Culvert Roughness Elements for Native Utah Fish Passage: Phase II

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Culvert Roughness Elements for Native Utah Fish Passage: Phase II

Suzanne Kim Monk

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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Native fishes have become an increasingly important concern when designing fish passable culverts. Many operational culverts constrict waterways which increase velocities and prevent upstream passage of small fish species. The current method to ensure fish passage is to match the average cross sectional velocity to the sustained swim speed of the fish. This study investigates the passage rates of leatherside chub (*Lepidomeda aliciae*) and speckled dace (*Rhinichthys osculus*) at three sites (an arch culvert with substrate bottom, box culvert with bare bottom, and a stream section with no culvert) located on Salina Creek near Salina, UT. It was found that fish were able to pass through all of the sites. However, fish were able to take advantage of the habitat within the culvert that had a substrate bottom more effectively than within the culvert that had no substrate within the barrel. This was reflected in population density estimates at each of the three test sites for each species. It was also found that the substrate at the arch culvert and stream sites scaled with the fish measured in this study. The $D_{50}$ and $D_{84}$ were 44 and 205 mm at the arch culvert site and 26 and 126 mm at the stream site. The average fish length was 76 mm for the chub and 64 mm for the dace. It is recommended that (1) a culvert size that produces a velocity equal to the prolonged swim speed of target fish in the near boundary region (2 cm above the bed) be used in the future, and (2) substrate that scales with the target fish species be placed in the culvert barrel.

Keywords: fish passage, culvert hydraulics, native Utah fishes
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1 INTRODUCTION

Culvert design standards favor small barrels for economic reasons; this may result in restriction of the stream such that the average velocity presents a flow barrier for non-salmonid fish species. Some such species are southern leatherside chub \((Lepidomeda aliciae)\) and speckled dace \((Rhinichthys osculus)\). To counteract this, when considering fish passage, average velocities are matched to sustained fish speeds (Hotchkiss and Frei, 2007). This conservative practice may result in oversized culvert barrels and more expensive and invasive projects. Fish may be able to take advantage of decreased velocities near the boundary that would enable them to expend less energy and pass upstream successfully through culverts with an average velocity that exceeds their sustained swim speed. Results from Phase I of this project showed that fish do the best in a laboratory treatment that simulates a natural environment with substrate that scales with the size of the fish \((D_{50} \text{ of the substrate is on the order of the length of the fish})\). Research in this Phase II project has been conducted to determine if this conclusion holds in the field and whether or not the results can be applied to retrofitting and designing new culverts in Utah.

1.1 Scope

Only native Utah non-salmonid fish were considered in this study. The results are for use in designing, retrofitting, and replacing of culverts managed by Utah Department of
Transportation (UDOT). Results may have implications for other regions and fish species that were not studied, but would necessitate further research.

1.2 Objectives

This study takes advantage of the conclusions made in Phase I of this project and applies them to the field in order to test fish in their natural habitat. The results from Phase I and the methods used during this study focus on the way native non-game fishes in southern Utah take advantage of reduced velocity zones near boundaries specifically within culverts. The results provide useful insight into how fish are able to pass through excessive velocity barriers in their natural environment. These results may be applied to design standards for retrofitting and design of new culverts.

1.3 Document Organization

A literature review of background information and current design practices are set forth. Following, there are sections describing the research methods, data collection, and results, written such that the study should be easily replicable. Finally, a discussion of the results, conclusions, and recommendations are made. Appendices with additional information are also included.

1.4 Literature Review

The main consideration in culvert design is hydraulic conveyance and flood capacity. Other considerations, such as allowable headwater and tailwater elevations, are also taken into account. These design factors alone usually result in a structure that is smaller than the stream channel. This contracts flow, increases in-barrel velocities, and may result in scour downstream
of the culvert. Concern for fish passage led to new culvert designs that adjusted mean design velocities to match swimming capabilities of fish (Hotchkiss and Frei, 2007). Recently, passage for other aquatic animals such as frogs and turtles has been highlighted. A culvert is defined as a barrier to passage when the capability of the species in question is exceeded (Norman et al. 2011).

Many culverts that exist today were designed without concern for animal movement. This caused fragmentation of the ecosystems and thereby fragmented populations of animals in the watershed (Trombulak and Frissell 2000). Disconnecting populations negatively affects biodiversity as smaller, disconnected populations are more prone to chance elimination (Farhig and Merriam 1985). In non-fragmented areas, after an event causes local extinction of a certain species, the area is often able to be repopulated by a nearby population that is larger and more stable (Allan and Castillo 2007). Population fragmentation must be considered when designing culverts. Culverts that allow for aquatic organism passage promote ecosystem health by allowing movement for seeking food, shelter, and mating partners, escaping predation, and moving in response to seasonal changes or natural disturbances (Jackson 2003).

Aquatic organism passage focuses primarily on fish at this time. The most common obstructions for fish at culverts are excessive water velocities, drops at inlets or outlets, physical barriers (e.g. weirs, baffles, debris), excessive turbulence, and insufficient water depth for fish to swim. Culverts should allow fish passage at a range of flow conditions, especially at times when movement is more likely such as during migratory seasons (Norman et al. 2011). However, fish likely will not move during high-flow events, so passage does not need to be ensured for storm events during which fish likely will not choose to move. Fish passable culverts should also be designed so that non-fish species will be able to pass through the culvert. Design procedures are
not commonly tailored for a specific species except when an existing culvert is rehabilitated based on a species of interest. Many conservative designs suggest matching the culvert to the surrounding stream by sizing the culvert barrel so that it does not contract the stream at all, embedding the culvert or using an open bottom culvert, and using substrate similar to the surrounding streambed. By meeting these criteria, the engineer assumes that the culvert would present no more of a challenge than the animal’s natural habitat would (Norman et al. 2011).

A common design procedure to ensure specific species fish passage is to match the average cross-sectional velocity to the prolonged swim speed of the fish (Powers 1997). Average velocity is recognized as a conservative parameter, but since little is known about how fish use reduced velocity zones within a culvert, it is a safe and conservative predictor (Lang et al. 2004).

In order to more effectively design for fish passage, some basic fish biology should be known. Fish have two muscle systems for different swimming methods. The red muscle system is used when aerobic respiration is appropriate (during low-stress activities) and the white muscle system is used when anaerobic respiration is appropriate (during periods of high-intensity activities). For this reason, the white muscle system may only be used for a short time before the fish becomes fatigued (Behlke 1991). Fish have three movement types in combinations of these muscle systems: sustained, prolonged, and burst. Sustained movement is an aerobic exercise so it can be maintained for very long periods of times. Prolonged movement uses both red and white muscle systems, so it can be maintained for a maximum of 200 minutes. Burst movement uses only the white muscle system and can be maintained for only seconds. After reaching exhaustion by any of these types of movement, the fish requires a period of rest before continuing. Because of this, fish can fail to pass through a culvert for many reasons such as excessive length, high velocities, or the presence of an outlet drop (Kilgore et al. 2010).
Considerations must also be made for a range of species and life stages of fish. Although some culverts may be passed by stronger, mature fish, the same culvert may not allow smaller or younger fish to pass (Norman et al. 2011). In some areas it is prudent to design for the “least species” of the area, or the weakest swimmer. By ensuring that the weakest swimmer is able to pass upstream, all other fish should also be able to pass upstream.

A distinction should also be made between groups of fish that have different methods of swimming. Many fish are classified as benthic fish, or those that regularly dwell at the bottom of a stream or lake. These fish generally have down-turned mouths to facilitate feeding, flat stomachs, and observations show that they are well-equipped to take advantage of boundary layers (Esplin and Hotchkiss 2011). Some other fish are classified as mid-column swimmers, or those that regularly dwell within the water column. These fish are generally found in pools and deeper, slow-water sections of streams (Wilson and Belk 2001). Differences in dispersal, or how far a fish will normally move, are also important distinctions to be made since some fish will not choose to move through culverts, even if they are physically capable of passage.

In Phase I of this study, native Utah fishes were tested in a laboratory facility using three scenarios: a bare Plexiglas flume, a bare flume with strategically-placed cylinders, and a natural substrate treatment. Fish were found to perform the best and most naturally in the substrate treatment tests and energetic calculations showed that fish expended the least amount of energy in the substrate treatment. These results and observations led to the conclusion that fish are able to pass upstream most easily in a substrate treatment and that the treatment should roughly scale with the size of the fish (Esplin and Hotchkiss 2011).
2 RESEARCH METHODS

2.1 Purpose

The goal of designing for fish passage is to create a system that allows for fish movement throughout the system, not necessarily to simply promote the movement of fish. Fish are more likely to move from habitats of a lower quality to search for better habitat (Belanger and Rodriguez, 2002). The objective of this study is to test the hypothesis that fish are able to move more easily through culverts with natural substrate in the bottom than through bare culverts. This hypothesis is based on Phase I results. We believe that the species of fish used in this experiment are representative of species of similar functional groups and that the tests may be applicable to culverts throughout Utah.

2.2 Experimental Design

This study is based on tests completed during Phase I that show that fish are most easily able to traverse a flume in a treatment where natural substrate on the order of the size of the fish is placed. This allows the fish to be able to move in a natural manner. We decided that culverts would be chosen with three different substrate “treatments:” one was completely filled with natural substrate, one had no substrate, and the third was a natural section of the stream with no culvert.
2.3 Experimental Setup

All test sites were located within a 1 kilometer stretch of Salina Creek. Sites were chosen along Salina Creek because of the availability of appropriate, non-perched culverts and adequate populations of native Utah fishes.

The creek is part of the Sevier River drainage located in Fish Lake State Park in Southern Utah. The most upstream site (the arch culvert) is located at 38°54.898’N 111°44.038’W; the middle site (the stream section) is located at 38°54.901’N 111°44.204’W; and the downstream site (the box culvert) is located at 38°54.893’N 111°44.337’W. The relative locations of each site are shown in Figure 2-1 below. The elevation is approximately 1755 meters (5758 feet).

![Figure 2-1: Map of Salina Creek with Test Sites](image)

The stream segment tested has a variety of pools and riffles with depths from 0.25 to 1.5 m. The depth is approximately 0.48 m (ranging from 0.08 to 0.53 m) in the arch culvert and 0.24 m (ranging from 0.16 to 0.30 m) in the box culvert. The overall gradient is approximately 1.67 percent.
2.3.1 Fishes

Salina Creek has four main fish species: speckled dace (*Rhinichthys osculus*), mountain sucker (*Catostomus platyrhanchus*), mottled sculpin (*Cottus bairdi*) and southern leatherside chub (*Lepidomeda aliciae*). Only speckled dace and southern leatherside chub were included in the study because there were high densities of only chub and dace species in the area and they are representative of their respective functional groups. Of the four species found, only the leatherside chub is a mid-column swimmer; the other three species are all benthic swimmers.

2.3.2 Culvert and Stream Description

The upstream culvert is a bottomless corrugated metal arch culvert that spans the entire stream. It is 21.45 m long and 7 m wide with cobble-sized substrate on the bottom. An upstream view of the culvert is shown in Figure 2-2.

![Figure 2-2: View from Upstream of the Culvert (Taken 27 May 2011)](image-url)
The stream section is located between the two culverts and is of similar length to the two culverts (21 m). It has fairly uniform substrate and depth. An upstream view of the site is shown in Figure 2-3.

![Figure 2-3: View of the Stream Site from Upstream (Taken 26 July 2011)](image)

The downstream culvert is a double barreled concrete box with a span of 6.40 m and rise of 3.19 m. The culvert is 19.1 m long and was completely clear of substrate for the entire length. There were some woody debris caught on the upstream side of the culvert during the time of this study. An upstream view of the culvert is shown in Figure 2-4.

Tests were performed in August rather than mid-summer due to a late spring runoff peak; flows were still returning to base flows during the testing period. Despite this, fish were still able to move throughout the area and testing had to be completed before the fall when the fish would no longer be moving.
2.3.3 Velocity Characterization

A pygmy meter was used to measure velocities near the stream bed or culvert bottom at each site. The pygmy meter was useful for simplifying the data collection procedure. Measurements were taken at the depth above the substrate that corresponds to benthic species swimming position. Using an acoustic Doppler velocimeter (ADV) to take measurements was considered, but the idea was discarded since only the x-velocity measurement was needed and using the Pygmy meter was more suited to fieldwork.
3 DATA COLLECTION

3.1 Mark and Recapture

We used a short-term mark-recapture study to assess fish passage through each test site. Fish were marked on 26 July 2011 and the recapture event was 15-16 August 2011. At each test site, we captured approximately 60 southern leatherside chub and 60 speckled dace in 50 m reaches both downstream and upstream (total of 120 fish per species per test site) using a back-pack electroshocker. We divided the fish into four groups that represented the possible combinations of capture and release locations. Half of the fish from each capture location were released at the capture location (e.g. captured and released downstream of a test site), while the other half were released at the opposite capture location (e.g. captured downstream and released upstream). We released half of the fish in the opposite location of capture to act as a motivator or stimulant to encourage movement. Each group at each test site was uniquely batch marked using a one of four colors of visible elastomer tags (Northwest Marine Technology, Inc.; Shaw Island, Washington) at one of three locations on the fish (dorsal insertion of caudal fin, ventral insertion of caudal fin, and posterior insertion of anal fin). We measured the standard length (SL) of each fish to the nearest mm. Fish less than 40 mm SL represented young of year fish and could not be captured efficiently (Rasmussen and Belk 2011); therefore, we did not include these fish in the study. Southern leatherside chub were 40-119 mm SL, and did not significantly vary in size
across test sites. Speckled dace were 40 – 80 mm SL, and were significantly larger at the box culvert. Fish were released approximately 10 m downstream or upstream of the test site.

For the recapture event, we completed two-pass depletions of 10-m stream segments by electroshocking. We started 250 m downstream of the box culvert, and completed the depletion effort in 88 segments, or 880 m of stream, ending 120 m upstream of the arch culvert. Included in these 88 segments were two 10-m segments within each of the test sites which were used to estimate the density of fish utilizing the test sites as habitat. For each 10-m segment, we recorded the total number of fish of each species captured for each pass, as well as the SL and batch mark for each recaptured fish.

3.2 Flow Measurements

Flow was calculated by measuring velocity using a pygmy meter at a specific cross-section on the downstream end of the arch culvert at the conclusion of each field event: marking, recapture, and velocity testing. Measurements were taken approximately every foot (0.3 m) from bank to bank using 30-second interval.

3.3 Pebble Count

A pebble count was completed at each test site after the recapture event. Samples were taken systematically at even-spaced marks along a measuring tape that was stretched between banks across each site. The tape made a zig-zag pattern across the area as shown in Figure 3-1. Particles were selected approximately 1 ft (0.3 m) apart. A yardstick was inserted at each point straight down from the tape and whatever the stick was touching was then measured, excepting biological material. Samples were measured with a gravelometer (pictured below). Larger samples were measured with the yardstick in millimeters and smaller particles were classified as
sand. A pebble count was not performed for the box culvert site since it was completely bare except for some sand that had deposited behind the debris dam.

Figure 3-1: Pebble Count Setup in the Stream Test Site (Taken 15 October 2011)

3.4 Velocity Measurements

Near-boundary velocities were measured with a pygmy meter across the entire area of each test site. The pygmy meter was kept as near to the boundary as possible (approximately 2 cm above; Figure 3-2).

Due to the large area being measured and the need to complete measurements within one day so flows did not vary too much, measurements were across the entire area of each site. At the two culvert sites, measurements were taken in a 1-m by 1-m grid pattern. At the stream site, measurements started as close as possible to the right bank while maintaining adequate depth to get a reading and then continued with 1 meter between each measurement. The last point was taken as close as possible to the left bank. The cross sections at the stream were spaced 1 m
apart. Just as with the velocity measurements taken to calculate flow, all point velocity measurements were taken over 30 second time intervals.

Figure 3-2: Pygmy Meter in Position Used for Taking Velocity Measurements
4 RESULTS

4.1 Fish Data

We recaptured 139 of the 349 marked southern leatherside chub and 72 of the 363 marked speckled dace. During the 3-wk study, the majority of the recaptured fish had not moved more than 100 m upstream or downstream. However, five southern leatherside chub had moved 130 – 420 m downstream, one southern leatherside chub moved 130 m upstream, and one speckled dace moved 150 m downstream. All of these far-moving fish passed through at least one of the test sites. Recaptured southern leatherside chub were significantly larger in the box culvert than in the arch culvert, but recaptured fish from the stream site were not significantly different in length compared to the culvert sites. Recaptured speckled dace were significantly larger from the box culvert than from the other two test sites, consistent with patterns observed in the marking event (Table 4-1).

Table 4-1: Mark and Recapture Data for All Sites in Salina Creek, UT. Standard Length Measured in mm

<table>
<thead>
<tr>
<th>Species</th>
<th>Location</th>
<th>Number Marked</th>
<th>Mean Length (SE)*</th>
<th>Number Recaptured</th>
<th>Mean Length (SE)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leatherside chub</td>
<td>Arch</td>
<td>109</td>
<td>71.4 (1.48)a</td>
<td>36</td>
<td>75.2 (2.45)a</td>
</tr>
<tr>
<td></td>
<td>Stream</td>
<td>121</td>
<td>71.6 (1.39)a</td>
<td>66</td>
<td>78.0 (1.83)ab</td>
</tr>
<tr>
<td></td>
<td>Box</td>
<td>119</td>
<td>75.6 (1.40)a</td>
<td>37</td>
<td>84.8 (2.61)b</td>
</tr>
<tr>
<td>Speckled dace</td>
<td>Arch</td>
<td>121</td>
<td>60.4 (0.79)a</td>
<td>19</td>
<td>63.1 (1.69)a</td>
</tr>
<tr>
<td></td>
<td>Stream</td>
<td>120</td>
<td>61.4 (0.80)a</td>
<td>30</td>
<td>63.8 (1.45)a</td>
</tr>
<tr>
<td></td>
<td>Box</td>
<td>122</td>
<td>67.3 (0.79)b</td>
<td>23</td>
<td>70.2 (2.09)b</td>
</tr>
</tbody>
</table>

*Significant differences between means within a column for each species are noted with different letters.
The superscripts on values within the mean length columns indicate differences and similarities within a species and capture event. For example the length of chub did not differ significantly from each other when they were marked. However, when they were recaptured there were differences: although the lengths of fish from the arch and stream sites do not differ (indicated by the letter a) and the lengths of fish from the stream and box sites do not differ (indicated by the letter b) the lengths of fish from the arch and box site do differ significantly (indicated by the mismatched letters).

The best fit logistic regression model for the comparison of fish passage was the reduced model with no interactions (i.e. three fixed effects and covariate). The probability (not ability) of fish passage was significantly different among groups, but did not vary significantly by test site, species, or length (Table 4-2). Groups that included fish that were released at the opposite location of capture were much more likely to pass through a culvert than fish released where they were captured regardless of the direction of passage (Figure 4-1 and Figure 4-2). Group 1 includes fish captured downstream and released downstream. Group 2 includes fish captured downstream and released upstream. Group 3 includes fish captured upstream and released downstream. Group 4 includes fish captured upstream and released upstream.

Table 4-2: Probability of Passage Based on Different Effects

<table>
<thead>
<tr>
<th>Effect</th>
<th>DF</th>
<th>Wald Chi-Square</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Site</td>
<td>2</td>
<td>0.1446</td>
<td>0.930</td>
</tr>
<tr>
<td>Group</td>
<td>3</td>
<td>52.8861</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Species</td>
<td>1</td>
<td>0.0586</td>
<td>0.809</td>
</tr>
<tr>
<td>Length</td>
<td>1</td>
<td>0.0189</td>
<td>0.891</td>
</tr>
</tbody>
</table>
The purpose of dividing the groups in this way was to separate the variables of upstream versus downstream passage and volitional versus motivated passage. These results show that
although fish do not usually choose to move through the culverts, they are able to when given adequate motivation. They were statistically more likely to move downstream without motivation and upstream with motivation.

The density of southern leatherside chub within the test sites did not differ significantly among test sites (Figure 4-3) but were significantly greater in the representative pool habitat than in the three test sites. The pool habitat was a length of stream selected after recapture based on observations of habitat throughout the shocked length of stream. Although recapture did occur at this site, no marking occurred. It was located upstream of the arch culvert and should not be confused with the stream site where marking did occur. Speckled dace had the lowest density in the box culvert, intermediate density in the arch culvert, and the highest densities in the riffle test site and representative pool habitat (Figure 4-3).

![Figure 4-3: Population Densities for Each Species at Each Site](image-url)
4.2 **Statistical Analysis**

We used a logistic regression model (Proc LOGISTIC; SAS Institute Inc. 2008) to compare the probability of passage of the two species through the test sites. The response variable was binomial indicating passage or no passage; we considered a fish to successfully pass through the test site if it moved completely through the test site, either upstream or downstream. The model included three fixed effects: species, test site, and group. We ran the full model (all possible interactions of the fixed effects) and reduced models, and used model selection techniques (AIC) to determine the best fit model (Burnham and Anderson 2004; Johnson and Omland 2004). Length (SL) was used as a covariate in the full and reduced models.

To estimate the extent to which fish utilized each test site for habitat, we estimated the density of each species in each test site using the Zippin method (Hayes et al. 2007):

\[
\hat{N} = \frac{n_2^2}{n_1 - n_2} \tag{4-1}
\]

where

\( \hat{N} \) = estimated density

\( n_1 \) = number of fish removed on the first pass

\( n_2 \) = number of fish removed on the second pass

Populations were then normalized by the area of each site in order to facilitate comparison between these data and other studies.

We combined data for the first and second pass from both 10-m sections within each test site. The 95% confidence intervals (CI) were estimated using the following equation (Hayes et al. 2007):

\[
CI = \hat{N} \pm 1.96 \times SE \tag{4-2}
\]
where
\[ SE = \frac{n_1n_2\sqrt{n_1+n_2}}{(n_1-n_2)^2}. \] (4-3)

We also estimated the density of each species from two representative pool segments (50 – 70 m upstream of arch culvert and outside of the stream test site) because southern leatherside chub prefer pool habitat (Wilson and Belk 2001) and the test sites represent fast-water habitats. We assumed that densities among test sites were significantly different if the 95% ranges for CI did not overlap.

4.3 Velocity Characterization

Flow measurements were compared to USGS measurements that were taken upstream at site 10205030 on Salina Creek near Emery, Utah (U.S. Geological Survey 2012). The comparisons as well as all of the USGS measurements for the time period of study are shown in Figure 4-4.

The difference in the measured values and the USGS values is probably due to the increase in drainage area between the two measurement sites. There is a significant increase in the drainage area between the site where USGS measurements were recorded and the study site. It should also be noted that this is a flashy area and there can be a large discrepancy between average daily flow measurements and instantaneous flow measurements.

The USGS data also show the late spring peak that delayed testing until August and the wide range of flows in the channel during the testing period.
Small-scale velocity characterization was performed by taking point measurements at each site using the pygmy meter. The resulting velocity maps (Figure 4-5 through Figure 4-7) are shown below for each site. Flow is from right to left and velocity contours are shown in cm/s.

Figure 4-4: Measured Flows and USGS Measured Discharges

Figure 4-5: Velocity Contour Map at Arch Culvert Site 2 cm Above the Streambed; Flow is From Right to Left and Mean Velocity is 34.4 cm/s
Velocities are uniformly higher in the box culvert, the overall variation is greater at the other two sites, and the velocity distributions at the stream and arch culvert sites are similar.

4.4 Substrate Classification

Using the data collected from the pebble counts, particle size distributions were created and representative diameters were determined. The particle size distributions and summary table are shown below (Figure 4-8 and Table 4-3).
Table 4-3: Representative Diameters of Substrate from Each Site

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Arch Culvert</th>
<th>Stream Site</th>
<th>Difference (arch - stream)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{16}</td>
<td>11</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>D_{50}</td>
<td>44</td>
<td>26</td>
<td>18</td>
</tr>
<tr>
<td>D_{84}</td>
<td>205</td>
<td>126</td>
<td>79</td>
</tr>
</tbody>
</table>

The distributions are similar in shape, but the substrate measured at the arch culvert is larger. The range of sizes is very similar, but a higher percentage of cobble-sized (larger than 64 mm) particles were found at the arch culvert.

4.5 Temporal Passage Probability

Average flows for each month at the test sites were calculated using average flows at the USGS gaging station upstream on Salina Creek and scaling techniques. Scaling was performed based on the drainage area (51.8 mi\(^2\) at the USGS site and 209 mi\(^2\) at the test sites) and an exponent calibrated using measured flow data presented Figure 4-4.
Table 4-4: Average Daily Flow by Month

<table>
<thead>
<tr>
<th>平均日流量 (cfs)</th>
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<tbody>
<tr>
<td>January</td>
<td>10.0</td>
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<tr>
<td>February</td>
<td>9.7</td>
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<tr>
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<tr>
<td>October</td>
<td>15.5</td>
</tr>
<tr>
<td>November</td>
<td>13.1</td>
</tr>
<tr>
<td>December</td>
<td>11.0</td>
</tr>
</tbody>
</table>

In order to connect results regarding near-boundary velocities and passage rates, calculations were made to determine the critical flow for fish passage. The critical flow here is defined as being the flow where the velocity 2 cm above the boundary is equal to the prolonged swim speed of the fish. These flows were compared with average monthly flows on Salina Creek to determine during which months each site would become a barrier to fish movement. Flows that will initialize sediment movement are also included for comparison with critical flows for fish passage. These values are shown in Table 4-5.

Flows were calculated using Manning’s equation with a measured slope of 0.068% and Manning’s n values that were either calculated or assumed based on the substrate type. An n value of 0.0289 was calculated at the arch culvert and the n value at the stream site was assumed to be the same. An n value of 0.014 was assumed for the concrete box culvert (Chow 1959). The flow at which bedload movement would begin was determined using Shield’s method of allowable shear stress (Shields 1936).
The prolonged speed of each fish was used as the parameter to determine critical flow. The prolonged velocity of the leatherside chub is 1.77 ft/s (54 cm/s) and 2.26 ft/s (69 cm/s) for the speckled dace (Aedo 2008). A critical flow for fish passage was not calculated for the dace at the arch culvert and stream sites. This is because the flow necessary to limit fish passage at these sites is greater than a 500 year flood. The frequency of the floods necessary to begin movement at the stream and box culvert sites are greater than 500 years and less than two years, respectively. The critical flow to move substrate within the arch culvert is greater than the maximum capacity of the culvert, so it was not included in the table.

<table>
<thead>
<tr>
<th></th>
<th>Fish Critical Flow (cfs)</th>
<th>Barrier (% of year)</th>
<th>Bedload Flow (cfs)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>chub</td>
<td>dace</td>
<td>chub</td>
</tr>
<tr>
<td>Arch Culvert</td>
<td>276</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>Stream Site</td>
<td>271</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>Box Culvert</td>
<td>25</td>
<td>51</td>
<td>25%</td>
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</table>

The flow at the box culvert exceeds the critical flow for chub between June and August and for dace during June and July. Additionally, it is likely that the bed will be mobilized before fish passage is inhibited so great care must be taken in ensuring that substrate remains within the barrel of the culvert. Appendix D presents maps comparing the areas within each site where the near-boundary velocities at critical flow or a fish passable design flow (where the average velocity is equal to the fishes’ prolonged speed).

4.6 Data Evaluation and Discussion

Field passage rates verify results of laboratory work performed in Phase I. In Phase II, fish were able to pass through all types of obstacles, some of which, by traditional fish passage
design standards, should have rendered the condition impassable. The passage success also shows that fish are physically able to move through these obstacles, but that they may not choose to, as shown through the comparison of motivated passage and unmotivated passage. The groups that were switched had much higher probability of passage than the fish that were not switched. This shows that fish are unwilling to move from their current habitats when they are acceptable and fish movement is limited to times of need. However, there were some reasons other measurements and calculations were necessary to complete this research. At the time of testing, average velocities at the sites were not great enough to prevent passage because they were not greater than the prolonged swim speeds of the fish in question. It is useful to note that the sites tested in this study are relatively short, and passage differences may be more pronounced in longer culverts. However, fish were found upstream and downstream of each site which shows that they were able to pass through each of the three sites.

Population density estimates, velocity contour maps, and critical flows were used as additional indicators of whether fish would be able to pass through the sites. Population density estimates showed that the arch culvert had more desirable habitat than the concrete box. The difference between the two culvert estimates is attributed to the presence of substrate. Chub population densities were elevated at the box culvert due only to the presence of the debris dam. However, fast water habitats, like both culverts and the stream site, are not optimal environments for chub because they are mid-column swimmers and do better in slow water habitats like pools, as evidenced in the pool section part of Figure 4-3. Differences in population densities at different sites are more easily seen when observing dace data rather than chub data.

Velocity contour maps showed the range of velocities as well as the amount of variation at each site near the substrate. The velocity heterogeneity seen at the arch culvert site was similar
to that seen at the stream site which implies that fish will be able to behave within the arch culvert just as they do within the natural stream segment. However, velocity patterns were more one dimensional in the box culvert and consistently higher except near the entrance downstream from the debris dam. Velocities in this wake region were almost zero.

Critical flows are useful in comparing average flows and velocities to the fishes’ prolonged swim speeds. Instead of using the average velocity as the design parameter that is matched to the fishes’ prolonged swimming speed, the near-boundary velocity, where the fish will be swimming, is matched to the prolonged swimming speed. This would result in smaller barrels that would still allow fish to swim upstream. When testing this parameter, it was found that the arch culvert is not a barrier to either species of fish and the box culvert is only a barrier to chub 25% of the year (three months) and to dace 17% of the year (two months). This is encouraging and, again, supports findings from Phase I that suggest that placing substrate allow fish to swim upstream through culverts where the mean velocity exceeds prolonged fish swim speeds.

Phase I concluded that substrate that scales with the size of the fish would provide adequate velocity heterogeneity for successful fish passage. A comparison of representative substrate diameters and average fish length is shown below in Table 4-6.

<table>
<thead>
<tr>
<th>Table 4-6: Comparison of $D_{50}$, $D_{84}$, and Fish Length</th>
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<tbody>
<tr>
<td>Marking</td>
</tr>
<tr>
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</tr>
<tr>
<td>Arch Culvert Site $D_{50}$ (mm)</td>
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<tr>
<td>Arch Culvert Site $D_{84}$ (mm)</td>
</tr>
<tr>
<td>Stream Site $D_{50}$ (mm)</td>
</tr>
<tr>
<td>Stream Site $D_{84}$ (mm)</td>
</tr>
<tr>
<td>Chub Length (mm)</td>
</tr>
<tr>
<td>Dace Length (mm)</td>
</tr>
</tbody>
</table>
The average substrate size at the stream site is between approximately 35 and 40% of the average fish length and the average substrate size at the arch culvert is between 58 and 70% of the average fish length. This shows that the substrate sizes and fish lengths are of the same order of magnitude. The D_{84} and D_{50} bound the range of lengths of the fish measured during marking and recapture events. The D_{84} may be a better measure than the D_{50} because it is only found sporadically throughout the streambed and would provide specific sites for fish to rest.

The variation in velocity provided by the substrate within the arch culvert and at the stream site aided in fish passage. The variation caused by the substrate enabled fish to find more easily navigable paths through the culvert than they would have been able to otherwise.
5 CONCLUSIONS

5.1 Conclusions

The findings of this research verified the conclusions made during Phase I. Fish were found to pass through culverts where the average velocity exceeded their prolonged swimming speeds and substrate that scaled with the size of the fish allowed fish to pass upstream more easily than through bare culverts. This may be due to the additional habitat that substrate within the culvert provides and by providing better habitat for fish within culverts, fish should be able to pass through culverts more easily.

A comparison of fish length and substrate diameter also support conclusions from Phase I. The average standard lengths of both chub and dace and the average particle diameter at the arch culvert and stream sites showed that they are of the same order of magnitude. The $D_{50}$ and $D_{84}$ of both the stream and arch culvert sites bound the range of fish lengths measured during testing. This scaling factor is recommended for native Utah fishes. Larger fishes in Utah, should be able to pass any culvert made passable for the smaller native species.

Critical flows should be used as a design parameter in future culvert design. It would allow culverts to be more economical while still ensuring fish passage. This parameter will be a good substitute for the current standard of matching the average flow velocity to prolonged swim speed since that is already recognized as being conservative.
It is important to note that the two species of fish that were tested belong to different functional groups. Dace are benthic swimmers and generally perform better in fast-water segments like those usually found in culverts or riffles. It may be necessary to design for fish that are least equipped to swim near the boundary when designing for fish passage in order to ensure fish passage for many species and functional groups.

These results may be applied to current culvert design practices to more easily provide for fish passage. More information may be necessary on the amount of variation that is necessary for the substrate and the relationship between fish length and the size of the substrate. However, this finding should simplify culvert design processes when fish passage is necessary for native Utah fishes. Simply filling the culvert with substrate similar to that in the near stream reaches could result in smaller and less expensive culverts.

5.2 **Limitations of Conclusions**

These conclusions should only be applied to watersheds with small native fishes that belong to the same functional groups as the ones tested. The general findings should be widely applicable, but more research would be necessary to verify the findings in other areas and with other functional groups.
6 RECOMMENDATIONS

Current federal fish passage design standards for culverts often require placed substrate significantly larger than what is found in the adjacent stream reaches to ensure stability during the design discharge (Kilgore et al. 2010). While this study shows that substrate that scales with fish length improves fish passage, the impact of using substrate consistently larger than fish length is unknown.

The role of turbulence generated by placed substrate is unknown. Field-collected acoustic Doppler velocimetry data may reveal the impact of turbulence on fish passage. Turbulence measurements from the field where fish are tested should provide insight into the gradation of substrate necessary to minimize the barrier to fish as they pass upstream and perhaps even provide areas that the fish may use as habitat. Some turbulence measurements completed using Phase I data are presented in Appendix C.

It may be useful to move towards a probabilistic approach to fish passage in future research. This would enable engineers and biologists to determine the probability that fish may be able to pass through a culvert at many different times of the year. A necessary minimum probability of passage would need to be established for culvert design. This approach would allow engineers to more easily confer with biologists when designing culverts after having made calculations similar to those in this study, and biologists would be able to determine whether or not times when the culvert is passable or impassable are critical.
REFERENCES


APPENDIX A.  FISH MARKING DATA

This section includes a spreadsheet of data recorded at the fish marking event. Mountain suckers were marked but not included in the final report due to insufficient numbers.
Table A-1: Marking Data at Arch Culvert Site

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<th>Date: 8/26/2011</th>
<th>Date: 8/26/2011</th>
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</thead>
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<td><strong>Site:</strong> Arch</td>
<td><strong>Site:</strong> Arch</td>
<td><strong>Site:</strong> Arch</td>
</tr>
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<td><strong>Upstream</strong></td>
<td><strong>Upstream</strong></td>
<td><strong>Downstream</strong></td>
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<tr>
<td><strong>Released:</strong> Upstream</td>
<td><strong>Released:</strong> Downstream</td>
<td><strong>Released:</strong> Upstream</td>
<td><strong>Released:</strong> Downstream</td>
</tr>
<tr>
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<td><strong>Color:</strong> Green</td>
<td><strong>Color:</strong> Pink</td>
<td><strong>Color:</strong> Green</td>
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<tr>
<td><strong>Position:</strong> Dorsal caudal fin</td>
<td><strong>Position:</strong> Anal fin</td>
<td><strong>Position:</strong> Ventral caudal fin</td>
<td><strong>Position:</strong> Ventral caudal fin</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Chub</strong></th>
<th><strong>Dace</strong></th>
<th><strong>Sucker</strong></th>
<th><strong>Chub</strong></th>
<th><strong>Dace</strong></th>
<th><strong>Sucker</strong></th>
<th><strong>Chub</strong></th>
<th><strong>Dace</strong></th>
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APPENDIX B. FISH RECAPTURE DATA

This section includes a spreadsheet of data recorded during the recapture event.
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APPENDIX C. PHASE I TURBULENCE

The role of turbulence in determining good habitat for fishes has recently begun to be investigated. Habitat selection is correlated with turbulence; given similar velocity ranges, fish tend to choose areas with less turbulence (Shaf et al. 1983). Swimming ability is either unaffected or negatively affected by turbulence, depending on the orientation and size of the turbulence. Eddies that are similar in size to the length of the fish turns the fish so that it cannot orient itself but smaller eddies seem to have no effect. Similarly eddies in the horizontal plane have less of an effect on fish since they can move more easily in that direction in reaction to the eddies. Eddies in the vertical plane cause more difficulty since fish cannot flex in that direction (Pavlov et al. 2000). Fish likely choose positions based on downstream velocity, turbulence, and eddy size and orientation, preferring low velocities and turbulence, and small, horizontally-oriented eddies (Smith et al. 2005).

C.1 Turbulence Characterization

In order to investigate the turbulence that fish were experiencing, velocity measurements collected using an ADV (SonTek 16-MHz Micro Acoustic Doppler Velocimeter) from Phase I of this research were used. Turbulent kinetic energy and turbulence intensity were calculated across a representative area of substrate in the flume and compared to velocities at the same areas.
C.2 Turbulence Measurements

Velocity measurements were taken using an ADV in a laboratory flume with placed substrate in a 10-cm by 10-cm grid over an area of 1.2 m by 3.6 m. Measurements were taken 1 and 5 cm above the substrate boundary at two flows with cross sectional-based average velocities of 0.75 and 0.9 m/s. Data were then filtered using an average correlation of 30% and sound to noise ratio (SNR) values of 5 dB. The resulting data were then used to calculate turbulent kinetic energy and turbulence intensity.

C.3 Turbulence Calculations

Turbulence calculations using the flume data from Phase I were performed using the following equations (Reynolds 1974).

\[ TKE = \frac{1}{2}(u'^2 + v'^2 + w'^2) \]  
\[ u' = u - \bar{u} \]  
\[ TI = \sqrt{u'^2 + v'^2 + w'^2} \]

where

- \( TKE \) = turbulent kinetic energy
- \( u', v', w' \) = fluctuating velocity in x, y, and z
- \( u \) = instantaneous velocity
- \( \bar{u} \) = time averaged velocity
- \( TI \) = turbulence intensity

The TKE is the average of its fluctuations over the time of measurement. This measurement is associated with eddies in turbulent flow. TI is the root mean square of the fluctuating velocity. Both of these parameters are related to changes from the mean velocity at a point.
The following are velocity contour maps 1 and 5 cm above the substrate in the flume measured when the cross sectional average velocity were 0.9 m/s and 0.75 m/s (Figures C-1 through C-4). The map is shown in plan view with flow from right to left. Contours are in 10 cm/s increments.

Figure C-1: Velocity Contour Map 1 cm Above the Bed at 0.75 m/s; Flow is From Right to Left; Units are cm/s

Figure C-2: Velocity Contour Map 5 cm Above the Bed at 0.75 m/s; Flow is From Right to Left; Units are cm/s
Figure C-3: Velocity Contour Map 1 cm Above the Bed at 0.9 m/s; Flow is From Right to Left; Units are cm/s

Figure C-4: Velocity Contour Map 5 cm Above the Bed at 0.9 m/s; Flow is From Right to Left; Units are cm/s

Velocity magnitude (x, y, and z) were used in creating these velocity maps. The velocities ranged from 5 to 215 cm/s. The measurements taken 1 cm above the bed had a wider range of velocity measurements, but also included some of the lowest measured velocities.

The following figures are contour maps showing the turbulent kinetic energy 1 and 5 cm above the substrate at both velocities (Figures C-5 through C-8). Again, the map is shown in plan view with flow from right to left. Contours are in 250 cm²/s².
Figure C-5: Turbulent Kinetic Energy Contour Map 1 cm Above the Bed at 0.75 m/s; Flow is From Right to Left; Units are cm²/s²

Figure C-6: Turbulent Kinetic Energy Contour Map 5 cm Above the Bed at 0.75 m/s; Flow is From Right to Left; Units are cm²/s²

Figure C-7: Turbulent Kinetic Energy Contour Map 1 cm Above the Bed at 0.9 m/s; Flow is From Right to Left; Units are cm²/s²
Figure C-8: Turbulent Kinetic Energy Contour Map 5 cm Above the Bed at 0.9 m/s; Flow is From Right to Left; Units are cm²/s²

The turbulent kinetic energy ranged from 14 to 14,950 cm²/s². Due to the wide range of values and uniform contours and coloring among the four plots, the maps created for measurements taken 5 cm above the bed look to be fairly uniform. The highest values were found at points where the velocity changed abruptly between that and the points immediately surrounding it. Many of these points with very high values correspond to high velocities and others do not. Overall the turbulence intensity is much lower 5 cm above the bed than 1 cm above the bed.

The following figures are contour maps showing the turbulence intensity 1 and 5 cm above the substrate at both velocities (Figures C-9 through C-12). Again, the map is shown in plan view with flow from right to left. Contours are in 10 cm/s.

Similar to the turbulent kinetic energy maps, the maps created for measurements 5 cm above the bed look to be fairly uniform. The maps created to represent 1 cm above the bed have both the highest and the lowest calculated values. Again, turbulence intensity is dependent upon the fluctuation in velocity rather than the absolute velocity so the areas of high turbulence intensity do not always correspond to areas of high velocity.
Figure C-9: Turbulence Intensity Contour Map 1 cm Above the Bed at 0.75 m/s; Flow is From Right to Left; Units are cm/s

Figure C-10: Turbulence Intensity Contour Map 5 cm Above the Bed at 0.75 m/s; Flow is From Right to Left; Units are cm/s

Figure C-11: Turbulence Intensity Contour Map 1 cm Above the Bed at 0.9 m/s; Flow is From Right to Left; Units are cm/s
Turbulence variation plays a part in the fishes’ choices when passing through the area. Although the turbulence measurements presented here do not represent the exact turbulence from the test sites, there still should have been similar patterns in turbulence and similar amounts of variation at the two sites with substrate. The variation enables fish to choose a path of least resistance, minimizing the resistance that they encounter in the form of high velocities and turbulence or eddy size and orientation.
APPENDIX D. CRITICAL FLOW VELOCITY MAPS

The following are contour maps showing the velocity 2 cm above the bed. Areas shown in red represent areas where the velocity exceeds the prolonged speed of the fish. Flow is from right to left in plan view and velocity contours are labeled in cm/s. All measurements were calculated based on actual field measurements.

Figures D-1, D-3, D-5, D-7, D-9, and D-11 are velocities based on a flow where the average velocity is equal to the prolonged speed of the fish. Figures D-2, D-4, D-6, D-8, D-10, and D-12 are velocities where the near-boundary velocity is equal to the prolonged speed of the fish. Figures D-1 through D-4 are maps for the arch culvert site, Figures D-5 through D-8 are at the stream site and Figures D-9 through D-12 are for the box culvert site.

Figure D-1: Near-Boundary Velocities at Arch Culvert at Flow Where Average Velocity is Equal to Chub Prolonged Speed; Flow from Right to Left, Velocity in cm/s
Figure D-2: Near-Boundary Velocities at Arch Culvert at Critical Flow for Chub; Flow from Right to Left, Velocity in cm/s

Figure D-3: Near-Boundary Velocities at Arch Culvert at Flow Where Average Velocity is Equal to Dace Prolonged Speed; Flow from Right to Left, Velocity in cm/s

Figure D-4: Near-Boundary Velocities at Arch Culvert at Critical Flow for Dace; Flow from Right to Left, Velocity in cm/s
Figure D-5: Near-Boundary Velocities at Stream Site at Flow Where Average Velocity is Equal to Chub Prolonged Speed; Flow from Right to Left, Velocity in cm/s

Figure D-6: Near-Boundary Velocities at Stream Site at Critical Flow for Chub; Flow from Right to Left, Velocity in cm/s

Figure D-7: Near-Boundary Velocities at Stream Site at Flow Where Average Velocity is Equal to Dace Prolonged Speed; Flow from Right to Left, Velocity in cm/s
Figure D-8: Near-Boundary Velocities at Stream Site at Critical Flow for Dace; Flow from Right to Left, Velocity in cm/s

Figure D-9: Near-Boundary Velocities at Box Culvert at Flow Where Average Velocity is Equal to Chub Prolonged Speed; Flow from Right to Left, Velocity in cm/s

Figure D-10: Near-Boundary Velocities at Box Culvert at Critical Flow for Chub; Flow from Right to Left, Velocity in cm/s
Figure D-11: Near-Boundary Velocities at Box Culvert at Flow Where Average Velocity is Equal to Dace Prolonged Speed; Flow from Right to Left, Velocity in cm/s

Figure D-12: Near-Boundary Velocities at Box Culvert at Critical Flow for Dace; Flow from Right to Left, Velocity in cm/s