocity to be consistently accounted for in design standards (Hotchkiss and Frei 2007), consequently current hydraulic design standards commonly compare average cross-sectional velocity to fish swimming speeds which is conservative (Hotchkiss and Frei 2007). It has been proposed that longer culverts with natural substrate may not represent a barrier if fish can rest in reduced velocity zones (Hotchkiss and Frei 2007). This is the hypothesis we tested.

Suitable resting places in culverts can be created by placing obstacles in the flow. Cylinders and cubes are extreme shapes with less and more drag respectively, and natural boulders lie in the middle. Cylinders were chosen for our study because they produce a well understood wake pattern and provide conservatively less drag than natural boulders (Heimerl et al. 2008). Corrugations or other artificial gravel-boulder roughness elements generate more favorable boundary conditions than do less-roughened culverts (Behlke 1991). Measurements in one culvert revealed that fish preferentially swam in a region with velocities that were 20% of the average for the cross section (Behlke 1991). Behlke recommended using 40% of the average velocity for evaluating the design of culverts with 5 cm corrugations, and 80% of the average for the outlet region, though values as low as 10% were measured (Behlke et al. 1993). To be conservative 50% of the average velocity was used in all of Behlke's design equations (Behlke 1991).

It has been observed that fish choose habitats not only based on average flow velocity but also on the degree of variation in flow velocity (Liao 2007). Swimming kinematics are different in natural streams with obstacles present than in the steady flow often used in laboratory flumes (Liao 2007). It has been postulated that lack of stream simulation in terms of alteration of flow, substrate, and velocity is the most likely cause for barriers to passage through culverts (Coffman 2005). Fish are attracted to turbulent flows if their mechanisms of stability are sufficient for a given hydrodynamic environment (Liao 2007). Since fish are not equally sensitive to disturbances in all planes, perturbation direction relative to the body plays a pivotal role in determining the nature of the response (Liao 2007). Fish appear particularly sensitive to vertically oriented perturbations (Liao 2007) so, if practicable, provisions should be made for fish to avoid extended zones of downward-directed water accelerations (Behlke 1991).

In research conducted by Patrick D. Powers, juvenile salmon were observed swimming in the reduced velocity zone along the culvert wall. Surprisingly, more fish were observed passing through smooth pipe than rough pipe with similar maximum velocity values. He proposed that the turbulence in the reduced velocity boundary layer hindered passage.(Powers 1997)

As fish navigate upstream past obstacles, they often exhibit flow refuging and station holding behaviors. Flow refuging is when fish exploit regions of reduced flow velocity (Liao 2007). Station holding is the ability of fish to maintain position in a current relative to the earth frame of reference without actively swimming (Liao 2007). However, these fish behaviors depend on the flow rate. Generally in fast flows, fish are displaced from behind obstacles and in low flows they avoided them altogether (Liao 2007). At higher velocities waves and vortices tend to disorient smaller fish and frequently bounce them from slower velocities near boundaries to higher velocities where they may be swept downstream (Behlke 1991). Whether environmental vortices affect fish behavior depends largely on the spatial scale of vortical flows relative to the fish size (Liao 2007). As a rule of thumb the scale of the vortices should not exceed the length scale of the fish (Brent Mefford of United States Bureau of Reclamation, personal communication 2010). Observations of fish swimming behind half cylinders showed that the most energetically favorable positions were in front in the bow wake, or entrained directly behind with their noses nearly touching the cylinder (Liao 2007). It has also been observed that fish prefer swimming in schools as they can swim for a longer duration with lower tail-beat frequency and respiratory rates compared with fish swimming alone (Liao 2007). These mechanisms theoretically increase the thrust of an individual by terms of percentages without additional energy expenditure (Liao 2007).

Traditionally fish swimming speed modes are split into sustained swimming (>200 min.), prolonged swimming (15 sec-200 min) and burst swimming (<15sec) (Coffman 2005). The prolonged swimming mode is used when moving through a culvert, and burst swimming is used when entering and exiting a culvert (Coffman 2005). Red muscle is the aerobic engine used by fish for long term swimming, namely prolonged and sustained modes. White muscle is the anaerobic engine that can provide four times the power output of red muscle but only for a short time. White muscle is used for burst swimming and a long rest is required to eliminate lactic acid build-up before the muscle can be used again. In this way outlet conditions may affect the fish when it arrives at the inlet (Behlke et al. 1993). Fish attempt to get through the most difficult spots as quickly as possible as less energy is used, but more power is required so they have to budget their use of white muscle. Fish entering a culvert do not know the length so they appear to take power precautions that may or may not bring success in delivering the necessary energy to negotiate the culvert. At the inlet end, just before exiting the culvert, fish can usually find a rest area in which they may survey the situation ahead. They do not enter higher velocity flow and entrance drawdown (sharp slope) until they are prepared to do so. It is possible that they rest long enough to recharge their white muscle engine but it is doubtful. (Behlke 1991)

Reduced tailbeat frequency is thought to correspond to reduced energy expenditure (Liao 2007). However, the use of tailbeat frequency, slip, and the Strouhal number are inappropriate for measuring performance of thrust based locomotion in unsteady flows (Liao 2007). Instead utilizing a profile drag equation, swimming power and energy delivery capabilities can be used to predict swimming performance in more complicated environs (Behlke et al. 1993).

According to the FHWA, a successful fish crossing will ensure passage for the weakest swimming fish species of concern (Hotchkiss and Frei 2007). Among native Utah fish body size was the biggest determinate of fish swimming ability and passage (Aedo, Belk and Hotchkiss 2009). Therefore for our study, the least native Utah species were chosen to be the Leatherside chub and Longnose dace, the smallest midstream and benthic fish respectively.

Leatherside chub are a sensitive species in Utah and throughout their known range. The Leatherside chub (*Gila copei*) are native to eastern and southern parts of the Bonneville Basin of

Utah, Wyoming, and Idaho (Sigler and Sigler 1987). Populations have been severely impacted by man, as is common with other native fishes of the arid western United States (Walser et al. 1999). Leatherside chub spawn between June and August and can be found in slow low gradient streams (Johnson et al. 1995).

Longnose dace (*Rhinichthyscataractae*) are benthic and inhabit the region directly above the substrate (Edwards et al. 1983). They have strong cover and shelter seeking behavior during all seasons of the year. Their spawning may occur as early as May and as late as August. They inhabit fast water areas and are usually collected in streams with surface velocity above 45 cm/s (1.5 ft /s) and as high as 182 cm/s (6.0 ft /s). (Edwards et al. 1983)

This study focuses on the excessive velocity barrier issue for such native non-game fishes of Utah. We hope to further understand the swimming patterns of non-salmonids and account for their utilization of reduced velocity zones in hydraulic design. It is hoped that this research can start to address some of the unknowns when it comes to how fish utilize turbulence and boundary layers to improve engineering design of fish passage culverts.

2 RESEARCH METHODS

2.1 Purpose

The goal is to create systems that do not necessarily promote the movement of fish, but allow it. In poor quality habitat fish are more likely to move. The objective of this study is to test the hypothesis that the energy used by fish differs when they swim upstream in different conditions: flow around cylinders, flow over substrate, or flow in a bare flume. We propose that the species used in the experiment are representative of similar species in similar systems and the test results may be widely applicable.

We quantified the fish response by measuring water velocities faced in each setup and the time spent navigating the flume and used these values to calculate estimated energy expenditure. The test variables were (1) species differences or functional form, and (2) flow patterns. Other factors that could affect the response include water temperature, time of year, time of day, lighting, and health and life stage of the fish. Best efforts were made to eliminate the confounding effects of these variables through randomization and strict testing protocol.

2.2 Experimental Design

This section describes the preliminary research done in order to design our experiment. Specifically how we chose the size and spacing of cylinders. Previous research conducted by Joseph Webb at BYU showed that native Utah fishes use roughness elements in culverts to increase their upstream passage rate (Webb 2008). This work extends his project by testing near-prototype-scale roughness elements in a flume with native Utah fishes (Phase I). The roughness elements in Webb's experiments were 10 cm diameter concrete cylinders oriented vertically. The cylinders were uniformly spaced 1.1 m on center in the downstream direction, and 4 cm from the flume wall along both sides creating a small grid. We started by replicating Webb's setup matching his flowrate and slope, then we took Acoustic Doppler Velocimetry (ADV) measurements behind the cylinders as shown in Figure 2-1 and further explained in section 3.2.2 of this report. We then created similar setups using cylinders of 12.5 cm and 15 cm in diameter and mapped the wakes behind these cylinders in a similar manner to determine if there was a more optimal size and spacing than was used in Webb's research. The optimal setup is one that would produce the lowest and most uniform velocity in a given region behind the wake. Figure 2-1 shows where we took velocity measurements behind the cylinders. Figure 2-2, Figure 2-3 and Figure 2-4 are graphs of velocity as a fraction of mean velocity (v_o) behind a 10 cm cylinder in rows A, B and C, respectively. When referring to the control and cylinder setups the boundary is the bottom of the flume, however in substrate setup the boundary is the surface of the rocks. Row A has the most uniform low velocities of the three rows, which occurs at 65 and 75 cm behind the cylinder. We confirmed Webb's experiments where he observed fish swimming 70 cm behind the cylinders. Figure 2-5, is preserved with the 135 cm spacing. From these initial ADV tests the optimal size and spacing of cylinders was determined to be 15 cm diameter cylinders spaced 135 cm on center with the layout shown in Figure 2-7.

Test flow rates for the dace and chub were determined based on swim data from previous fish tests done at BYU (Aedo, Belk and Hotchkiss 2009). Webb reported a 1.09 m/s average velocity for Longnose dace, which when replicated resulted in a Froude number of approximately 1 and produced surface waves. As a lower velocity would be required to reduce the wave action, after consulting with Dr. Belk and Dr. Hotchkiss, a mean speed of 0.9 m/s mean control velocity was chosen as sufficient to challenge the fish and provide differentiation between the control and experimental setups. Aedo reported a Longnose dace mean burst speed of 1.2 m/s and mean prolonged speed of 0.73 m/s. The chosen speed of 0.9 m/s is 30% of the difference between the prolonged and burst speed. The Leatherside chub reported mean burst speed was 1.2 m/s, and mean prolonged speed was 0.54 m/s. Based on this, 30% of the difference, 0.75 m/s, was chosen as the mean testing velocity for the control setup for chub. (Aedo, Belk and Hotchkiss 2009)

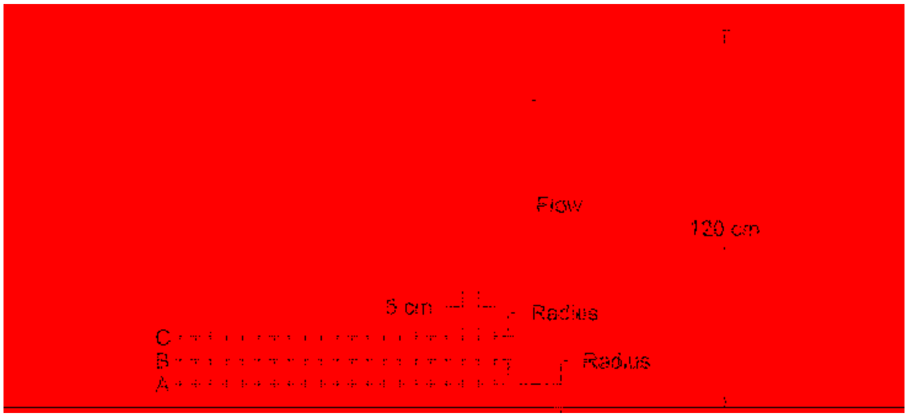

Figure 2-1: Plan View of ADV Points Taken Behind Cylinders

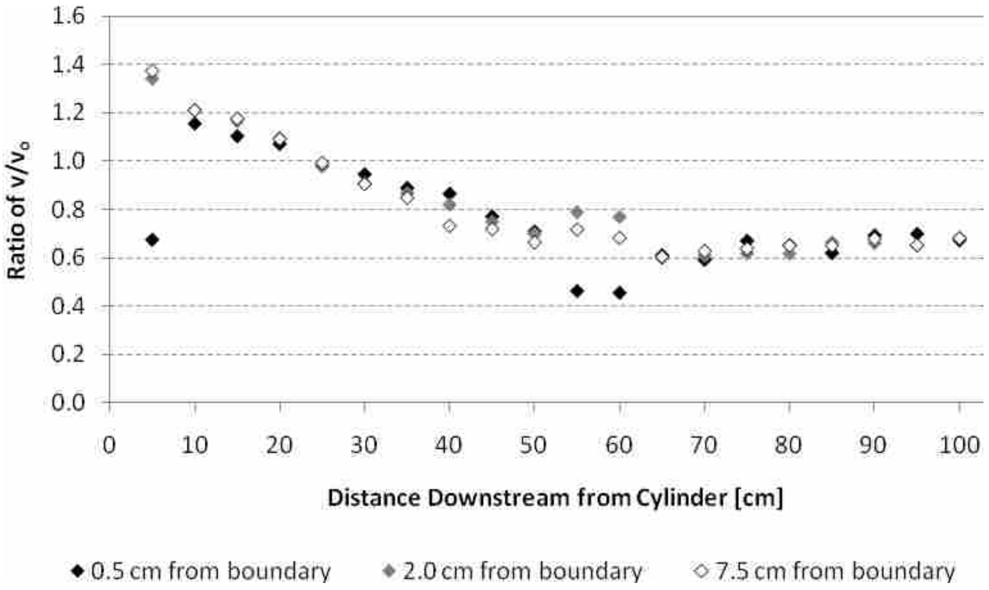

Figure 2-2: Dace Velocity (0.9 m/s) for Row A, 10 cm Cylinder

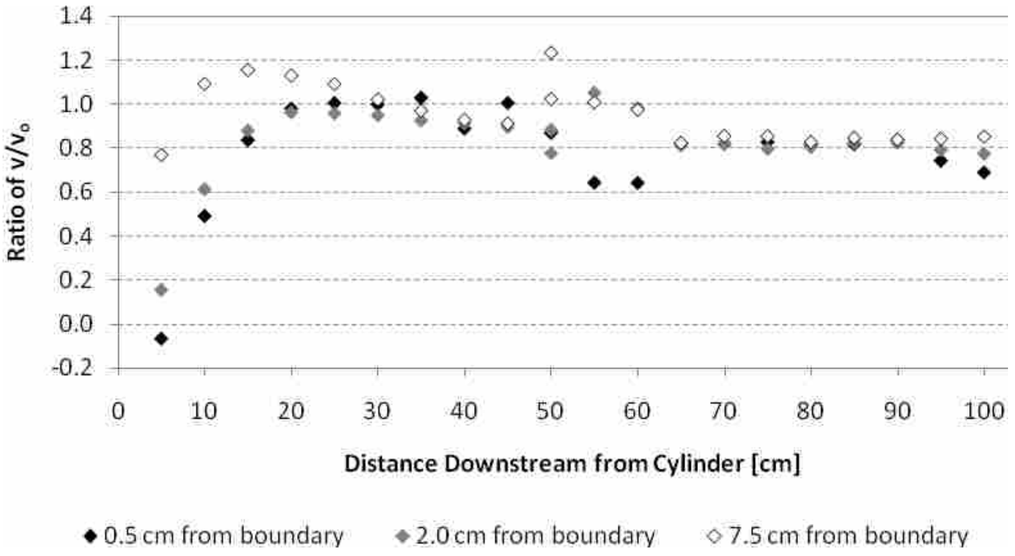

Figure 2-3: Dace Velocity (0.9 m/s) for Row B, 10 cm Cylinder

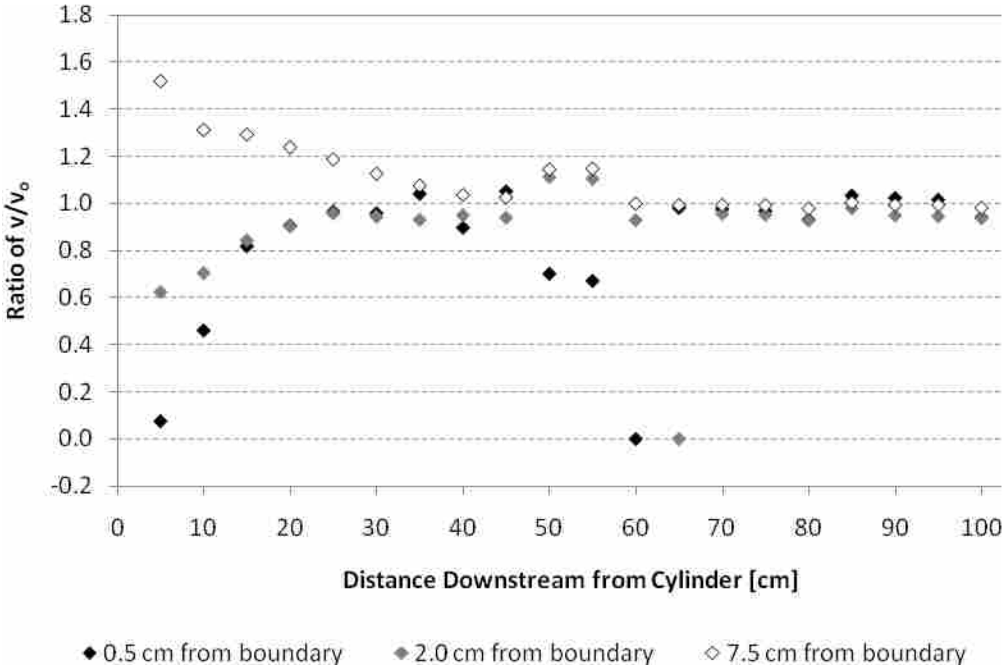

Figure 2-4: Dace Velocity (0.9 m/s) for Row C, 10 cm Cylinder

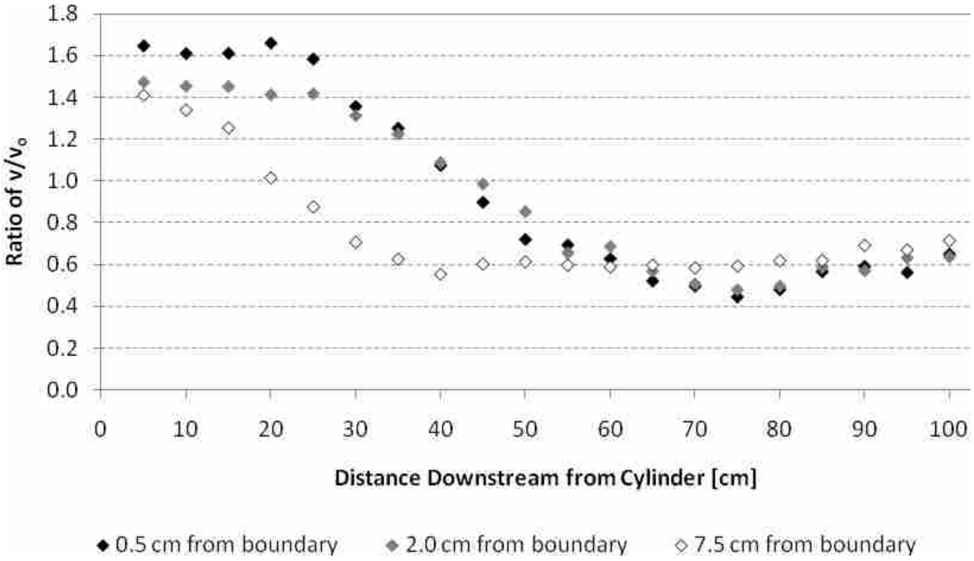

Figure 2-5: Dace Velocity (0.9 m/s) for Row A, 15 cm Cylinder

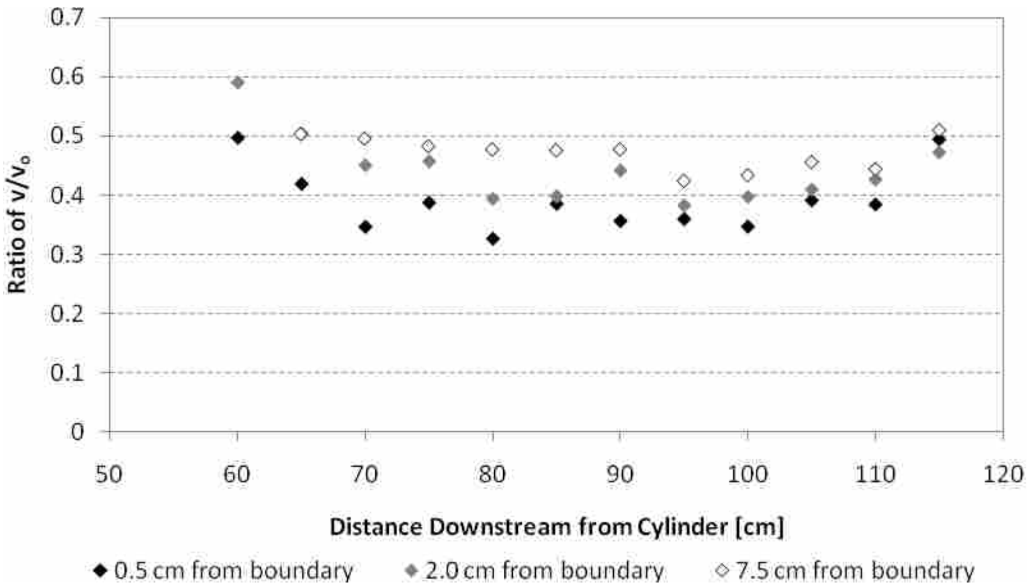

Figure 2-6: Dace Velocity (0.9 m/s) for Row A, Two 15 cm Cylinders Spaced 135 cm on Center

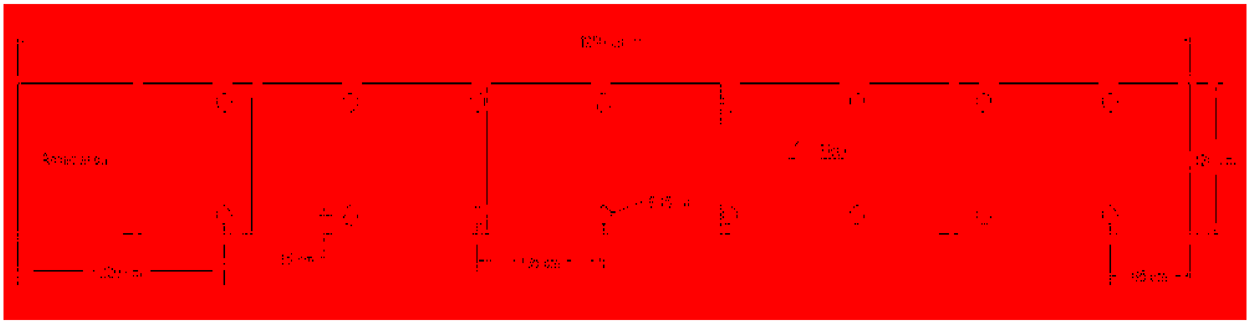

Figure 2-7: Flume in Plan View with 15 cm Cylinders

2.3 Experimental Setup

The final experimental design includes three setups. The control setup, Figure 2-8 is the bare Plexiglas flume. The cylinder setup, Figure 2-9, is the bare flume with cylinders placed according to Figure 2-7. Finally, the substrate setup,Figure 2-10, is laid out as described in section 2.3.3.

Figure 2-8: Control Setup

Figure 2-9: Cylinder Setup

Figure 2-10: Substrate Setup

2.3.1 Flume

All flume tests were carried out in the Brigham Young University department of Civil and Environmental Engineering fluid mechanics laboratory. A 12.5 m long by 1.2 m wide Plexiglas recirculating laboratory flume was used for these experiments. The flowrate, tailwater, and slope in the flume are all adjustable. To measure flow rate in the flume, the 35.6 cm diameter supply line is equipped with an inline nozzle Venturi meter. The Venturi meter is connected to a differential pressure transducer with a digital display which displays change in head in inches (Δh) which is calibrated to the flowrate, Q, in ft^3/s with the following equation.

$$Q = 15.1511\sqrt{\Delta h} \tag{2.1}$$

Dace tests were run at a flowrate of 0.203 m^3/s (7.18 ft^3/s) and chub tests were run at a flowrate of 0.154 m^3/s (5.43 ft^3/s). The slope was set at 0.20% for all tests and both upstream and downstream depths were measured each time to ensure consistency of flow conditions.

The headworks arrangement consists of an elbow duct and a settling region. The settling region is equipped with a 7.62 cm thick polycarbonate honeycomb flow straightener. As surface waves formed at higher flow rates a board was floated on the surface at the inlet section following the flow straightener to reduce this effect, shown in Figure 2-11.

Figure 2-11: Flume Headworks

2.3.2 Accoustic Doppler Velocimetry

All velocity measurements were taken with a SonTek 16-MHz Micro Acoustic Doppler Velocimeter. The three pronged sensor takes 3D velocity readings in a $\approx 0.3 \text{ cm}^3$ sampling volume 5cm below the probe tip. Output data includes signal to noise ratio (SNR) and correlation (COR) values that can be used to filter out noise in the acoustic reflections. SNR values are recommended to be at least 15dB, but for mean current measurements it can be as low as 5dB. COR values are ideally greater than 70% but for mean velocity measurements over variable terrain values as low as 30% can be used. (SonTek 2001)

All data points were taken in the locations shown in Figure 2-1. The measurements were filtered with two criteria: SNR values greater than 15dB and COR above 70% or 50%. This resulted in at least 70% good points. These values for SNR and COR were impractical for measurements taken just above substrate due to high turbulence and surface variation. Following SonTek standards SNR values above 5dB and COR values over 30% were used as cut-off values for ADV points taken just above the substrate.

2.3.3 Substrate

Substrate was taken from the same reach of Soldier Creek (Thistle, Utah area) where fish were caught. The surface of the streambed, commonly known as the armor layer, was shoveled into 5 gallon buckets and transported to the lab. Forty-one buckets of substrate sufficiently covered the flume bottom to an approximate 5 cm depth. A liner was used to protect the acrylic flume bottom and was marked off into 41 sections, each associated with a bucket. Four buckets were randomly selected for a sieve analysis to determine particle size distribution and check distribution similarity between the 41 sections. The sieve analysis % finer and particle size distribution for sections 19, 22, 25, and 40 are shown in Figure 2-12 and Table 2-1 respectively.

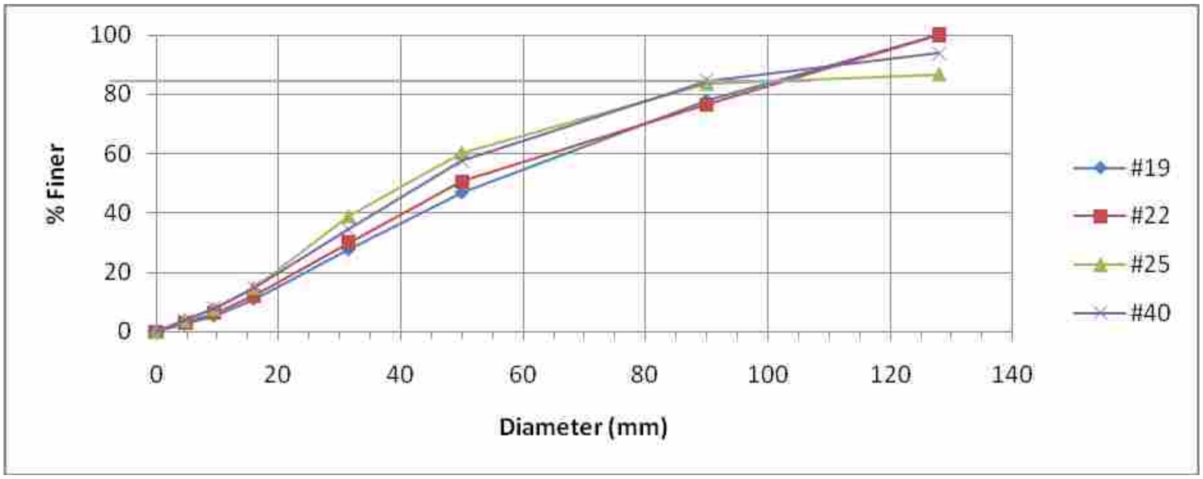

Figure 2-12: Sieve Analysis of 4 Randomly Selected Samples

Table 2-1: Particle Size Distribution of 4 Randomly Selected Samples

	#19	#22	#25	#40	Mean	St. Dev.	Geo. Mean
Total Mass [kg]	33.16	30.64	30.07	30.63	31.13	1.38	31.10
D16 [mm]	21	19	15.5	15.5	17.75	2.72	17.60
D50 [mm]	54	49	39	42.5	46.13	6.69	45.76
D84 [mm]	99.5	102	91	88	95.13	6.69	94.95

3 DATA COLLECTION

This section presents the protocol followed for fish capture, care and testing. The form used to record test data is included in Appendix A. Testing was conducted starting on June 21st and continuing through July 23rd, 2010. All fish capture, care and testing was in accordance with the Institutional Animal Care and Use Committee (IACUC) protocol #10-0401.

Motivation was conducted on fish that remained in the same position for at least 15 minutes. Fish motivation consisted of tapping the caudal fin with a wooden dowel to startle the fish enough to move out of its current position. If the fish quickly found refuge again it was allowed to remain there another 15 minutes before repeating the motivation. Fish were not corralled up the flume, but instead efforts were made to accurately test their swimming abilities while remaining within the allotted time period.

The protocol for the experiments is as follows:

1) Catch fish- Fish are caught from Soldier Creek, after which the fish are kept in tanks in Rm. 188 of the John A. Widtsoe building (WIDB) for 48-60 hours before testing.
    a) Dace size: 65-80 mm
    b) Chub size: 75-90 mm
2) Acclimate in WIDB
    a) Keep fish in cooler from capture overnight (to regulate temperature change to less than 1°C/hr).

    b) Transfer fish into tanks and let them acclimate before testing.
    c) Do not feed fish for 24 hours before testing.

3) Transportation
    a) Remove fish to be tested from holding tank with small fish net.
    b) Place fish in a bucket of "aged" water taken from the same room as holding tank (to equalize temperature).
    c) Carefully transport bucket to Rm. 171 of the W. W. Clyde Building (CB) by way of a cart.

4) Measurements (can be completed during acclimation or testing)
    a) Print “worksheet” for the specific test that is being run.
    b) Fill in all measurements that are called for (Δh, slope, water depth, temperature, treatment, species, fish length, etc.). Make sure all measurements are accurate as specific conditions may have to be recreated later on.

5) Acclimation in flume
    a) Start blue power box to supply power to the flume and its instruments.
    b) Make sure the gap between the tailgate and the Plexiglas is covered so that small rocks won’t get lodged in the gap hindering tailgate operation.
    c) Using the flume’s control panel, start pumps simultaneously at a frequency of 25 Hz. Remove air from Venturimeter by slightly unscrewing the bolts on either side of the monitor until water streams out both holes. Wait about 10 seconds and tap each water tube to make sure that air is removed from the system.
    d) Raise the tailgate to back up the water.

  - e) Adjust frequency so that v = 0.2 m/s and S = 0.20% (about 25 Hz on both pumps, d = 20 cm, Δh = 10). Raise tailgate to 12.1 cm.
  - f) Put down the containment gate (at the upstream end of the trolley).
  - g) Move fish from the bucket into the acclimation area with a small net.
  - h) Let the fish remain in the acclimation section for one hour.
- 6) Testing
  - a) Adjust the frequency and slope for the species being tested. Set the pumps at the recommended Hz then make sure Q is accurate after step c.
    - i) Dace: v = 0.9 m/s and S = 0.20% (about 57.0 Hz on both pumps, d = 19 cm, Δh = 150).
    - ii) Chub: v = 0.75 m/s and S = 0.20% (about 45.2 Hz on both pumps, d = 16 cm, Δh = 102).
  - b) Lower the tailgate all the way. Double check after step c.
  - c) Raise containment gate and start timing.
  - d) Check and record the positions of the fish every five minutes for one hour. Note fish location on the information sheet as shown on previous records. Also record when fish reach the top or if they escape and fall into the reservoir. Time 0:00 to 1:00 hr
    - i) Motivate fish with a small rod if they stay in the same area for too long (15 minutes).
    - ii) Remove fish at the conclusion of the test, or mid-test if deemed necessary due to extreme exhaustion or impingement.
    - iii) Measure and record the length of the fish before putting it back into the bucket.
  - e) Use startle motivation on the fish that have not succeeded by the end of the hour. Record results every five minutes for fifteen minutes after the end of the hour.

7) Transportation and further care of fish
    a) After motivating the fish that had not attempted to move, remove fish from flume with dip net, measure and record their lengths, and return them to their original bucket with bubbler.
        i) If any fish are in the reservoir, remove them as soon as is convenient within 24 hours.
    b) Transport them back to the WIDB.
    c) Remove fish from the bucket with dip net.
    d) Fish should either be kept for other research purposes in a separate tank or disposed of at the end of each week per IACUC protocol.
8) Measurements
    a) Record any change in temperature or position of cylinders.
    b) Shut off the flume and the power box.

boundary layers to improve engineering design of fish passage culverts.

4 RESULTS

4.1 Fish Data

Figure 4-1 and Figure 4-2 show passage results split by motivation which was administered according to the testing protocol. Raw data for all tests are included in a summary table in Appendix A. In Appendix B are maps of the velocity distribution 5cm above the surface of the substrate, and typical velocity profiles for the control and cylinder setups. Absolute velocity is reported in these drawings to allow for comparison between setups, as the flow rate was held constant but not the average velocity. This is also more convenient as the average velocity is difficult to define in the substrate setup. However relative velocity can be used for application of these results to other flow rates, so average velocity for the control and cylinder setups are reported in Table 4-1.

Table 4-1: Measured Average Velocity by Species and Setup

Species	Control Velocity [m/s]	Cylinder Velocity [m/s]
Chub	0.75	0.62
Dace	0.87	0.72

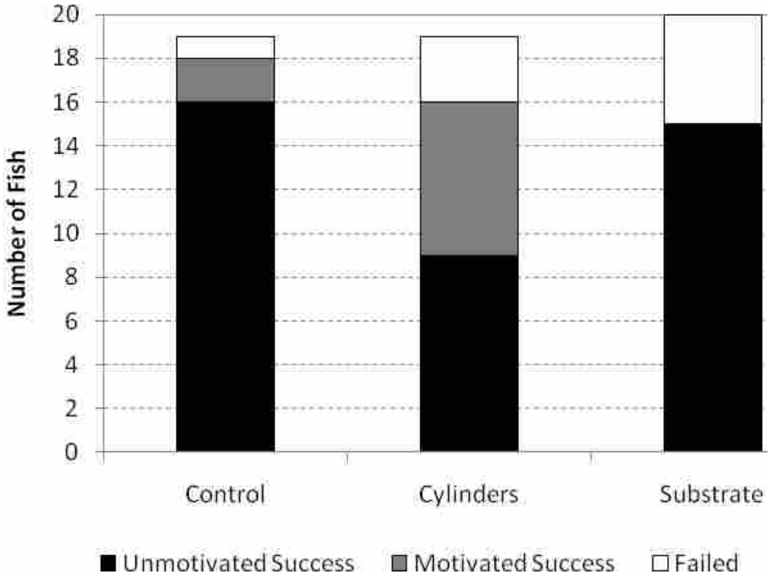

Figure 4-1: Chub Swim Test Success Graph

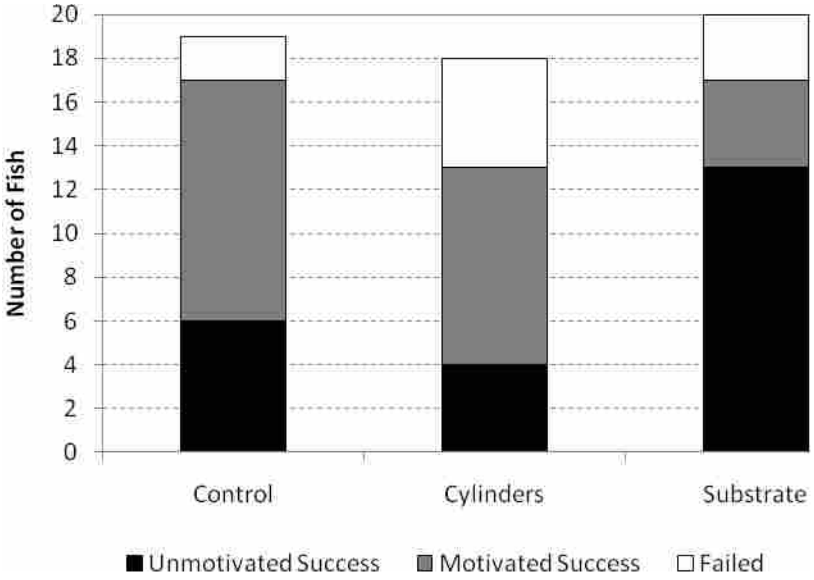

Figure 4-2: Dace Swim Test Success Graph

4.2 Velocity Characterization

This section includes velocity contour maps for each experimental setup at both 1 cm and 5 cm above the respective boundaries for each test setup. In the control and cylinder setups the boundary is defined as the floor of the flume, and in the substrate setup it is the surface of the rocks. An ADV test section plan view, Figure 4-3, is also included for reference, however in the cylinder velocity plots important cross sections just outside of the section are included. Comparisons and energy expenditure calculations are in section 4.3 *Statistical Analysis*. Typical velocity profiles for the control and cylinder setups are included in Appendix C.

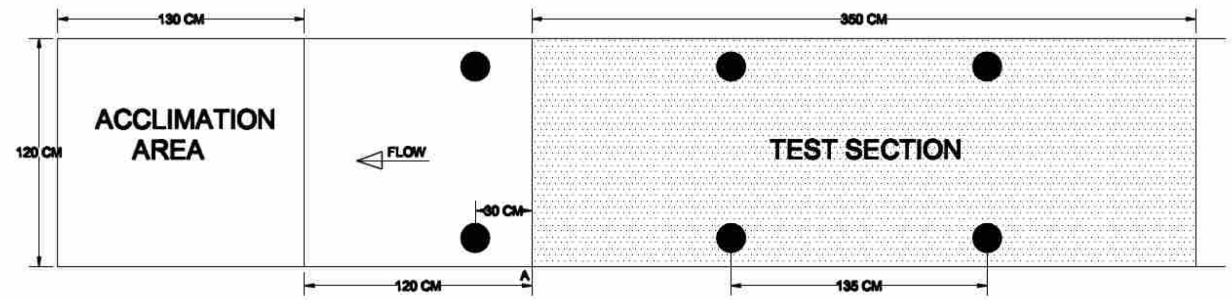

Figure 4-3: Test Section Plan View

Figure 4-4: Test Section, Substrate

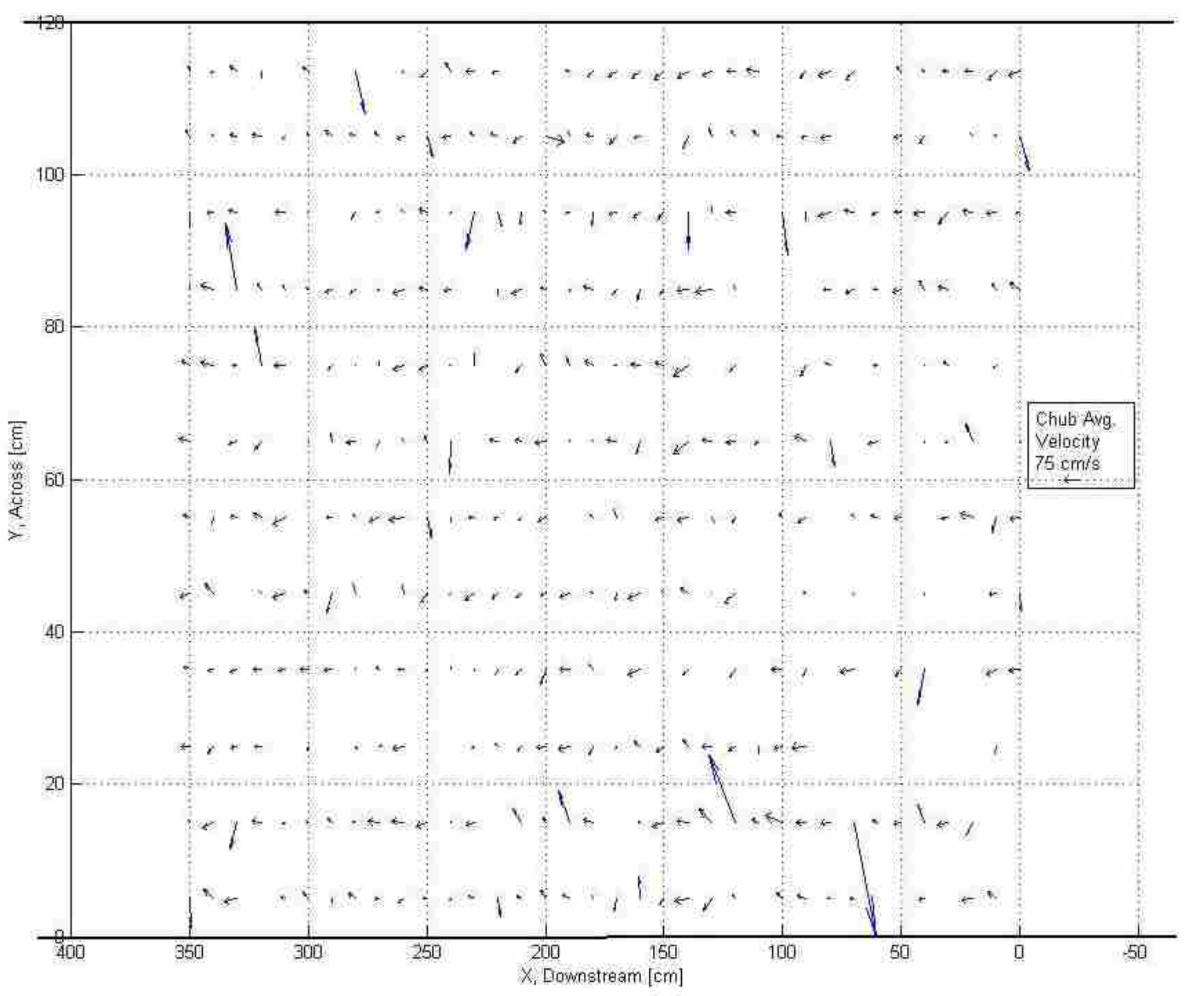

Figure 4-5: Chub Substrate Test Plan View, Velocity Vectors 1 cm above Boundary

424 velocity measurements were taken in a 10 X 10 cm grid across the testing section. An average of 5175 measurements were averaged at each location with a minimum of 1143 measurements at any single location. Contours are labeled in units of cm/s.

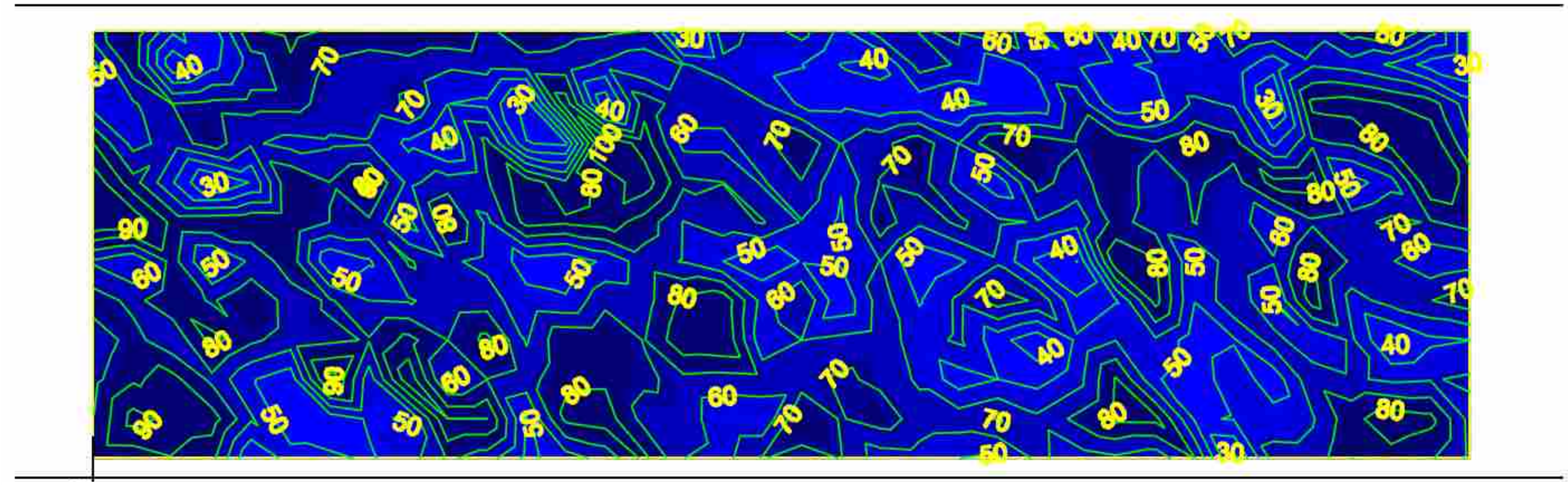

Figure 4-6: Dace Substrate Test Plan View, Velocity Contours 5 cm above Boundary

365 velocity measurements were taken in a 10 X 10 cm grid across the testing section. An average of 3476 measurements were averaged at each location with a minimum of 425 measurements at any single location. Contours are labeled in units of cm/s.

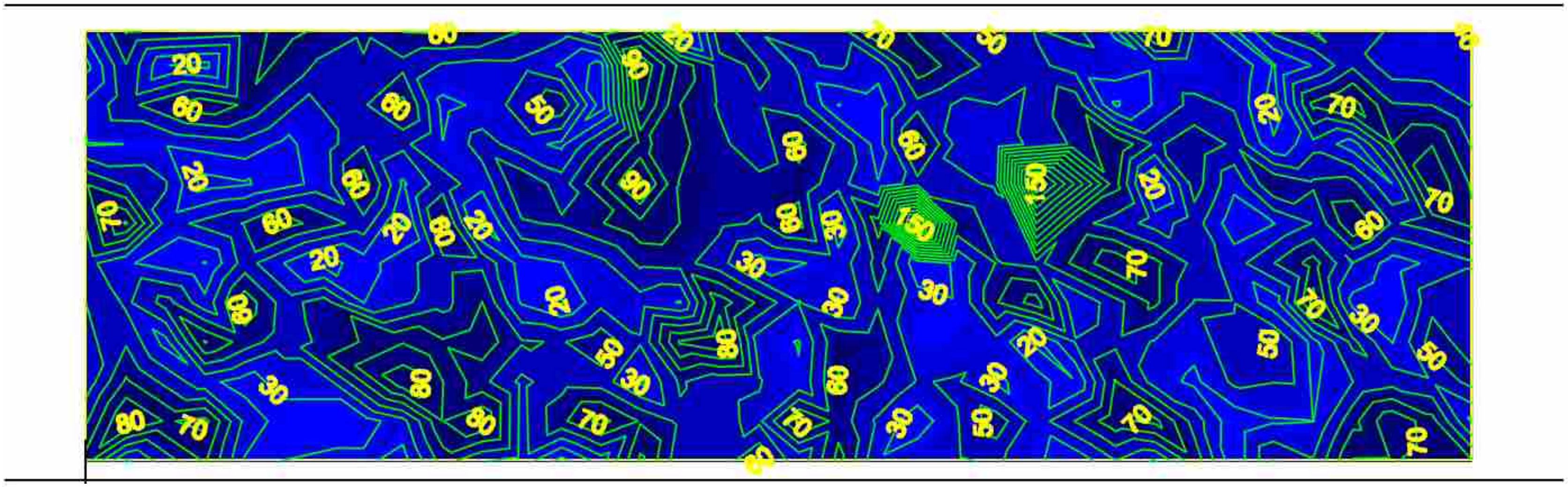

Figure 4-7. Dace Substrate Test Plan View, Velocity Contours 1 cm above Boundary

426 velocity measurements were taken in a 10 X 10 cm grid across the testing section. An average of 4860 measurements were averaged at each location with a minimum of 995 measurements at any single location. Contours are labeled in units of cm/s.

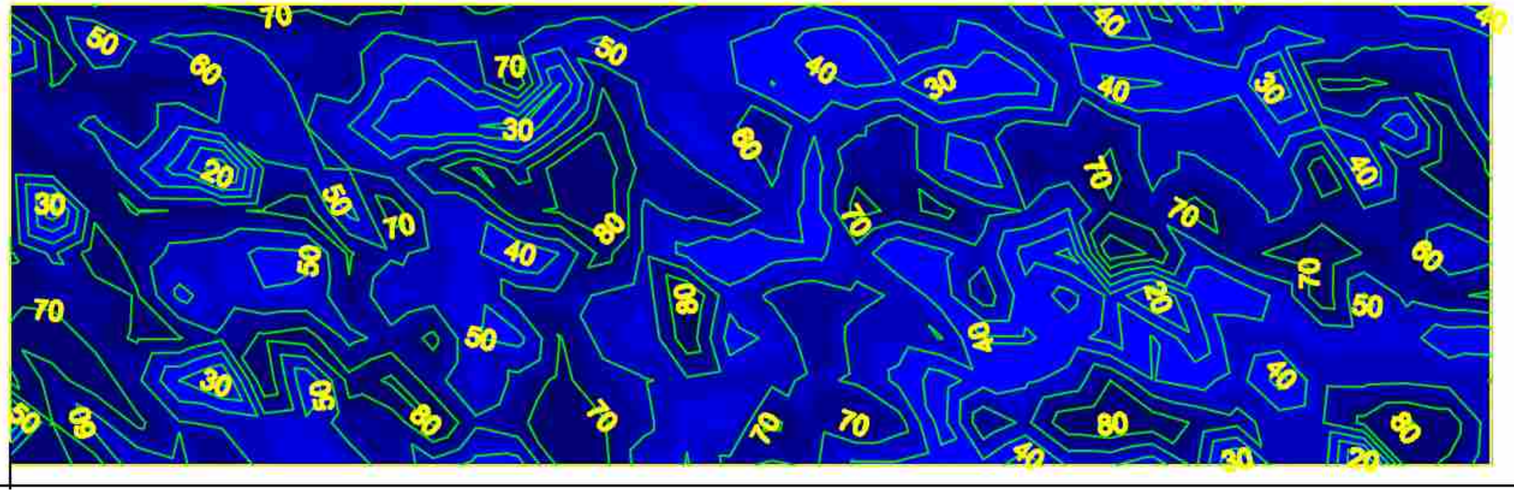

Figure 4-8: Chub Substrate Test Plan View, Velocity Contours 5 cm above Boundary

352 velocity measurements were taken in a 10 X 10 cm grid across the testing section. An average of 3233 measurements were averaged at each location with a minimum of 400 measurements at any single location. Contours are labeled in units of cm/s.

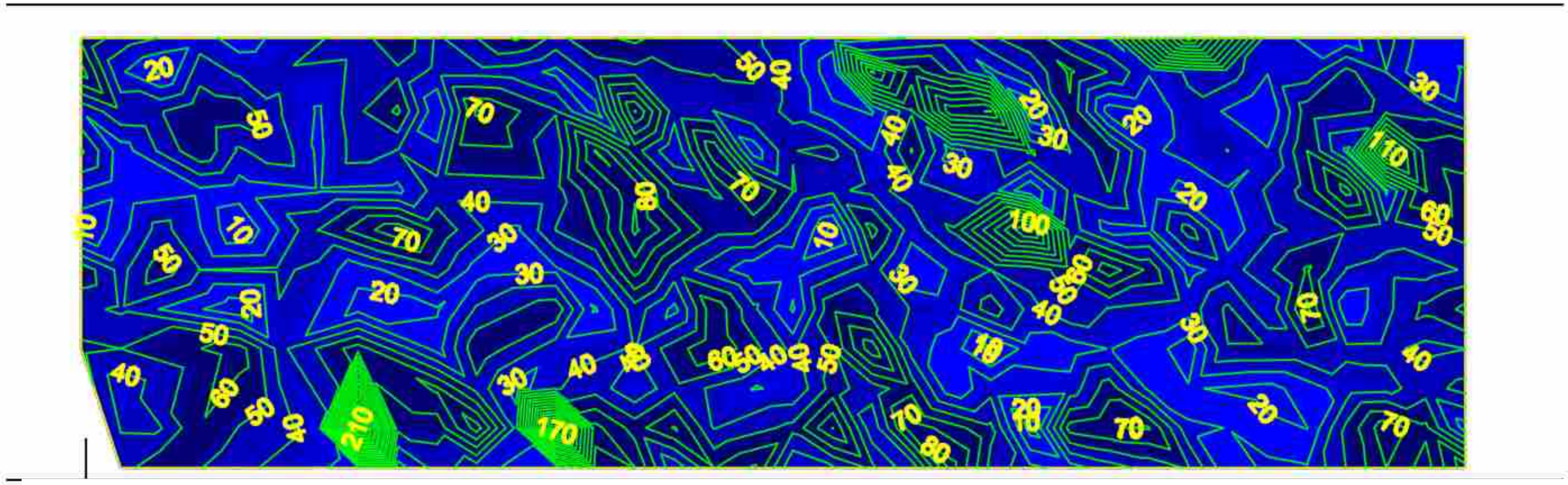

Figure 4-9: Chub Substrate Test Plan View, Velocity Contours 1 cm above Boundary

24 velocity measurements were taken in 2 cross-sections which were extrapolated across the testing section. An average of 2286 measurements were averaged at each location with a minimum of 1888 measurements at any single location. Contours are labeled in units of cm/s.

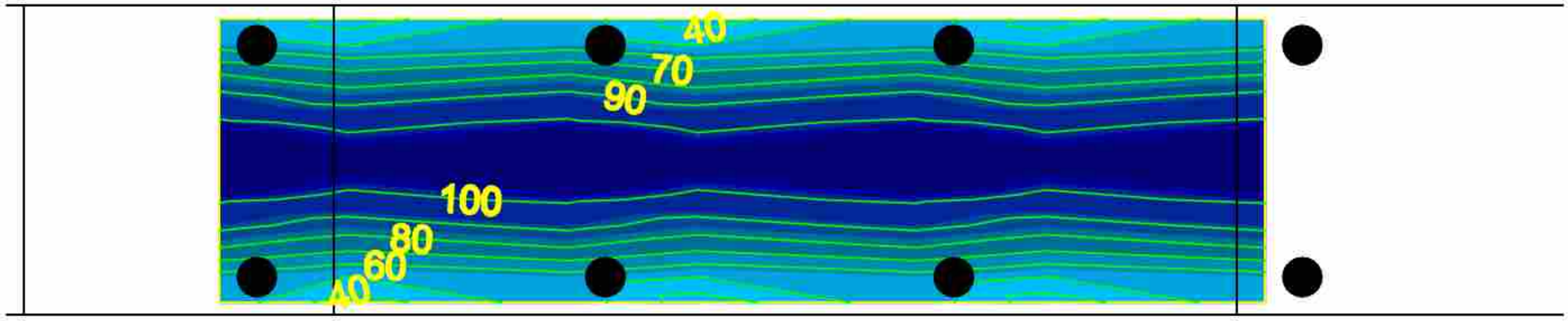

Figure 4-11: Dace Cylinder Test Plan View, Velocity Contours 5 cm above Boundary

41 velocity measurements were taken in 2 cross-sections and corner points between cylinders which were extrapolated across the testing section. An average of 2155 measurements were averaged at each location with a minimum of 812 measurements at any single location. Contours are labeled in units of cm/s.

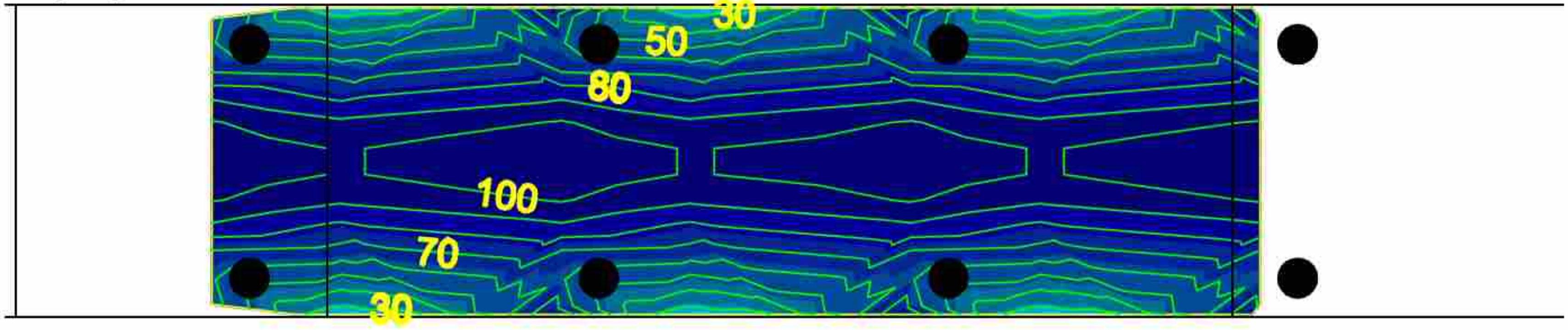

Figure 4-10: Dace Cylinder Test Plan View, Velocity Contours 1 cm above Boundary

24 velocity measurements were taken in 2 cross-sections which were extrapolated across the testing section. An average of 2115 measurements were averaged at each location with a minimum of 1634 measurements at any single location. Contours are labeled in units of cm/s.

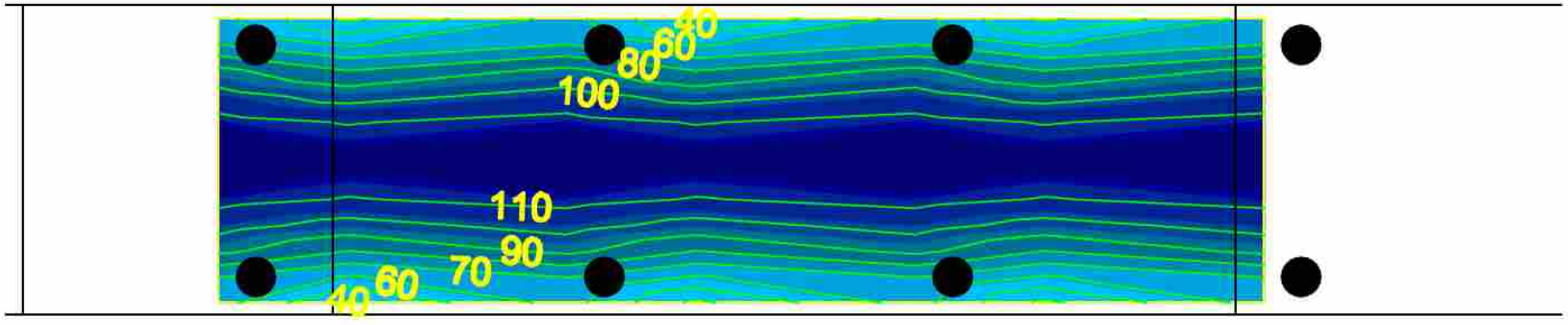

Figure 4-13: Chub Cylinder Test Plan View, Velocity Contours 5 cm above Boundary

36 velocity measurements were taken in 2 cross-sections and corner points between cylinders which were extrapolated across the testing section. An average of 2061 measurements were averaged at each location with a minimum of 353 measurements at any single location. Contours are labeled in units of cm/s.

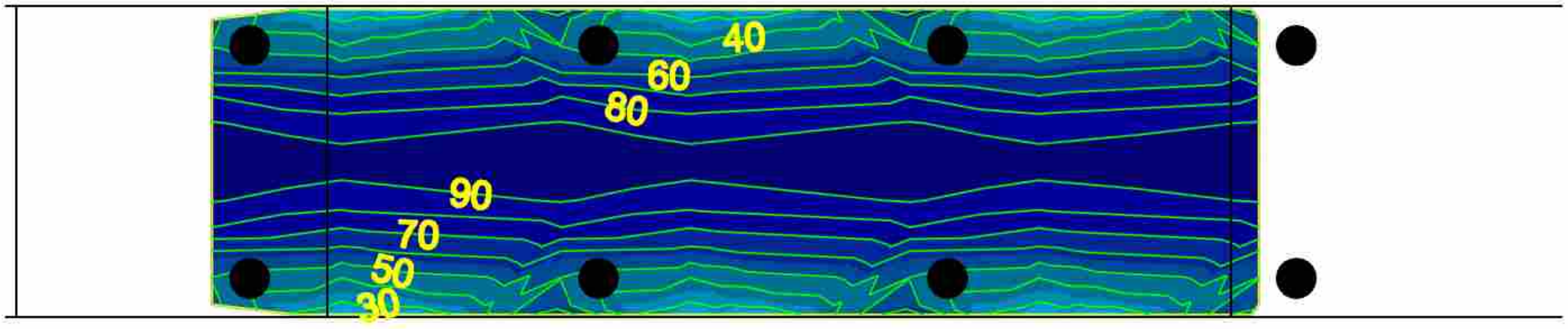

Figure 4-12: Chub Cylinder Test Plan View, Velocity Contours 1 cm above Boundary

11 velocity measurements were taken in a cross-section which was extrapolated across the testing section. An average of 2841 measurements were averaged at each location with a minimum of 2162 measurements at any single location. Contours are labeled in units of cm/s.

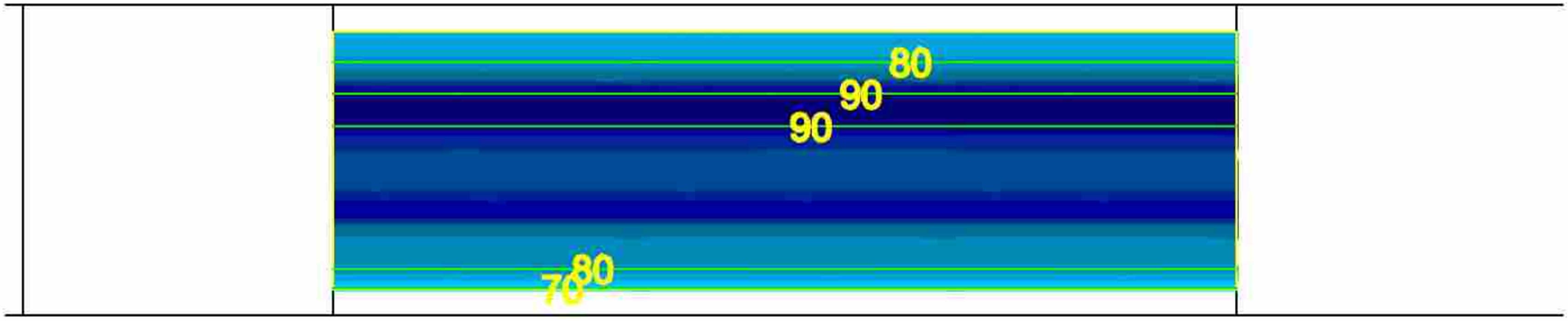

Figure 4-14: Dace Control Test Plan View, Velocity Contours 5 cm above Boundary

17 velocity measurements were taken in a cross-section including corner points which was extrapolated across the testing section. An average of 2779 measurements were averaged at each location with a minimum of 1545 measurements at any single location. Contours are labeled in units of cm/s.

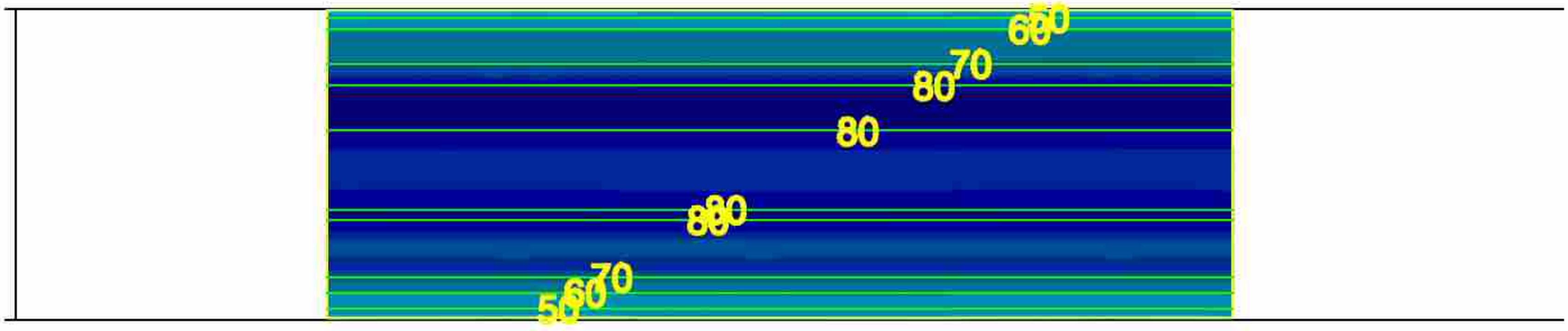

Figure 4-15: Dace Control Test Plan View, Velocity Contours 1 cm above Boundary

11 velocity measurements were taken in a cross-section which was extrapolated across the testing section. An average of 2629 measurements were averaged at each location with a minimum of 2207 measurements at any single location. Contours are labeled in units of cm/s.

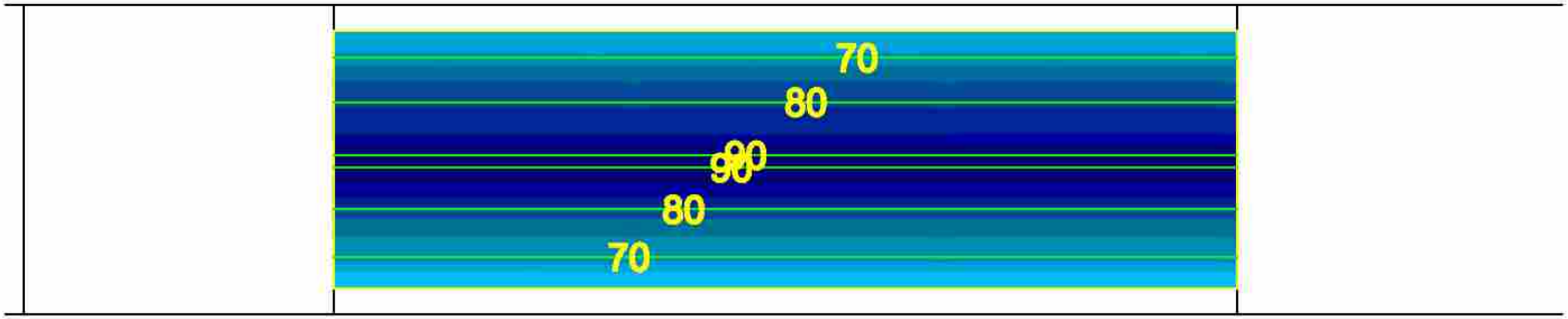

Figure 4-16: Chub Control Test Plan View, Velocity Contours 5 cm above Boundary

17 velocity measurements were taken in a cross-section including corner points which was extrapolated across the testing section. An average of 2551 measurements were averaged at each location with a minimum of 942 measurements at any single location. Contours are labeled in units of cm/s.

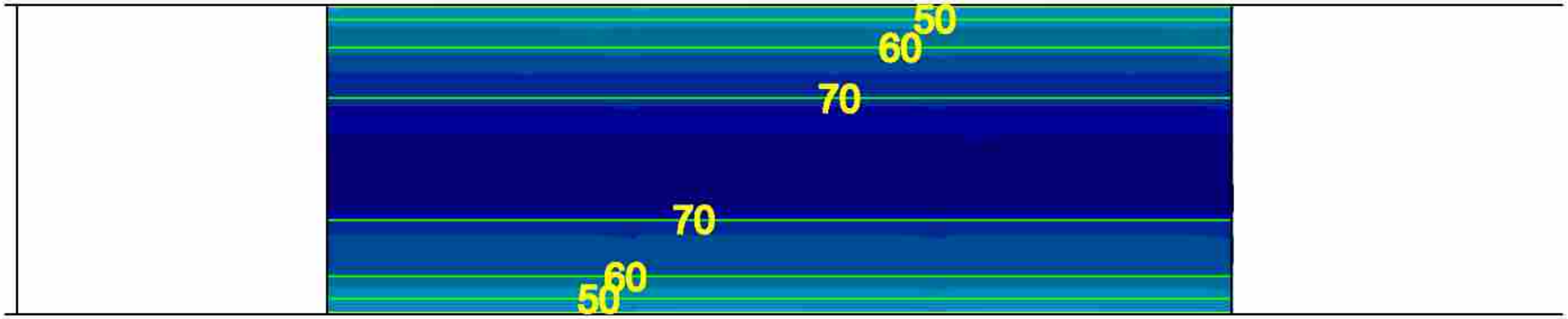

Figure 4-17: Chub Control Test Plan View, Velocity Contours 1 cm above Boundary

4.3 Statistical Analysis

The sample size ranged from 18-20 fish. Those fish that did not attempt to navigate the flume were removed from the sample. The statistical analysis includes a statistical regression with passage as the response variable and species and experimental setup and their interaction as the predictor variables. No significant correlation was found necessitating a different approach to analyzing the data, which is presented in the following section.

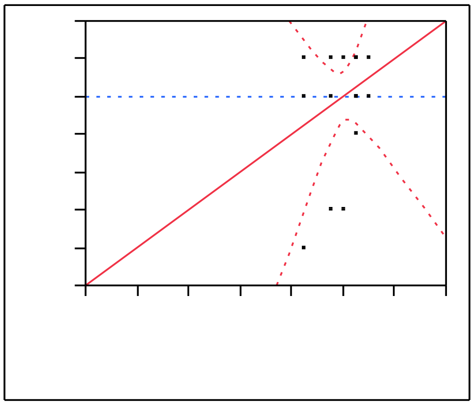

Figure 4-18: Actual by Predicted Plot

Table 4-2: Summary of Fit

RSquare	0.086957
RSquare Adj	-0.16667
Root Mean Square Error	1.527525
Mean of Response	4
Observations (or Sum Wgts)	24

4.4 Data Evaluation

As passage rate proved not indicative of the observed fish behavior, energy expenditure was instead chosen as a predictor variable. Energy expenditure is a function of the net propulsive power that a fish delivers to its surroundings and the time spent swimming through the element (Behlke 1991). The faster a fish moves through the most difficult points the less energy it uses in transiting the culvert. Especially when the end of an element cannot be seen from the beginning, fish attempt to minimize power by seeking out locations where their propulsive force can be minimized and moving through the most difficult spots as quickly as possible (Behlke 1991). As mentioned in the literature review, it has been observed that fish choose habitats not only based on average flow velocity but also on the degree of variation in flow velocity (Liao 2007). As fish were able to pass all of our experimental setups, our goal with energy expenditure calculations is to determine what is adaptively optimal for the fish. It would seem a summation of energy output required to pass each system could be calculated from water velocities and fish swimming speeds to compare the experimental setups. As fish position was observed and recorded every five minutes and water velocities have been measured throughout the flume in each setup, energy expenditure could be directly calculated. However, the lack of consistency in swimming paths, patterns and time to pass not only between experimental setups and species but often between fish in the same experimental run makes such direct calculations not only difficult but inconclusive. Compare for example the energy expenditure for a fish that took 50 minutes to pass in the substrate but spent the time freely navigating the flow and foraging for food compared to that of a fish that swam in a straight line and struggled consistently to pass the control setup in 8 minutes. Even if their energy expenditure in passing the obstacle was the same, the behavior of the first fish is closer to natural behavior and more adaptively optimal. Energy calculations are further complicated by the difference in energy expenditure between the white and red muscle systems fish use to swim.

Instead of attempting to mathematically account for behavior, a more general approach to match what is known about habitat preferences of fish and the biological processes behind fish movement can be utilized to compare experimental setups and more quantitatively present what was observed qualitatively. It is known that fish prefer variability, and pass through high velocity sections as quickly as possible and then spend more time in lower velocity regions. So the optimal swimming environment would provide high velocity variability with frequent low velocity zones. A look at the velocity contour maps allows for a general comparison. The substrate provides the greatest variation in velocities and habitat. The cylinders provide predictable low velocity pockets but not as low or frequent as exists in the substrate. The control setup results in a very uniform flow with the narrowest range of velocities. Figure 4-20 through Figure 4-23 can be used to compare the variability of each setup.

Fish in the control and cylinder setups were observed swimming almost exclusively in the corners of the rectangular flume. So the swim path length was considered the same in each setup and the flow velocities faced along that swim path were easily measured and compared. Figure 4-20 and Figure 4-21 show the velocity profile faced by a fish swimming up the corners, 1 cm above the floor and 1 cm from the wall of the flume.

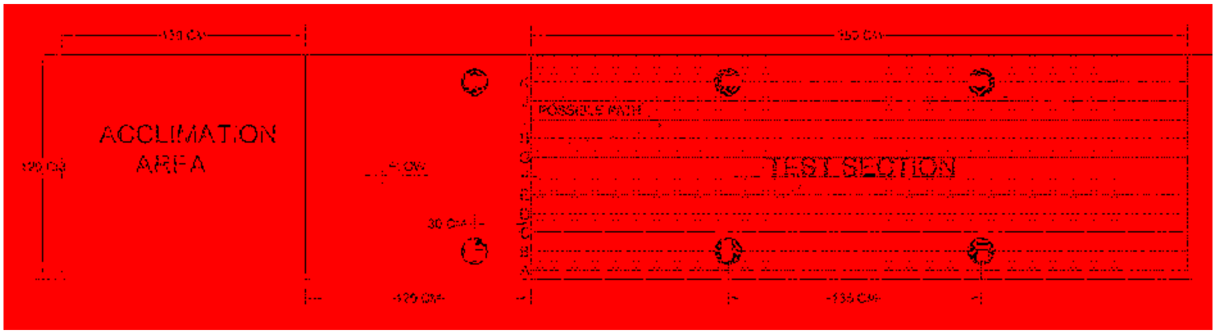

Figure 4-19: Test Section with Profile Labels A-K

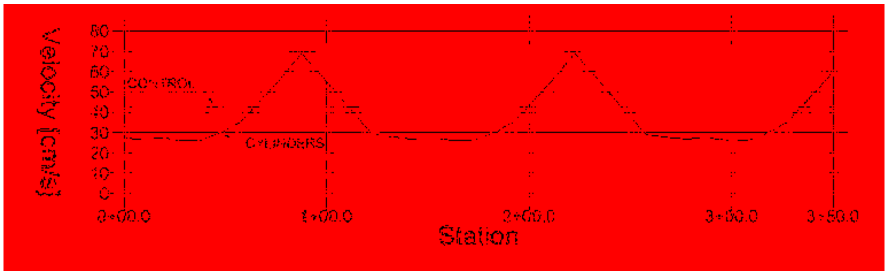

Figure 4-20: Dace Test Section Velocity Profile 1 cm from Horizontal and Vertical Boundaries

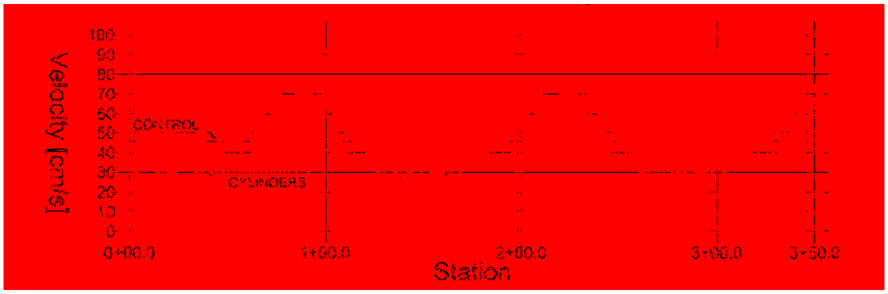

Figure 4-21: Chub Test Section Velocity Profile 1 cm from Horizontal and Vertical Boundaries

The substrate experiment is not as easily quantified and compared to the other tests as fish did not follow a consistent swim path. Their swim paths varied significantly both vertically and horizontally. Not only does it become difficult to measure the velocity profile faced by any given fish, but the swim paths were much longer than in the control and cylinder setups. To give a representative sample, 12 different profiles were taken across the test section of the flume. Eleven of the profiles were straight lines at regular intervals, and a twelfth was a possible swim path a fish may have chosen to minimize energy expenditure. The 12 profiles for each species are shown in the following figures.

Figure 4-22: Dace Test Section Substrate Profiles 1 cm above Boundary

Figure 4-23: Chub Test Section Substrate Profiles 1 cm above Boundary

5 DISCUSSION AND CONCLUSIONS

5.1 Discussion and Conclusions

When energy expenditure requirements were sufficiently low, we observed that fish needed little or no motivation to move upstream. However, when energy requirements increased due to higher velocities, the need for motivation increased to a point. We refer to the energy expenditure level under which fish no longer moved upstream of their own volition as the station holding line. The way in which different species of fish expend energy affects when they exhibit station holding behavior. Benthic swimmers are better equipped to take advantage of near boundary low velocity regions which means they can expend energy more efficiently and postpone exhaustion. Midstream swimmers are not as comfortable near the boundary and frequently make forays into higher velocity regions which speeds their exhaustion. There is a line beyond the station holding line where high velocities and lack of refuge caused fish to burst swim in search of a resting place. The energy expenditure level resulting in burst behavior will hence be called the burst line. This swim behavior theory can be used to explain the results in Figure 4-1, the Chub swim test success graph, and Figure 4-2 the Dace swim test success graph. In both graphs it can be seen that success in the substrate treatment was high with little or no motivation. Fish were observed swimming up and downstream several times during substrate treatment tests, and foraging for food in the crevasses between rocks. The majority of fish in the substrate treatment never exhibited station holding behavior. Unmotivated success decreased and motivated success increased in the cylinder test compared to the substrate test for both species. In the cylinder test, several fish moved upstream without station holding, many fish reached the station holding line, and some reached the burst line. It can be concluded that the cylinder setup was sufficient to provide holding for most fish, but not enough refuge to allow freedom of movement or other naturally observed behaviors such as foraging for food. The control test shows the difference between the benthic and midstream species. All fish in the control test exhibited station holding behavior. The benthic swimming Dace were able to use the small boundary region above the Plexiglas flume bottom to hold position and avoid bursting for as long as possible. The Dace that succeeded in the control test, both motivated and unmotivated, did so very quickly. They burst all the way to the top of the flume in one or two minutes. The midstream swimming Chub reached the burst line more quickly as they could not use the boundary layer as efficiently as the Dace. For this reason very few required motivation; they could not hold position which forced them to move either upstream or down for the duration of the test.

Using our energy expenditure model with the station holding and burst lines to explain observed fish behavior leads us to the conclusion that rocks provide better refuge for fish than singular cylinder obstacles or no obstacles at all. This seems an obvious conclusion, as fish are adapted to swimming in their natural habitat, but the theories about fish swimming behavior explored along the way may prove useful when observing fish and designing structures for fish passage.

The fish swim behavior model is supported by ADV measurements. Velocity profiles for the control and cylinder setups give insight into how energy expenditure would differ as a fish navigated upstream under different conditions. ADV measurements showed that the location where fish chose to hold behind cylinders had significantly lower velocities than those that existed in the control setup. However, in the highest turbulence region directly behind and next to the cylinders, measured velocities were significantly higher than in the control setup. Energy expenditure would be less during station holding allowing white muscle tissue to recharge before bursting through the high velocity and turbulence region around the cylinder to the next station holding region. In the velocity maps for the substrate test, regions with even lower velocities than the station holding region in the cylinder setup were frequently observed. The velocity maps show how a fish could easily move between low velocity areas with only occasionally being required to burst through a high velocity region. Due to this variability in the flow regime of the substrate test, fish can take advantage of low velocity regions and expend less energy as they move upstream.

5.2 Limitations of Conclusions

Conclusions made concerning energy expenditure of fish are largely observational. Velocity characterization was coupled with previous research on energy expenditure and fish behavior (Behlke 1991) to draw conclusions.

6 RECOMMENDATIONS

As rocks provide significantly improved refuge compared to single cylinder obstacles or no obstacles at all, we propose that only rocks be tested in the field for Phase II. Different sizes of substrate with varying size distributions can be tested to determine what ratio between the scale of rock and the fish scale provides the best refuge with least reduction of flow rate.

Further research could also be done on velocity profiles near the boundary for different substrates. It would be useful to find a relationship between D50, D80, D20 etc. and the effect on turbulence and/or velocity.

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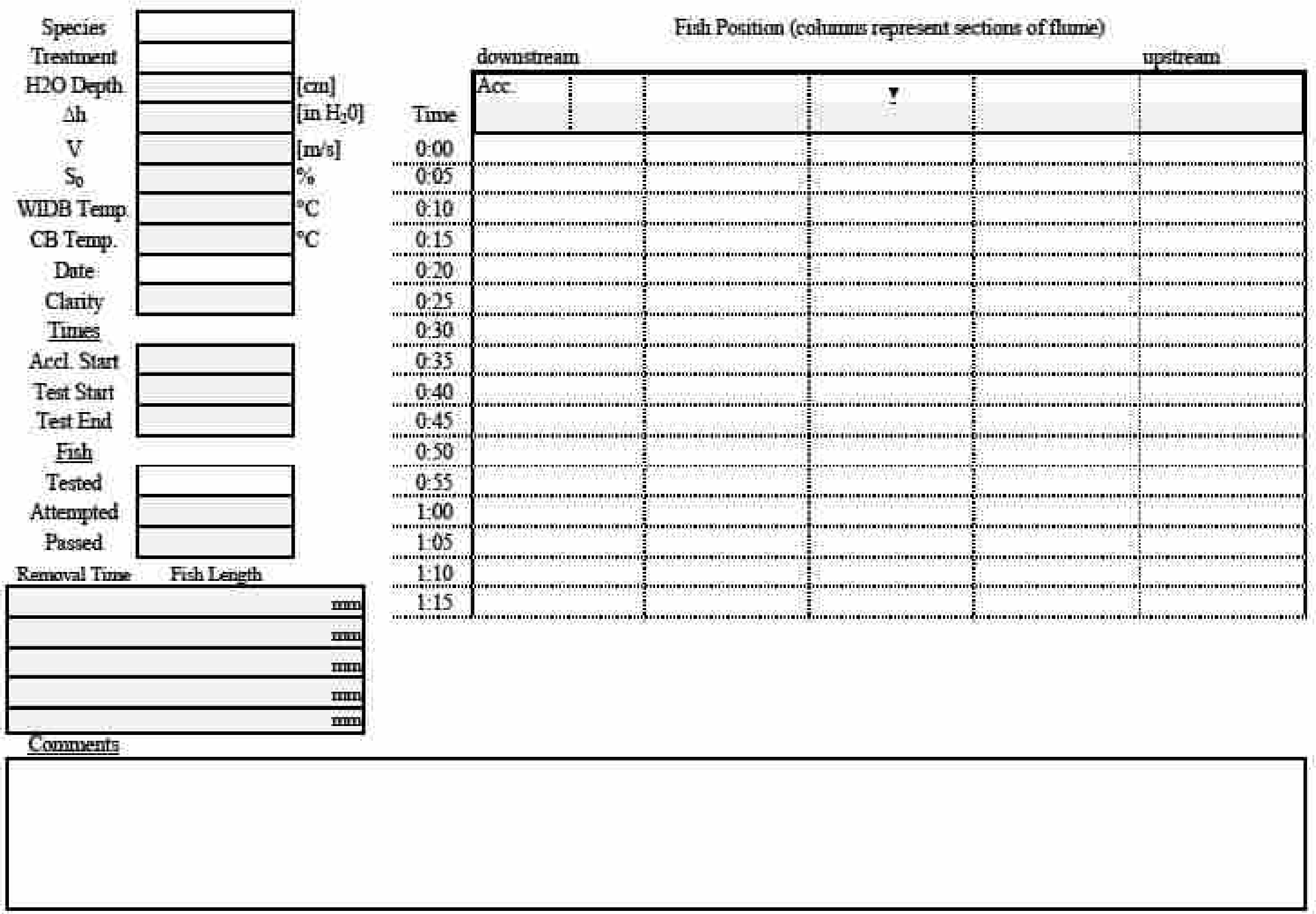
APPENDIX A. DATA

Included in this section are the fish testing worksheet used to gather data followed by tables of the raw data collected during all of the tests.



Species		
Treatment		
H2O Depth		[cm]
Δh		[in $H_2$0]
V		[m/s]
S_0		%
WIDB Temp		°C
CB Temp.		°C
Date		
Clarity		
Times		
Accl. Start		
Test Start		
Test End		
Fish		
Tested		
Attempted		
Passed		

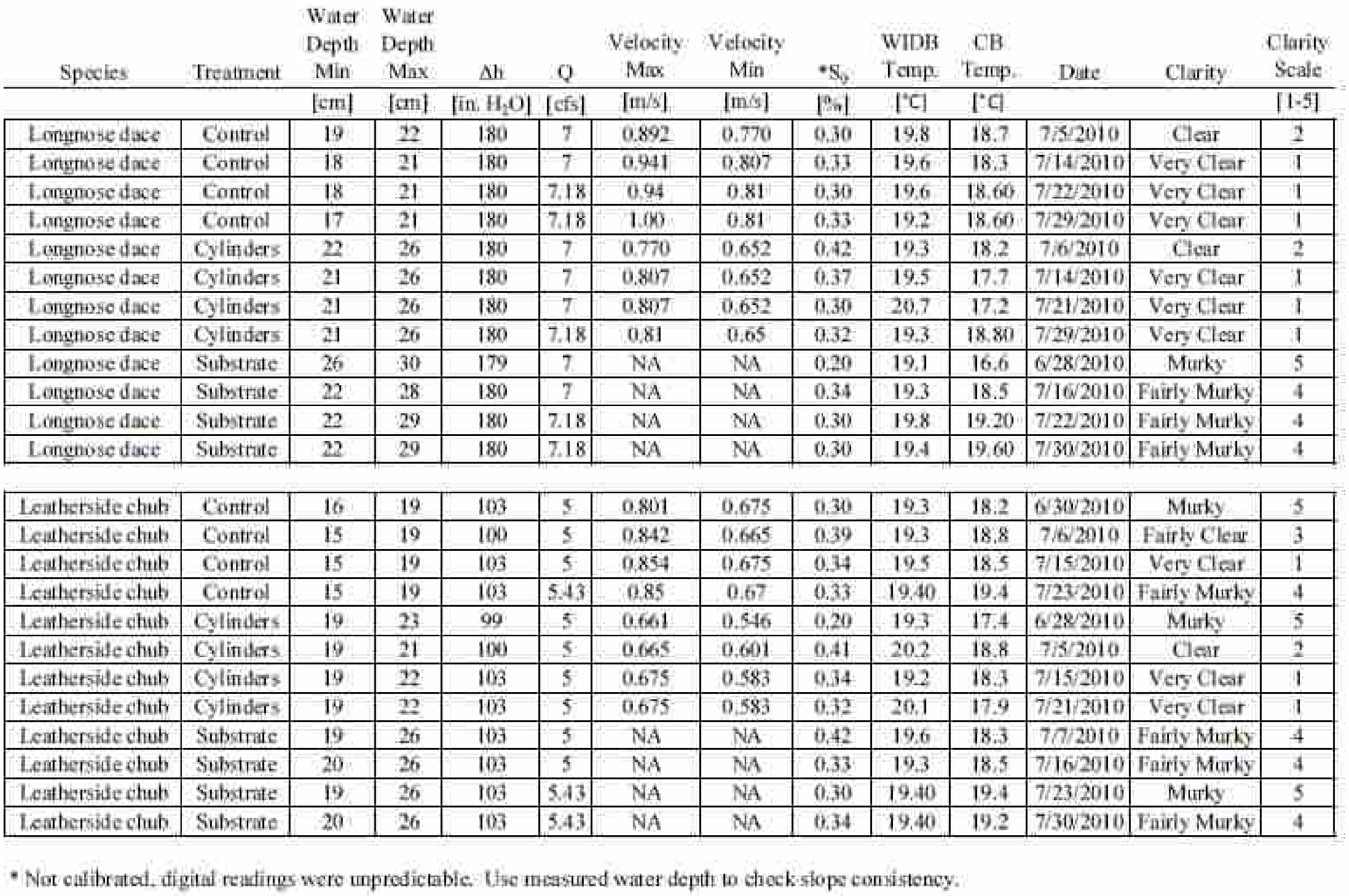
Removal Time	Fish Length
	mm
	mm
	mm
	mm
	mm

Comments

Fish Position (columns represent sections of flume)

	downstream					upstream
Time	Acc.		▼			
0:00						
0:05						
0:10						
0:15						
0:20						
0:25						
0:30						
0:35						
0:40						
0:45						
0:50						
0:55						
1:00						
1:05						
1:10						
1:15						

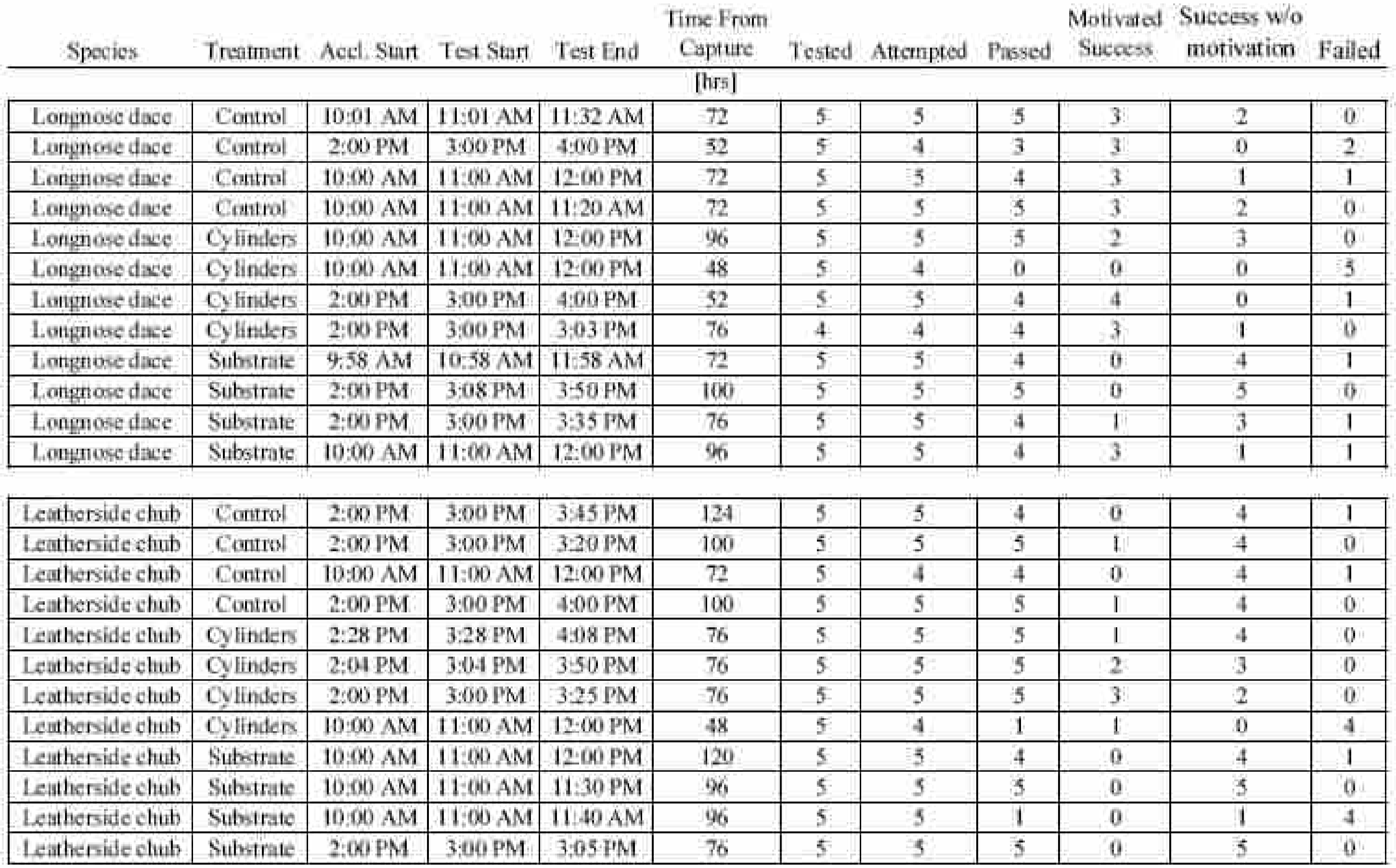
Figure A-1: Fish Testing Worksheet



Species	Treatment	Water Depth Min	Water Depth Max	Δh	Q	Velocity Max	Velocity Min	$^*S_0$	WIDB Temp.	CB Temp.	Date	Clarity	Clarity Scale
		[cm]	[cm]	[in. H_2O]	[cfs]	[m/s]	[m/s]	[%]	[°C]	[°C]			[1-5]
Longnose dace	Control	19	22	180	7	0.892	0.770	0.30	19.8	18.7	7/5/2010	Clear	2
Longnose dace	Control	18	21	180	7	0.941	0.807	0.33	19.6	18.3	7/14/2010	Very Clear	1
Longnose dace	Control	18	21	180	7.18	0.94	0.81	0.30	19.6	18.60	7/22/2010	Very Clear	1
Longnose dace	Control	17	21	180	7.18	1.00	0.81	0.33	19.2	18.60	7/29/2010	Very Clear	1
Longnose dace	Cylinders	22	26	180	7	0.770	0.652	0.42	19.3	18.2	7/6/2010	Clear	2
Longnose dace	Cylinders	21	26	180	7	0.807	0.652	0.37	19.5	17.7	7/14/2010	Very Clear	1
Longnose dace	Cylinders	21	26	180	7	0.807	0.652	0.30	20.7	17.2	7/21/2010	Very Clear	1
Longnose dace	Cylinders	21	26	180	7.18	0.81	0.65	0.32	19.3	18.80	7/29/2010	Very Clear	1
Longnose dace	Substrate	26	30	179	7	NA	NA	0.20	19.1	16.6	6/28/2010	Murky	5
Longnose dace	Substrate	22	28	180	7	NA	NA	0.34	19.3	18.5	7/16/2010	Fairly Murky	4
Longnose dace	Substrate	22	29	180	7.18	NA	NA	0.30	19.8	19.20	7/22/2010	Fairly Murky	4
Longnose dace	Substrate	22	29	180	7.18	NA	NA	0.30	19.4	19.60	7/30/2010	Fairly Murky	4
Leatherside chub	Control	16	19	103	5	0.801	0.675	0.30	19.3	18.2	6/30/2010	Murky	5
Leatherside chub	Control	15	19	100	5	0.842	0.665	0.39	19.3	18.8	7/6/2010	Fairly Clear	3
Leatherside chub	Control	15	19	103	5	0.854	0.675	0.34	19.5	18.5	7/15/2010	Very Clear	1
Leatherside chub	Control	15	19	103	5.43	0.85	0.67	0.33	19.40	19.4	7/23/2010	Fairly Murky	4
Leatherside chub	Cylinders	19	23	99	5	0.661	0.546	0.20	19.3	17.4	6/28/2010	Murky	5
Leatherside chub	Cylinders	19	21	100	5	0.665	0.601	0.41	20.2	18.8	7/5/2010	Clear	2
Leatherside chub	Cylinders	19	22	103	5	0.675	0.583	0.34	19.2	18.3	7/15/2010	Very Clear	1
Leatherside chub	Cylinders	19	22	103	5	0.675	0.583	0.32	20.1	17.9	7/21/2010	Very Clear	1
Leatherside chub	Substrate	19	26	103	5	NA	NA	0.42	19.6	18.3	7/7/2010	Fairly Murky	4
Leatherside chub	Substrate	20	26	103	5	NA	NA	0.33	19.3	18.5	7/16/2010	Fairly Murky	4
Leatherside chub	Substrate	19	26	103	5.43	NA	NA	0.30	19.40	19.4	7/23/2010	Murky	5
Leatherside chub	Substrate	20	26	103	5.43	NA	NA	0.34	19.40	19.2	7/30/2010	Fairly Murky	4

* Not calibrated, digital readings were unpredictable. Use measured water depth to check slope consistency.

Figure A-2: Fish Testing Raw Data p.1



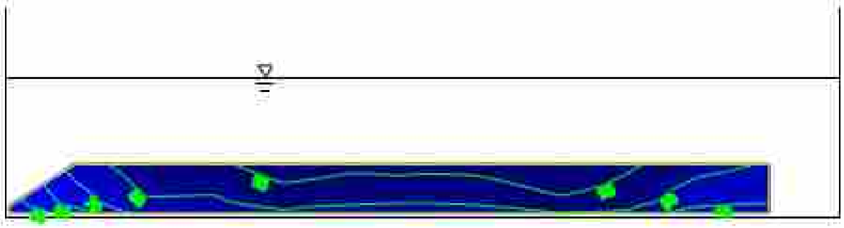
Species	Treatment	Accl. Start	Test Start	Test End	Time From Capture [hrs]	Tested	Attempted	Passed	Motivated Success	Success w/o motivation	Failed
Longnose dace	Control	10:01 AM	11:01 AM	11:32 AM	72	5	5	5	3	2	0
Longnose dace	Control	2:00 PM	3:00 PM	4:00 PM	52	5	4	3	3	0	2
Longnose dace	Control	10:00 AM	11:00 AM	12:00 PM	72	5	5	4	3	1	1
Longnose dace	Control	10:00 AM	11:00 AM	11:20 AM	72	5	5	5	3	2	0
Longnose dace	Cylinders	10:00 AM	11:00 AM	12:00 PM	96	5	5	5	2	3	0
Longnose dace	Cylinders	10:00 AM	11:00 AM	12:00 PM	48	5	4	0	0	0	5
Longnose dace	Cylinders	2:00 PM	3:00 PM	4:00 PM	52	5	5	4	4	0	1
Longnose dace	Cylinders	2:00 PM	3:00 PM	3:03 PM	76	4	4	4	3	1	0
Longnose dace	Substrate	9:58 AM	10:58 AM	11:58 AM	72	5	5	4	0	4	1
Longnose dace	Substrate	2:00 PM	3:08 PM	3:50 PM	100	5	5	5	0	5	0
Longnose dace	Substrate	2:00 PM	3:00 PM	3:35 PM	76	5	5	4	1	3	1
Longnose dace	Substrate	10:00 AM	11:00 AM	12:00 PM	96	5	5	4	3	1	1
Leatherside chub	Control	2:00 PM	3:00 PM	3:45 PM	124	5	5	4	0	4	1
Leatherside chub	Control	2:00 PM	3:00 PM	3:20 PM	100	5	5	5	1	4	0
Leatherside chub	Control	10:00 AM	11:00 AM	12:00 PM	72	5	4	4	0	4	1
Leatherside chub	Control	2:00 PM	3:00 PM	4:00 PM	100	5	5	5	1	4	0
Leatherside chub	Cylinders	2:28 PM	3:28 PM	4:08 PM	76	5	5	5	1	4	0
Leatherside chub	Cylinders	2:04 PM	3:04 PM	3:50 PM	76	5	5	5	2	3	0
Leatherside chub	Cylinders	2:00 PM	3:00 PM	3:25 PM	76	5	5	5	3	2	0
Leatherside chub	Cylinders	10:00 AM	11:00 AM	12:00 PM	48	5	4	1	1	0	4
Leatherside chub	Substrate	10:00 AM	11:00 AM	12:00 PM	120	5	5	4	0	4	1
Leatherside chub	Substrate	10:00 AM	11:00 AM	11:30 PM	96	5	5	5	0	5	0
Leatherside chub	Substrate	10:00 AM	11:00 AM	11:40 AM	96	5	5	1	0	1	4
Leatherside chub	Substrate	2:00 PM	3:00 PM	3:05 PM	76	5	5	5	0	5	0

Figure A-3: Fish Testing Raw Data p.2

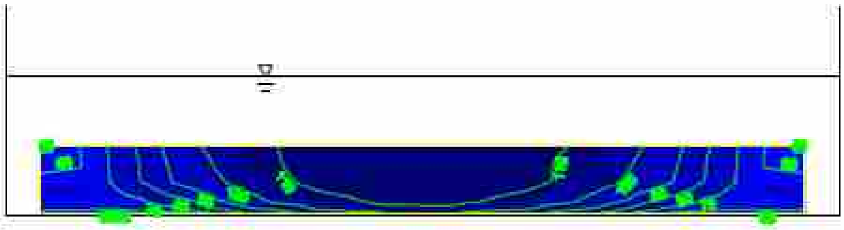
APPENDIX B. CYLINDER VELOCITY PROFILES

This section includes typical velocity profiles at key locations in the cylinder setup.

DACE CONTROL - TYPICAL



DACE CYLINDER - HIGH TURBULENCE
7cm behind downstream edge of cylinder



DACE CYLINDER - HOLDING POSITION
35cm in front of upstream edge of cylinder

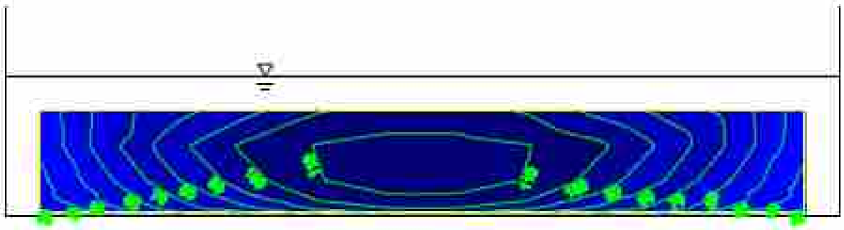
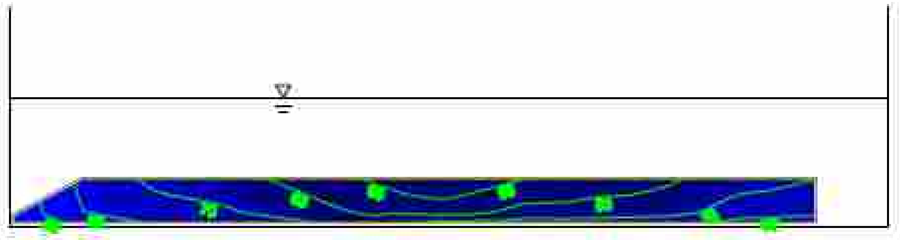
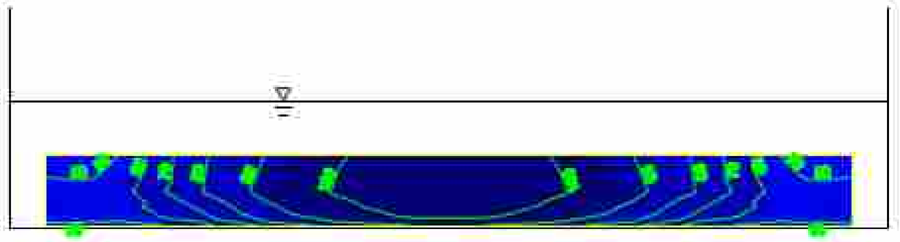


Figure B-1: Dace Velocity, Key Location Profiles for Cylinder Setup.

CHUB CONTROL - TYPICAL



CHUB CYLINDER -HIGH TURBULENCE
7cm behind downstream edge of cylinder



CHUB CYLINDER - HOLDING POSITION
35cm in front of upstream edge of cylinder

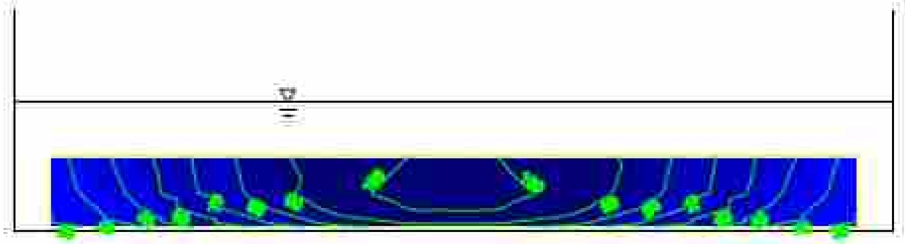


Figure B-2: Chub Velocity, Key Location Profiles for Cylinder Setup.

APPENDIX C. UNIT CONVERSION FACTORS

1 Meter (m) = 3.28 Feet (ft)

1 Centimeter (cm) = 0.394 Inches (in)

1 Cubic Meter/Second (m^3/s) = 35.31 Cubic Feet/Second (cfs)