

ADVANCED STUDIES OF FISH PASSAGE THROUGH CULVERTS: 1-D AND 3-D
HYDRAULIC MODELING OF VELOCITY, FISH ENERGY EXPENDITURE, AND A
NEW BARRIER ASSESSMENT METHOD

by

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Matthew David Blank

April 2008

To
Jeannette
for her love, trust and faith

and

To
My Mom
for her love, kindness and support

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LIST OF EXPRESSIONS

u - instantaneous velocity component in x-direction
 v - instantaneous velocity component in y-direction
 w - instantaneous velocity component in z-direction
 u' - velocity fluctuation (random turbulent contribution) in x-direction
 v' - velocity fluctuation (random turbulent contribution) in y-direction
 w' - velocity fluctuation (random turbulent contribution) in z-direction
 U - average velocity component in x-direction
 V - average velocity component in y-direction
 W - average velocity component in z-direction
 $\vec{v}$ - instantaneous velocity vector
 $\vec{V}$ - average velocity vector
 $\vec{v'}$ - average velocity vector fluctuation (random turbulent contribution)
 u'_{RMS} - root mean square of velocity fluctuation in x-direction
 v'_{RMS} - root mean square of velocity fluctuation in y-direction
 w'_{RMS} - root mean square of velocity fluctuation in z-direction
 V_{OCC} - occupied velocity, velocity at the location the fish is occupying
 V_{AVE} - average cross sectional velocity
 V_i - velocity in a subsection of flow
 V_f - swimming velocity of fish
 V_w - velocity of water parallel to fish swimming direction
 V_{GRD} - absolute velocity of fish with respect to ground
 n - number of samples
 κ - turbulent kinetic energy
 ρ - water density
 t - time
 ∇ - del operator
 μ - dynamic viscosity of water
 p - instantaneous pressure
 P - average pressure
 p' - random turbulent contribution of pressure
 S_{MX} - gravity force in the x-direction
 S_{MY} - gravity force in the y-direction
 S_{MZ} - gravity force in the z-direction
 ε - rate of dissipation of turbulent kinetic energy
 μ_t - eddy viscosity
 σ_t - empirically derived constant
 σ_ε - empirically derived constant
 $C_{1\varepsilon}$ - empirically derived constant
 $C_{2\varepsilon}$ - empirically derived constant

LIST OF EXPRESSIONS – CONTINUED

C_μ - empirically derived constant
 E - strain tensor
 δ - Kronecker delta
 i, j - indices for Einstein notation
 f - volume of fluid function
MSE - mean squared error
 α - energy coefficient
 β - momentum coefficient
 g - acceleration due to gravity
 k_s - roughness height
 r^2_{mod} - measure of correlation between predicted data and measured data
 r^2_{fit} - measure of correlation between data and fitted regression line
 a_i - area of subsection of flow
 A - cross sectional area
 Re - Reynolds number
 λ - kinematic viscosity of water
 F_T - thrust force of fish
 F_D - drag force
 F_{VM} - virtual mass force
 G - gravity force
 B - buoyancy force
 P_f - power
 E_f - energy expenditure
 t_i - time it takes fish to swim an increment of path length
 Δt - time it takes fish to swim an increment of path length
 Δx - increment of fish path length
 C_d - drag coefficient
 C_p - pressure component of drag
 C_f - frictional component of drag
 A_s - wetted surface area of fish
 α_f - experimentally derived constant
 β_f - experimentally derived exponent
 L_f - fish length
 y - depth of water
 S_o - channel or culvert slope
 S_f - energy slope
 Q - flow rate
 R - hydraulic radius
 n - Manning's roughness coefficient
 Z - section factor for critical flow

LIST OF EXPRESSIONS – CONTINUED

b – culvert bed width
 z – culvert side slope
 x – fish path length
 K – experimentally derived constant
 ϕ – experimentally derived exponent
 θ – experimentally derived exponent
 x_c – distance to end of “near-field” region
 y_c – critical depth

ABSTRACT

Fish passage through culverts is an important component of road and stream crossing design. Although no comprehensive inventory of the number of culverts on fish-bearing streams in the United States is available, there is an estimated 1.4 million stream-road crossings. The most common physical characteristics that create barriers to fish passage include excessive water velocity, insufficient water depth and large outlet drop heights. Over the past decade, interest in the effect culvert barriers have on aquatic systems has grown; accordingly, various passage assessment techniques have been used to determine whether a structure is a barrier and to what degree (its “barrierity”). Recent research has shown that determining the barrierity of a culvert is not trivial, and that different methods are often not congruent in their classification of “barrierity”.

The purpose of this research was to investigate the effect of velocity on fish passage in great detail by: testing the use of computational fluid dynamics (CFD) for estimating the 3-D velocity field through a culvert; quantifying velocity diversity through culverts for a range of flows; characterizing the energy expenditure paths through a culvert and identifying the passageways Yellowstone cutthroat trout used to successfully negotiate passage; and developing and testing a new barrier assessment method. The research was done, in part, by studying fish passage through culverts in Mulherin Creek, an important spawning tributary for Yellowstone cutthroat trout migrating from the Yellowstone River.

Comparisons between predicted and observed velocities show 86% and 82% of variation in the observed velocity data were explained by the CFD model, for flow rates of $1.44 \text{ m}^3/\text{s}$ and $0.87 \text{ m}^3/\text{s}$, respectively. The diverse velocity field through the culvert barrel created a range of energy expenditure paths through the entire culvert length. Fish movement observations showed successful passage only for trout seeking and using the minimum energy path created, in part, by the skew between the upstream channel and the culvert. This research investigated a new hydraulic approach to assessing barriers that uses the 3-D velocity field. Comparisons between estimated passage and measured passage show the 3-D method most accurately indicated passability compared to a 1-D method.

BACKGROUND AND LITERATURE REVIEW

Introduction

Fish and aquatic organism passage through culverts is an important component of road and stream crossing design. Culverts represent an economical means of conveying water underneath roadways and have been used as such for decades. They also can provide an environment that passes fish and other aquatic organisms if they are properly designed and maintained. On the other hand, they can inhibit or prevent the upstream and downstream passage of fish and aquatic organisms (Roni et al., 2002; Warren and Pardew, 1998).

Data presented at the National Fish Passage Summit held on February 15 and 16, 2006 in Denver, CO indicated that there are over 2.5 million barriers from culverts, dams and canals on streams and rivers in the United States (USFWS, 2003).

Although no comprehensive inventory of the number of culverts on fish-bearing streams in the United States is available, there is an estimated 1.4 million stream-road crossings (USFWS). A report to the House of Representatives in 2001 prepared by the United States General Accounting Office states that over 10,000 culverts on fish bearing streams on federal lands exist in Oregon and Washington alone (USGAO, 2001). The report further states that neither agency knows the degree to which these culverts may impede fish passage, though at the time it was prepared, government agencies responsible for management of federal lands in these states had identified 2,600 barrier culverts and estimated it would cost \$375 million to restore fish passage through all of these culverts.

Examples of the number of culvert barriers from various parts of North America further highlight the problem. Sixty-one percent of culvert crossings in the Notikewin watershed and 74% of culvert crossings in the Swan river watershed, both in Alberta, likely impede fish movement (Tchir et al., 2004). Researchers classified 46% (13 of 28) of culverts inventoried in Del Norte County, CA as temporary or partial barriers and 36% (10 of 28) as total barriers (Taylor, 2001). In Whatcom County, WA, researchers assessed the passage status of culvert crossings on 1,673 crossings, 837 (50%) are barriers to fish passage (Whatcom County Public Works, 2006). A study designed to assess culvert barriers to fish movement along the Trans Labrador Highway found 22 of 47 (47%) culverts probably allowed passage of all size classes of fish and 25 of 47 (53%) culverts were barriers (Gibson, 2005). In Montana, the U.S. Forest Service (USFS) has catalogued over 1,500 culverts on fish bearing streams on National Forest Lands. Of these 47% are classified as barriers, 15% as passable, and 38% are unclassified (Williams, 2007).

Fish passage presents a complex challenge to engineers, hydrologists and biologists due in part to the dynamic nature of the system, both physically and biologically. The interactions between the physical and biological elements further complicate the problem. There are many physical factors that determine whether a fish can or cannot pass through a culvert; insufficient water depth, large outlet drop height and excessive water velocity comprise the most common physical factors (Baker and Votapka, 1990; Votapka, 1991; Fitch, 1995). Biological factors such as a fish's swimming ability, its motivation and behavior play an equally important role in passage.

Research in fish passage can be split into three areas. The first major area is the assessment of culverts/road crossings. The second major area is the effect of culverts/road crossings on aquatic systems and aquatic organisms. The third major area is the design and retrofit of road crossings that provide for fish and other aquatic organisms.

This thesis focuses primarily on the assessment of barriers to fish movement and the physical factors, in particular, velocity, which affect the “barrierity” of a crossing structure. Barrierity is defined as the degree to which a crossing acts as a barrier to fish passage. For instance, a road crossing may act as a barrier during high flow periods of the year, yet be passable during low to intermediate flows. Culverts are typically categorized into total barrier (no passage regardless of species and flow), temporal barrier (structure that is passable only at certain flow rates), partial barrier (structure that is a barrier to a size-class or life stage only) or passable (Flosi et al., 2002).

This thesis is organized into six sections with the first section (including this introduction) stating the specific goals and objectives related to the study. This section also provides background information on fish passage and summarizes a fish passage study performed in Montana to investigate the effect of culvert crossings on fish distributions in a large drainage basin during low flow. The second section of the thesis presents the development and validation of a computational fluid dynamics (CFD) model. The third section details an investigation into the propagation of velocity patterns created by stream geometry upstream of a culvert. The fourth section includes an investigation into the various energy paths through a culvert over a range of flows, and the energy paths used by fish to pass the culvert. The fifth section presents a new barrier assessment

method and a comparison to a conventional assessment technique. The last section describes research conclusions and recommendations.

Research Goals and Objectives

The overarching goal of this research is to better understand the diversity of water velocity in culverts, to explore how complex stream velocity patterns may propagate through the culvert barrel, and to investigate the use of the diverse velocity field by fish migrating upstream. Velocity diversity in open channels can be complex, especially in natural stream channels that have very irregular shapes with irregular substrate and woody debris that further complicates the geometry (Chow, 1959). In some instances, these diverse velocity patterns created by stream geometry may assist fish movement through culvert crossings or other potential physical barriers (Behlke, 1991). Additional goals include the development and testing of a new barrier assessment method.

The specific objectives of the project were to:

- (1) Quantify both spatially and temporally the velocity diversity in culverts;
- (2) Develop and validate a 3-D CFD model for culvert flow;
- (3) Investigate the extent that inlet velocity patterns propagate through the culvert;
- (4) Quantify the energy expenditure paths of trout at a range of flows;
- (5) Explore how flow rate, leap region and water temperature affect leaping success into a culvert; and

- (6) Develop and test a new barrier assessment method that uses the 3-D velocity field to estimate the barrierity of a structure.

Two specific hypotheses are tested: (1) diverse velocity patterns created by stream geometry upstream of the culvert barrel propagate through the culvert barrel, and (2) an advanced barrier assessment method that predicts the 3-D velocity field is more accurate at quantifying the barrierity of a crossing than a barrier assessment method that uses only 1-D velocity fields.

The new barrier assessment method estimates the 3-D velocity field (hydraulic environment) in the culvert crossing and compares the estimated hydraulic environment to the known swimming abilities of fish to define the barrierity of the crossing. A simpler method that uses 1-D hydraulic computations and fish swimming abilities is also presented for comparison with the new method. Each of these methods is presented using a comprehensive field data set collected over the last three years at Mulherin Creek, a tributary to the Yellowstone River near Gardiner, Montana. The methods estimate passage over most of the ice-free period of the year for two trout species that inhabit the creek: Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*) and rainbow trout (*O. mykiss*).

Factors Influencing Fish Passage

There is a long history (decades) of research in fish passage through culverts, and a very long history (centuries) of research in hydraulic structures. This literature review begins by describing the factors that influence fish passage through culverts. It then presents studies focused on assessing fish passage through culverts. In particular, there is

a discussion of a basin-wide fish passage evaluation performed by the author of this study and Drake Burford, M.Sc. Ecology, in the Clearwater River drainage in western Montana (Cahoon et al., 2005; Burford, 2005; Blank et al., 2006). Data from that project are used herein.

The physical factors influencing fish passage through a culvert will be presented as they would be encountered by a fish ascending a culvert. Figure 1 shows a side view of a culvert with the common factors that limit passage.

The first potential obstacle to passage is presented on the approach to a culvert. Obstacles there may include a jump into the culvert. This jump may be too high for the fish to physically maneuver. Jumping abilities vary by species and by size (Hoar and Randall, eds., 1978). As an example, recent studies to investigate relationships between jump height, water depth and fish size for brook trout (*Salvelinus fontinalis*) show jumping performance to be strongly affected by jump height, water depth and fish size (Brandt et al., 2005; Kondratieff and Myrick, 2006). This research showed that although larger fish could leap greater heights, smaller fish were capable of leaping a greater number of body lengths than larger fish; and the probability of successfully leaping over an obstacle was inversely proportional to leap height.

The hydraulics of the jump location appear to play a role in the ability of successfully leaping an obstacle and leaping behavior in some salmonids. Salmon and sea trout were observed using the upwelling momentum provided, in some instances, by a hydraulic jump that formed on the downstream side of the plunging outfall in natural falls (Stuart, 1962). The hydraulic jump also appeared to stimulate leaping behavior (Stuart, 1962). Pacific salmon were observed to accelerate from the bottom of pools below falls

by using burst swimming to the surface rather than leaping from near the surface itself (Lauritzen, 2002).

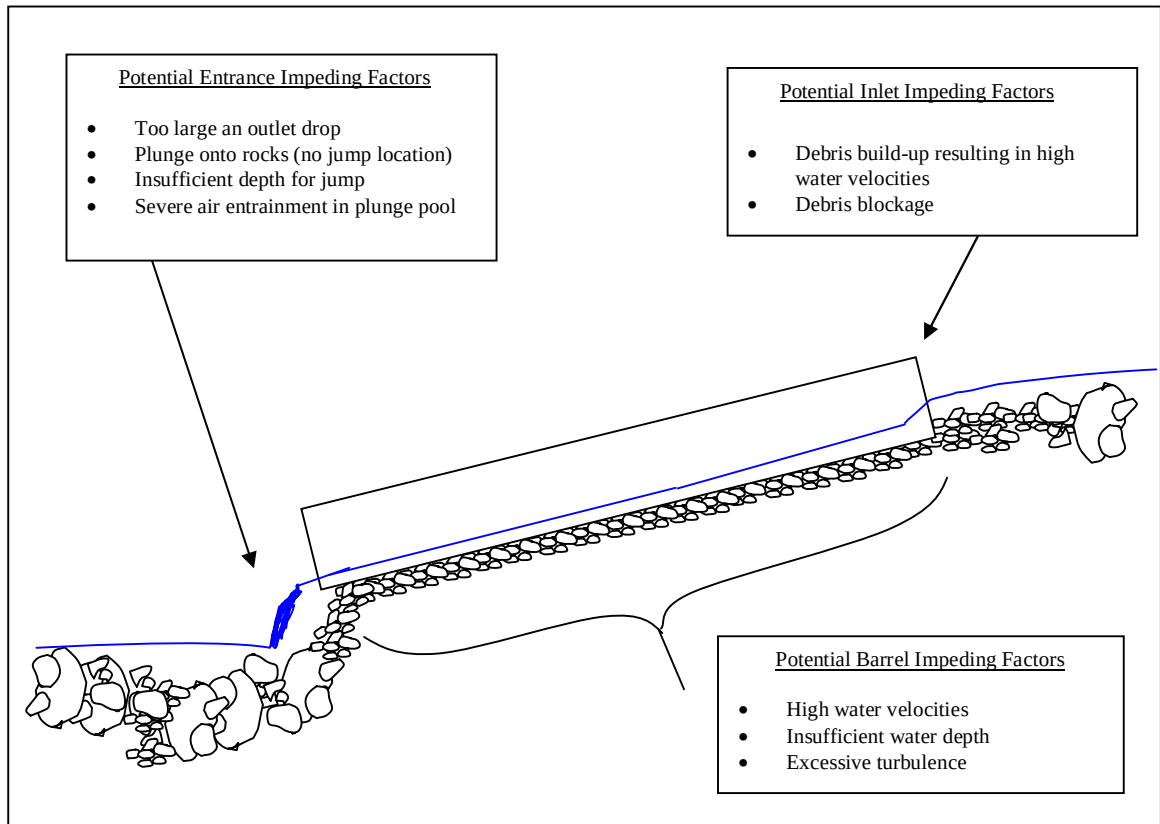


Figure 1. Side view of culvert showing some potential impeding factors to fish passage.

The ratio of leap height (or height of fall) to pool water depth plays a role in successful leaps over natural falls and into manmade structures like culverts. Early research identified a ratio of 1:1.25 (height:depth) as optimum for leaping in salmon and sea trout (Stuart, 1962). Lab studies show successful leaping of brook trout for ratios as low as 1.0:0.5 (Brandt et al., 2005). Lauritzen also observed salmon successfully leaping over natural obstacles at ratios around 1.0:0.5 (Lauritzen, 2002).

Once inside a culvert, water depth becomes a factor in passage. If there is insufficient depth in the culvert, the fish cannot swim upstream regardless of velocity. Research from the Clearwater River drainage showed small brook trout and westslope cutthroat trout (*O. c. lewisi*) negotiated water depths as low as 31 mm (average length of adults = 97 mm) (Cahoon et al., 2005; Burford, 2005; and Blank et al., 2006). Researchers have suggested minimum water depths for passage of trout should equal 80 mm (Saltzman and Koski, 1971), 120 mm (Lauman, 1976) and 150 mm (Baker and Votapka, 1990).

Water velocity can be a critical factor for passage and may become the controlling factor as flow and velocity increase in the stream and culvert. Data collected by Warren and Pardew (1998) suggest that increased water velocity through culverts restricts fish passage for warm water fish species. Several studies have placed a value around 1.22 m/s as an upper threshold for passage of resident trout (Saltzman and Koski 1971; Lauman, 1976; Belford and Gould, 1989). A recent study of Yellowstone cutthroat trout passage through a series of five culverts in Montana found velocity to be the only significant parameter for indicating the probability of passage (Cahoon et al., 2007a). Other factors that proved to significantly affect passage success, using a single factor analysis, were fish length (smaller fish had more success), water temperature (fish had more success at higher temperatures) and outlet drop height (fish were more successful at negotiating smaller drops). Irrelevant factors in this study were culvert slope, length, number of attempts, sex and species. This study documented fish passing through culverts with an average velocity up to 2.71 m/s.

Adult Arctic grayling (*Thymallus arcticus*), juvenile Coho salmon (*O. kisutch*) and juvenile Chinook salmon (*O. tshawytscha*) have been observed utilizing the lower velocity regions that develop along the boundaries, such as the sides and bed of culverts (Travis and Tilsworth, 1986; Kane et al., 2000; Pearson et al., 2005). The researchers speculated that fish were seeking to minimize their energy expenditure by traveling against the lower velocities. In some cases, fish may not have been able to pass without seeking and using the lower velocity areas.

The length of the culvert and the availability of resting areas in the culvert can affect passage success. Belford and Gould found trout passed more easily through a culvert when rocks were placed within the culvert barrel than through a culvert barrel free of rocks (Belford and Gould, 1989). These rocks were thought to provide resting areas for the fish during passage upstream through the culvert.

The inlet of the culvert also can present challenges to fish. Excessive sediment can deposit on the upstream end of the culvert (Kane and Wellen, 1985). This deposition may result when culverts constrict flow by having widths less than the upstream active or bankfull channel width; or when the culvert slope is less than the upstream channel slope (Kane and Wellen, 1985). Sediment buildup at the culvert inlet can steepen inlet slopes and increase water velocities (Behlke, 1991).

The inlet area also presents the last potential challenge the fish must overcome for successful passage through a culvert. When fish are swimming through velocity challenges like culverts they often use their burst speed to pass (Behlke, 1991). Fish have an exhaustion point related to the type of swimming mode, and for burst swimming the range is up to 15 seconds (Hoar and Randall, eds., 1978). Therefore, this last potential

obstacle can create barriers because the fish may have already used a large percentage of its available energy by this point in the crossing and is nearing exhaustion.

There are other hydraulic factors, such as air entrainment, vorticity, and turbulence that affect swimming abilities and potentially passage (Stuart, 1962; Powers, 1997; Lauritzen, 2002; Enders et al., 2003). These factors are complicated and more research is needed to understand their role in passage. In addition, they are easily confounded with velocity.

Fish locomotion is an important biological factor that interacts with the physical environment and plays a key role in passage. Temperature, dissolved oxygen, motivation to swim upstream, gender, physical condition, disease and sexual maturity all affect fish locomotion (Macphee and Watts, 1976; Wardle, 1980; Baker and Votapka, 1990; Bell, 1991; Kynard and O’Leary, 1993). Fish swimming is often discussed as three regimes: sustained swimming, prolonged swimming, and burst swimming (Hoar and Randall, eds., 1978). Another important swimming classification is the critical velocity. The following definitions for these speeds are taken directly from Hoar and Randall, eds. (1978).

“Sustained Swimming: A spectrum of swimming activities and speeds that can be maintained for an indefinite period – in operational terms for longer than 200 min – and does not involve fatigue. Metabolism is aerobic and the activities would include foraging, station holding, schooling, cruising at preferred speeds in negatively buoyant fish, and steady swimming at low speeds, including migration.”

“Burst Swimming: Rapid movements of short duration and high speed, maintained for less than 15 sec. Energy is made available largely through anaerobic processes. Burst activity may be subdivided into an acceleration period and a sprint, when swimming speed is high but steady.”

“Prolonged Swimming: Covers a spectrum of speeds between burst and sustained and is often categorized by steady swimming with more vigorous efforts periodically. The swimming period lasts between 15 sec and 200 min and if maintained will end in fatigue. Energy is supplied from either both aerobic and anaerobic processes.”

“Critical Swimming Speed, U_{crit} : This is a useful operational term for comparing swimming speeds of different fish. Swimming speeds of individual fish of the same species but different swimming abilities, because of differing physiological states, can be compared by expressing the swimming speed as $\%U_{crit}$.”

“Fatigue: A fish is fatigued when it collapses and can no longer maintain a given swimming speed.”

An analogy with humans could be viewed as follows: a human walks at a sustained speed, jogs at a prolonged speed, and sprints at a burst speed. Swimming ability is related to the species of fish and the size of the individuals within a given species (Hoar and Randall, eds., 1978).

Two modes of swimming ability, prolonged and burst, are unsustainable and the mechanisms for switching from one to another are not very well understood (Castro-Santos, 2005). The fact that two unsustainable modes exist implies that there is not a single relationship that describes the swim speed-fatigue time relationship. Maximum distance achieved depends on which mode the fish utilize and the behavior and strategy used to shift from one mode to the next (Castro-Santos, 2005). A recent study showed anadromous clupeids used a distance-maximizing strategy to pass through a velocity challenge, whereas nonclupeids did not (Castro-Santos, 2005).

Field Studies of Fish Passage through Culverts

Over the years, there have been many field based studies of fish passage. A sampling of some of these studies provides an interesting overview and progression of fish passage research.

A field study performed in the mid-80s in Poplar Creek, Alaska found 78% of Arctic grayling attempting to swim through a culvert were successful when the outlet velocity was 2.2 m/s and 95% were successful when the velocity was 2.1 m/s (Travis and Tilsworth, 1986). At the time, the Alaska Department of Fish and Game (ADF&G) had set passage criteria based on maximum water velocities attained during a mean annual flood discharge for varying culvert lengths. The culvert studied was 33 m long and 1.52 m in diameter. The culvert slope was 0.5% with a 30.5 cm outlet drop. Velocity passage criteria for this pipe was set at 0.55 m/s following the ADF&G criteria. This study found grayling began their spring spawning migration in mass during the very beginning of the falling limb of that season's hydrograph.

Belford and Gould (1989) studied trout passage through six culverts of various types and materials in Southwest Montana. They developed a relationship between swimming distance and passable average bottom water velocities. For culverts from 0 to 20 meters in length, average velocities from 1.67 to 0.83 m/s permitted passage; and for culverts from 20 to 100 meters in length, average velocities from 0.83 to 0.64 m/s permitted passage, respectively.

A study performed by the Washington Department of Fish and Wildlife (WDFW) in cooperation with Washington State Department of Transportation (WSDOT) explored whether juvenile coho salmon use the low velocity region along the culvert wall to pass,

and the relationship between mean velocity and turbulence (Powers, 1997). The study compared passage through corrugated and smooth culverts, and found fish used the low velocity region along the culvert wall to pass, but only when maximum velocities were less than 0.61 m/s. The corrugated culvert seemed to impede passage more than the smooth pipe at velocities greater than 0.61 m/s. Powers (1997) speculated that greater turbulence caused by the corrugations impeded juvenile coho salmon passage at this flow. The researchers in this study recommend additional work to investigate the effect of turbulence on fish passage success.

Warren and Pardew (1998) studied 21 culverts in west-central Arkansas using a mark-recapture technique. Their study examined the effect of four different types of crossings on warm water fish movement during base and summer low flows. Results from their study showed that fish movement was an order of magnitude lower in culvert crossings than through open-box, fords and natural reaches. No movement was detected through slab crossings. In addition, they found water velocity to be inversely proportional to fish passage.

Rosenthal investigated passage of warm water fish species through five culverts in eastern Montana (Rosenthal, 2007). This study found comparable passage rates between reference reaches (natural stream reaches without culverts) and culverts for four species and restricted passage through culverts compared to reference reaches for one. Conversely, in Arkansas, Rajput (2003) found fish were less than 50% likely to move across reaches with culverts compared to control reaches without culverts. Passage through culverts was measured only at locations without plunge pools (Rajput, 2003). Findings from work done in Virginia and West Virginia found cyprinid passage through

culverts was negatively correlated with culvert slope, the product of slope x length, and velocity (Coffman, 2005).

The Clearwater River Project

The Clearwater River basin-wide culvert study focused on the following question: How do culverts influence fish populations across a large drainage basin in Montana? This study combined fish, habitat, hydraulic and hydrologic data collection and analysis to assess fish passage across the upper Clearwater River Drainage, see Figure 2. The primary species studied were bull trout (*S. confluentus*), westslope cutthroat trout and brook trout. The study used a tiered approach to analyze fish passage. These tiers can be summarized as follows:

- Level I - Hydraulic data collection and analysis with FishXing at all 46 sites.
- Level II - Upstream and downstream fish population characteristics at 21 sites.
- Level III - Mark-recapture studies at 12 sites.

Results from the FishXing model (FishXing, 1999) from analysis of all 46 culverts indicate 76% to 85% are barriers at low flow, depending on selection of minimum water depth. The upstream and downstream fish population characteristics analysis of a subset of 21 culverts indicated little or no significant difference in population characteristics (upstream characteristics compared to downstream characteristics). The direct passage analysis of a subset of 12 culverts indicated no passage restriction at four culverts, some degree of passage restriction at seven culverts and no passage at one. Direct passage study results may suggest more passage occurred at low flows than the other methods suggest.

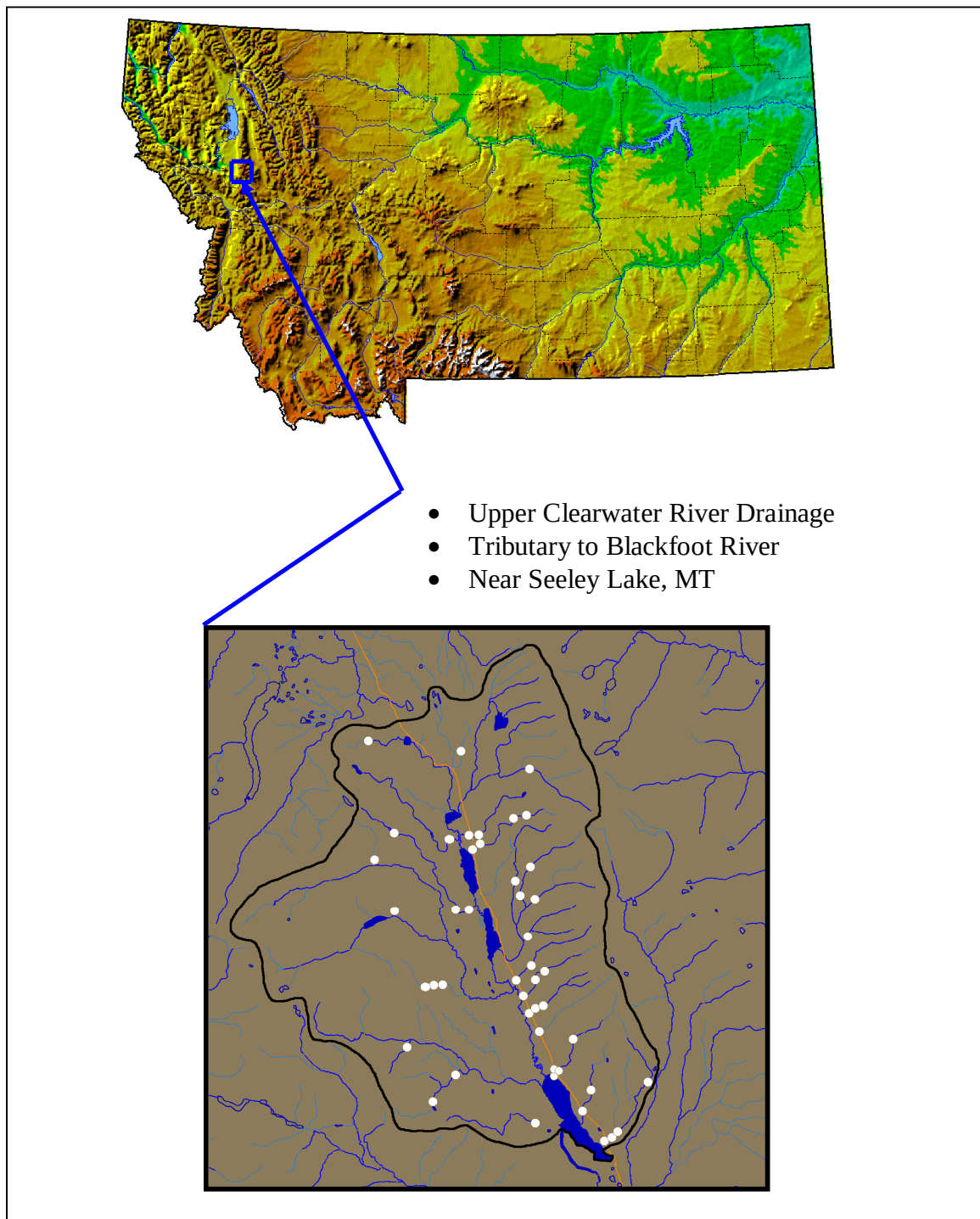


Figure 2. Upper Clearwater River Drainage location. White dots are culvert study sites.

One of the interesting findings from the Clearwater study was that congruency between the three assessment methods was inconsistent. Table 1 summarizes results for study sites where multiple methods were applied. For example, at site 19 FishXing identified the structure as a barrier to both adult and juvenile trout; however, a direct passage study result of 0.13 indicates more fish moved through the culvert than a natural stream reach, and the population characteristics sample did not show any significant difference between the average length or abundance of trout. Burford (2005), Cahoon et al. (2005) and Blank et al. (2006) provide a more thorough description of the Clearwater River study.

Table 1. Summary of results for different assessment methods used for the Clearwater Fish Passage Study.

Site Identification	FishXing Results ¹		Direct Passage Results ²	Upstream vs. Downstream Population Characteristics ³	
	Adult	Juvenile	Passage Indicator	Size	Abundance
2	B	B	-0.36	no	no
11	B	P	0.2	yes	no
19	B	B	0.13	no	no
20	B	B	0.03	no	no
23	P	P	-0.56	no	no
27	B	B	-0.19	no	no
28	B	B	-0.54	no	no
33	B	B	-0.85	yes	no
35	B	B	-0.69	no	no
43	B	B	-0.22	no	no

Table Notes: 1) FishXing was used to analyze passage for adult trout (cutthroat trout with a length of 150 mm) and juvenile trout (rainbow trout with a length of 60 mm). A “B” means the program identified the structure as a barrier, and a “P” means the program identified the structure as passable. 2) Direct passage results range from -1 to 1, with a negative value indicating more fish moved through a natural control reach as compared to a culvert and a positive value indicating the opposite. 3) A “yes” in the portion of the table comparing upstream vs. downstream population characteristics means there was a statistically significant difference and a “no” means there was not a statistically significant difference.

Fish passage studies by Coffman (2005) and Rajput (2003) also show incongruency between different methods used to assess barriers to fish passage. Coffman (2005) assessed the accuracy of three predictive models by comparing their estimate of passability to passage assessments using a mark-recapture technique. The models failed to accurately indicate passage approximately 50% of the time. Although, model prediction improved after revising the predictive model parameters based on the data from the mark-recapture experiments.

Solcz (2007) performed a passive integrated transponder (PIT) tag study in Mulherin Creek from 2005 through 2006. Part of his study included comparing measured passage success using PIT tags against the predicted “passability” using FishXing of two culverts: the first is the box culvert (Culvert 1) without baffles included in this study and the second was a circular, steel culvert located upstream of the box culvert. His data show that FishXing successfully classified Culvert 1 as a barrier at flows greater than 1.4 m³/s compared to no documented passage at flows greater than 1.5 m³/s. However, FishXing identified the steel culvert as impassable at all flows, thus a total barrier, compared to field observations (n = 7) showing 77.8% of individuals successfully passing this culvert at discharges from 0.6 to 1.7 m³/s.

There are several possible explanations for the inconsistencies in assessing road crossings/culverts as potential fish barriers. Using fish population characteristics from samples collected upstream and downstream of a culvert may not show the effect of a barrier because there is sufficient habitat upstream and downstream of the structure to maintain viable populations. Or, perhaps, the road crossing has not been in place long enough for it to affect the upstream or downstream populations of fish. Another possible

reason for the lack of inference from the Clearwater population characteristics data is that perhaps fish samples were not collected over a large enough distance (sample reaches were only 94 m).

One plausible explanation why a hydraulic approach to assess passage has had varied success is that perhaps using only a 1-D characterization of velocity is not sufficient to accurately predict passage. Several researchers suggest fish are able to pass through structures by utilizing the lower velocity regions that develop along the sides of a culvert (Travis and Tilsworth, 1986; Behlke, 1991; Kane et al., 2000; Pearson et al., 2005). Lab studies (Rajaratnam et al., 1988, 1989, 1990, 1991a, 1991b; Rajaratnam and Katopodis, 1990; Pearson et al., 2006), field studies (Kane and Wellen, 1985; Belford and Gould, 1989; Cahoon et al., 2005; 2007a, 2007b) and hydraulic theory (Chow, 1959) all show how velocity varies both vertically and horizontally across a given section of flow. Present day 1-D hydraulic models of culvert flow do not allow prediction of how velocity varies across a given section of flow. Therefore, increasing the understanding of velocity diversity through culverts, how that diversity is created and investigating the ability of more advanced mathematical techniques such as CFD to predict 3-D flow fields and, subsequently, fish passage is a valid and useful endeavor.

The remainder of this thesis explores the velocity factor in greater detail to further the understanding of the diversity of velocity in culverts, the creation of diverse velocity patterns by the upstream channel and how those patterns propagate through a culvert, and various fish energy expenditure paths created by velocity diversity through culverts. In addition, a new barrier assessment method that uses the 3-D velocity field to predict passage is developed and tested.

COMPUTATIONAL FLUID DYNAMICS MODEL DEVELOPMENT

Computational fluid dynamics (CFD) refers to the solution, by numerical methods, of the equations that govern fluid flow. Numerical methods are used because there is no existing analytical method to solve these equations, unless they are greatly simplified.

This section of the thesis presents the development of a CFD model to describe the velocity field in the primary study culvert, quantifies the velocity pattern in a baffled and unbaffled culvert, and details the validation of the CFD model against measured velocity fields in the unbaffled culvert.

Introduction

Research in the use of CFD for assessing open channel flows has increased tremendously in the past ten to fifteen years. Much of this work has been conducted by quantitative geomorphologists using the advanced modeling techniques to explore flow processes that (using present techniques) are impossible or difficult to measure. Table 2 provides a summary of some of these CFD studies. The table includes the authors, the title of the research, and the application/objective of each study.

Recent CFD studies of velocity patterns of fishways have been completed. A study by Khan investigated the energy paths created by a vertical slot fishway (Khan, 2006). This study did not verify the accuracy of the model; rather it referenced other studies designed to validate CFD models using similar mathematics. Chen developed a three-dimensional (3-D) CFD model to investigate the meandering flow in rivers and

Table 2. CFD studies involving streams and rivers, amended from Booker 2000.

Author (s)	Title	Application/Objective
Lane, Richards and Chandler (1995)	Within-reach spatial patterns of process and channel adjustment.	Application of a 2-D CFD model to a pro-glacial fluvial environment.
Lane (1998)	Hydraulic modeling in hydrology and geomorphology: a review of high resolution approaches.	Discussed advantages and disadvantages of CFD as a tool for geomorphological investigation.
Lane and Richards (1998)	High resolution, two-dimensional spatial modeling of flow processes in a multi-thread channel.	Application of 2-D CFD model to a pro-glacial fluvial environment.
Mosselman (1998)	Morphological modeling of rivers with erodable banks.	Added a bank erosion model to a CFD code and applied it to River Ohre.
Nicholas and Walling (1998)	Numerical modeling of floodplain hydraulics and suspended sediment transport and deposition.	Application of finite element method to River Culm, Devon. Predicted flow depths, velocities, patterns of suspended sediment dispersion and deposition.
Bates, Horrit and Hervouet (1998)	Investigating two-dimensional, finite element predictions of floodplain inundation using fractal generated topography.	Simulated hypothetical floodplain with topography produced from scaling information derived from fractal analysis of a real DTM.
Bradbrook, et al. (1998)	Investigation of controls on secondary circulation in a simple confluence geometry using a 3-D numerical model.	Investigated changes in flow structure through simulation of various geometry.
Hodkinson and Ferguson (1998)	Numerical modeling of separated flow in river bends: Model testing and experimental investigation of geometric controls on the extent of flow separation at the concave bank.	Compared modeled and measured flow for a natural bend on the River Dean using near-bed and near-surface waters.
Lane et al. (1999)	The application of computational fluid dynamics to natural river channels: 3-D versus 2-D approaches.	Investigated benefit of utilizing 3-D models to improve predictive ability and utility as compared to 2-D models.
Booker, Sear and Payne (2001)	Modeling 3-D flow structures and patterns of boundary shear stress in a natural pool-riffle sequence.	Investigated flow patterns and shear stress in riffle-pool sequence using 3-D CFD modeling and field measurement.
Nicholas (2001)	Computational fluid dynamics modeling of boundary roughness in gravel-bed rivers: an investigation of the effects of random variability in bed elevation.	Investigated through simulation and experiment the mean and turbulent characteristics of open-channel flow over two contrasting gravel beds.
Olsen (2003)	3-D CFD modeling of self-forming meandering channel.	Computed meandering pattern in an initially straight alluvial channel and compared to flume study data.
Booker (2003)	Hydraulic modeling of fish habitat in urban rivers during high flows.	Applied a 3-D model to simulate hydraulic patterns in two urban river reaches of the River Tame.
Hardy et. al. (2003)	Assessing the credibility of a series of computational fluid dynamic simulations of open channel flow.	Explored the use of a Grid Convergence Index for assessing the credibility of CFD simulations of open channel flow.
Rameshwaran and Naden (2003)	3-D numerical simulation of compound channel flows.	Applied CFD to estimate turbulent flow in compound channels.

channel/culvert systems (Chen, unpublished). His model showed that flow will adjust to the cross sectional geometry of the river or channel/culvert system.

CFD has been used to model open channel velocities for assessment of fish habitat in Britain. Booker used SSIIM, a 3-D CFD code, to simulate hydraulic patterns in two engineered reaches of the River Tame (Booker, 2003). Velocity patterns in each reach and at several flow regimes were compared to the maximum sustainable swimming speeds of fishes inhabiting the river. The analysis did not include any field measurement of fish movement, just comparison of predicted velocities to swimming abilities.

As previously mentioned in Chapter 1, past methods for estimating velocity patterns in culverts have used primarily 1-D approaches. This approach can estimate average hydraulic characteristics, such as water depth or velocity, at a cross section of interest, but it is unable to define how velocity varies with depth or across a section of flow. In addition, it does not define the turbulence in water, which has been shown to be important for fish passage, especially juvenile salmonid fish passage (Powers, 1997; Pearson et al., 2005, 2006). Advances in measuring flow velocities and turbulence, like the acoustic Doppler velocimeter (ADV), and in modeling flow velocities using advanced mathematics such as 3-D CFD provide the ability to assess the 3-D nature of the flow field. The ability to study flow patterns in 3-D and model them is relatively new (~last 10 to 20 years); therefore, it presents a prime opportunity to explore its accuracy and ability to assess fish passage.

Other researchers are characterizing culvert flow patterns in 3-D and are investigating the use of 3-D CFD techniques for estimating hydraulic patterns in culverts (Richmond, 2008). However, it is important to understand that 3-D flow characteristics

are highly complex and vary considerably from one structure or setting to the next. In addition, there are many ways to construct CFD models of flow, each utilizing different boundary conditions, initial conditions, meshing, and turbulence models (to name just a few). The use of CFD to analyze hydraulic environments and environmental problems has recently (within the last decade) emerged as a powerful and practical tool (Bates, P.D., Lane, S.N. and Ferguson, R.I., eds., 2005). Therefore, furthering the validation of 3-D CFD at predicting complex velocity patterns, and simply characterizing 3-D flow patterns and turbulence are extremely important areas of research (Hotchkiss and Frei, 2007).

Last, but certainly not least, fish live in a highly 3-D environment and are very sensitive to a variety of hydraulic conditions. The recent advances in measuring and modeling the flow environment in 3-D provide an outstanding opportunity to explore the aquatic world more realistically and, hopefully, with greater accuracy and understanding.

Methods

Methods for this part of the research included development of a numerical model of the velocity field in the primary study culvert (Culvert 1) using ANSYS-CFX. In addition, field data were collected to characterize the velocity field in both Culvert 1 and Culvert 2 in one-dimension (1-D) and 3-D; to measure hydrologic data representing stream flows for most of the ice-free periods of the year; and to measure physical parameters representing the geometry of the culvert crossing and near-stream characteristics.

Field Data Collection

This research included an in-field component. Field data for the velocity study included collection of hydrologic, hydraulic and biological data. The time period for data collection was April of 2004 through September of 2006, representing three runoff seasons. Mulherin Creek was the study site. Only physical data collection (hydrologic, hydraulic and physical geometry of the site) will be described in this section. The biological data collection will be discussed in Section IV, Energy Paths. The physical data collection described within this section is used in Section III, Propagation of Inlet Velocity, Section IV, Energy Paths, and Section V, New Barrier Assessment Method.

Study Site: Mulherin Creek is a tributary to the Yellowstone River with their confluence near Gardiner, Montana (Figure 3). Mulherin creek is a high gradient stream, with an average gradient from the headwaters to the mouth of 11.6%, and an average gradient of 2% to 5% through the study reach. Large substrate, primarily cobble and boulder, dominates the drainage with some bedrock control in the vicinity of the study reach. The stream had base flows around 0.28 cubic meters per second (m^3/s) with a flow of 2.74 m^3/s measured in June 1983 (USGS, 1986). Average bankfull width is approximately eight meters (m). The stream has low sinuosity through most of the study reach.

Several native species inhabit Mulherin Creek including: Yellowstone cutthroat trout, mountain whitefish (*Prosopium williamsoni*), white sucker (*Catostomus commersoni*), longnose sucker (*C. Catostomus*), mountain sucker (*C. platyrhynchus*), mottled sculpin (*Cottus bairdi*), and longnose dace (*Rhinichthys cataractae*). Non-native species in the creek include: rainbow trout and brown trout (*Salmo trutta*).

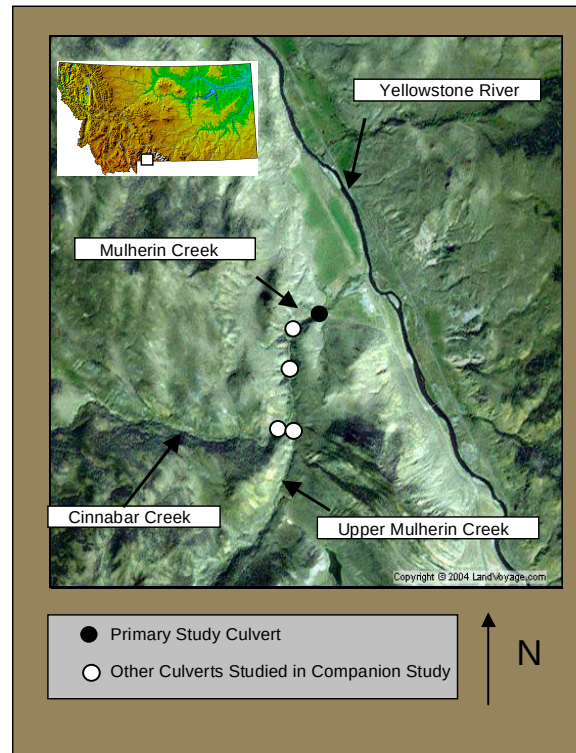


Figure 3. This map shows the Mulherin Creek drainage with the study culvert and other culverts that were included in a companion study.

Site selection was a critical aspect of this study and was done in the following manner with consideration of several key aspects. Potential study sites were identified by reviewing a culvert inventory provided by the Gallatin National Forest, and discussing potential culvert sites with Montana Fish, Wildlife, and Parks (MFWP) biologists and USFS biologists and hydrologists. Field visits to twenty potential sites were performed and culverts were assessed based on several factors. First and foremost, the study stream needed to have several culverts large enough to allow entry and measurement of internal

velocities and water depths. The culverts needed to provide a range of physical conditions and fish passage enhancement structures.

Second, the stream had to have healthy populations of rainbow and Yellowstone cutthroat trout, providing relevance to today's emerging fish passage issues. Yellowstone cutthroat trout are a Species of Special Concern in Montana (MTNHP and MFWP, 2006). Mulherin Creek is the major spawning tributary in that section of the Yellowstone River drainage (Byorth, 2005; Derito, 2004).

Third, the stream had to have a large runoff volume with good base flow throughout the year. This reason is important in that it allowed for measurement of velocities over a range of flow rates covering different time periods of the year.

Fourth, the watershed needed to be within a reasonable distance from Bozeman to allow for frequent site visits, and it had to be accessible during most of the year.

Fifth, baffles are an important option for retrofitting culverts to improve passage conditions. By including baffled pipes in the study, the study provides information related to how baffles function in terms of their influence on the flow environment.

Hydrologic and Hydraulic Data: Hydrologic and hydraulic data were collected utilizing several different types of instruments and methods. These data were collected to measure the spatial and temporal diversity of velocities, to provide boundary conditions for the computational models, to validate the computational models, and for comparisons between fish movement and hydraulic conditions in Culvert 1.

Most of the hydraulic measurements were collected in the primary study culvert, Culvert 1. However, a few data sets were collected in Culvert 2 which is a baffled culvert with very similar dimensions to Culvert 1. Data sets from Culvert 2 are included

to show the dramatic difference in the hydraulic environment between a culvert without fish passage enhancement structures and a culvert with fish passage enhancement structures. To look at differences, velocities on a plane 0.06 meters above the bed in Culvert 1 and 2 collected at the same flow rate were analyzed using Mann Whitney tests. This plane is of interest because it is where migrating trout were observed. Appendix A includes photos of Culvert 1 for three different flow rates, and photos of Culvert 2.

A gaging station was constructed at Culvert 1 to record water depth for creation of a stage-discharge relationship. A Trutrack®, model TM-1000 served as the stage meter and measured water height, air temperature and water temperature. The stilling well was constructed of 2-inch Schedule 40 PVC and secured to the side of the culvert.

Discharge was estimated a minimum of 10 times each year using the U.S. Geological Survey (USGS) 0.6 times depth method (USGS, 1982). Velocity data for discharge estimation was collected with a Pygmy meter. Discharge transects were established within Culvert 1 and in a downstream, stable reach of Mulherin creek. A stage-discharge relationship was created following USGS protocols (USGS, 1982).

Water depths at the culvert inlet, at selected cross sections within the culvert, and at the culvert outlet were measured in two ways: using a graduated rod or with staff gages mounted to all four corners of the culvert. When using the graduated rod, water creates a wake effect, which results in a slightly higher than actual water elevation on the upstream-side and a slightly lower than actual water elevation on the downstream side of the rod. To accommodate for this, water elevations were set as the midpoint between the upstream and downstream water elevation measurements. The accuracy of the water heights is approximately +/- 1 cm.

Numerous water velocity data sets (both 1-D and 3-D) were collected to provide boundary conditions for the computational model, calibration and validation data sets for the computational model, and velocity maps that represent the hydraulic conditions in the culverts at a range of flows. A Pygmy meter with a hand-held computer collected the 1-D velocity data sets. An acoustic Doppler velocimeter (ADV) with a signal processor connected to a lap-top computer collected the 3-D velocity data sets (Figure 4).



Figure 4. Photograph of the inlet region of Culvert 2 and the ADV harness and meter.

All data were collected using a cartesian coordinate system with the y-coordinate parallel to the earth's gravity force. 1-D refers to the instruments capability to collect only an average velocity in a direction parallel to the instrument orientation. 3-D refers to the instruments ability to collect velocities in all three directions: x, y and z.

Both 1-D and 3-D inlet velocity data sets were collected at a range of flows at the culvert inlet cross section. Typically, each inlet velocity data point measurement and the incremental discharge of that measurement represents less than 5% of the total discharge of the inlet cross section (Figure 5).

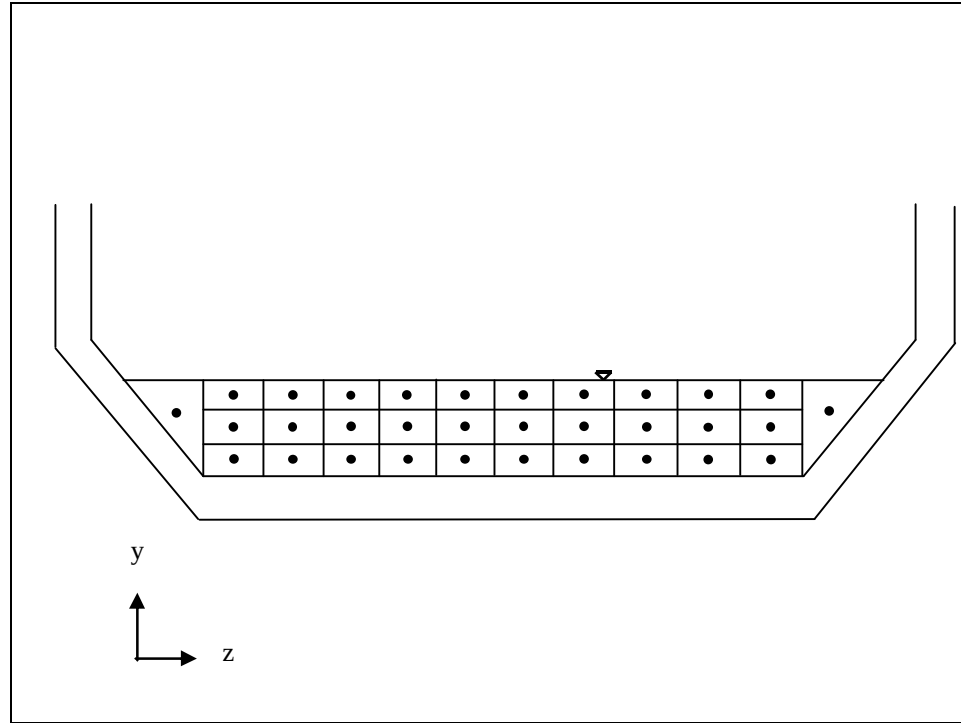


Figure 5. Typical velocity sampling pattern collected at the inlet of a culvert. Vertical scale is exaggerated for illustration purposes.

Patton (2006) found this density of sampling points to provide an adequate depiction of the velocity diversity at a culvert inlet. The typical spacing was 0.15 m to 0.3 m in the horizontal direction and 0.03 m to 0.06 m in the vertical direction.

A trolley-type system was designed and constructed to collect 3-D velocity data sets. A harness made of 2-inch square aluminum tubing held the ADV at the measurement point. The harness was secured to the sides of the culvert and rested on a level plane. This harness allowed for estimates of the x, y, and z magnitude of velocity at a point in space while minimizing the disturbance of the water by allowing nothing other than the meter to penetrate the water surface. This approach completely eliminates the

creation of artificial velocity readings from the inevitable disruption of flow when standing in the water to collect measurements.

Plan view velocity data sets were collected to provide the pattern of velocities in a horizontal plane parallel to the culvert bed. Plan view data sets were collected with a Pygmy meter for a couple of reasons. First, the Pygmy meter allowed for quick collection of velocity points to minimize the change in velocities caused by a change in discharge in this highly diurnal stream. Second, the water depth was often too shallow and/or fast, exceeding the abilities of the ADV. The ADV can measure water velocities up to 2.4 m/s; however, water velocity in the culvert barrel often approached or exceeded that threshold.

Figure 6 shows a typical sampling pattern for the plan view velocity maps. All samples were collected at an elevation of 0.06 m above the culvert bed, with a streamwise (in the direction parallel to the downstream flow of water) spacing of 2 m and a spanwise (in the direction perpendicular to the downstream flow of water) spacing of 0.3 m. This sampling elevation was chosen because fish were observed swimming at this depth to pass through the culvert, and other studies observed fish swimming close to the bottom of the culvert bed (Kane and Wellen, 1985; Behlke, 1991; Kane et al., 2000).

The 1-D meter estimates the velocity by recording the number of revolutions made by the cups per second. This rotational rate is correlated to the velocity of the water in the laboratory by the manufacturer of the instrument. This meter was set to average velocity readings collected over a 20 second (s) time period. The meter is attached to a graduated rod during measurements.

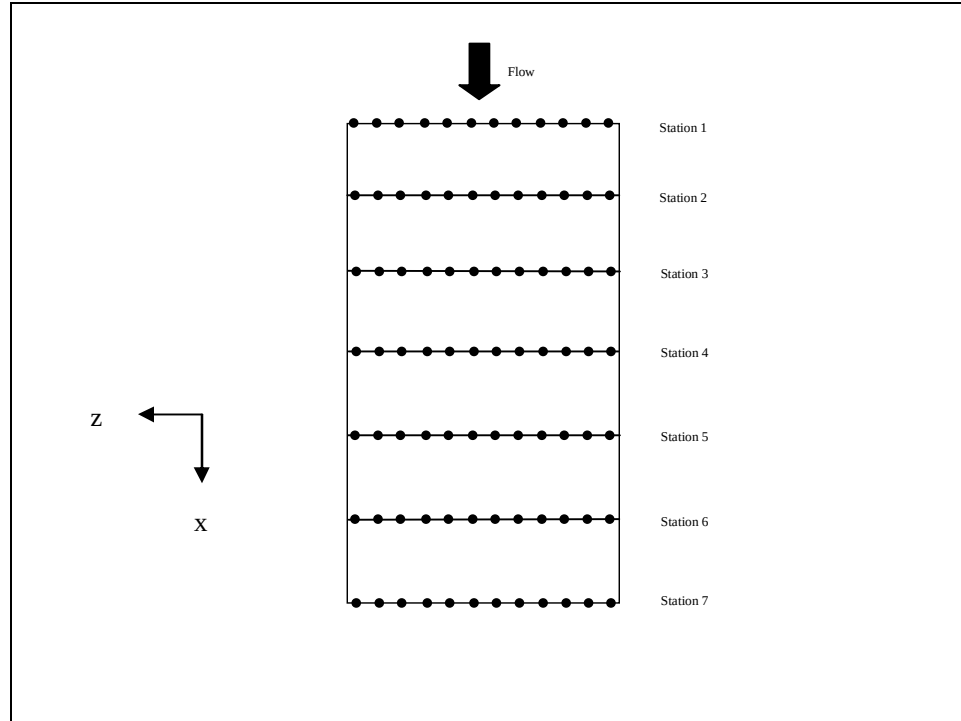


Figure 6. Location of velocity observations collected on a plane 0.06 m above the culvert bed. The dots show the location of each observation. Measurement spacing in x direction was ~ 2 m, and measurement spacing in z direction was ~ 0.15 to 0.3 m.

The ADV meter relies on acoustic technology to estimate the point velocity in the water (Sontek, 2007). The meter has a transmitter that transmits a sound wave. Three receivers separated by 120 degrees from one another receive the reflected sound waves. The sampling volume resembles a cylinder in shape and is located 10 centimeters (cm) from the transmitter. The diameter of the cylinder is set by the transmitter at 6.0 millimeters (mm). The height of the sampling volume is a function of the transmit pulse and receive window, and can be set by the user. For this study, it was set at 7.2 mm. The meter uses the Doppler shift theory in that the in-coming frequency of the sound waves will be shifted from the outgoing frequency of the sound waves. The magnitude of this shift is used to estimate the magnitude of x, y and z velocity vectors.

The ADV sampled at a frequency of 25 Hz which allowed for estimation of turbulence at the sample point from the fluctuations in the velocity magnitudes. Each point sample was collected over a 2 minute time interval. Recent research shows that for estimating turbulence parameters a sample time period of 60 to 90 seconds is sufficient for most river type settings (Buffin-Belanger and Roy, 2005). To further investigate the time period for each velocity sample point, an assessment was performed by comparing the turbulent kinetic energy (TKE), which is an estimate of the magnitude of turbulence, to the number of samples used to calculate it.

TKE is computed from the ADV data in the following manner. The standard deviation of the velocity fluctuation in a given direction, for example the x-direction, at a point is equal to the root-mean square of the velocity fluctuations, u' , measured over the sampling time period:

$$u' = u - U \quad (2.1)$$

$$u'_{RMS} = \sqrt{\frac{\sum (u')^2}{n}} \quad (2.2)$$

where u is the instantaneous velocity at a specific time and space in the x-direction; U is the average velocity in the x-direction; u' is the component of fluctuating velocity in the x-direction (deviation between the time specific velocity and the average in the x-direction due to turbulent motion); and n is the number of velocity samples.

TKE is calculated from the root-mean square of the velocity fluctuations in each direction: u' , v' and w' :

$$TKE = \frac{1}{2}[(u'_{RMS})^2 + (v'_{RMS})^2 + (w'_{RMS})^2] \quad (2.3)$$

where v' is the component of fluctuating velocity in the y-direction; w' is the component of fluctuating velocity in the z-direction.

Figure 7 compares the TKE to the number of samples used to calculate TKE (representing the time period) at three different spatial locations in a cross section. Velocity data was collected on July 21, 2004. This figure shows that TKE reaches a relatively constant value at a given location around 80 samples. A sample represents one second of velocity data collection in this exercise.

The discharge of the stream can fluctuate during the course of a day. Typical daily fluctuations can occur due to snowmelt, rain storms, and evapotranspiration. To minimize the change in discharge during a sampling event, data was collected as quickly as possible. 1-D inlet velocity data sets were collected during periods without any rainfall and a typical duration from start to finish was one to two hours. If a rain event occurred during data collection, that data set was rejected. The 3-D data sets were collected late in the summer to limit the influence of rainfall as this time of year is typically drier than other times of the year.

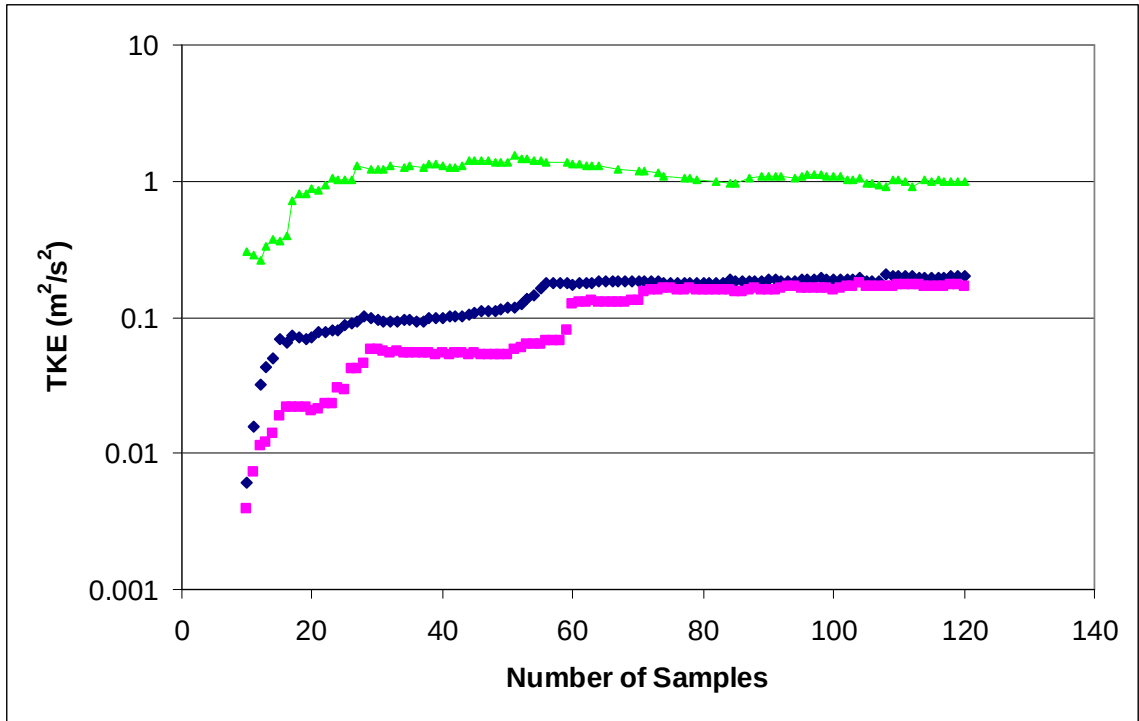


Figure 7. Comparison between TKE and the number of samples taken for three different sampling points in a cross section.

Even though care was taken to collect data that represented a steady state condition with regard to changing discharge, discharge and velocity did change during the measurements. To quantify a typical variation in velocities at a culvert inlet, three data sets were collected consecutively and compared statistically. The Pygmy meter and the ability to place the meter in the exact position on consecutive measurements provides some measure of error to this analysis in addition to the error inherent to the instrument and the turbulent nature of the flow field.

The physical characteristics of Culvert 1, Culvert 2 and near-stream characteristics were measured using a total station surveying instrument. This information was used for constructing flow models. A detailed topographic survey of the upstream and downstream stream channel was performed. The topographic survey

included the thalweg of the channel as well as several key cross sections (for instance the cross section at the outlet pool). Other physical characteristics measured include: culvert slope, length, type, and outlet drop.

Numerical Model Development

A numerical model of the fluid flow through Culvert 1 was created using ANSYS-CFX. The purpose of the model was to investigate the velocity field through the culvert barrel for a range of flows, to predict the velocity field for estimation of fish energy expenditures, and to aid in other hypothesis testing. In addition, the accuracy of using 3-D CFD techniques for prediction of water depths and velocities through Culvert 1 was investigated. The first part of this section describes some of the theory behind fluid motion and the governing equations of fluid motion. The second part describes the specifics of the model as developed using ANSYS-CFX.

Theoretical Model of Fluid Flow: The continuity equation stems from the physical principle of mass conservation. Applied to a fluid element, the equation dictates that the mass flow in and out of the surfaces of the fluid element must be equal to the time rate of change of mass within the fluid element (Anderson, 1995).

The Navier-Stokes equations are derived by applying Newton's second law along with the continuity equation and a constitutive relationship to describe the motion of viscous fluids. Newton's second law when applied to a moving fluid element requires that the net force acting upon the fluid element is equal to its mass times the acceleration of the element (Anderson, 1995). The continuity and Navier-Stokes equations written in conservation form (stationary frame of reference) are:

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{v}) = 0 \quad (2.4)$$

x-momentum (Navier-Stokes):

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \bar{v}) = -\frac{\partial p}{\partial x} + \nabla \cdot (\mu \nabla u) + S_{MX} \quad (2.5)$$

y-momentum (Navier-Stokes):

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \bar{v}) = -\frac{\partial p}{\partial y} + \nabla \cdot (\mu \nabla v) + S_{MY} \quad (2.6)$$

z-momentum (Navier-Stokes):

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \bar{v}) = -\frac{\partial p}{\partial z} + \nabla \cdot (\mu \nabla w) + S_{MZ} \quad (2.7)$$

where ρ is water density; t is time; $\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$; $\bar{v}$ is the instantaneous velocity

vector; v is the instantaneous y-component of velocity; w is the instantaneous z-

component of velocity; p is the instantaneous pressure; S_{MX} is the gravity force in x-

direction, S_{MY} is the gravity force in y-direction; S_{MZ} is the gravity force in z-direction; and μ is the dynamic viscosity of water.

These equations describe the instantaneous motion of fluids in space and time and do not account for the effects of turbulence on fluid motion. Turbulence in water adds additional stresses to fluids. These stresses are often referred to as Reynolds' stresses after Osborne Reynolds, who first described them (Versteeg and Malalasekara, 1995). Reynolds proposed the idea that flow at a point is always unsteady, and that the instantaneous velocity at a point over time is equal to a mean component and a fluctuating component. Figure 8 shows a time series for the instantaneous $u(t)$ velocity component in the x-direction. The mean value (U) is shown by the solid line and the “scatter” about the mean represents the fluctuating component u' .

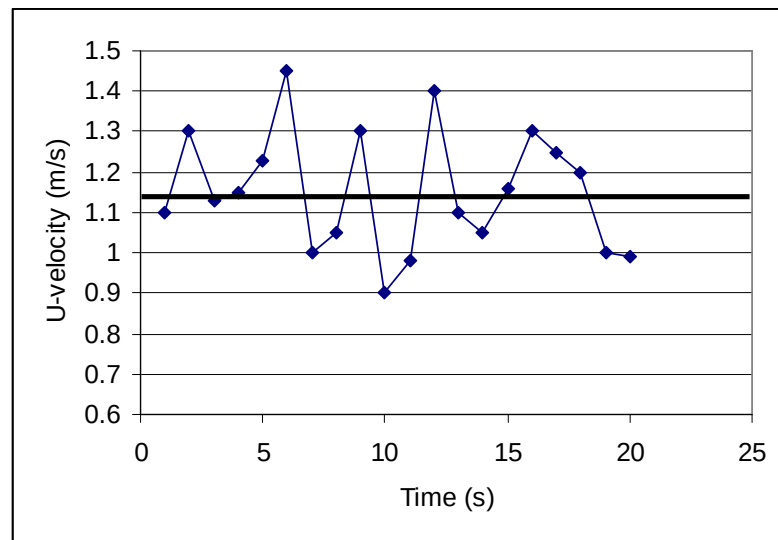


Figure 8. Chart shows a series of instantaneous velocity values collected at a point in a culvert.

To show the influence of turbulent perturbations on the mean flow, the instantaneous flow variables in equations 2.4 to 2.7 are replaced by the sum of the mean and fluctuating components:

$$\bar{v} = \bar{V} + \bar{v}' \quad (2.8)$$

$$u = U + u' \quad (2.9)$$

$$v = V + v' \quad (2.10)$$

$$w = W + w' \quad (2.11)$$

$$p = P + p' \quad (2.12)$$

where $\bar{V}$ is the average velocity vector in Cartesian coordinates, $\bar{v}'$ is the average velocity fluctuation; U is the average velocity in the x-direction, V is the average velocity in the y-direction; W is the average velocity in the z-direction; P is the average pressure; and p' is the random contribution of pressure due to turbulence.

After a large amount of algebra, the turbulent flow equations (or Reynolds averaged Navier Stokes equations) can be written:

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U \bar{V}) = -\frac{\partial P}{\partial x} + \nabla \cdot (\mu \nabla U) + \left[-\frac{\partial(\rho \overline{u'^2})}{\partial x} - \frac{\partial(\rho \overline{u'v'})}{\partial y} - \frac{\partial(\rho \overline{u'w'})}{\partial z} \right] + S_{Mx} \quad (2.13)$$

$$\frac{\partial(\rho V)}{\partial t} + \nabla \cdot (\rho V \bar{V}) = -\frac{\partial P}{\partial y} + \nabla \cdot (\mu \nabla V) + \left[-\frac{\partial(\rho \overline{u'v'})}{\partial x} - \frac{\partial(\rho \overline{v'^2})}{\partial y} - \frac{\partial(\rho \overline{v'w'})}{\partial z} \right] + S_{My} \quad (2.14)$$

$$\frac{\partial(\rho W)}{\partial t} + \nabla \cdot (\rho W \bar{V}) = -\frac{\partial P}{\partial z} + \nabla \cdot (\mu \nabla W) + \left[-\frac{\partial(\rho \overline{u'w'})}{\partial x} - \frac{\partial(\rho \overline{v'w'})}{\partial y} - \frac{\partial(\rho \overline{w'^2})}{\partial z} \right] + S_{MZ} \quad (2.15)$$

The Reynolds averaged Navier Stokes equations now contain an additional six unknowns. Prior to accounting for turbulence, there were four equations and four unknowns (u, v, w, p). Now, there are four equations and ten unknowns: the additional six unknowns are $\overline{u'^2}, \overline{v'^2}, \overline{w'^2}, \overline{u'v'}, \overline{u'w'}, \overline{v'w'}$. This problem is often called the turbulence closure problem (Anderson, 1995; Versteeg and Malalaskara, 1995).

A series of different models have been developed over the years to approximate the effects of turbulence and to aid in solving turbulent flow problems. These models are referred to as turbulence models. One of the earlier models developed was the κ - ϵ model (Launder and Spaulding, 1974).

Launder and Spaulding developed a form of the κ - ϵ model called the standard κ - ϵ model (Launder and Spaulding, 1974). This model uses two equations: one to represent the turbulent kinetic energy (κ), and a second to represent the rate of dissipation of turbulent kinetic energy (ϵ).

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho k \bar{V}) = \nabla \cdot \left[\frac{\mu_t}{\sigma_k} \nabla k \right] + 2\mu_t E_{ij} \cdot E_{ij} - \rho \epsilon \quad (2.16)$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \epsilon \bar{V}) = \nabla \cdot \left[\frac{\mu_t}{\sigma_\epsilon} \nabla \epsilon \right] + C_{1\epsilon} \frac{\epsilon}{k} 2\mu_t E_{ij} \cdot E_{ij} - C_{2\epsilon} \rho \frac{\epsilon^2}{k} \quad (2.17)$$

The eddy viscosity (μ_t) in this equation is as follows:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (2.18)$$

where σ_τ , σ_ε , $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ are constants; i and j are indices used to represent Einstein notation, and E is the strain tensor. These constants were determined by comprehensive data fitting to a wide range of turbulent flows (Versteeg and Malalaskaara, 1995).

The Boussinesq approach is used to approximate the Reynolds' stresses. Boussinesq first expressed this theory in 1877. The theory states that the turbulent stresses are proportional to the mean rate of deformations (Versteeg and Malalaskaara, 1995). The κ - ε model uses the following equation for this approximation:

$$-\overline{\rho u'_i u'_j} = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (2.19)$$

where δ_{ij} is the Kronecker delta, which is 0 unless $i = j$, then $\delta_{ij} = 1$.

ANSYS-CFX uses a multiphase model, with air and water representing the two phases of fluid, to model the “free-surface”. The free-surface represents the interface between air and water. ANSYS-CFX solves for the free-surface using the volume of fluid (VOF) method. The VOF method (after Hirt and Nichols, 1981) works in the following manner.

For the case of air and water as the two fluids, the approach defines a function (f) that has a value of unity at a point occupied by water and zero elsewhere. The average value of f in a cell represents the fractional volume of fluids in that cell; a value of 1 corresponds to a cell full of water, a value of 0 corresponds to a cell void of water (or full of air), and a value of f between 0 and 1 must therefore contain the free-surface. For 3-D flow, f is constrained by the following equation:

$$\frac{\partial f}{\partial t} + U \frac{\partial f}{\partial x} + V \frac{\partial f}{\partial y} + W \frac{\partial f}{\partial z} = 0 \quad (2.20)$$

This constraint equation is essentially solved in sequence with the continuity and Reynolds averaged Navier Stokes equations to approximate the free-surface. An example of how this equation is solved for 2-D flow is shown in Figure 9. Discrete values of f are located at grid point (i,j) in a mesh.

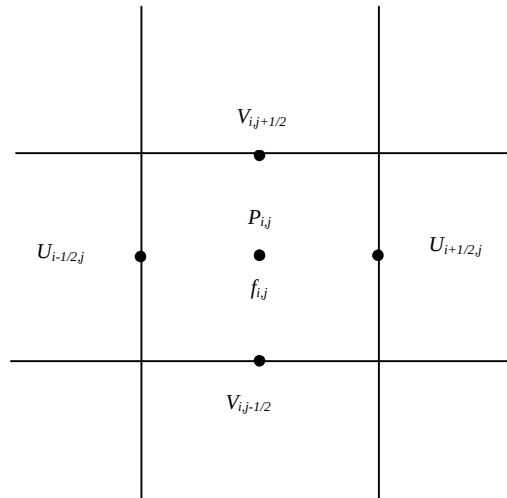


Figure 9. Location of flow variables, including pressure (P) and velocity (U, V), and the volume of fluid function (f) in a typical mesh cell.

The solution proceeds through one iteration by first approximating the fluid velocities (U, V) and pressure (P) by solving the Reynolds averaged Navier Stokes equations using the previous time-step values. Then the f function is solved for by using the neighboring cell values and the approximated velocities (U, V , and P).

ANSYS-CFX Model Development: ANSYS-CFX uses the finite volume method to solve the equations of fluid motion. Discretization of the integral form of the governing equations (continuity and Navier-Stokes) is the finite volume method (Anderson, 1995). Discretization of the partial differential equations (PDE) represents the finite difference method. Discretization is the process by which the integrals or PDEs are transformed into algebraic equations which can then be solved utilizing numerical methods. The details of the model of culvert flow developed using ANSYS-CFX are discussed in the following paragraphs.

The first step in creating a model is to describe the geometry of the model. The geometry (which represents the domain) was constructed using a drawing program within ANSYS Workbench. The geometry for this solution included only the bottom half of the culvert (Figure 10). For the range of flows analyzed with this model, the water depth never exceeded 0.6 m (1.0 m is the height of the modeled area). Therefore, the geometry used still accounted for the water, the free-surface interface and some air above the water. Using only one-half of the culvert as the domain reduced the computational effort.

Meshing is the next step for developing a model. Meshing is the process of partitioning the domain (fluid and air in culvert) into a grid upon which the equations are solved. The mesh size was initially set at 0.06 m.

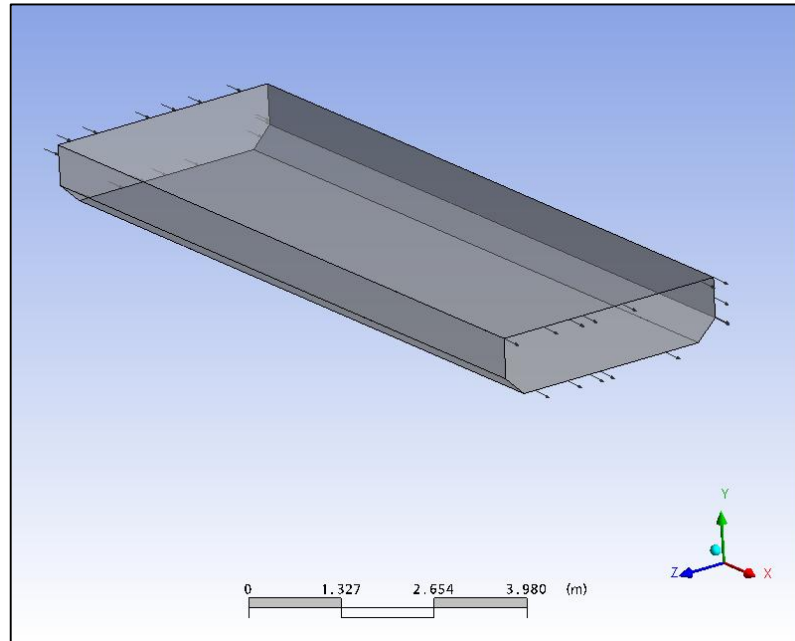


Figure 10. Geometry of culvert used in flow model.

The mesh can be refined in areas with steep velocity gradients to increase the solution accuracy. In open channels like the culvert, the velocity is zero at the bed and increases very quickly in the y-direction (steep gradient). Therefore, the initial mesh was inflated along the culvert bed and sides (see Figure 11).

As the solution progresses, ANSYS-CFX can re-mesh areas of the solution domain to increase the accuracy of the solution. This process is called mesh adaptation and is typically done in areas of the domain where large changes occur. For the culvert model, mesh adaptation was done in areas with the greatest change in volume fraction between air and fluid (along the free-surface interface).

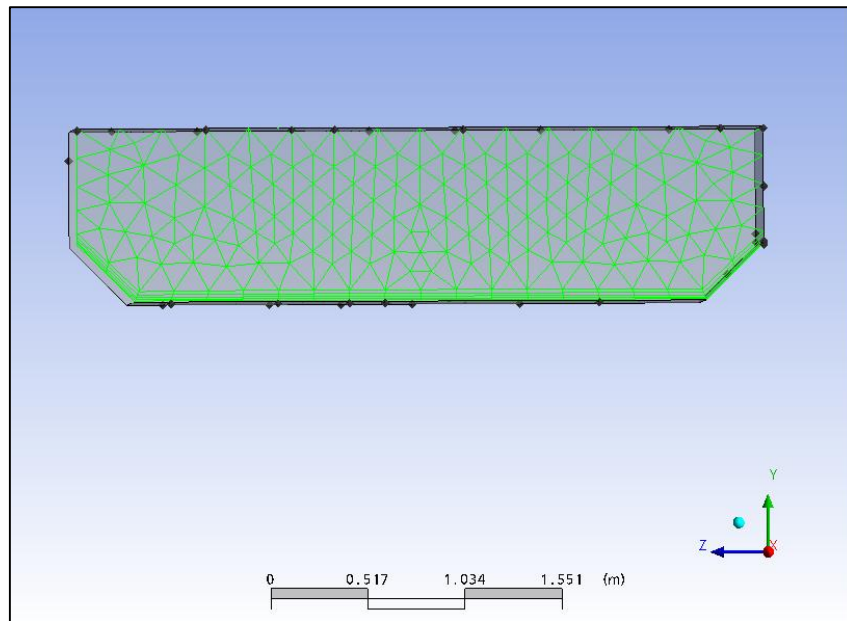


Figure 11. Diagram showing the initial mesh for the culvert flow model.

Boundary conditions are applied to the sides or faces of the domain. An inlet boundary condition using mass flow rate was set at the culvert inlet. Wall boundary conditions were used on all sidewalls (four surfaces) and the culvert floor (one surface). The wall boundary condition applies a no-slip condition, which indicates water flow is zero at the culvert bed and sidewall. The boundary wall type was set as a rough wall and the roughness height was initially set using values from Schlichting and Gersten (2000) for surfaces similar to the concrete bed of the culvert.

The initial roughness value was set using data for asbestos cement as an approximation of the roughness of the box culvert; the roughness of the structure in the field is different (especially for structures that have been in place for years) because the scouring action of water and sediment has changed it. Therefore, a calibration procedure

was performed by changing the roughness height from the initial value and comparing the predicted water surface to the measured water surface for a known flow rate. The final roughness height (k_s), and the value used in subsequent modeling efforts, was selected as the height that minimized the difference between the measured and predicted water depths ($k_s = 0.001$ m). Figure 12 shows the percent difference between measured and actual water depths for different roughness heights.

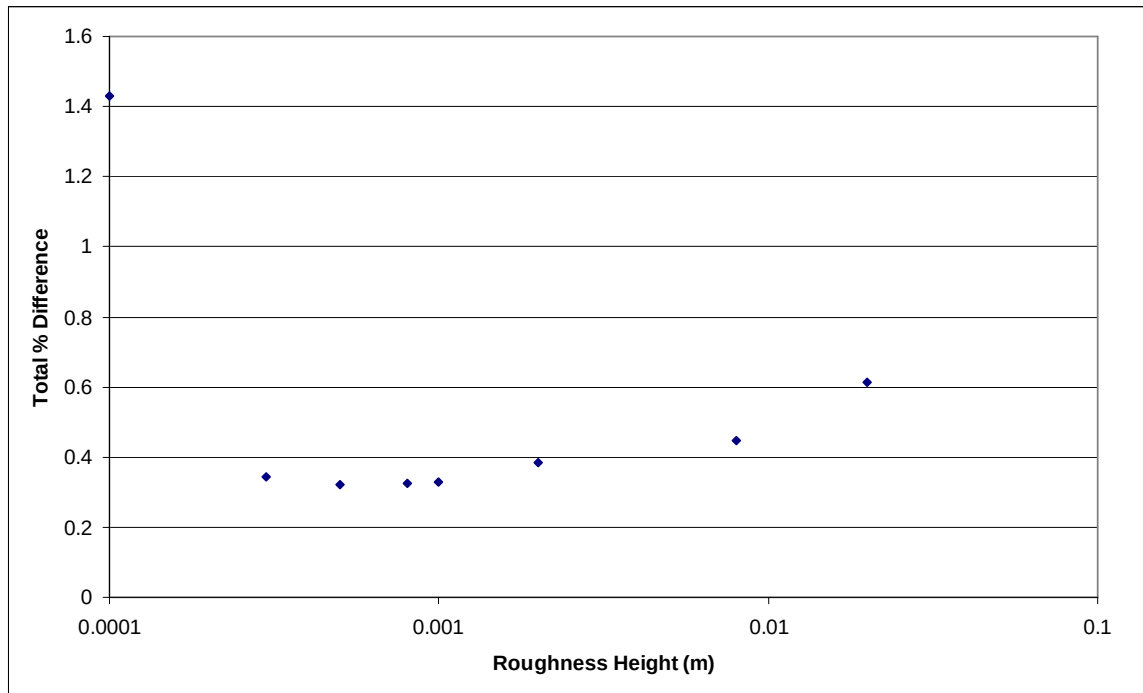


Figure 12. Graph showing the percent difference between predicted and observed water surfaces for different roughness values.

A static pressure boundary condition that represented the depth of water at the culvert outlet was used as the boundary condition for the outlet of the culvert. A free-slip or symmetry boundary condition was used for the top of the model.

Initial conditions were given to begin the solution process. The mass flow rate, provided as a grid of water velocities at the culvert inlet, was typically used to initiate the inlet boundary of the model. Inlet conditions were either field measured values of velocities or velocities estimated using regression relationships built from the measured fields. The water velocities within the domain of the culvert were set equal to 0 m/s for all solutions. The depth of water at the culvert outlet, either measured or estimated using regression relationships built from measured depth/flow relationships, was used for the culvert outlet boundary condition.

To initiate the solution of the free-surface, a step function was used to represent the depth of water at the culvert inlet. The step function describes the volume of fluid for both the water and air at the inlet of the culvert. For instance, at heights greater than the water depth at the culvert inlet, the step function returns a value of zero for the water volume fraction and one for the air volume fraction. At heights less than the water depth at the culvert inlet, the step function returns a value of one for the water volume fraction and zero for the air volume fractions.

The time step for the momentum and turbulence models was set to 0.1 s. The time step for the VOF equation was set to 0.02 s. A residual of 0.0001 was set as the target for model convergence. Appendix B includes an example input code for the ANSYS-CFX model.

Results and Discussion

The physical characteristics of Culvert 1 and 2 are summarized in Table 3.

Both culverts are very similar in dimension with the main difference being the offset baffles in Culvert 2.

Table 3. Summary of physical characteristics of culverts studied in the Mulherin Drainage.

Culvert Type	Slope (%)	Outlet Drop (m)	Length (m)	Internal Structure
Box (1)	1.1	0.49	11.13	None
Box (2)	0.8	0.48	9.33	Offset Baffles

Velocity Measurements

Maps of inlet and plan view velocities in Culvert 1 and 2 were constructed using AUTOCAD Land Desktop. An example of a 3-D inlet velocity pattern collected at Culvert 1 is shown in Figure 13. The velocity pattern shows a faster portion of flow on the right side of center. This faster flow is due to the skew of the culvert and upstream channel. The flow is mainly in the x-direction (into the page), with small components of flow in the y- and z-direction. The TKE is greatest in the area with the largest velocities, which is expected as turbulence is proportional to velocity.

Figure 14 presents a plan view of u -velocity contours (isocontours) at 0.06 m above the bed in Culvert 1. The contours clearly show the skewed inlet pattern propagating into the culvert, the region of faster flow on the right side of the culvert, and the slower flow on the left side.

Figure 15 shows a contour map of u -velocities collected on a plane 0.06 m above the culvert bed (the same plane as in Culvert 1 and Figure 14 above) in Culvert 2, the

baffled pipe. Comparison of the two figures shows the large difference in the pattern of flow between Culvert 1 and Culvert 2. The offset baffles in Culvert 2 dissipate energy, increase water depth and create low velocity regions. Appendix C includes maps of inlet and plan view velocities in these culverts for various flow rates.

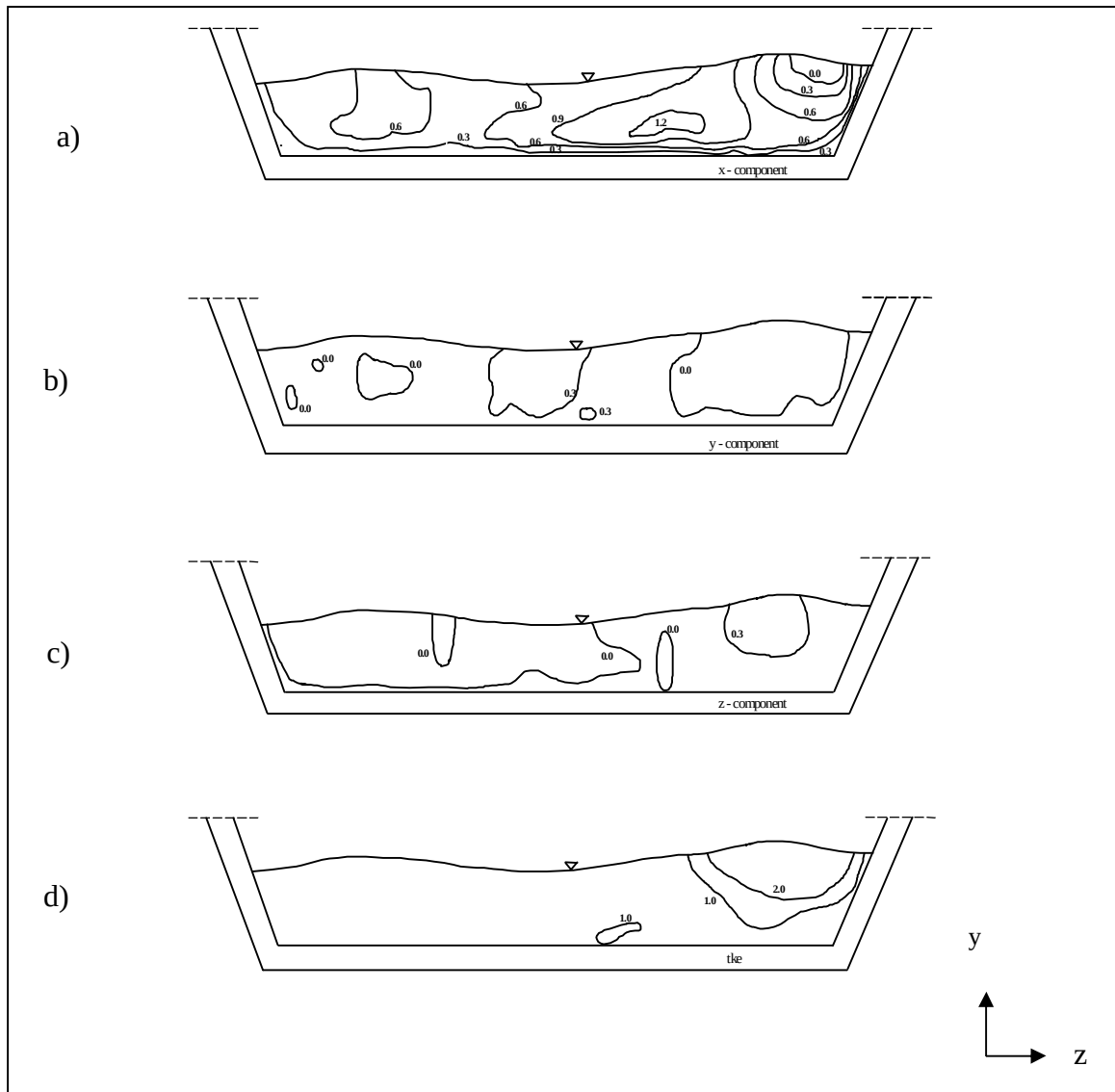


Figure 13. x-, y-, and z-velocity components and TKE contours at inlet of Culvert 1 collected on August 8, 2004. Discharge during measurement averaged $0.85 \text{ m}^3/\text{s}$. Velocity contours are in m/s. Note: Only bottom portion of culvert is shown; dashed lines on sides are breaks. a) x – component of velocity, b) y – component of velocity, c) z – component of velocity, and d) TKE.

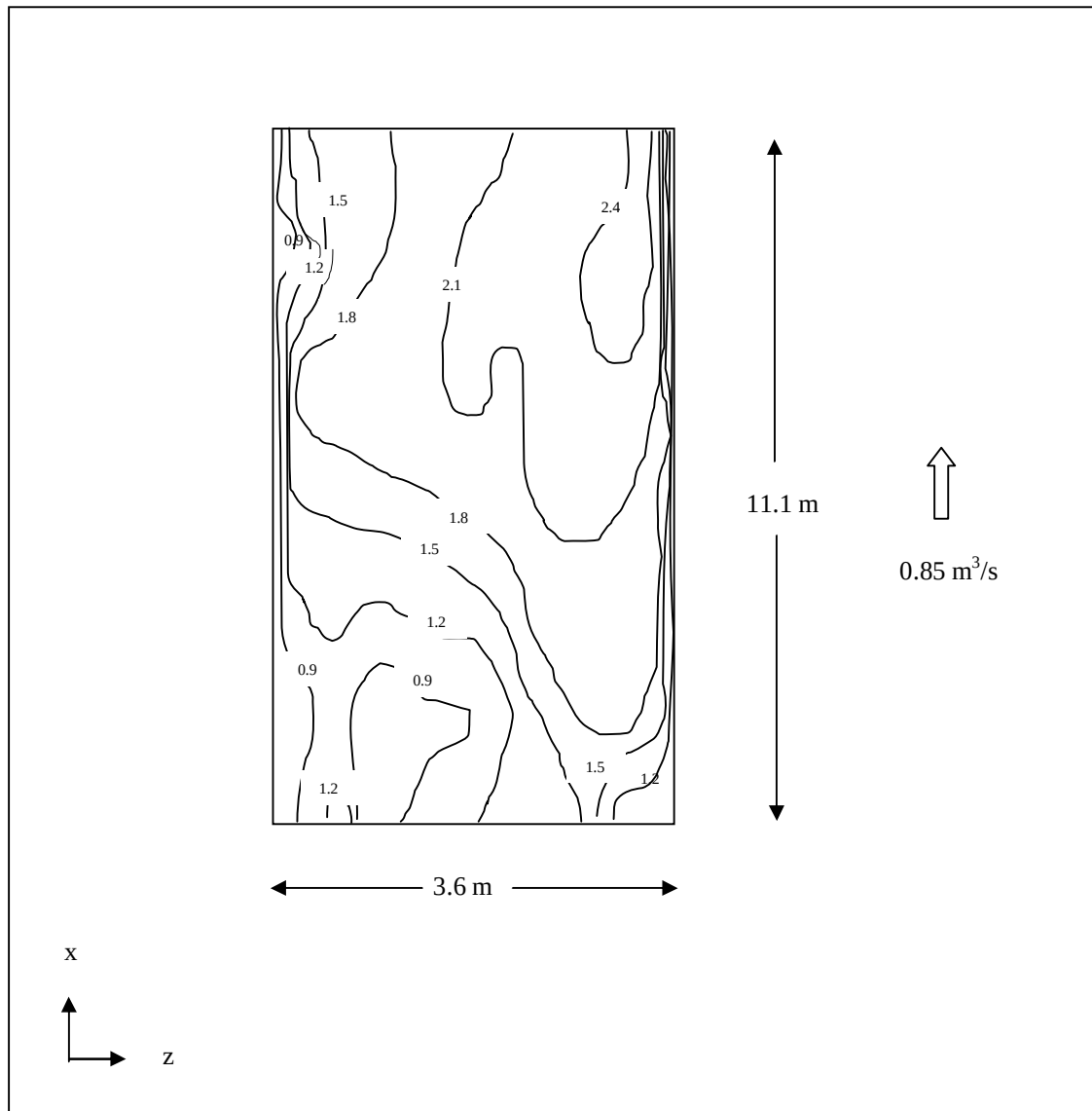


Figure 14. August 9, 2004 plan view of u -velocity in Culvert 1 collected with Pygmy meter. Velocity contours are in m/s. Measurements collected at 0.06 m above the culvert bed.

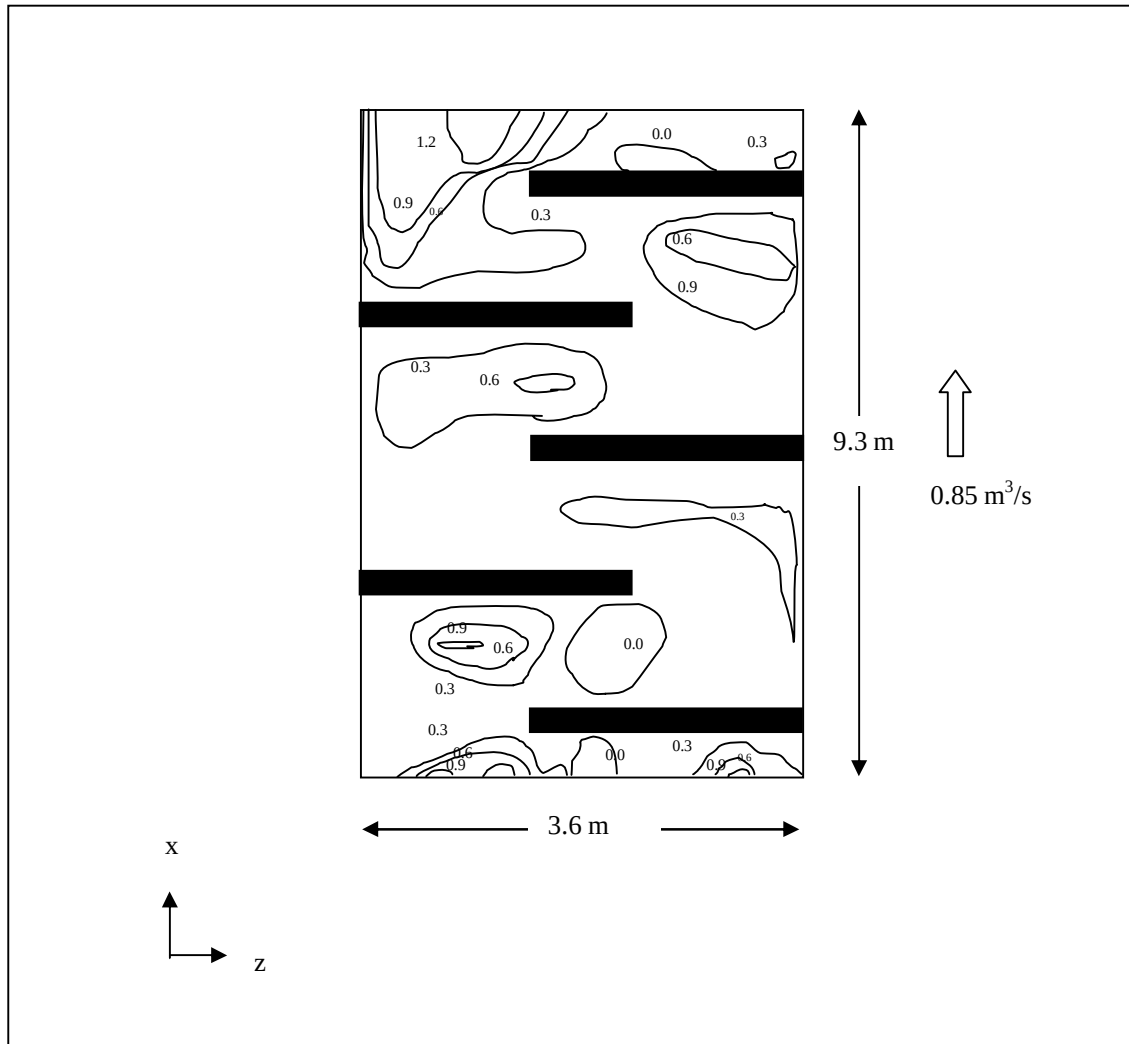


Figure 15. August 4, 2004 plan view of u -velocity in Culvert 2 collected with ADV meter. Velocity contours are in m/s. Measurements collected at 0.06 m above the culvert bed. Black rectangles in figure are baffles.

Velocities in Culvert 1 and Culvert 2 on a plane 0.06 m above the culvert bed are compared using box plots in Figure 16. These velocities were collected at the same discharge. Because the data were not normally distributed and variances were not equal, a non-parametric test, the Mann-Whitney test, was used to assess differences in velocities

between the baffled and unbaffled culvert. Not surprisingly, the difference in mean water velocity between the culverts was found to be highly significant ($p\text{-value} < 0.001$, $CI = 95\%$).

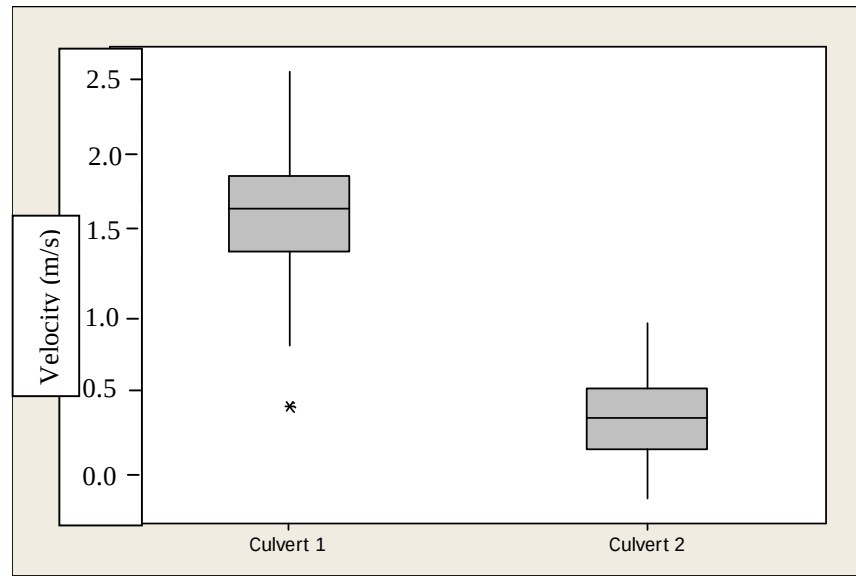


Figure 16. Box plot of velocity in Culvert 1 and Culvert 2 at $0.85 \text{ m}^3/\text{s}$. Velocities were collected on a plane located 0.06 meters above the culvert bed. Sample size was 60 measurements in each culvert. The box plots show the 1st and 3rd quartiles, which are equivalent to the 25th and 75th percentiles, of the velocity distributions. The horizontal line represents the median.

To assess the consistency of the inlet velocity data sets, three inlet velocity data sets were collected subsequently. Figure 17 shows a box plot of inlet velocities (labeled 1, 2 and 3 in order of collection) collected on July 28, 2006. Because the data were not normally distributed and the variances were not equal, a non-parametric test, the Kruskal Wallis test, was used to assess if the three velocity data sets had the same median. The Kruskal Wallis test results indicate there is not a significant difference between the medians of the three inlet velocity data sets. This result shows that velocity fluctuations

due to changing discharge were likely kept to a minimum during collection of inlet data sets.

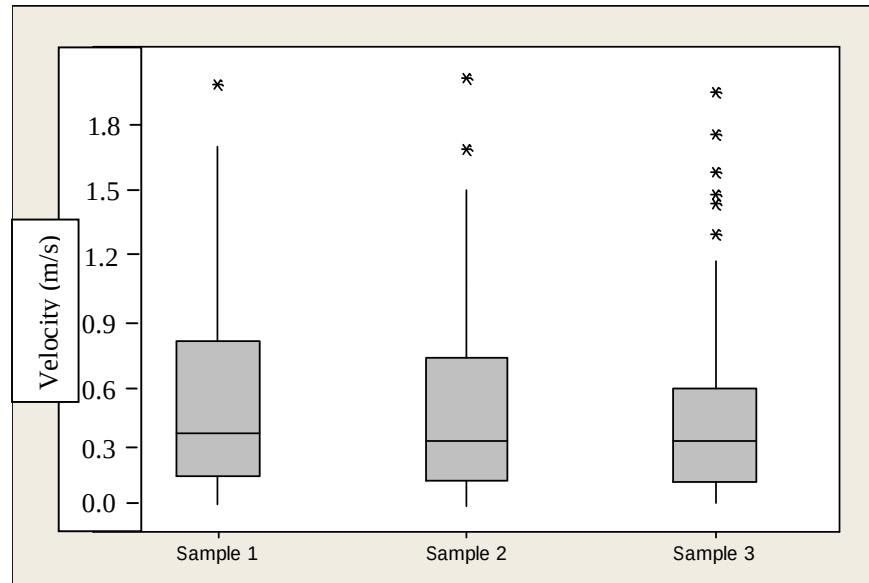


Figure 17. Box plot of inlet velocities collected as subsequent data sets at Culvert 1. The box plots show the 1st and 3rd quartiles, which are equivalent to the 25th and 75th percentiles, of the velocity distributions. The horizontal line represents the median.

Model Validation

The ANSYS-CFX model was validated against two separate velocity data sets: one collected on July 13, 2004 and a second collected on August 9, 2004. These data sets represent a relatively high (July 13) and a low (August 9) flow rate based on the stream hydrograph from 2004 to 2006. Model validation included comparison of the measured water surface along the centerline of the culvert to the predicted water surface, and comparison of measured velocities on a plane 0.06 m above the culvert bed to the predicted velocities.

Figure 18 shows a comparison between the predicted and measured water surface for field data collected July 13, 2004. Overall, the model did very well in predicting the

measured water surface with the exception of the water surface height near the inlet and outlet of the culvert. One possible explanation for the inlet discrepancy is the fact that the water surface is not flat at the inlet to the culvert; it has a superelevated water surface on the right side (see Figure 13). The boundary condition; however, for the inlet assumes the water surface is flat. In addition, the inlet region of the culvert is highly chaotic, making precise measurements of the water surface height quite difficult, adding uncertainty to the measurements. The discrepancy may also be due to the fact that the comparison is made at the inlet and outlet boundary conditions. There is potentially numerical error present in the inlet and outlet boundaries that may affect the predicted water surface.

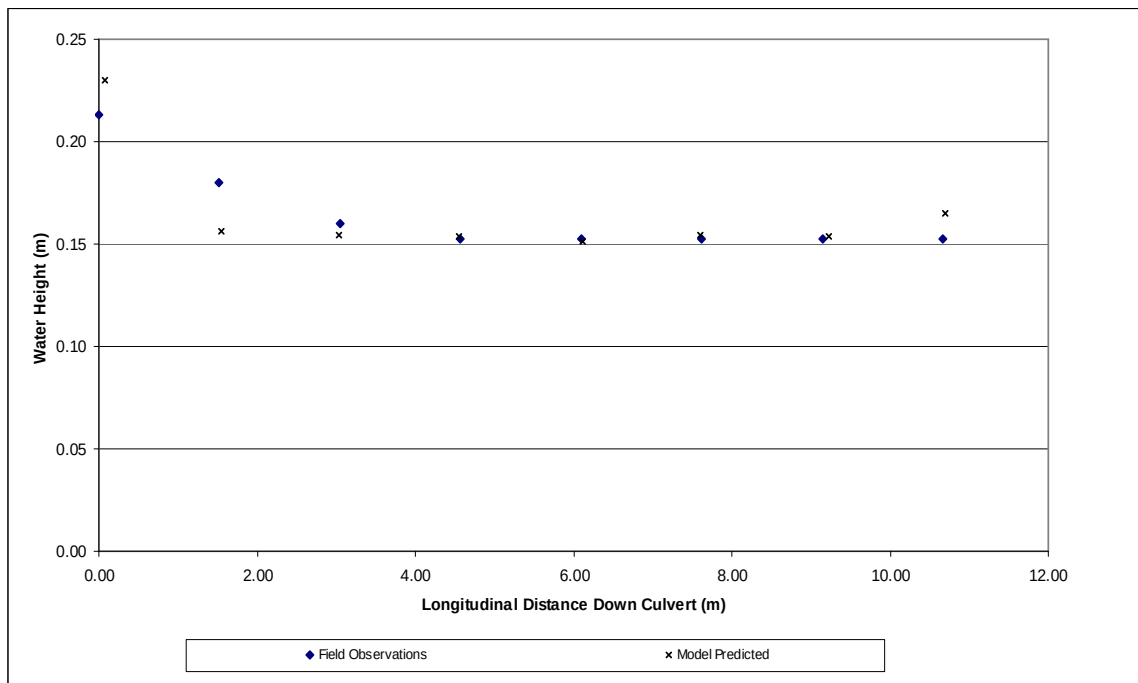


Figure 18. Water surface comparison between predicted water surface and measured water surface for model of flow July 13, 2004.

The model predicted velocities on a plane 0.06 m above the culvert bed with good accuracy. Figure 19 shows the observed velocities collected on July 13, 2004; and Figure 20 shows the model predicted velocities.

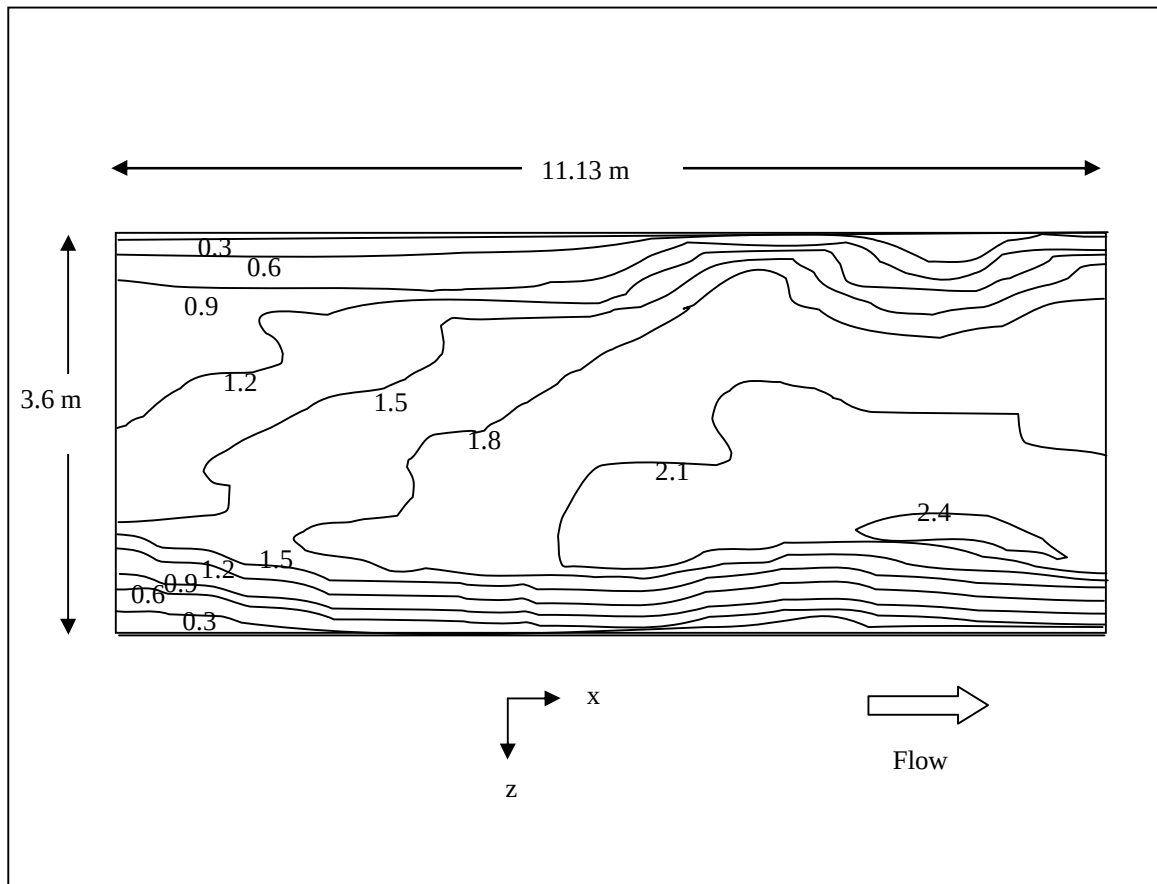


Figure 19. Observed velocities on a plane 0.06 m above the bed of Culvert 1. Observations collected on July 13, 2004. Velocity units are m/s and the contour interval is 0.3 m/s. Flow direction is left to right.

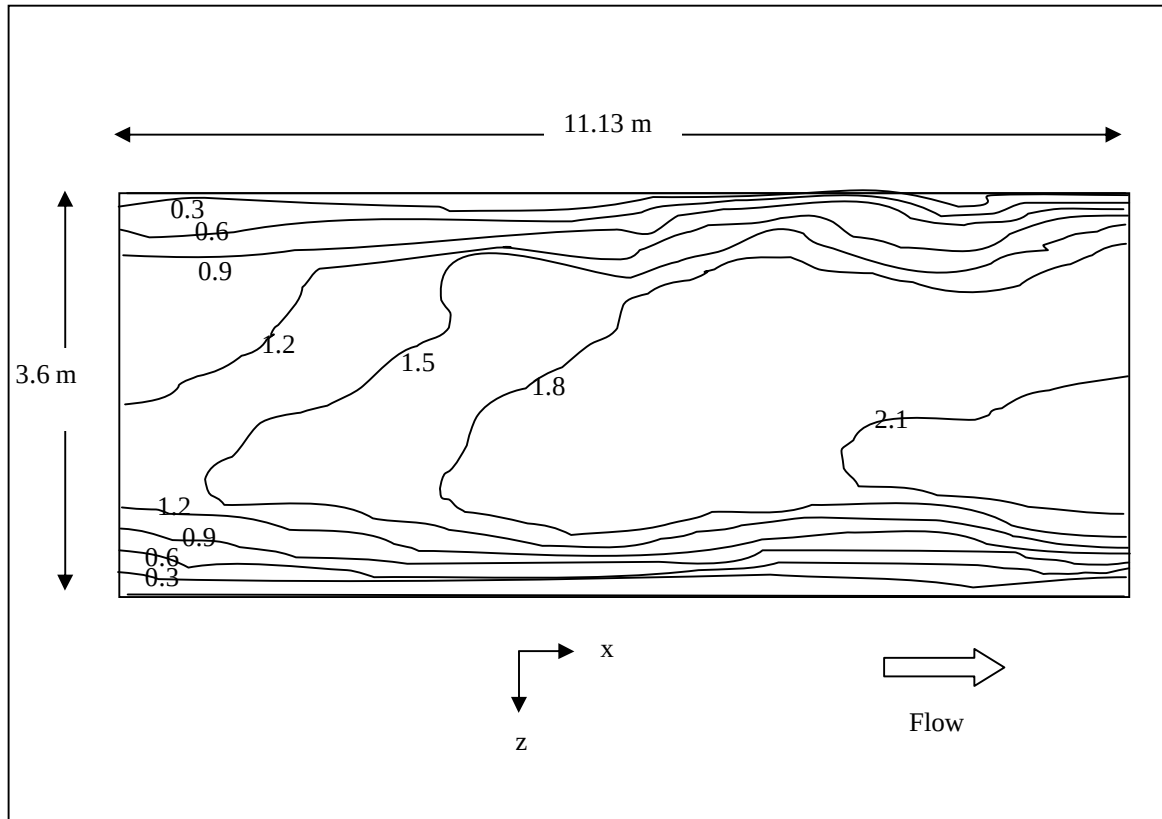


Figure 20. Velocities on a plane 0.06 m above the bed of Culvert 1 predicted with ANSYS-CFX model. Predictions for data collected on July 13, 2004. Velocity units are m/s and the contour interval is 0.3 m/s. Flow direction is left to right.

Figure 21 shows a plot of predicted velocities against observed velocities. The accuracy of the model was further evaluated by calculating two correlation coefficients: r^2_{mod} and r^2_{fit} . r^2_{mod} is a measure of the correlation between the predicted data and the measured data; and r^2_{fit} is a measure of the correlation between the data and the fitted regression line. These values were calculated following procedures described in McKittrick et al. (2004).

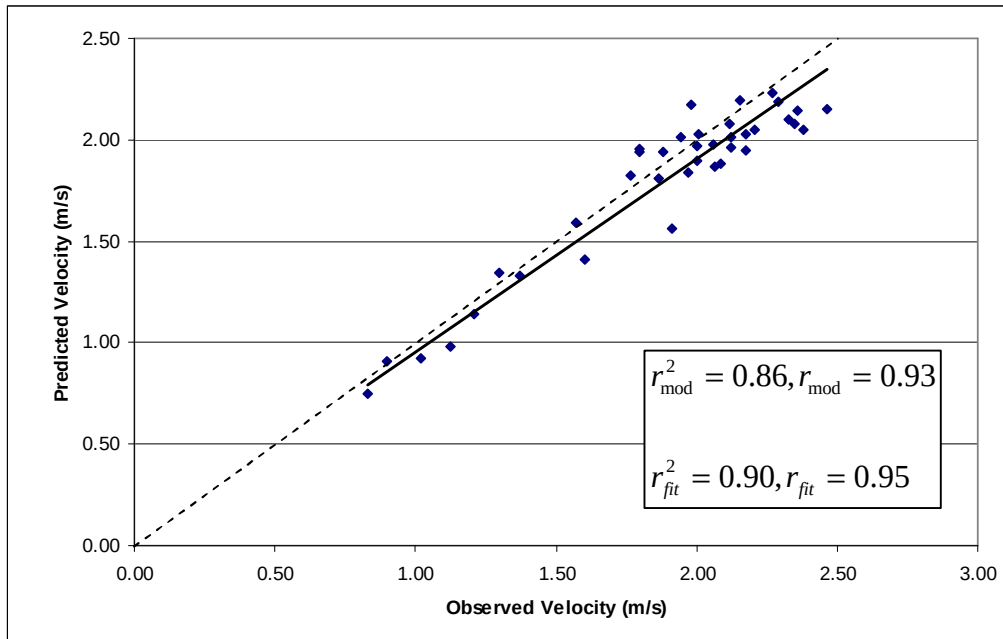


Figure 21. Predicted velocities graphed against observed velocities in Culvert 1 for model validation of July 13, 2004 data. Flow rate was $1.44 \text{ m}^3/\text{s}$. The dashed line on the graph represents a 1:1 line. The solid line is a linear fit to the data.

Based on the correlation coefficient, $r_{\text{mod}}^2 = 0.86$, 86% of variation in the observed velocity data were explained by the model, 14% was not. This value shows the model did reasonably well at predicting the data especially considering the variability in the data. The linear fit to data line is below the 1:1 curve fit indicating the model estimates are slightly low.

Figure 22 is a map of the percent difference between the observed and predicted velocities. The area with the largest percent difference (14%) is on the left side of the culvert looking downstream. A possible explanation for this is that the inlet boundary for the model is a flat water surface. As previously mentioned, the actual surface is superelevated towards the right side looking downstream, which reflects the centrifugal

force (due to the skew of the culvert) tending to move the region of higher momentum to the right side of the culvert entrance. This transfer of momentum is then bounced back towards the left side of the culvert; somewhat like a ping pong ball. The inlet boundary conditions for the model do not include the superelevation of the water surface which may explain the larger percent difference.

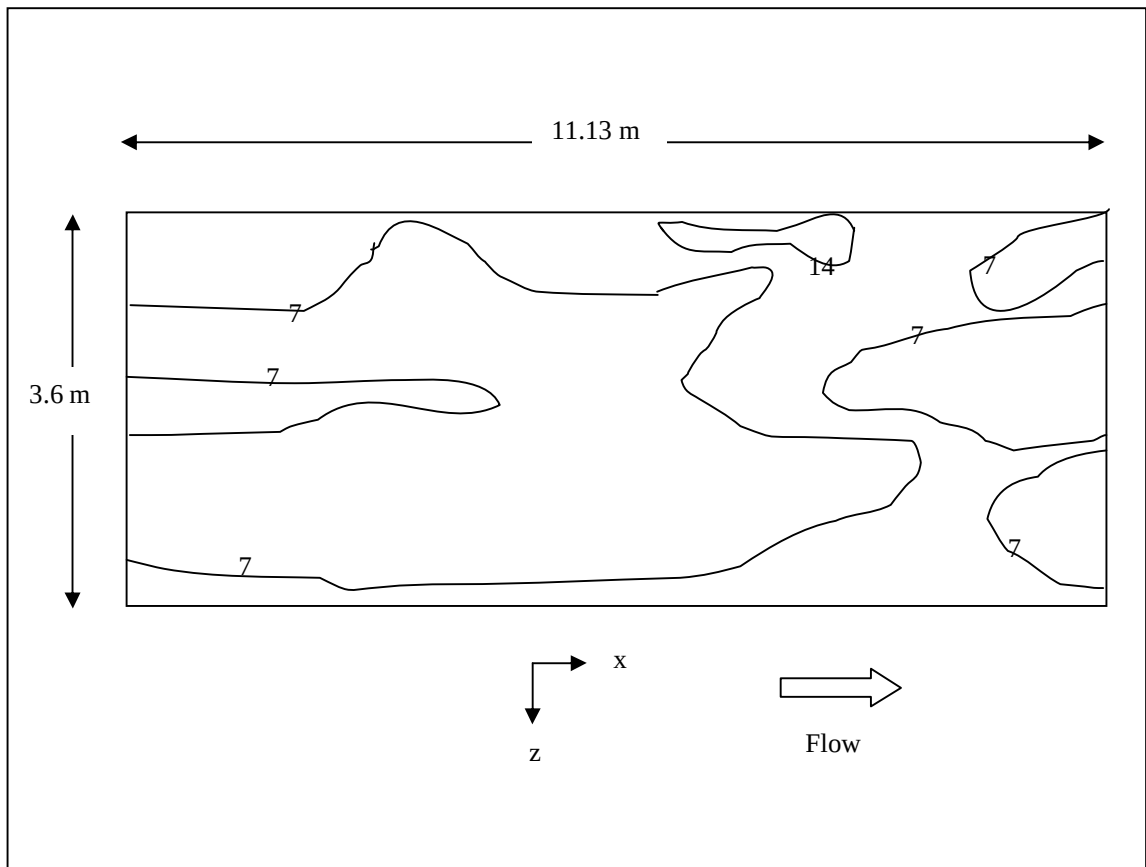


Figure 22. Percent difference between observed and predicted velocities, contours calculated on a plane 0.06 m above the bed of Culvert 1. Observations and predictions for data collected on July 13, 2004. Percent difference contour interval is 7%. Flow direction is left to right.

Figure 23 shows the measured velocity contours for the August 9, 2004 flow rate in Culvert 1. These observed contours show a slightly more irregular pattern than the July 13, 2004 contours. This is likely due to the fact that certain irregularities in the culvert bed influence the flow pattern more at lower flow depths. Also, as flow decreases, the affects of bed roughness are amplified.

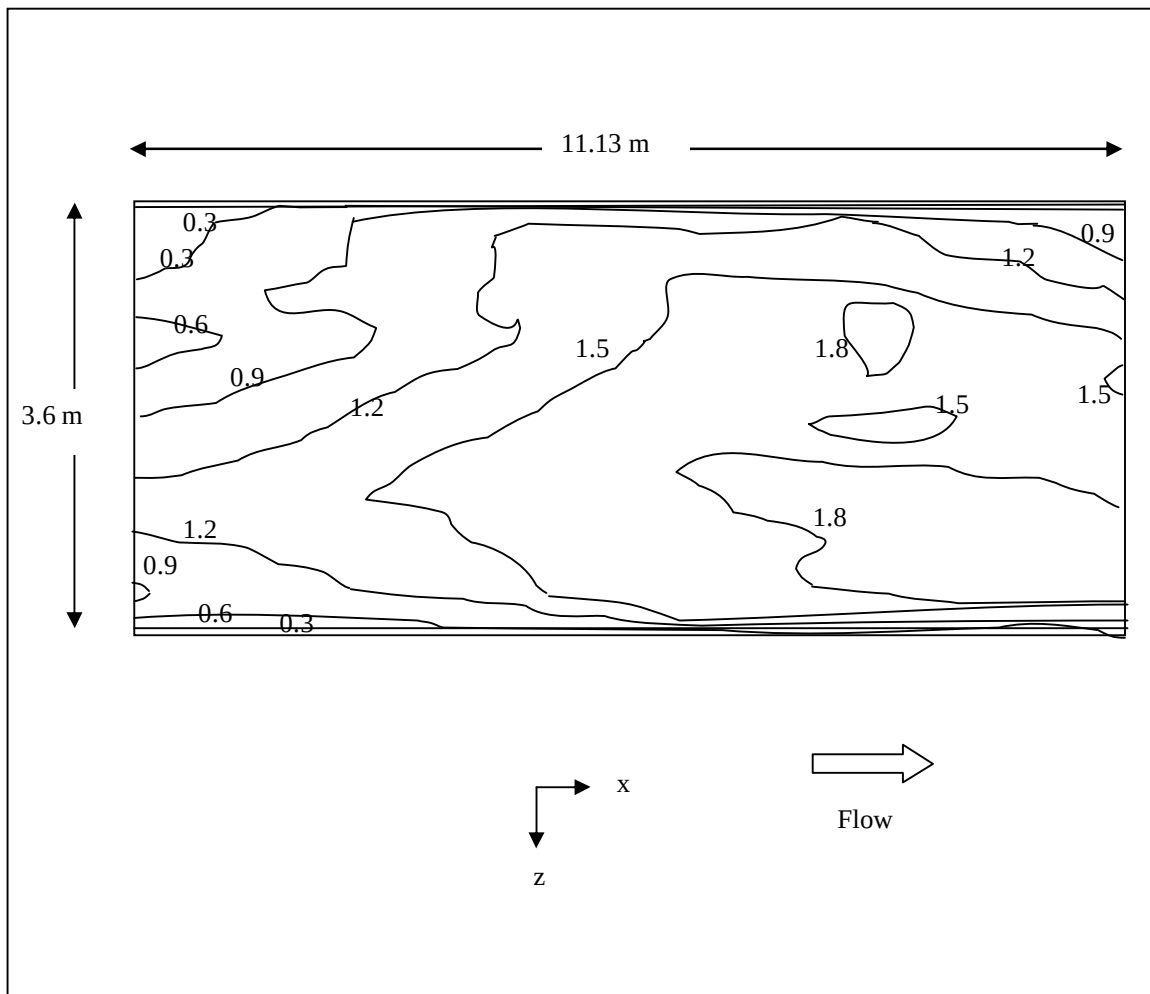


Figure 23. Observed velocities on a plane 0.06 m above the bed of Culvert 1. Observations collected on August 9, 2004. Velocity units are m/s and the contour interval is 0.3 m/s. Flow direction is left to right.

Figure 24 shows the model predicted velocity contours for August 9, 2004. The model captures the general pattern of the velocity contours fairly well simply by visual comparison of the observed and predicted patterns.

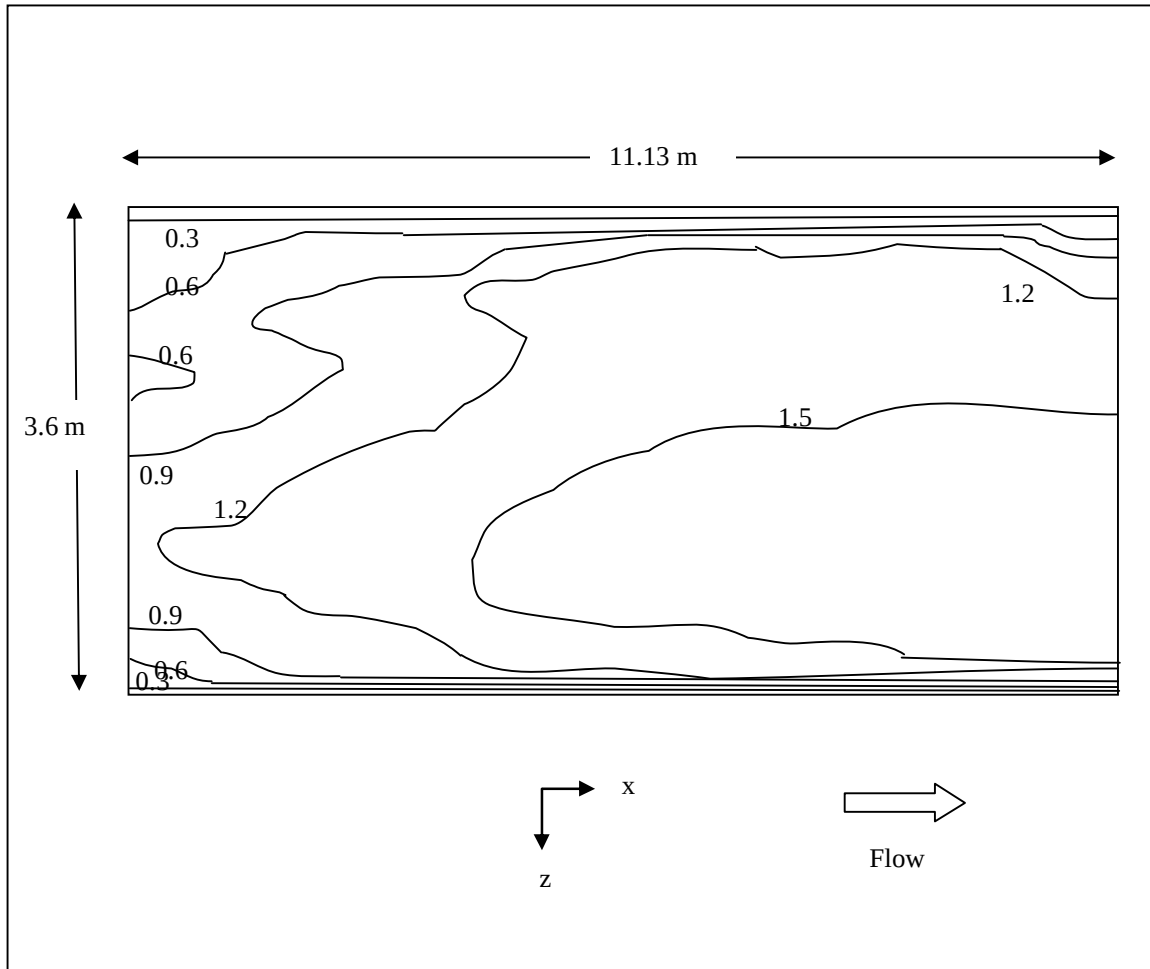


Figure 24. Velocities on a plane 0.06 m above the bed of Culvert 1 predicted with ANSYS-CFX model. Predictions for data collected on August 9, 2004. Velocity units are m/s and the contour interval is 0.3 m/s. Flow direction is left to right.

Figure 25 shows a graph of the predicted velocities at points in the plane compared to observed velocities. The graph and correlations show the model predicted the velocities reasonably well; however, the accuracy is slightly less than the July 13, 2004 model.

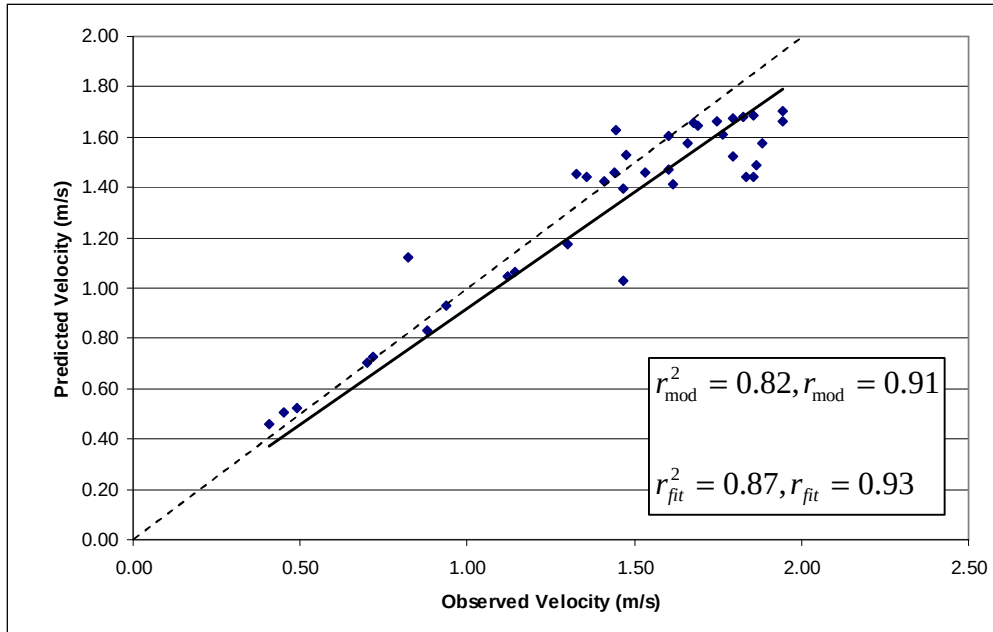


Figure 25. Predicted velocities graphed against observed velocities in Culvert 1 for model validation of August 9, 2004 data set. Flow rate was $0.87 \text{ m}^3/\text{s}$. The dashed line on the graph represents a 1:1 line. The solid line is a linear fit to the data.

Based on the correlation coefficient, $r_{\text{mod}}^2 = 0.82$, 82% of variation in the observed velocity data were explained by the model, 18% was not. Like the model of July 13, 2004 data, the correlation coefficient shows the model did reasonably well at predicting the data especially considering the variability in the data, although there is more variability in this case that is not accounted for by the model. The linear fit to data

line is below the 1:1 curve fit indicating the model estimates are slightly low, and that the model is predicting high velocities with less accuracy than low velocities.

Figure 26 shows a plot of the percent difference between the observed and predicted velocities. Percent differences in this model ranged from 0% to 21%.

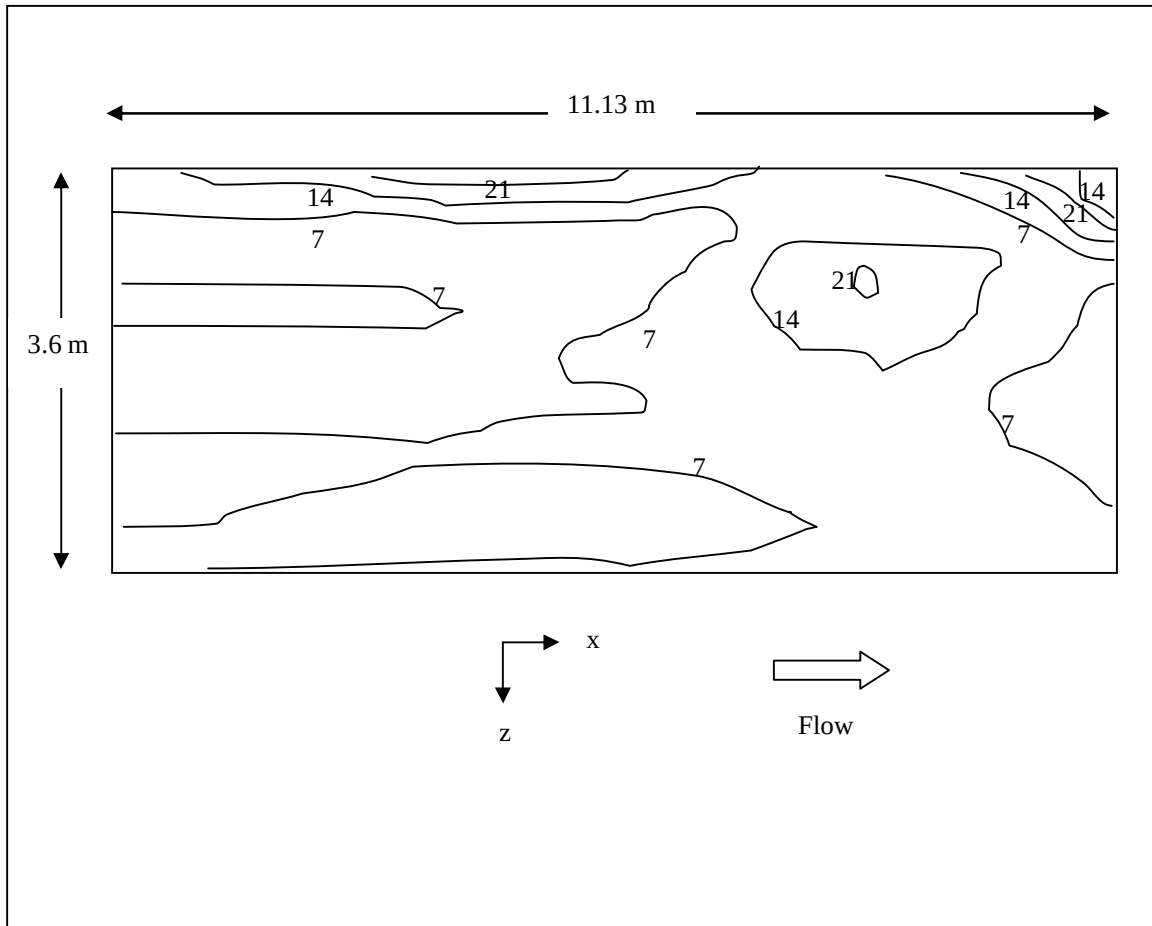


Figure 26. Percent difference between observed and predicted velocities, contours calculated on a plane 0.06 m above the bed of Culvert 1. Observations and predictions for data collected on August 9, 2004. Percent difference contour interval is 7%. Flow direction is left to right.

Model Accuracy

The ANSYS-CFX model proved to be as accurate as similar models of open channels used in other studies. For instance, Booker used SSIIM, a 3-D CFD code, to simulate hydraulic patterns in two engineered reaches of the River Tame (Booker, 2003). The velocity patterns in each reach at several flow regimes were compared to the maximum sustainable swimming speeds of fishes inhabiting the river. The study did show good agreement between the modeled velocity field and field recorded velocity profiles (with R^2 values of 0.80 and 0.92) for the two reaches studied.

Sources of Error

Several sources of measurement error exist as the measurements were collected in a field environment. The relatively crude measurement of water depth provided error to the model inlet and outlet conditions. In addition, the inlet boundary for the model was set as a flat surface when in actuality it has a fairly irregular surface. The inlet boundary condition may represent the largest source of error.

The instruments and method used to orient the equipment provided a source of potential error. This source for error applies more to the 1-D meter than the 3-D meter. The Pygmy meter is attached to a graduated rod and held by hand when taking measurements. Attempts were made to hold the rod vertically; however, the rod is likely tilted at times, thus providing another source of error. The 3-D meter is fastened to a stiff harness and only the receivers and transmitter penetrate the water surface.

The potential for fluctuating discharge during the measurements is another possible source of error. Attempts were made to collect data sets during time periods with the least amount of change in flow; however, it is impossible in a field setting to be

sure the discharge did not fluctuate over the course of the measurements. This is especially true with the 3-D measurements with the ADV, which usually take 4 to 8 hours to collect an inlet profile.

Last, there is always the possibility of human errors in recording the information.

Summary

A 3-D CFD model describing the velocity field through Culvert 1 was developed. ANSYS-CFX was the platform used to build the model. Detailed measurements of the velocity field were collected to characterize the velocity field both spatially and temporally through both culverts. The measurements were also used to validate the 3-D CFD model of culvert flow.

Velocity patterns in the baffled and unbaffled culvert differ significantly as expected. The upstream channel geometry is skewed relative to Culvert 1, the unbaffled culvert. This skew creates a region of higher flow on the right side of the culvert and lower flow on the left side. Velocity measurements show the pattern created by the upstream geometry propagates into the culvert barrel and creates a diversity of velocities.

The CFD model predicted velocities through Culvert 1 with good success. Comparisons between the predicted and observed velocities for two different flow rates show the model accurately describes the velocity field on a plane 0.06 m above the bed in Culvert 1 with r^2_{mod} of 0.86 for July 13, 2004 model ($Q = 1.44 \text{ m}^3/\text{s}$) and r^2_{mod} of 0.82 for August 9, 2004 model ($Q = 0.87 \text{ m}^3/\text{s}$).

PROPAGATION OF INLET VELOCITY

Velocity is a key factor in fish passage. The extent of our understanding of velocity in streams, through man-made structures, and fish behavior related to it is growing, yet still quite limited. The purpose of this section of the thesis is to investigate the linkage between the upstream channel and culvert flow, and the extent that inlet velocity patterns propagate through a culvert barrel.

Introduction

Hydraulic engineers have been analyzing velocities, water depths and flow patterns in various culverts with and without baffles for decades. A series of laboratory experimental studies in Canada investigated the hydraulic conditions in culverts with several different types of baffle systems: offset baffles, slotted-weir, weir baffles, spoiler baffles; and Alberta fish weirs and baffles (Rajaratnam et al., 1988; Rajaratnam et al., 1989; Rajaratnam and Katopodis, 1990; Rajaratnam et al., 1990; Rajaratnam et al., 1991). Equations relating discharge, flow depth, slope, and diameter were developed for each configuration. Patterns of flow in culverts do exist as evidenced by a correlation between dimensionless discharge and relative flow depth for six different baffle systems (Ead et al., 2002).

A group led by Rajaratnam conducted laboratory experiments on a smooth circular pipe with diameter 0.305 m and slopes of 1%, 3% and 5% for several flow rates to analyze water surface profiles and velocity profiles (Rajaratnam et al., 1991b). They found the depth of flow in the centerplane becomes approximately constant for x_c , the longitudinal distance from the entrance greater than about 15 times the critical depth y_c .

In this region, the velocity profiles tended to stabilize to a more uniform distribution, with the maximum velocity reaching a constant value. Also, their experiment showed that a very thin boundary layer was still developing at this point. They termed this region the “near-field” of the entrance region.

The classic one-dimensional model of velocity distribution, the Prandtl-Von Karmen law, uses a logarithmic form to estimate velocity as a function of distance above the channel bed (Chow, 1959). The logarithmic profile indicates velocities will increase with distance above the channel bed with a maximum at the surface. Velocity distributions in natural, open-channels often have maximum velocities below the surface due to irregular shapes and unsteady flows, making the logarithmic profile inaccurate at times. Also, friction between the air and water surface can influence surface water velocities.

Based on principles of entropy-maximization used in statistics, Chiu developed an equation to predict the 2-D velocity distribution in open channels (Chiu, 1988). Using Chiu’s equation, Choo (1990) further evaluated its accuracy at predicting velocity distributions and the energy and momentum coefficients, α and β , respectively. He found the equation predicted velocities better than the Prandtl-von Karman law and the simple power law.

Within the past 20 years culvert designs began to incorporate natural substrate within the barrel to slow water down and provide a diversity of velocities. As a result of their increased use, studies of the velocity fields in these types of culverts were performed. As an example, White studied prediction of velocity profiles in countersunk culverts (White, 1996). He developed an equation to predict velocities that was based on

the commonly used logarithmic velocity distribution. The equation constants, slope and intercept, were approximated using field data collected at 28 culverts. White found that the equation generally underestimated the proportion of cross-sectional area of flow with velocities less than or equal to 0.30 m/s or 0.61 m/s. Those velocities are commonly referenced as passable for juvenile salmonids. Building on this work, House et al. (2005) developed a method to estimate percent passable area in stream simulation culverts. Similar to the earlier work, the method was conservative in that it underestimated the percent passable area in these culverts.

Behlke was one of the first to recognize that fish utilize local zones of low velocity to pass through culverts. Along these lines, he suggested that an occupied velocity should be used for assessing fish passage through a culvert. He measured velocities in two partially-full culverts and found the ratio of V_{occ}/V_{ave} depended on location and ranged from 1.0 to 0.8 (Behlke, 1991). V_{occ} is the velocity at the location the fish is occupying, and V_{ave} is the average cross section velocity in the culvert. Behlke also observed that velocity patterns created by upstream channels that are skewed in alignment with the culvert can propagate into the culvert barrel, though he never quantified this relationship (Behlke, 1991).

Experiments in a culvert test bed in Washington state have explored the relationship between flow, culvert type, and configuration and behavior of juvenile coho salmon (Pearson et al., 2006). These researchers used an ADV to map velocity and estimate turbulence parameters in retrofit baffle and unbaffled culverts. They found juvenile coho do use the low-velocity pathways to pass culverts and that these pathways differ between baffled and unbaffled configurations (Pearson et al., 2006).

As these studies show, velocities in culverts are diverse and the ability to predict them is progressing; yet it is still not perfect. Past studies characterized velocities within the culvert barrel and developed 1-D and 2-D methods to predict velocity distributions. These studies did not investigate the effects of the connection between the upstream channel and the culvert, with the exception of a few anecdotal observations.

This part of the thesis investigates the linkage between the upstream channel and Culvert 1 at Mulherin Creek. The upstream channel is skewed approximately 40 degrees from the culvert alignment. This skew forces the water to the right side of the culvert and creates a lower velocity region on the left side of the culvert looking downstream. In other sections of the thesis, the use of this lower velocity region by trout to pass the culvert is described.

The hypothesis tested to evaluate the propagation of velocity was: diverse velocity patterns created by stream geometry upstream of the culvert barrel propagate through the culvert barrel.

Methods

The methods used to investigate the propagation of velocity included both computations with the CFD model to approximate velocities through the culvert barrel, and detailed field measurements of 1-D and 3-D velocities in Culvert 1.

Three different measures were used to investigate velocity propagation. The first two are hydraulic measures of velocity diversity: energy coefficient (α) and momentum coefficient (β), and the third is a statistical measure: mean squared error (MSE). Before describing the process for estimating these measures, there is a need to discuss the use of

them as a measure of velocity propagation. The energy and momentum coefficients account for velocity diversity in open channel flows. They are often assumed to be one for many hydraulic computations, especially in channels with fairly straight alignments and regular cross sections. In channels with irregular geometries, these coefficients can commonly range as high as 1.6 for α and 1.2 for β (Chow, 1959). V.S. Kviatkovskii measured a value for α of 7.4 in a laboratory with a spiral flow under a turbine wheel (as cited in Chow, 1959).

By definition, MSE is a way of quantifying the amount by which an estimator differs from the “true” value of a quantity being measured. MSE measures the average of the square of the “error”: with the error in this application representing the difference between velocities at various points in a cross section and the overall average velocity of the cross section.

For the purpose of this investigation, these measures are used to identify the distance that inlet velocity patterns propagate through the culvert barrel. The idea is that once these parameters become constant, the effect of the diverse inlet velocity pattern on the pattern of velocity within the culvert barrel has ended.

Hydraulic and statistical parameters were calculated to assess the propagation of velocity through the culvert barrel. ANSYS-CFX was first used to estimate the velocities through the culvert barrel (Section II). Velocities were estimated for five different flow rates representing a range of flows from 0.51 m³/s to 1.19 m³/s

The resulting model velocities were exported from ANSYS-CFX to Microsoft Excel. Velocities were exported at seven cross sections spaced 1.5 m apart, starting at the culvert inlet and progressing downstream to the culvert outlet. A VBA program was

developed to calculate various hydraulic and statistical parameters from the data at each cross section. Appendix D contains the code and input spreadsheet for the VBA program. The program uses an Excel spreadsheet to provide data input and output.

Alpha, the energy coefficient, was calculated using the following equation:

$$\alpha = \frac{\sum_{i=1}^n V_i^3 a_i}{V_{AVE}^3 A} \quad (3.1)$$

where a_i is the incremental area for each point velocity; V_i is velocity in a subsection of flow; A is the area of the entire cross section; and other variables are as previously described.

Beta, the momentum coefficient, was calculated using the following equation:

$$\beta = \frac{\sum_{i=1}^n V_i^2 a_i}{V_{AVE}^2 A} \quad (3.2)$$

where the variables are as previously described.

MSE is calculated as follows:

$$MSE = \frac{1}{n} \sum_{i=1}^n (V_{AVE} - V_i)^2 \quad (3.3)$$

where n is the number of velocities in the cross section and all other variables are as previously defined.

Results and Discussion

Figures 27 and 28 show plots of alpha and beta, respectively, from the inlet to the outlet of Culvert 1. Figure 29 shows a plot of MSE from the inlet to the outlet. Based on visual assessment of the curves in these figures, the stream geometry, in this case, appears to affect flow up to approximately 5 to 6 m downstream from the inlet.

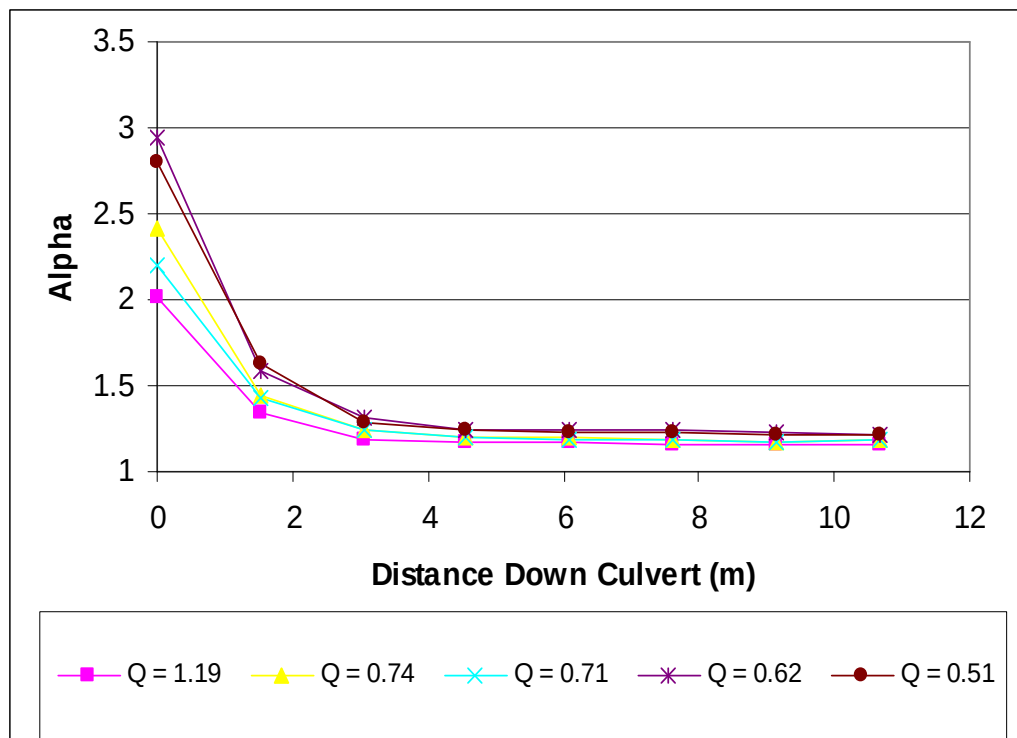


Figure 27. Graph of alpha in Culvert 1 from inlet to outlet; alpha calculated from ANSYS-CFX model predicted velocities. The flow rates (Q) are in m^3/s .

The lower flow rates have larger values of alpha and beta near the inlet. This result suggests that roughness elements create more diverse velocity patterns (and higher alpha and beta) at lower flows than at higher flows.

The data suggests that stream geometry in this case affects the flow pattern within the culvert to similar extents regardless of flow rate and corresponding inlet alpha and beta values.

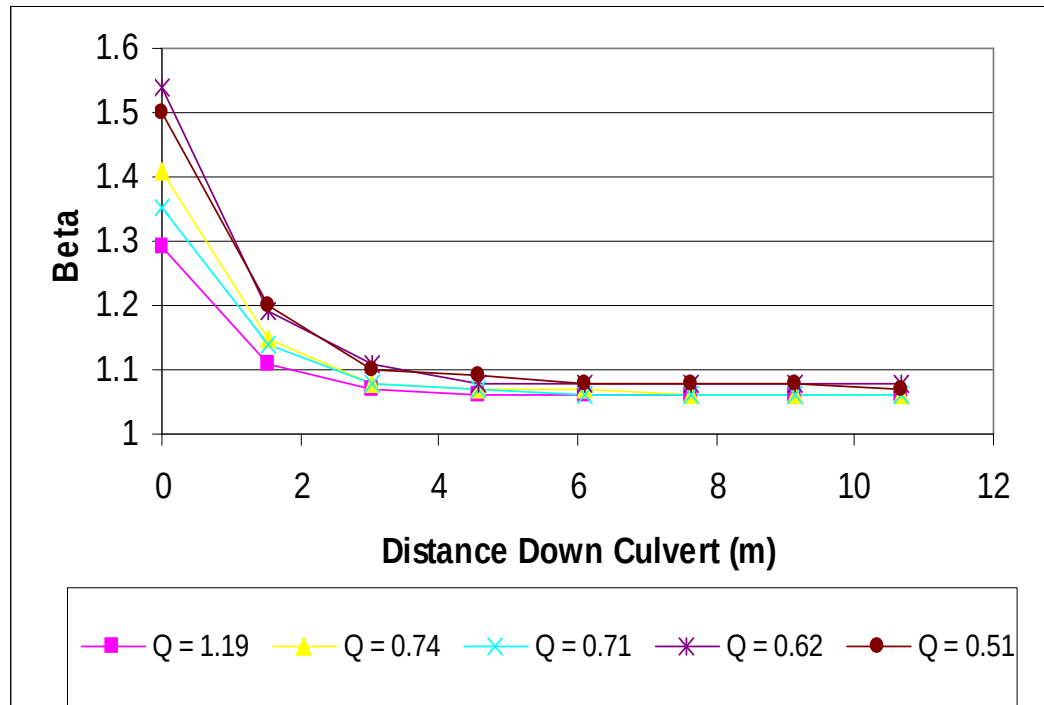


Figure 28. Graph of beta in Culvert 1 from inlet to outlet; beta calculated from ANSYS-CFX model predicted velocities. The flow rates (Q) are in m^3/s .

MSE values show a similar trend as alpha and beta, with the MSE reaching a relatively constant value around 6 m.

Based on the data in the graphs, it appears that the stream geometry upstream of the culvert barrel does not propagate through the culvert barrel in this case, but rather influences the velocity distribution for a distance of approximately 5 to 6 m downstream from the inlet. Figure 30 shows the location where the measures of velocity distribution

become relatively constant and appear to no longer be affected by the upstream geometry but rather, by the hydraulics within the barrel of the culvert. It is important to note that although the selected measures to assess propagation may have become relatively constant, the velocity still varies considerably from one side of the structure to the next.

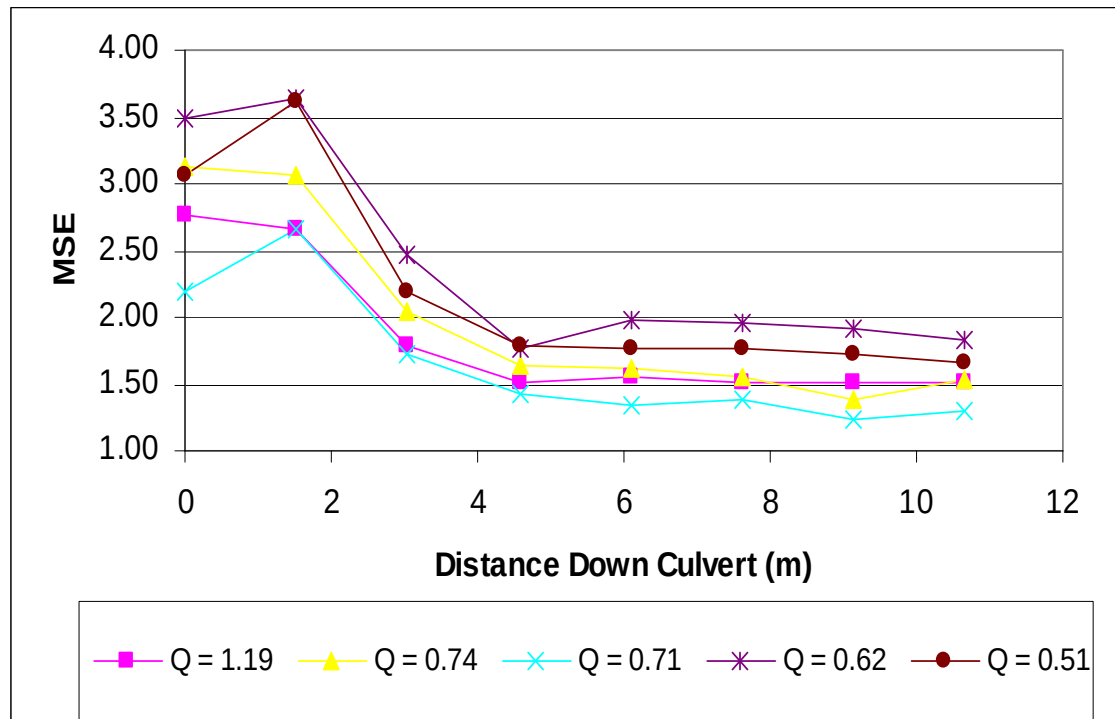


Figure 29. Graph of MSE in Culvert 1 from inlet to outlet; MSE calculated from ANSYS-CFX model predicted velocities. The flow rates (Q) are in m³/s.

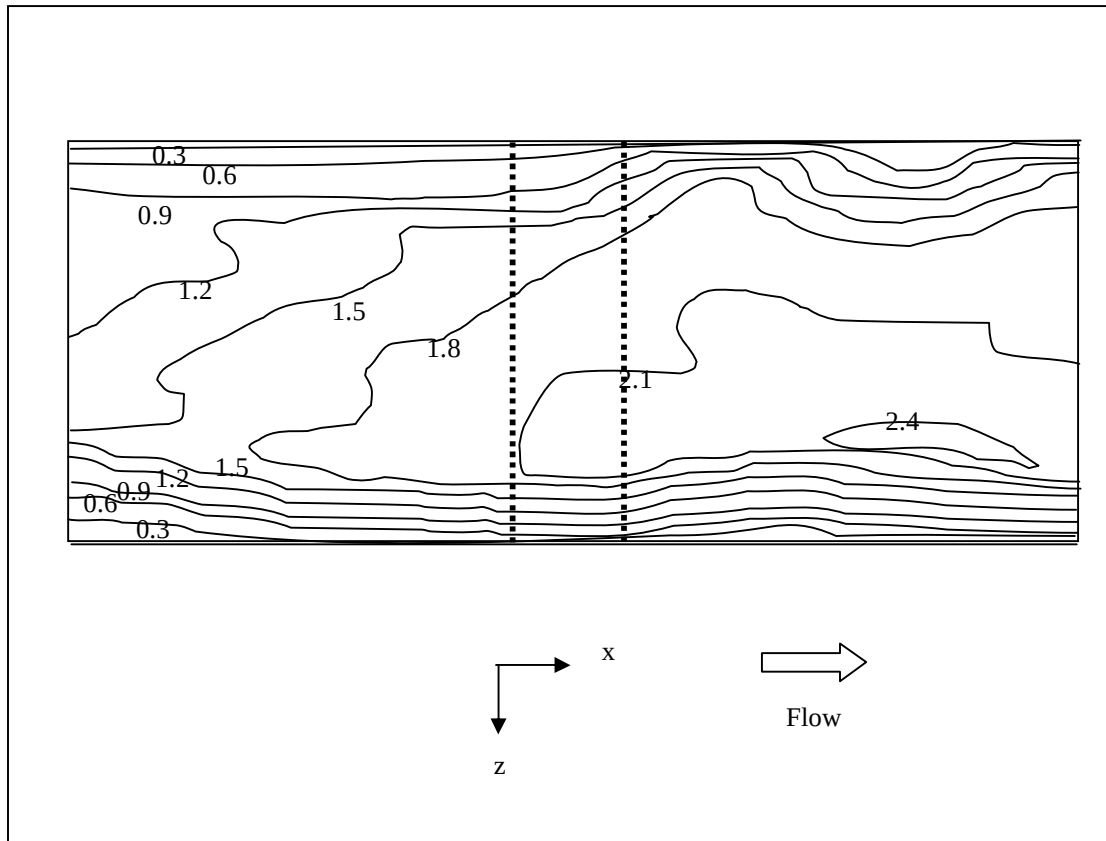


Figure 30. Plan view shows velocity isocontours in Culvert 1. The dashed lines show the approximate beginning of the region where flow in Culvert 1 appears to no longer be affected by the inlet region (to the left of the line), downstream from there the velocity pattern develops a more uniform flow distribution. Velocity contours are in m/s.

Summary

The connection of the upstream channel to Culvert 1 was investigated in this portion of the thesis. Based on calculations of alpha, beta and MSE at cross sections throughout the culvert barrel, the data suggests that diverse velocity patterns created by stream geometry (as estimated by these measures) do not propagate through the entire culvert barrel in this case. These measures become relatively constant at approximately 5 to 6 m from the culvert inlet.

ENERGY PATHS

Introduction

Fish seek to minimize the amount of energy they expend when swimming (Guiny et al., 2005; Weihs, 1973 and Hinch and Rand, 1998 as cited in Guiny et al., 2005).

Energy can be split into potential and kinetic portions. Water velocity is a critical factor in determining the passage success of fish and can be a barrier to their movement (Baker and Votapka, 1990; Fitch, 1995; Belford and Gould, 1989; and Warren and Pardew, 1998); therefore, the kinetic energy in moving water is of particular interest in this study. Previous portions of this thesis have shown how fishways can have complex flow fields with a large diversity of velocities and that the primary study culvert has a relatively diverse velocity field even though its geometry is simple. The diversity of velocities creates a range of energy paths through Culvert 1.

Fish utilize low velocity regions where they will expend less energy to pass upstream through culverts and other velocity challenges (Kane and Wellen, 1985; Behlke, 1991). Arctic grayling have been observed using low velocity regions to pass culverts in Alaska (Kane and Wellen, 1985). Researchers documented juvenile coho salmon using the low velocity pathways to accomplish passage in both a baffled and unbaffled condition (Pearson et. al., 2006).

The interaction of the flow field in fishways, fish swimming ability and behavior, and energy expenditure is a key area of research. Khan developed a hydrodynamic model of a vertical slot fishway to characterize the energy expenditure and drag forces along different paths through the fishway (Khan, 2006). By comparing the energy

expenditure along selected paths through the fishway to literature swimming abilities of various Pacific salmon species he identified those species capable of migrating through the fishway.

Lab studies of different fishways and fish movements through them developed methods for designing fishways with consideration of energy expenditure through the fishway flow field (Rodriguez et al., 2006; Guiny et al., 2005). Rodriguez et al. (2006) developed a method for evaluating fishway designs in terms of fish locomotion with a focus on design depth requirements and swimming capabilities of salmonids. Guiny et al. (2005) tested different fishways and measured the relative passage efficiency of juvenile Atlantic salmon (*Salmo salar*) through them. The study presented a “tentative” method for evaluating the energy expenditure of fish moving through different types of fishways that use weirs, slots, or orifices (Guiny et al., 2005).

Previous studies of fishway flow fields and energy expenditure generally focused on design methods for fishways and were completed in a laboratory setting. Katopodis (2005) has identified sound field research of fishways and fish behavior in a variety of physical and biological settings as a pressing need. The present study seeks to address this need by quantifying the energy paths through the primary study culvert over a range of flows, characterizing the paths used by Yellowstone cutthroat trout, and relating the energy expenditure of Yellowstone cutthroat trout to the maximum and minimum possible energy paths.

The objectives of this portion of the study were to:

- (1) determine the energy expenditure of Yellowstone cutthroat trout migrating upstream through Culvert 1;

- (2) identify the paths used by fish to move upstream through Culvert 1 and characterize the hydraulic environment along these paths;
- (3) quantify the minimum energy path, observed energy path, and maximum energy path in Culvert 1 for a range of flows; and
- (4) investigate the effect of leaping location, flow and temperature on successful leaps; and identify if there were preferred leaping locations.

Methods

As in previous sections, methods for this analysis included CFD modeling, in-field velocity measurements in the culvert and stream hydrology. In addition, fish sampling was conducted to explore the timing of fish movements relative to the hydraulic environment in the primary study culvert. The modeling, hydraulic and hydrologic methods will not be discussed in this section. See Section III, CFD Model Development and Validation, for a thorough discussion of those activities.

Biological Data Collection

Biological data were collected during the summer of 2004 to better understand how fish moved through the primary study culvert, and to compare their movements to a range of hydraulic conditions in the culvert. Two methods were used to collect fish movement data relative to a range of flows and times of the year. The first method used a mark-recapture technique with fish traps; and the second method used visual tracking of fish movement over a range of hydraulic conditions in and near the primary study culvert.

For method 1, trout were captured in a trap and tagged at a location approximately 200 m upstream of the confluence of the Yellowstone River and Mulherin Creek (Red Star in Figure 31).

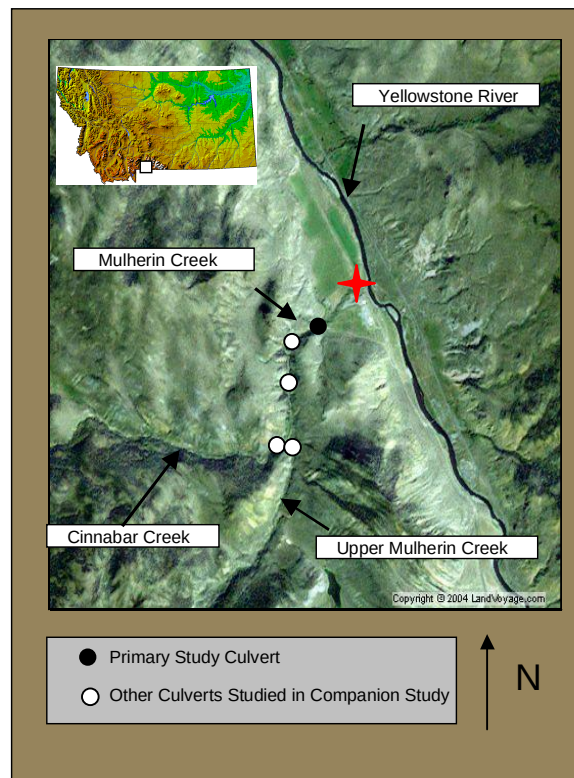


Figure 31. This map shows the location of the tagging trap, shown as the red star, in relation to the primary study culvert (Culvert 1) and the confluence of the Yellowstone River and Mulherin Creek.

This location was selected to capture Yellowstone cutthroat trout that migrate from the Yellowstone River into Mulherin Creek to spawn. Derito (2004) performed a study in the Yellowstone River drainage to evaluate the spatial and temporal differences in habitat use by rainbow and Yellowstone cutthroat trout. His study showed many

fluvial Yellowstone cutthroat trout used Mulherin Creek as spawning habitat; as well as some rainbow and hybrids (Derito, 2004).

Fences were placed across the entire stream channel to direct fish into the fish trap (Figure 32).



Figure 32. Picture of the tagging trap (trap #1) and fences that direct fish to the trap opening.

Once fish were captured, they were anesthetized with MS-222. Each fish was identified by species, their fork length was measured to the nearest millimeter, and their weights were collected using a scale. Visual implant (VI) alphanumeric tags were inserted in the periocular transparent tissue to allow identification of individual fish recaptured in traps placed further upstream in Mulherin creek. Tag retention studies show retention rates in wild cutthroat trout (*O. clarki*) were 87% at 1 to 60 days (McMahon et al., 1996). These rates were shown to decline to 50% at 270 to 430 days.

The mark-recapture experiment duration was within the 60 day time period so tag retention was thought to be reasonable for this study. Anesthetized fish were allowed to recover in a live well and subsequently released into a calm portion of the stream upstream of the trap and fences.

Two additional traps (Trap 2 and 3) were placed in the vicinity of Culvert 1: Trap 2 was placed approximately 50 m downstream of Culvert 1 and Trap 3 was placed approximately 25 m upstream of Culvert 1 (Figure 33). Trap locations were selected based on distance from the culvert, protection from the main force of high water flows, safety, and access. The mark-recapture method was a modification of a mark-recapture method used in the Clearwater River Project (Cahoon et. al 2005; Burford, 2005; Blank, 2006).

The purpose of Trap 2 was to capture any fish that had migrated from the tagging trap towards Culvert 1 – the distance between is approximately 1,500 m. The purpose of Trap 3 was to capture any fish that had migrated through Culvert 1. Traps 2 and 3 had fences to direct fish into the trap; unfortunately, due to the nature of Mulherin creek in this reach (medium gradient, incised channel and fast water) the fences could not cover the entire stream thus reducing the effectiveness of this method to recapture fish. This was the initial attempt to collect fish movement data relative to flow. The power of the study stream is such that it makes continuous measurements through peak flows extremely challenging (an important lesson learned from this experiment).

The traps were checked twice daily and any fish captured was first investigated for a tag. If they were tagged already, the tag number, trap number, date and time were recorded and the fish was immediately released. If they were not tagged (indicating they

had not been previously captured), they were anesthetized with MS-222, identified by species, the fork length was measured to the nearest millimeter, their weight was taken, and a VI tag was inserted. Anesthetized fish were allowed to recover in a live well and released into a calm portion of the stream upstream of the trapping location.

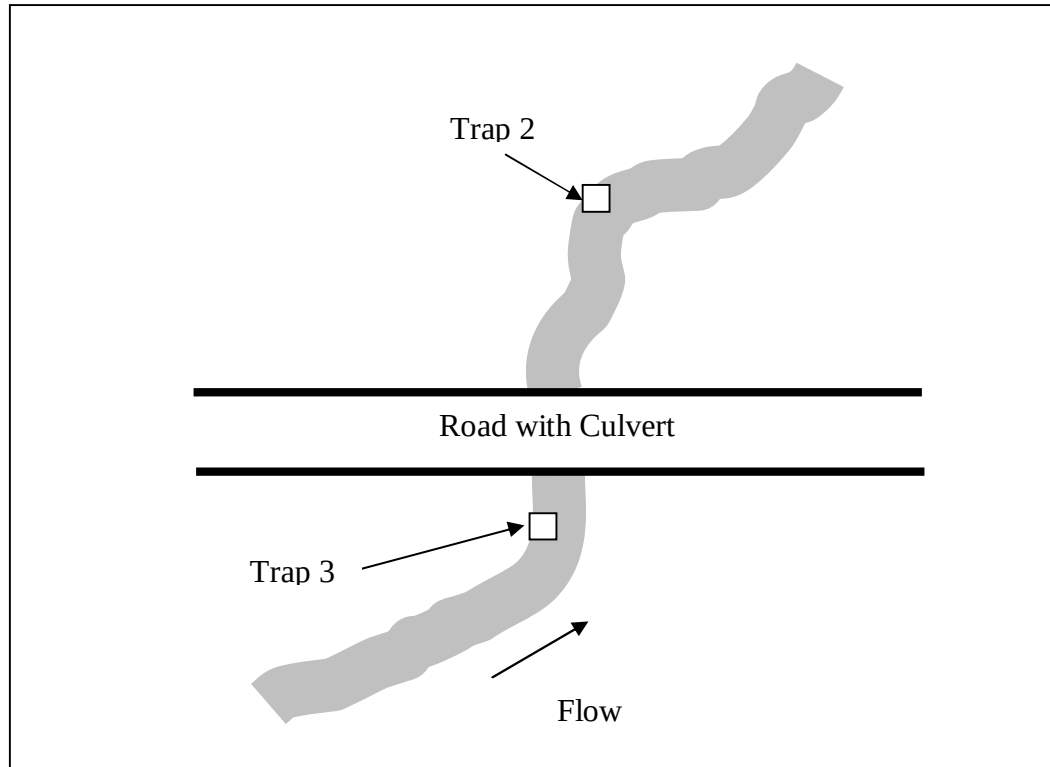


Figure 33. Diagram showing location of traps and culvert.

Fish movement timing was then estimated based on the initial capture location, date, and time and the subsequent capture location, date, and time. Fish movements were compared to the velocity field in the culvert during the time they were in the vicinity of the culvert and relative to continuous measurement of stream hydrology.

Method 2 involved visual observations of fish behavior to characterize how fish were leaping and swimming through the culvert. Past studies have used this technique with success to investigate the way trout, salmon, and grayling approach and ascend natural obstructions as well as culverts (Stuart, 1962; Kane and Wellen, 1985; Lauritzen, 2002; Pearson, 2006).

These observations were made from a position downstream of the culvert that allowed the observer to clearly see the outlet pool and upstream through the entire culvert barrel. To investigate the relationships between leaping location and passage through the structure, the culvert outlet pool was divided into four regions (Figure 34). Fish leaping and swimming behavior were identified relative to these four regions. Observations were split into three categories: unsuccessful leap attempt into the structure, successful leap attempt into the structure but unsuccessful passage upstream through it (fish became exhausted and was washed back downstream), and successful leap attempt and passage through the structure.

For trout that successfully passed through the structure, their path was recorded relative to markers placed along the culvert side walls. All observations were recorded in a field notebook. Observations were made over the course of several days during the time period when large numbers of trout were in the system. Typically, observations were made during the afternoon time period between 14:00 and 18:00. This time period allowed for good viewing conditions and corresponded to the time when fish movement was greatest. A companion study on Mulherin Creek verified that the greatest amount of movements occur during this observation time period (Cahoon et al., 2007a; Solcz, 2007).

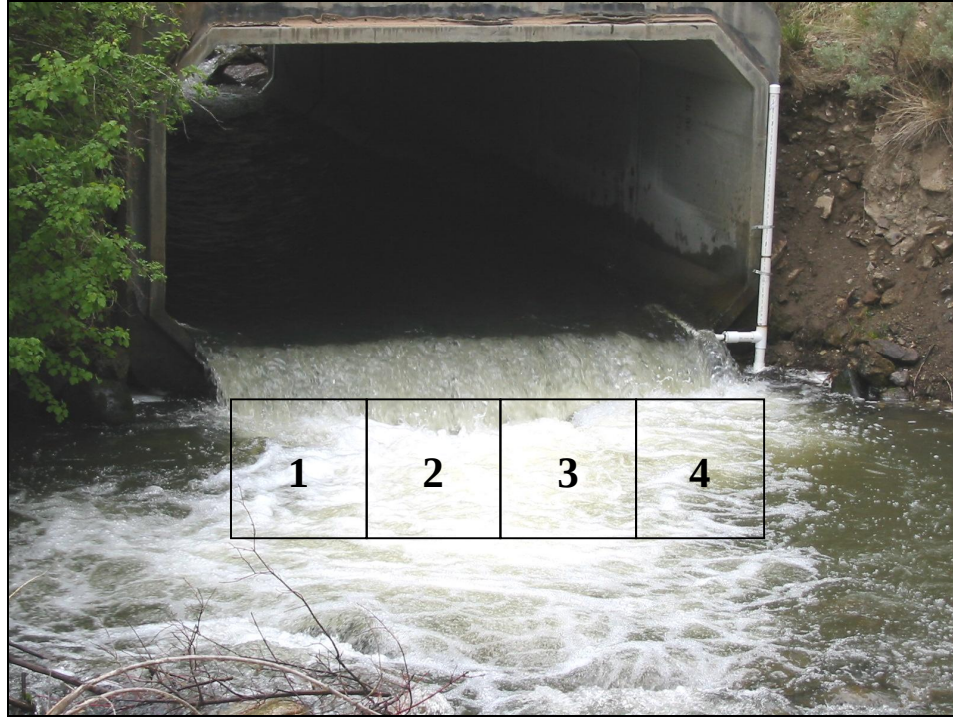


Figure 34. Diagram shows the division of the plunge pool into sections.

Calculation of Energy Paths

As previously described in Section III, the hydraulic conditions in the culvert were documented from April to November, 2004. Using the field measurements of the hydraulic environment and the results from the ANSYS-CFX model, energy expenditure paths were estimated through the culvert. A VBA program was created to estimate the energy expenditure paths (Appendix E). All energy expenditure paths were estimated on a plane approximately 0.06 m above the culvert bed. This plane was selected because it is the plane where fish were observed swimming upstream through the culvert. In addition, the water depth was typically very shallow (< 0.2 m) which prevented fish from moving vertically in the water column.

Energy expenditure through the culvert was calculated following methods described by Behlke (1991), Vogel (1994) and Webb (1995). Three energy expenditure paths were estimated for days with a minimum of three fish behavior observations: the maximum energy path, the minimum energy path, and the observed energy path. Energy paths were calculated for six different flow rates. Table 4 provides the date, flow rate, and number of fish behavior observations. These estimates represent the days with the greatest number of fish observations over the largest range of flows observed.

Table 4. Date, flow, and number of fish observations for energy path calculations.

Date	Flow (m ³ /s)	Number of Observations (n)
6/24/04	1.55	23
6/25/04	1.70	5
6/28/04	1.50	14
6/29/04	1.89	3
7/1/04	1.47	25
7/7/04	1.58	12

Calculations of maximum and minimum energy paths were done for ten potential starting points for fish ascending the culvert. The starting points were evenly spaced across the downstream outlet of the culvert. The energy path program calculates the minimum and maximum energy expenditure for each starting point according to an algorithm that incorporates rules on fish behavior. The overall minimum and maximum energy expenditure paths are then identified as the values with the least and greatest amount of energy expenditure.

For the remainder of this thesis, the directions for the movement of water and fish follow a consistent mathematical convention shown in Figure 35. The thesis explores the upstream migration of fish; therefore, the mainstream water velocity is negative and the fish velocity is positive.

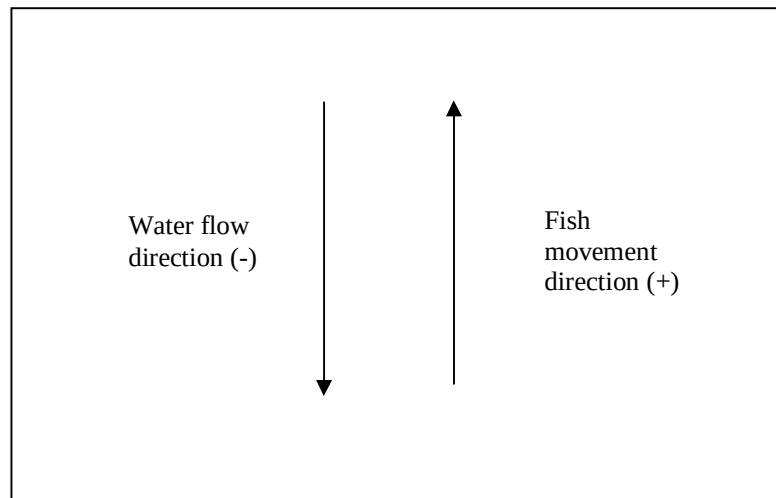


Figure 35. Diagram shows the sign convention for water flow relative to fish movement.

A swimming fish experiences several different forces as it moves through flowing water. Figure 36 shows the main forces acting on a swimming fish ascending upstream through a current.

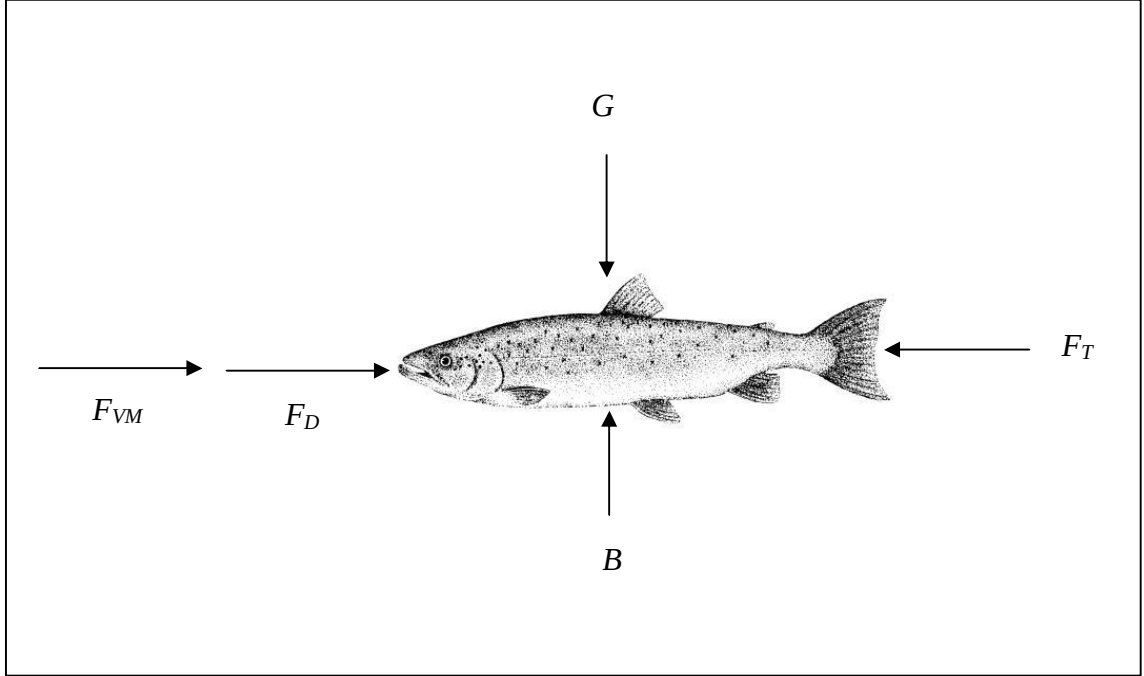


Figure 36. Diagram shows the main forces acting on a swimming fish (after Behlke, 1991 and Guiny et al., 2005). F_{VM} is the virtual mass force due to fish acceleration, F_D is the drag force, B is the buoyancy force, G is the gravity force and F_T is the thrust force.

Applying a force balance in the direction of a swimming fish, assuming the streamlines are straight, parallel and horizontal yields the following expression:

$$F_T = F_D + F_{VM} \quad (4.1)$$

There is a surface tension and water elasticity force which are considered negligible compared to the other forces (Guiny et al., 2005). The fish in this analysis is assumed to swim at a constant speed. Therefore, it is not accelerating and the virtual

mass force (F_{VM}) is zero. The culvert slope is nearly flat and fish swam along a path parallel to the culvert bed. Therefore, the components of the buoyant force (B) and gravity force (G) in the direction the fish moves are negligible compared to the other forces. Simplifying equation 4.1, the forces acting on the swimming cutthroat in this study become:

$$F_T = F_D \quad (4.2)$$

The power (P_f) a fish expends to overcome the drag force is a product of the drag force and the velocity of the fish (V_f).

$$P_f = F_D V_f \quad (4.3)$$

The energy expended by a cutthroat to pass through the culvert can be expressed as follows:

$$E_f = \int_0^t P_f dt \quad (4.4)$$

where the integration occurs over the time required for the fish to pass through the structure. The energy expenditure for a cutthroat to pass through the culvert along a path was calculated using piecewise integration of equation (4.4).

$$E_f = \sum_{i=1}^n P_{f_i} t_i \quad (4.5)$$

The time it takes for a fish to swim an increment of the path length is estimated using the following equation:

$$t_i = \Delta t = \frac{\Delta x}{V_f + V_w} \quad (4.6)$$

where Δx is the increment of the path length; V_w is the velocity of water parallel to the fish swimming direction.

The drag force on a fish can be estimated as follows:

$$F_D = 0.5 \rho C_d V_f^2 A_s \quad (4.7)$$

where C_d is the drag coefficient; A_s is the wetted surface area of a fish.

The drag coefficient is composed of a frictional component (C_f) and a pressure component (C_p) and can be represented as a function of the Reynolds number as follows:

$$C_d = C_f + C_p \approx 1.2 C_f \quad (4.8)$$

$$C_f = 0.074 \text{Re}^{-0.2} \quad (4.9)$$

When approximating the drag force of moving water on aquatic organisms, the Reynolds number is referred to as the local Reynolds number (Vogel, 1994):

$$\text{Re} = \frac{V_f L_f}{\lambda} \quad (4.10)$$

where λ is the kinematic viscosity of water, L_f is the length of the fish (Webb, 1971; Vogel 1994; Haefner and Bowen, 2002).

The surface area of a fish can be described as a function of its length (Khan, 2006; Webb, 1971). The relationship is typically expressed as a power function of the form:

$$A_s = \alpha_f L_f^{\beta_f} \quad (4.11)$$

where α_f is equal to 0.465; β_f is equal to 2.11 for this study (Khan, 2006).

Following the assumptions that: the fish is swimming at a constant velocity; streamlines are straight, parallel and horizontal; density of water is constant; and kinematic viscosity of water is constant (as well as all of the other underlying assumptions behind the development of the drag force equation, see Vogel (1994) for a thorough discussion); the only variables in the drag force equation become fish length (L_f). Figure 37 shows how drag force varies as a function of fish length. For comparison, the average length (331 mm) and +/- one standard deviation (31 mm) of length, based on data from 322 Yellowstone cutthroat trout captured during the study, are identified in Figure 37.

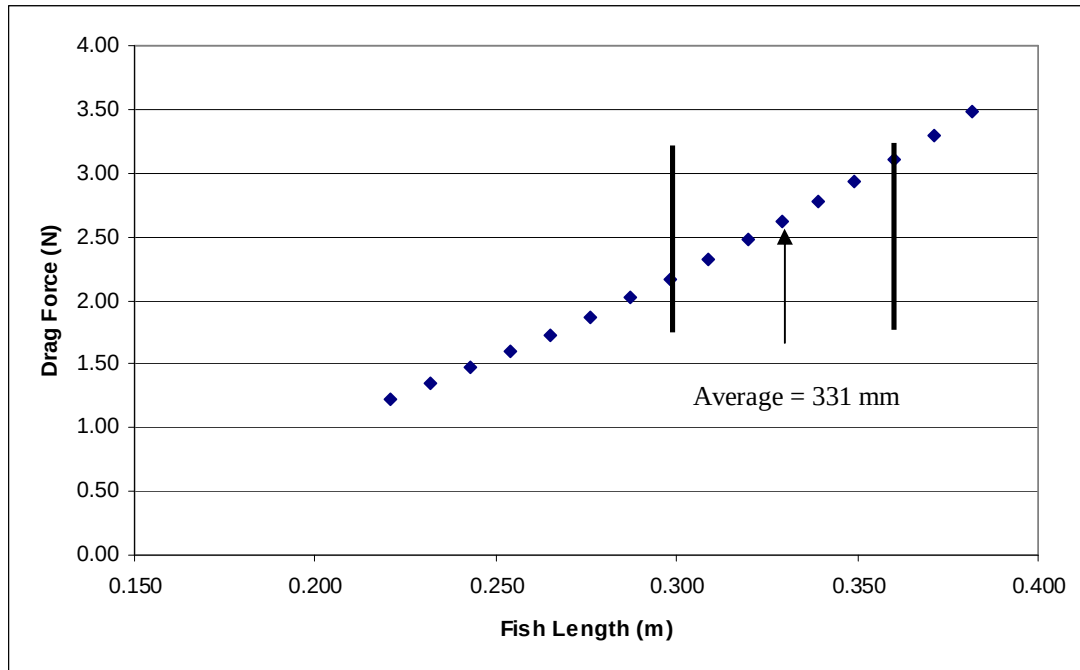


Figure 37. This graph shows how drag force varies as a function of fish length. The average Yellowstone cutthroat trout length from this study is identified on the graph and the bold vertical lines show +/- one standard deviation of length.

The VBA energy expenditure program uses a decision framework to determine the path of maximum and minimum energy expenditure. The horizontal plane of the culvert was divided into a 0.3 m x 0.3 m grid, and the velocity at each grid point was estimated using the ANSYS-CFX program. An important variable determining energy expenditure is water velocity which determines the time it takes for a fish to swim a given increment of distance. For minimum energy expenditure, the program selected the path by searching the velocities in the grid upstream, upstream and left, and upstream and right. The path with the lowest velocity is the minimum energy path. The program selected the grid point with the lowest velocity of the three potential paths. The position of the fish is moved to that grid point, and the procedure is repeated until the fish has

ascended the entire structure. Only continued upstream progress was allowed in the decision of potential paths through the structure.

A similar approach was used for the maximum energy expenditure, with the exception that the program is searching for the maximum velocity of the three potential paths. It is important to note that the maximum energy expenditure is dependent on the algorithm. If the algorithm did not require that a fish only progress upstream, there would be energy expenditure paths with a greater magnitude. Figure 38 depicts a decision framework for estimating energy expenditures.

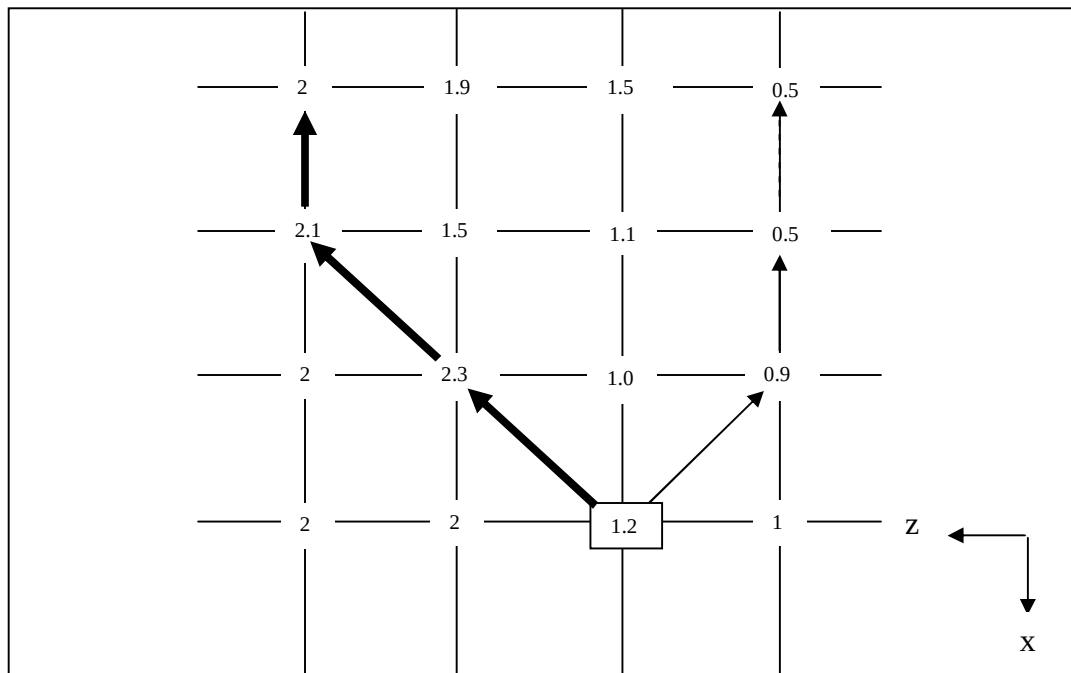


Figure 38. Diagram showing the decision process for estimating energy expenditure using the VBA program. The path shown with bold arrows is the maximum energy expenditure; and the path shown with the thin arrows is the minimum energy expenditure. Water velocities are shown at each grid point in m/s. The starting point is arbitrary.

The energy expenditure of observed movements through the structure was calculated in a different manner. The path is known in this case. The velocity was estimated for each grid point along the path using the ANSYS-CFX program. The energy expenditure was calculated using an EXCEL spreadsheet by equation 4.5.

For the energy expenditure calculations, the velocity of the fish was set at 4.1 m/s, the burst speed of cutthroat trout (Bell, 1991). Visual observations of fish movement through the culvert suggest that fish were using their burst speeds to swim upstream through the structure.

Unfortunately, there is a paucity of burst or darting swimming information in the literature for cutthroat trout. A thorough search only resulted in one reference: Bell, (1991). This parameter is very important for estimating energy expenditure; therefore, further discussion about it is presented in the results and discussion section to follow.

Leaping Data Analysis

Several different statistical tests were done to analyze the leaping data. Logistic regression was used to investigate the effect of leaping location, flow and temperature on successful leaps into the structure. Kruskal-Wallis tests were done to investigate differences in the number of leaps by region. All tests were performed at the 95% confidence interval (CI).

Results and Discussion

The results and discussion section is split into two parts: the first describes the field data collected, and the second describes the estimation of energy expenditure.

The mark-recapture experiment proved difficult to execute in the extreme flow conditions that develop during spring flood in Mulherin Creek. The traps were run from May 4, 2004 through July 2, 2004. The traps were removed from the creek during the highest flow period experienced during the end of May and the beginning of June. Even though the portion of the mark-recapture experiment designed to compare movements of trout through the study culvert was not as successful as planned, some interesting data was collected.

A total of 366 trout were captured: approximately 322 were identified as Yellowstone cutthroat trout, 23 were identified as rainbow trout and 21 were identified as hybrids (Yellowstone cutthroat x rainbow trout). Yellowstone cutthroat trout ranged in size from 120 mm to 420 mm, with an average of 331 mm. Rainbow trout ranged in size from 170 mm to 410 mm, with an average of 235 mm. Hybrids ranged in size from 180 mm to 420 mm, with an average of 320 mm.

Yellowstone cutthroat trout migrated into Mulherin Creek on the receding limb of the spring runoff flood when water temperatures exceeded 12 °C to 14 °C in the afternoon (Figure 39). The chart shows the relatively narrow time period that Yellowstone cutthroat entered Mulherin Creek, with the majority of the fish (75%) entering in a four day time period between June 21 and June 24, 2004. The largest number of fish (116) entered the creek on June 22, 2004, representing 32% of the total caught during the entire trapping period.

A total of 19 Yellowstone cutthroat trout were recaptured during the experiment, representing 6% of the initially tagged fish. Of the 19 recaptures, three were captured upstream of the culvert in Trap 3 verifying passage through the structure at flow rates of

1.33 m³/s (2 trout) and 1.54 m³/s (1 trout). Fifteen were recaptured downstream of the culvert in Trap 2 verifying movement from the tagging location to near Culvert 1, and one was recaptured in the original trap. The fences were opened at night towards the end of the experiment because many trout were observed attempting to pass back downstream through the closed fences.

Flows in Mulherin creek and the study culvert during the Yellowstone cutthroat migration averaged 1.4 m³/s. The peak flow for the 2004 spring runoff was recorded on June 6 at 3.1 m³/s.

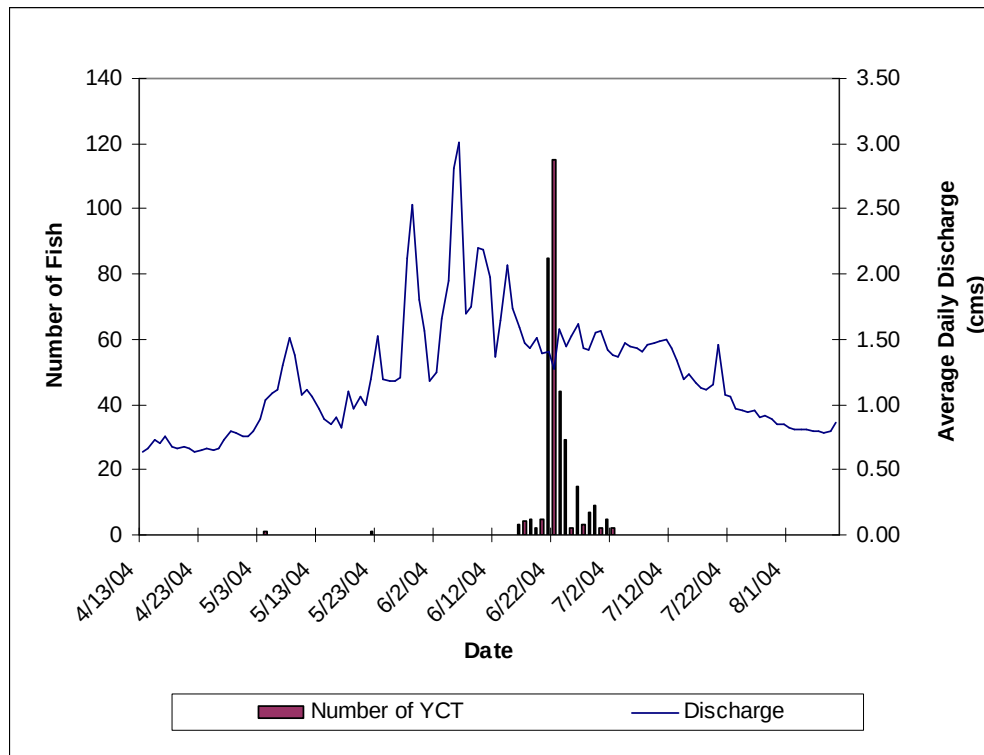


Figure 39. Graph showing the number of Yellowstone cutthroat trout captured in Mulherin Creek compared to the 2004 hydrograph.

Leaping behavior was recorded from June 16 to July 8, 2004; representing 13 days of observations and a total of 24 hours of observation time. Figure 40 shows an example of the recorded leaping events by category for observations collected on June 24, 2004; all other observation days are provided in Appendix F.

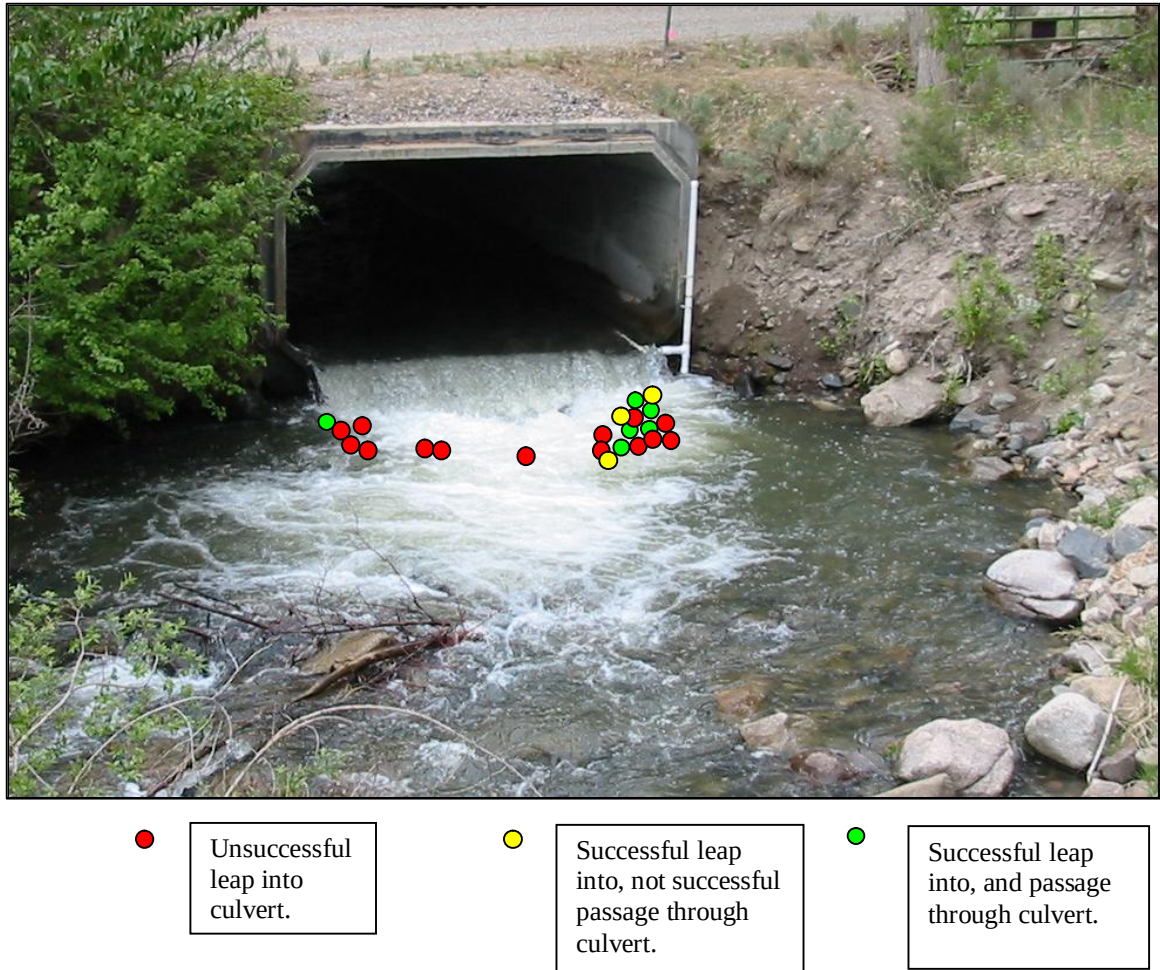


Figure 40. Diagram of leaping observations by category for June 24, 2004.

A total of 89 leaping attempts were observed, with 34 successful leaps into the culvert and 18 successful passes through the culvert (Figure 41). Fish that did not

successfully leap into the structure failed to do so for several reasons: (1) they often did not leap high enough to clear the downstream invert of the structure; (2) they occasionally leapt in a direction that did not take them toward the culvert entrance; and (3) some started their leap from a distance too far away from the downstream invert. The leap height in the plunge pool (measured from water surface in the plunge pool to the water surface in the culvert) averaged 0.60 m during the observation period. It fluctuated very little with changes in flow.

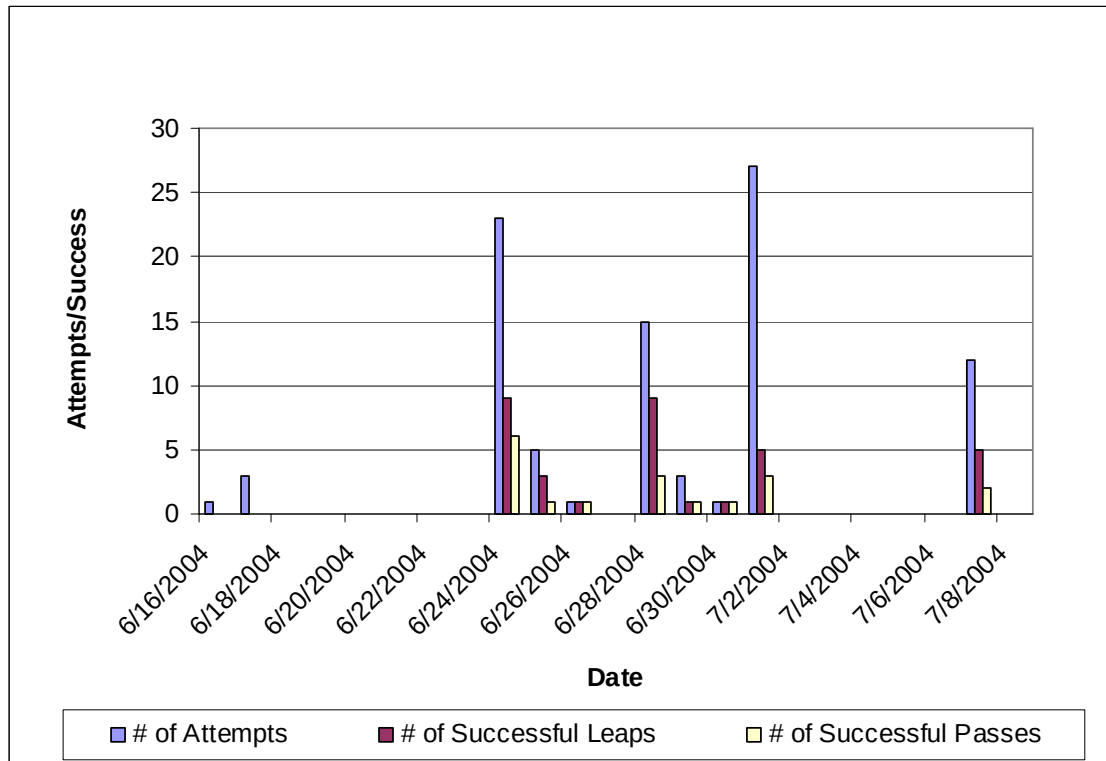


Figure 41. Summary chart showing the number of attempts, number of successful leaps into and the number of successful passes through the study culvert.

Two factors seemed to prevent trout that successfully leapt into the structure from successfully passing through the structure. The first was the angle that they landed in the culvert. If they did not land parallel to the main flow direction, they were washed out of the barrel. The water force increases as the angle of entry deviates from the main flow direction because a larger amount of surface area is exposed perpendicular to the main flow direction and force of water. The second reason they did not pass, even if they landed successfully, is that they entered the culvert and attempted to swim against the higher velocity regions of the culvert quickly reaching exhaustion and subsequently getting flushed back out of the culvert barrel.

The fish that successfully negotiated the leap into the structure and the swim upstream through it, typically entered the culvert on the side with lower velocities (river left) or if they entered on the side with higher velocities (river right) they immediately swam towards the lower velocity regions present on the river left side. Every one of the successful passes through the structure used the lower velocity region on the river left side of the structure to pass.

Table 5 summarizes the number of leap attempts by region of plunge pool. Results from statistical tests on the leaping data (leap attempts and successful leaps into the structure not successful passes through the structure) did not find any significant relationships. The null hypothesis for successful leaps was: successful leaps into the culvert are not affected by leap region, flow and temperature. Results from the logistic regression model indicate that the null hypothesis should be accepted and that leap region, flow and temperature did not have any significant affect on successful leaps (95% CI). The null hypothesis for the number of leap attempts was: the number of leap

attempts does not vary by leap region. Results from the Kruskal-Wallis test and Mann-Whitney tests on the effect of leap region on the number of leap attempts also showed no significant relationships at the 95% CI.

Table 5. Number of leap attempts by leap region at Culvert 1 plunge pool.

Date	Region 1	Region 2	Region 3	Region 4
June 23	2	0	0	1
June 24	5	2	1	16
June 25	1	1	2	1
June 26	1	0	0	0
June 28	1	0	6	7
June 29	0	0	2	1
June 30	0	0	0	1
July 1	8	3	5	9
July 7	2	2	5	4
Total	20	8	21	40

Figures 42 to 46 show plan view maps of the velocity contours and the maximum, minimum, and observed energy expenditure paths for five different days during which fish leaping and swimming observations were made.

Both the maximum and minimum energy paths show little change with flow rate. This should not be a surprise as the flow field in the structure is fairly consistent for all six days. The maximum energy paths started from between points six and eight on the downstream outlet of the culvert structure for all six observations. The flow field shows a higher velocity region that develops just right of the centerline of the structure, and a lower velocity region along the river left side of the structure. The high velocity region develops for two reasons: first the culvert is skewed from the upstream channel and the skew forces water to the outside (river right) side of the structure as it enters; and second,

the structure bottom is tilted slightly toward the river right side thus adding a component of the gravity force.

In all cases, the minimum energy path starts at point ten, the starting point located on the river left side of the structure for all flows. All minimum energy paths followed the river left side of the culvert.

Of the sixteen successful passes recorded for these six days, ten started from the river left side at point 10, and six started from other points. On June 24, one fish passed the culvert with a starting point on the river right side (point 1). On July 1, the three fish that passed the culvert started at points 2, 5 and 8. On July 7, the two fish that passed the culvert started at points 2 and 6.

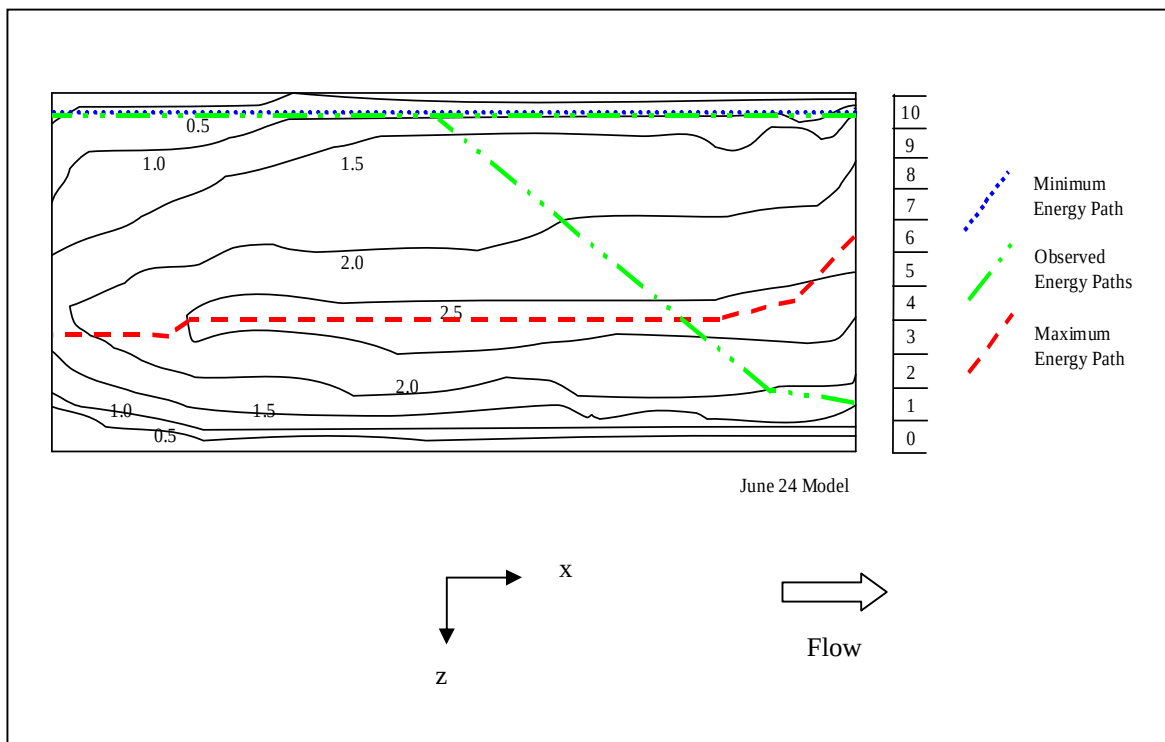


Figure 42. Maximum, minimum, and observed energy paths for fish on June 24, 2004. Contours refer to velocity in m/s.

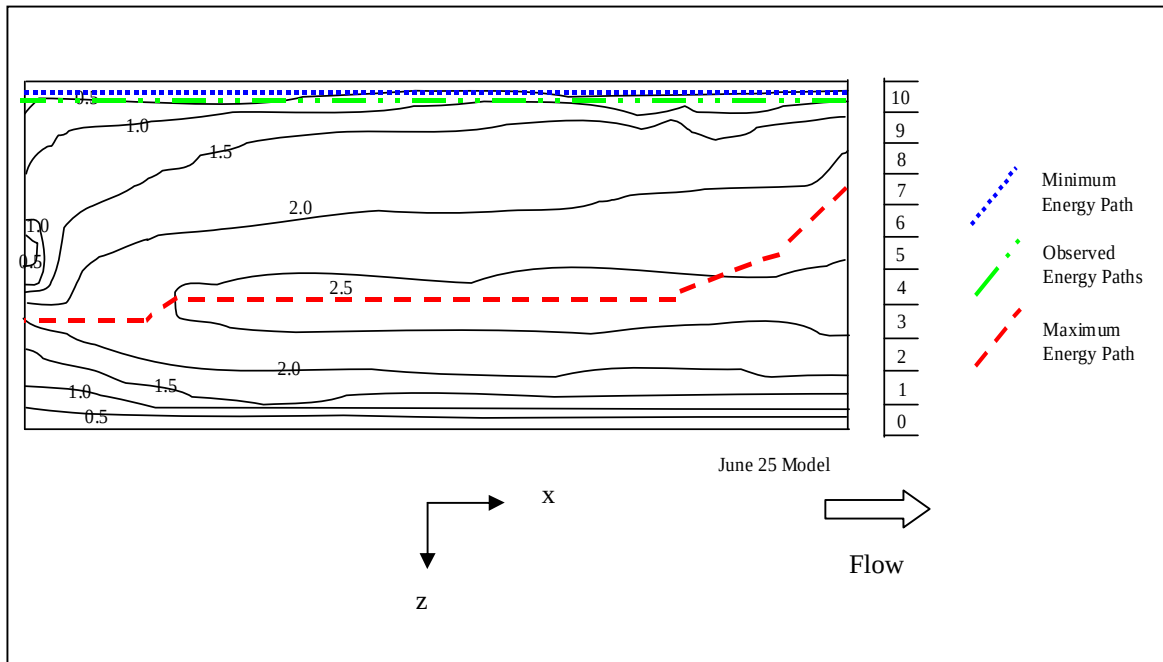


Figure 43. Maximum, minimum, and observed energy paths for fish on June 25, 2004. Contours refer to velocity in m/s.

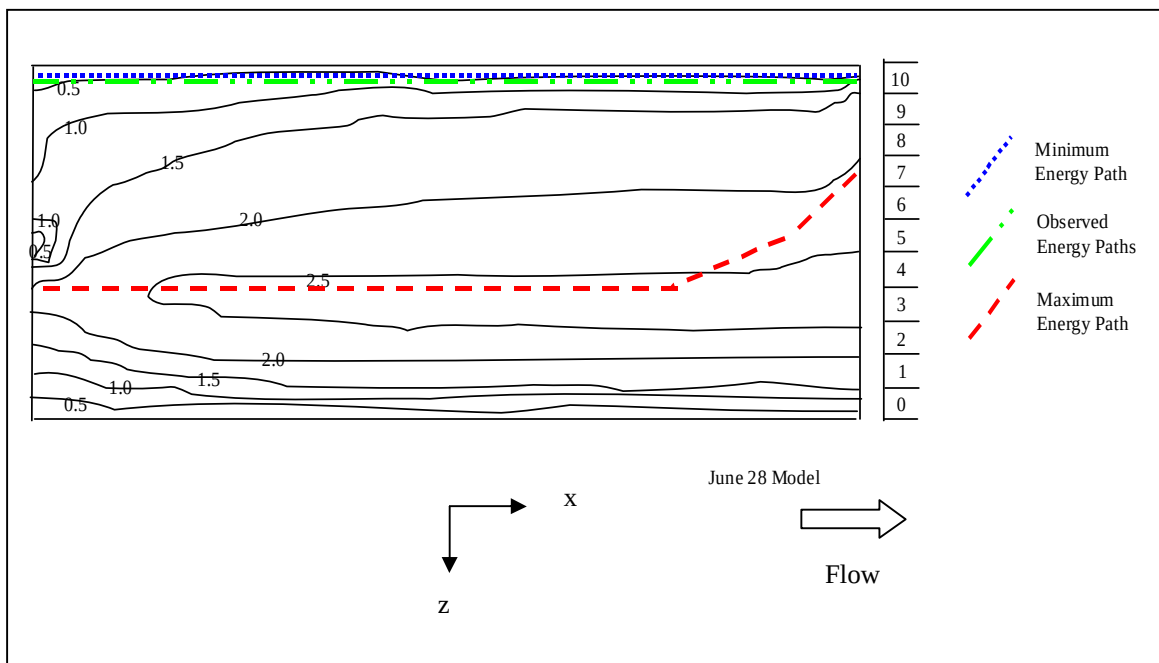


Figure 44. Maximum, minimum, and observed energy paths for fish on June 28, 2004. Contours refer to velocity in m/s.

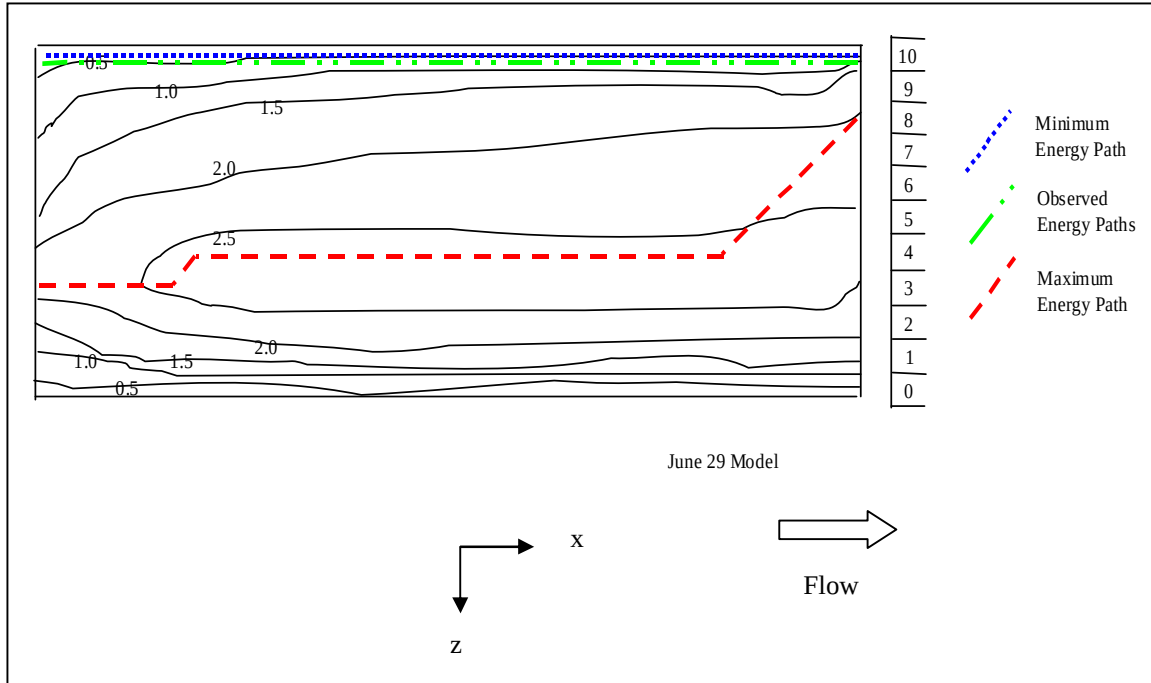


Figure 45. Maximum, minimum, and observed energy paths for fish on June 29, 2004. Contours refer to velocity in m/s.

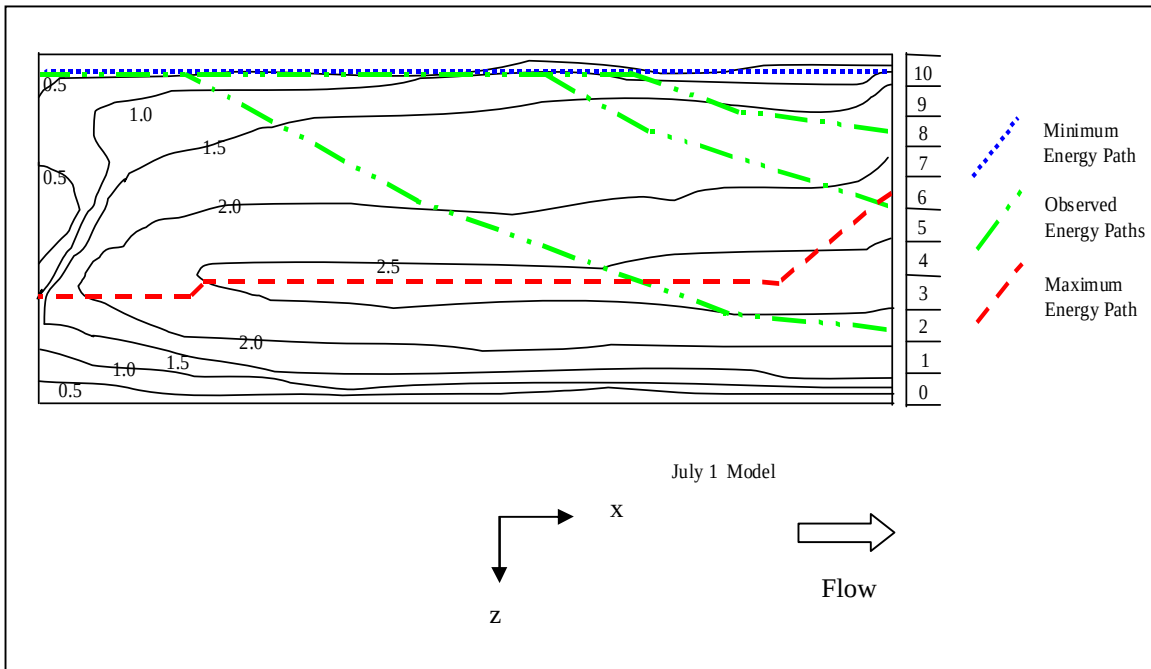


Figure 46. Maximum, minimum, and observed energy paths for fish on July 1, 2004. Contours refer to velocity in m/s.

The maximum, minimum, and average observed energy expenditure are listed in Table 6. The maximum energy expenditure ranged from a minimum of 68.37 joules (J) on July 1, 2004 to a maximum of 72.60 J on July 29, 2004. The minimum energy expenditure ranged from 40.52 J on July 1, 2004 to a maximum of 41.61 J on June 29, 2004. The average observed energy expenditure represents the average energy expenditure of all fish observed to pass through the structure on a given day. The average energy expenditure ranged from a minimum of 40.74 J on June 28, 2004 to a maximum of 46.20 J on July 7, 2004.

Table 6. Summary of maximum, minimum, and average observed energy expenditure of fish migrating upstream through Culvert 1.

Date	Flow Rate	Maximum Energy	Minimum Energy	Average Observed Energy
	m ³ /s	J	J	J
June 24	1.56	69.31	40.86	41.72
June 25	1.70	71.32	41.45	41.45
June 28	1.50	68.78	40.74	40.74
June 29	1.90	72.60	41.61	41.61
July 1	1.47	68.37	40.52	46.56
July 7	1.58	69.56	40.98	46.20

These data show two important observations depicted in Figure 47. First, the observed energy expenditures are very close to the minimum possible energy expenditures for all observation days. Optimal foraging theory states that animals forage in ways to maximize energy input and minimize energy output. This result seems to follow that theory with regards to minimizing energy output while passing difficult conditions. Another possible explanation is that the velocities in other regions of the

culvert are too great for passage to occur; therefore, fish have to seek and find the lower velocity paths for success.

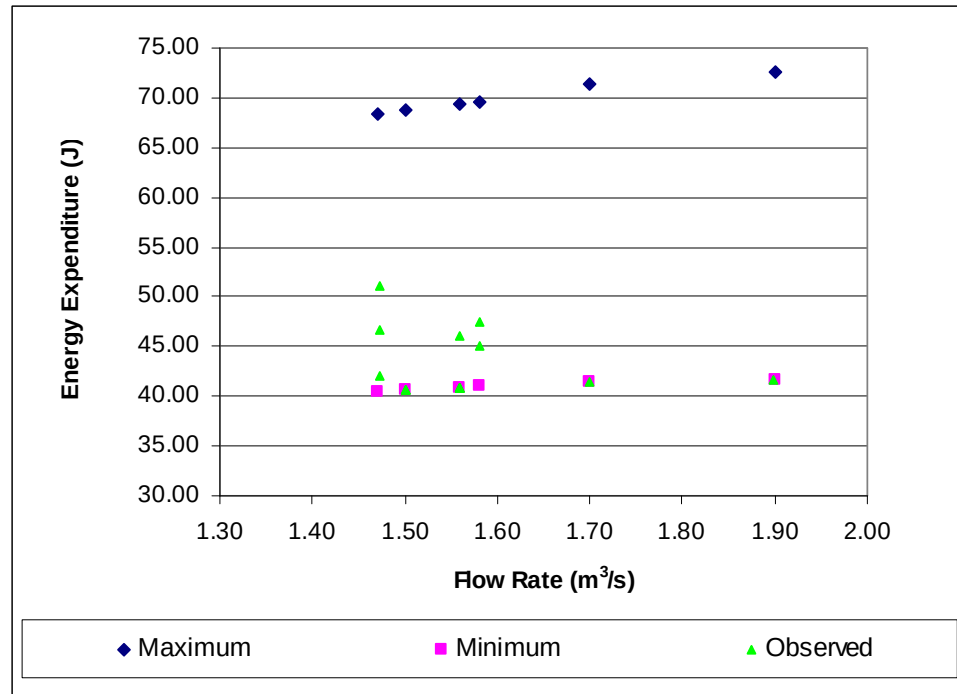


Figure 47. Graph showing the maximum, minimum and observed energy expenditure of trout migrating upstream through Culvert 1.

The data also agrees with findings from other researchers who noted fish using the low velocity zones to pass through hydraulic structures (Kane and Wellen, 1985; Behlke, 1991; Pearson, 2006). This research not only shows the use of the low velocity regions by Yellowstone cutthroat trout, but also provides an estimate of the actual energy expenditure of the trout passing through the structure. No other study has documented and quantified the energy expenditure for trout migrating through culverts in a field setting.

The second interesting result is the trend of observed energy expenditure shown on Figure 47. At lower flow rates fish successfully passed through the culvert from a greater number of potential starting points, and in doing so these fish used more energy than fish that passed at higher flow rates. At higher flow rates, only fish that attempted passage along the lower velocity side were successful. The number of total observations is low ($n = 16$) especially for the higher flow rates ($n = 2$).

Information on burst swimming of Yellowstone cutthroat trout is limited. The use of swimming abilities for surrogate species is a possible means around this problem. A recent study that evaluated the sustained swimming abilities of rainbow, Yellowstone cutthroat trout, and their hybrids, found Yellowstone cutthroat trout have a lower sustained swimming ability than rainbows and their hybrids (Seiler and Keeley, 2007). A review of burst swimming speeds for rainbow and cutthroat trout is summarized in Section V of this thesis. This review shows that rainbow trout have burst speeds less than the value used here for estimating energy expenditure for Yellowstone cutthroat trout. One question that should be investigated is: is it possible for a species of salmonid to have lower sustained and prolonged swimming abilities, yet a greater burst speed?

The observations of leaping behavior may seem rudimentary; however, they provided very useful data with regard to how fish passed through the structure, where and how they leapt into the structure, and the paths they followed through it. More advanced techniques, such as passive integrated transponder (PIT) tags, have been used at Mulherin Creek during a subsequent study (Cahoon et al., 2007a). The PIT tags allowed for excellent movement observations relative to mean flows through the structure; however,

they provide no insight into the details previously described related to leaping behavior, complex flow fields, and the paths used by fish to negotiate passage through the culvert.

Summary

The amount of energy expended by Yellowstone cutthroat trout that migrated through the primary study culvert has been quantified in this part of the thesis. The energy expenditure has been compared to the maximum and minimum energy expenditure paths for a range of flows with fish movement observations.

The paths that fish actually used to negotiate the difficult passage conditions in the culvert were also quantified. The observed paths are close to or equal to the minimum energy paths, and in all cases where fish successfully passed the culvert, they swam towards the low velocity region and the minimum path. This part of the thesis demonstrates and clearly quantifies the use of the lower velocity regions of the study culvert for passage by Yellowstone cutthroat trout.

Additional information on the burst-speed fatigue-time relationship of Yellowstone cutthroat trout and other species is necessary to improve our understanding of fish's swimming abilities, barrier assessments, and barrier designs. In addition, the behavior of trout with regards to swimming abilities is needed. For instance, do trout use a distance-maximizing strategy (i.e. attempt to swim at a speed that maximizes the distance they can travel through a given velocity challenge) when passing through velocity challenges (Castro-Santos, 2005)?

NEW BARRIER ASSESSMENT METHOD

Introduction

There are many different methods to analyze the barrier status of culverts, each with distinct advantages and disadvantages. For this discussion, these methods are split into direct and indirect assessments.

Direct assessments measure the amount of movement by fish in the field with an experiment and compare those movements directly to the measured hydraulic conditions within and near the culvert. Mark recapture designs have been used to assess fish passage (Cahoon et al., 2005; Burford, 2005; Belford and Gould, 1989; Warren and Pardew, 1998). Other researchers analyzed fish movement through a range of flow conditions using PIT tags and antennae placed at the upstream and downstream ends of a culvert (Cahoon et al., 2007a). These approaches can provide detailed information concerning both the passage status of a culvert and the hydraulic environment within and adjacent to the culvert that allowed or prevented passage; however, they can be labor-intensive and are only practical for assessing a smaller number of culverts. Radio tagging of fish is another method that can provide insight into fish movement behavior (Derito, 2004).

Indirect methods generally approximate fish movement potential by comparing the culvert physical conditions to the swimming abilities of the fish species of interest. The simplest indirect method involves identifying the barrier status of a culvert solely on the physical characteristics of the crossing. Physical characteristics typically include the outlet drop, culvert slope, and culvert length. Other factors include whether the culvert is

embedded with substrate or the degree to which the culvert simulates a natural stream reach. This approach sets thresholds for the physical characteristics that are based on field and laboratory studies that compared physical characteristics to movement of fish. For example, a threshold for culvert slope of 2% was set for corrugated metal pipes in Alaska (USFS, 2002). Culverts with slopes at or greater than 2% can develop water velocities that are difficult for salmonids to swim against without reaching fatigue. A key advantage to this method is the assessment of large numbers of crossings with a relatively small amount of physical and biological data, and a small amount of effort.

A more advanced indirect method estimates the average hydraulic conditions in a crossing for selected flow rates and compares those conditions to the swimming abilities (including time to fatigue) of the species of interest. Bainbridge was the first to recognize that an estimate of the maximum distance traveled by a fish could be derived by comparing their swimming ability to a velocity challenge (Bainbridge, 1960). The software program FishXing uses this approach and combines culvert characteristics (slope, length, roughness, etc.) and stream hydrology to model the hydraulic conditions in and near the culvert (FishXing, 1999). These hydraulic conditions are then compared to the swimming ability of the fish species of interest to determine the passage status. Although this method of analysis may be useful for assessing a large number of culverts with a relatively small amount of field data collection, caution must be used when interpreting the results, as recent research shows that this method can provide a conservative (i.e. more barriers to movement are predicted when compared to direct assessment results) estimate of the barrier status of culverts (Cahoon et al., 2007b; Karle, 2005).

Coffman (2005) assessed the accuracy of three predictive models (indirect methods) by comparing their estimate of passability to passage assessments using a mark-recapture technique. The models failed to accurately indicate passage approximately 50% of the time, although model prediction improved after revising the predictive model parameters based on data from the mark-recapture studies.

Species abundance, size structure, and genetic differentiation can also be used as an indirect approach to evaluate fish passage. Typically, these studies compare characteristics of fish samples taken from locations both upstream and downstream of the culvert. This upstream and downstream approach can provide valuable information about how culverts affect the abundance, size structure, and distribution of fish populations (Riley, 2003). On the other hand, results from these studies can be inconclusive as to the barrier status of the culvert because there may not be significant differences between the upstream and downstream samples even though the culvert may be a barrier (Cahoon et al., 2005; Burford, 2005).

Genetic differences between fish populations upstream and downstream of barriers is another method that has been used to identify the barrierity of a crossing. One recent study that investigated genetic differences of bullhead (*Cottus gobio*) upstream and downstream of a suspected barrier yielded inconclusive results. Researchers thought that perhaps the genetic isolation was too recent or that the culvert allowed partial movement of the species (Knaepkens et al., 2004).

Based on this discussion, it should be evident that the “perfect” method for identifying culvert barriers has not yet been developed. Therefore, there is a need to pursue research towards refining existing assessment methods and developing new

methods. To this end, a fish passage assessment method was developed that uses an estimate of the 3-D hydraulic conditions in the crossing and compares those conditions to the swimming abilities of the species of interest. This procedure is a new barrier assessment method and to the author's knowledge no similar method exists. A 1-D approach, similar to the one used in FishXing, was also developed to provide a comparison for the 3-D method.

Methods

In this section, the specifics of the 1-D model are presented first, then the details of the 3-D model are presented. Each model was used to estimate passage through the primary study culvert for water years 2004 to 2006. The species of interest was Yellowstone cutthroat trout. A flow rate threshold defines a discharge that is impassable to upstream migrating trout. Flows greater than the threshold are impassable, and flows less than the threshold are passable. In addition, comparisons between the flow rate thresholds predicted by the various models and observed fish movements are made and discussed.

These assessment methods only assess passage relative to flow or velocities. Neither low flow passage, which is controlled in part by the depth of water relative to the size and species of fish, nor jump heights are included in the assessment.

1-D Fish Passage Assessment

The 1-D model uses gradually varied flow hydraulics to estimate the hydraulic conditions in the structure. The hydraulic conditions are then compared to fish

swimming abilities to estimate passage. One form of the gradually varied flow equation is shown below (Chow, 1959):

$$\frac{dy}{dx} = \frac{S_o - S_f}{1 + \alpha \frac{(V_{AVE}^2 / 2g)}{dy}} \quad (5.1)$$

where dy/dx is the change in water surface with distance along the channel; g is the acceleration due to gravity; y is the water depth; S_o is the channel or culvert bed slope; S_f is the energy slope; and other variables are as previously described. This equation is a first-order differential equation that can be solved in a variety of ways.

For this application, the equation is solved using the standard step method. The continuity equation and Manning's equation for uniform flow are part of the solution to the gradually varied flow equation. The continuity equation for this solution is expressed as:

$$Q = V_{AVE} A \quad (5.2)$$

where Q is the flow rate in the channel; and all other variables are as previously described.

Manning's equation is used to estimate the energy slope in the gradually varied flow equation, and can be rearranged to the following form:

$$S_f = \left[\frac{Qn}{1.486AR^{\frac{2}{3}}} \right]^2 \quad (5.3)$$

where R is the hydraulic radius; n is the channel bed roughness; and all other variables are as previously described.

Boundary conditions need to be prescribed to initiate the numerical solution. For the primary study culvert, flow passes through the critical depth (the point of minimum energy) at the culvert inlet and becomes supercritical through the rest of the culvert barrel. This type of control occurred at this culvert during the study period. Based on this knowledge of how the flow is “controlled”, the boundary condition for the solution is set as the critical depth at the culvert inlet. Critical depth can be calculated using the following equation:

$$Z = \frac{Q}{\sqrt{g}} \quad (5.4)$$

Z is equal to the section factor for critical flow; and the other variables are as defined earlier. For trapezoidal channels such as Culvert 1, the section factor is equal to:

$$Z = \frac{[(b + zy)y]^{1.5}}{\sqrt{b + 2zy}} \quad (5.5)$$

where b is the culvert bed width; z represents the side slope; and the other variables are as defined earlier. Equation 5.5 only applies to the trapezoidal portion of Culvert 1, the

lowest part. The water depths assessed never exceeded the trapezoidal portion of the culvert; therefore, this equation is accurate for all analyses.

A Microsoft Excel spreadsheet was created to solve the gradually varied flow equation and to estimate water depths and average velocities through the culvert barrel for the range of flows measured in Mulherin Creek between 2004 and 2006. The gradually varied flow solution starts at the water depth at the culvert inlet and proceeds to solve for the water depth in the downstream or x-direction in a step-wise fashion. The step size was set to 0.3 m.

Fish passage was estimated using the following method which is based on the original observations of Bainbridge in 1960 (Bainbridge, 1960). Similar methods were used to identify barriers (Powers and Orsborn, 1986) and for fishway design (Hunter and Mayor, 1986). One key difference between the methods used by Powers and Orsborn (1986) and Hunter and Mayor (1986) and this method is that the velocity is not constant through the structure, but changes gradually with distance down the culvert barrel. A gradually varied flow method is also used by the FishXing Software (FishXing, 1999).

To provide an understanding of this method, the derivation for estimating the maximum distance a fish can travel against a velocity challenge is shown below in equation 5.6 (after Hunter and Mayor, 1986). The velocity of a fish swimming relative to a fixed frame of reference is:

$$V_{GRD} = \frac{dx}{dt} = V_w + V_f \quad (5.6)$$

where V_{GRD} is the absolute velocity of the fish with respect to the ground; and all other variables are as previously described. This equation can be rearranged and integrated to determine the distance the fish can swim for a given amount of time, assuming both the water velocity and the velocity of the fish are constant:

$$x = \int_0^t (V_w + V_f) dt \quad (5.7)$$

The velocity of a swimming fish can be described as a function of length and time in the form:

$$V_f = KL_f^\varphi t^{-\theta} \quad (5.8)$$

where K is an experimentally developed constant; t is the time of swimming; and φ and θ are experimentally developed exponents. This equation is developed experimentally for the fish species of interest. The relationship between fish swimming, length, and time has been developed for some, but not all fish species or life stages (Hoar and Randall, eds., 1978; Katopodis and Gervais, 1991). Substituting 5.8 into 5.7, integrating and simplifying yields:

$$x = \frac{V_f t + V_w t + \theta V_w t}{1 - \theta} \quad (5.9)$$

Recognizing that the maximum value of x occurs when $dx/dt = 0$ or $V_w = V_f$, this equation becomes:

$$x = \frac{\theta V_f t}{1 - \theta} \quad (5.10)$$

The 1-D approach used to estimate passage for this research uses the same concept as previously detailed. However, the approach is different because it includes the changing velocity through the culvert barrel rather than identifying the distance a fish can swim against a constant velocity. Equation 5.6 can be rearranged to determine the time it takes for a fish to swim a known distance at constant velocity:

$$t = \frac{x}{V_w + V_f} \quad (5.11)$$

The approach to estimate passage divides the culvert into sections that are 0.3 m long in the x-direction, the same interval that velocities are calculated using the gradually varied flow equation. Equation 5.11 is solved for the time it takes the fish to swim each 0.3 m section of the culvert, where the velocity (V_w) across each section is assumed to be constant and the fish is assumed to swim at a constant speed. The total time to pass the culvert is then calculated by summing the time it takes to pass each 0.3 m increment. This total time is then compared to the fatigue time for the species of interest. If the total time to pass the culvert for the flow rate of interest is greater than the time to fatigue, then the culvert is identified as a barrier due to excessive velocity at that flow. If the total time to

pass the culvert for the flow rate of interest is less than the time to fatigue, then the culvert is identified as passable at that flow rate.

3-D Fish Passage Assessment

This model of fish passage uses an approach similar to that previously described with a few key modifications. First and most importantly, the 3-D velocity field is used to estimate passage rather than the average 1-D velocity field. ANSYS-CFX is used to estimate the 3-D velocity field for the flow of interest. Second, possible paths a fish could take through the culvert are identified based on dividing the outlet of the culvert into ten equally spaced sections as described in Section IV. Third, the minimum energy path is determined by following procedures previously described in Section IV. Last, the velocities along the minimum energy path are then used to estimate passage in the same manner as described for the 1-D fish passage assessment. This approach assumes that fish will seek, find, and use the minimum energy path to pass the culvert.

Fish Swimming Abilities

Both methods for determining passage rely upon the swimming abilities of the fish of interest. The assessments were performed for only adult Yellowstone cutthroat trout. The size of the trout was set equal to 331 mm, the average size of 322 Yellowstone cutthroat trout captured in 2004. The trout were assumed to swim at burst speed, which is based on visual observations of fish attempting passage through the culvert. In addition, the burst speed was assumed to be constant.

Table 7 provides a summary of burst speed data for cutthroat trout and rainbow trout. The swimming speeds for rainbow trout are also included because there is only one

reference (to the author's knowledge) for burst speeds of cutthroat trout (Bell, 1991) and rainbows are often suggested as a possible surrogate species for cutthroat trout.

Table 7. Summary of burst swimming speeds for cutthroat trout and rainbow trout.

Species	Burst Speed	Burst Speed Range	Size Range	Time Range	Source and Notes
	m/s	m/s	cm	s	
Cutthroat Trout	4.12	-	-	-	Bell (1991).
Rainbow Trout	-	1.86 to 2.26	58 to 67	10 to 15	Paulik and Delacy (1957) as cited in Hoar and Randall, eds. (1978).
Rainbow Trout	-	5.36 to 8.17	61 to 81	1.5	Weaver (1963) as cited in Hoar and Randall, eds. (1978).
Rainbow Trout	-	0.3 to 2.5	14.3	0.08	Webb, as cited in Hoar and Randall, eds. (1978).
Rainbow Trout	-	0.3 to 1.8	14.3	0.04	Webb, as cited in Hoar and Randall, eds. (1978).
Rainbow Trout	0.83	-	-	-	Jones et al. (1974) as listed in FishXing Swimming Speed table.
Rainbow Trout	1.49	-	10.3 to 28	1 to 20	Bainbridge (1960) as cited in Hunter and Mayor (1986).
Rainbow Trout	1.87	-	10.3 to 81.3	1 to 20	Bainbridge (1960), Weaver (1963) and Beamish (1978) as cited in Hunter and Mayor (1986).
Rainbow Trout	3.09	-	61 to 81.3	1.6 to 12.5	Weaver (1963) and Beamish (1978) as cited in Hunter and Mayor (1986).

Note: The burst speeds with a * are estimated from length and time regression equations. The length was set equal to the average length of 322 Yellowstone cutthroat trout sampled in 2004, and the time was set to 5 seconds.

The 1-D and 3-D assessment methods use the burst speed for cutthroat trout shown in Bell (1991) and the burst speed equation listed in Hunter and Mayor (1986) for rainbow trout as shown in row eight of Table 7. This equation for rainbow trout was selected because the average size of Yellowstone cutthroat trout in this study was within the size range of the fish used to develop the equation, and the temperature in Mulherin Creek during the migration period was within the temperature range of the swimming speed experiments.

The time to fatigue for fish varies (Hoar and Randall, eds., 1978; Hunter and Mayor, 1986). Table 7 shows the time ranges for various burst speeds of rainbow and cutthroat trout. Based on the range of times in these studies, a time of five seconds was set as the fatigue time. The Hunter and Mayor equation is a function of time. The data cited in Bell (1991) for cutthroat trout does not include a fatigue time; therefore, the use of five seconds as the time to fatigue may be questionable.

Both the 1-D and the 3-D assessment methods were used to estimate passage for the primary study culvert for the entire measured hydrograph between 2004 and 2006. As previously described, two different estimates of swimming speed were also used. Therefore, a total of four different barrier assessments were performed. The results of these assessments and a discussion of those results are detailed in the next section.

Results and Discussion

Results for the 1-D and 3-D assessment methods are summarized in Figures 48, 49 and 50 for hydrographs measured in 2004, 2005, and 2006, respectively. These figures show the amount of passage that is estimated relative to the flow rate measured in Mulherin Creek at the culvert location. These three charts include passage assessment results for four hydraulic methods and a “window” or range showing observed passage for trout ($n = 21$). The four hydraulic methods and the predicted threshold flow for passable (less than the flow threshold) and impassable (greater than the flow threshold) are as follows:

- 1) Using 1-D flow and swim data in Bell (1991) for cutthroat trout, flow rates less than $0.85 \text{ m}^3/\text{s}$ are passable, and flow rates greater than $0.85 \text{ m}^3/\text{s}$ are impassable.
- 2) Using 1-D flow and Hunter and Mayor's (1986) data for rainbow trout, there is no passage at any flow rate because the average velocities are too great at all measured flow rates.
- 3) Using 3-D flow and swim data in Bell (1991) for cutthroat trout, flow rates less than $2.1 \text{ m}^3/\text{s}$ are passable, and flow rates greater than $2.1 \text{ m}^3/\text{s}$ are impassable.
- 4) Using 3-D flow and Hunter and Mayor's (1986) data for rainbow trout, flow rates less than $1.1 \text{ m}^3/\text{s}$ are passable, and flow rates greater than $1.1 \text{ m}^3/\text{s}$ are impassable.

The observed passage window, based on field observations of 21 trout passing the structure during 2004, ranges from $1.41 \text{ m}^3/\text{s}$ to $2.12 \text{ m}^3/\text{s}$.

Another way of expressing these results is the percent of time (based on the measured hydrograph compared to the estimated flow passage thresholds) that is estimated to be passable to Yellowstone cutthroat trout. Table 8 summarizes the percent of time that is passable for water years 2004, 2005, 2006, and all years combined. The

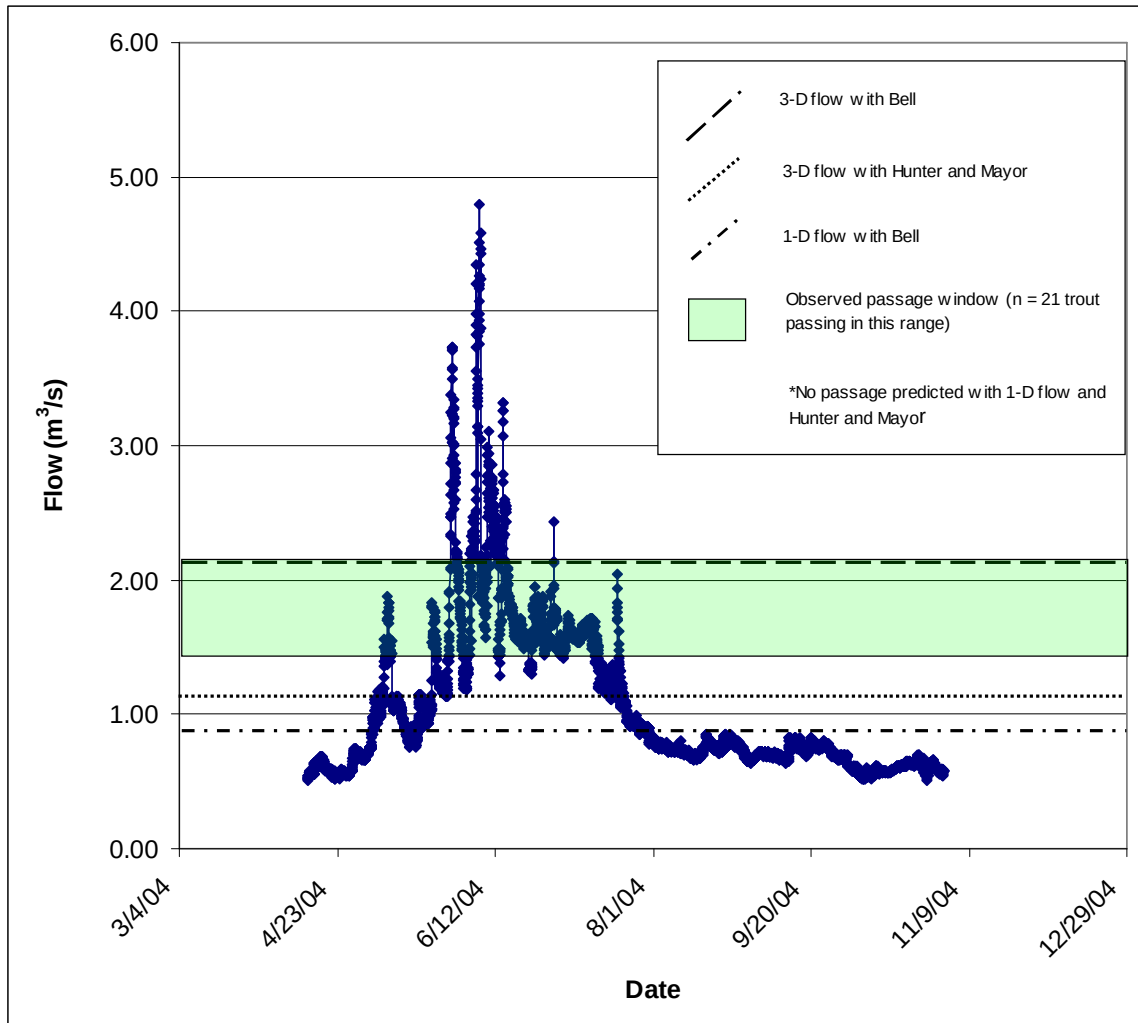


Figure 48. Estimated passage window at Culvert 1 for 2004 using all four assessment methods. Flow rates greater than the thresholds are impassable based on the method, and flow rates less than the thresholds are passable based on the method.

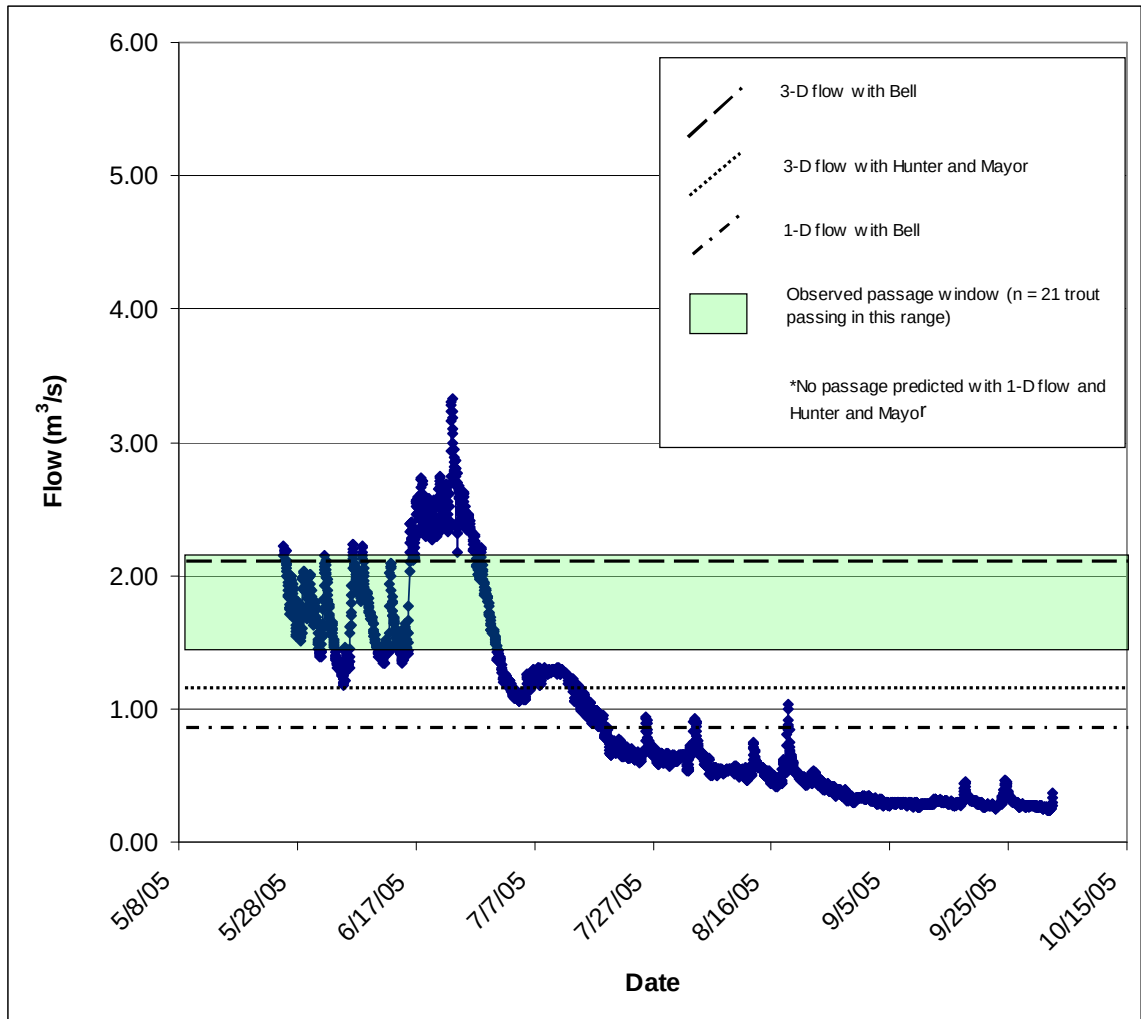


Figure 49. Estimated passage window at Culvert 1 for 2004 using all four assessment methods. Flow rates greater than the thresholds are impassable based on the method, and flow rates less than the thresholds are passable based on the method.

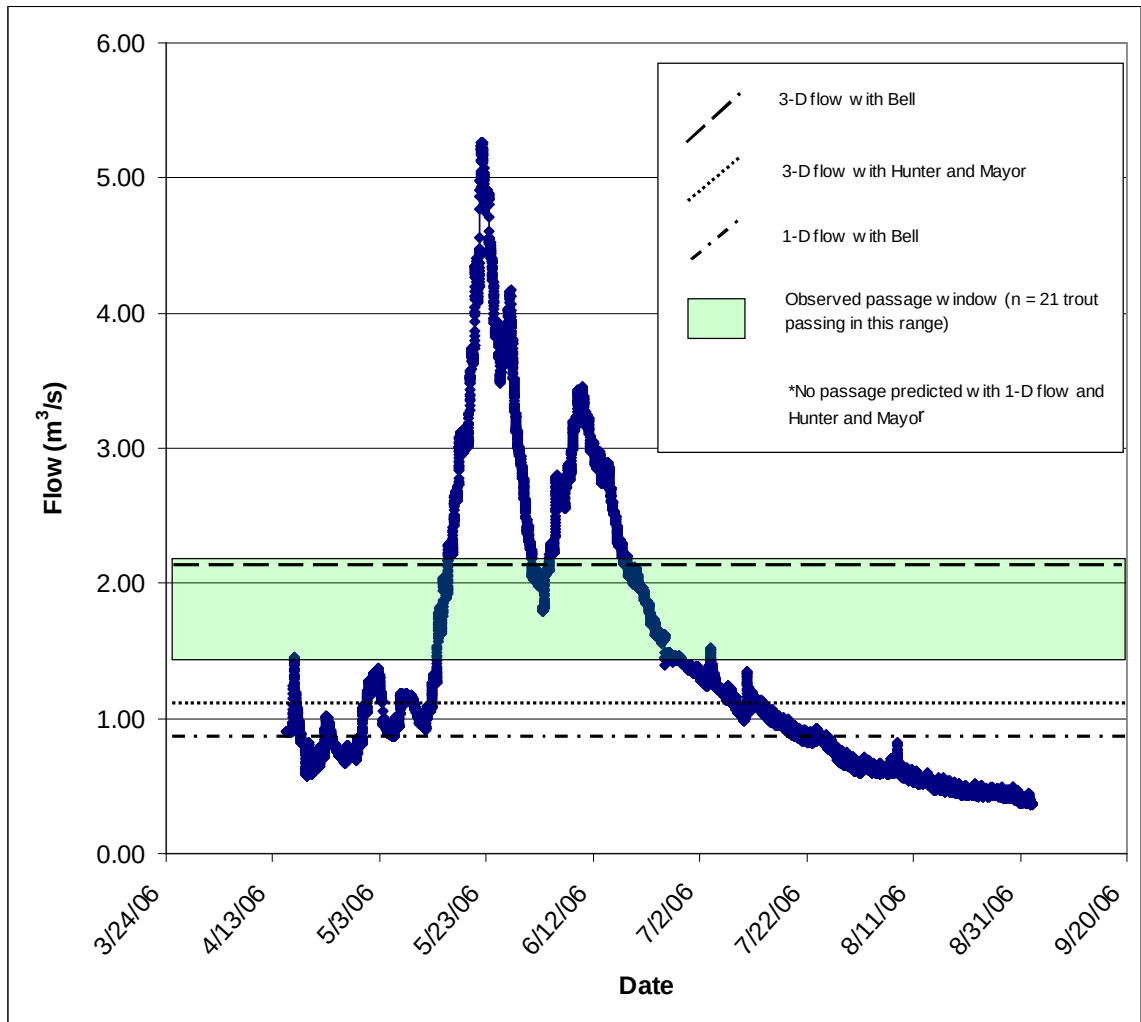


Figure 50. Estimated passage window at Culvert 1 for 2004 using all four assessment methods. Flow rates greater than the thresholds are impassable based on the method, and flow rates less than the thresholds are passable based on the method

results for all days combined show that the 1-D assessment method with the swim data in Bell (1991) estimates the primary culvert as passable 49% of the time; and the 1-D assessment method using Hunter and Mayor's (1986) data estimates the primary culvert as passable 0% of the time. The 3-D assessment method estimates that the culvert is passable for a greater amount of time than the 1-D method. The 3-D method using data

listed in Bell (1991) estimates the primary culvert as passable 85% of the time; and the 3-D assessment method using Hunter and Mayor's (1986) data estimates the primary culvert as passable 60% of the time.

Table 8. Summary of fish passage assessment method results.

Method	2004	2005	2006	All Years Combined
1-D with Bell	57%	49%	37%	49%
1-D with Hunter and Mayor	0%	0%	0%	0%
3-D with Bell	93%	84%	75%	85%
3-D with Hunter and Mayor	67%	62%	46%	60%

The 3-D assessment method estimates a greater amount of passage because the method uses a more accurate and realistic calculation of the flow field. The lower velocity region on the river left side of the culvert (see Figure 13, Section II) allows fish to swim upstream against velocities that are less than the average velocity in the culvert barrel; therefore, they are able to pass upstream at flow rates with high average velocities. The 1-D method compares passage to the average velocity only and therefore estimates less passage.

During the summer of 2004, 21 observations of fish passing through the culvert were recorded; 18 by visual assessment and three by trapping. Table 9 compares the passage assessment flow rate thresholds to the flow rates where passage was observed.

Table 9. Summary of passage assessment and observations of fish movement in the primary study culvert.

Number of Fish Observed Passing	Measured Flow Rate (m ³ /s)	1-D with Bell	1-D with Hunter and Mayor	3-D with Bell	3-D with Hunter and Mayor
6	1.55	Not Passable	Not Passable	Passable	Not Passable
3	1.50	Not Passable	Not Passable	Passable	Not Passable
2	1.70	Not Passable	Not Passable	Passable	Not Passable
1	1.90	Not Passable	Not Passable	Passable	Not Passable
1	2.12	Not Passable	Not Passable	Passable	Not Passable
3	1.47	Not Passable	Not Passable	Passable	Not Passable
2	1.58	Not Passable	Not Passable	Passable	Not Passable
3	1.41	Not Passable	Not Passable	Passable	Not Passable

Table 9 shows the most accurate method is the 3-D with the swim speed listed in Bell (1991). All other methods identified the culvert as a barrier even though observations showed fish movement through the culvert.

One drawback to the 1-D and 3-D method is that for a given flow rate the methods give a passable or not passable result (yes or no). In actuality, as the flow rate increases making passage more difficult, the amount of passage decreases probabilistically. Data collected in a companion study at Mulherin Creek shows this relationship (Cahoon et al., 2007a). Another example of the probabilistic nature of passage can be shown from jumping tests performed on brook trout. As the leap height was increased, the probability of successfully leaping over the obstacle decreased until the final threshold of 0.0 successfully making the leap was found for leap heights around 90 cm for trout 10 cm in length (Kondratieff and Myrick, 2006).

There are advantages and disadvantages to each of these methods. The 1-D method relies upon less data and less computational effort to describe the flow field. However, it proves to be less accurate because it only describes the 1-D average velocity

through the culvert and cannot predict the diversity both laterally and longitudinally through the culvert as the 3-D method can.

The greatest drawback to the 3-D method is the additional field data that is necessary to collect, the time required to capture the temporal changes to the inlet velocity pattern (a key boundary condition for the model), and the additional cost for computing the velocity field. As computer technology improves, this cost will likely become irrelevant.

Part of the decision to use one method or the other should incorporate the importance of the crossing and the desired accuracy of the assessment. As research into barriers continues, there seems to be a large number of temporal barriers – barriers that allow passage at some flows and times of the year, but not all. The primary study culvert is a classic, well-defined temporal barrier. One very important question related to barrier assessment is to consider which is least desirable: classifying a structure as passable when it is not, or classifying a structure as impassable when it is actually passable.

It would be a very interesting and useful exercise to evaluate several crossing sites using both methods to further explore their relative performance and evaluate their effectiveness across a range of physical and biological settings.

Summary

This chapter of the thesis presented a new approach, which incorporates the 3-D velocity field through a culvert, to estimate fish passage. A comparison of a 1-D method to the 3-D method showed that the 3-D method predicted a greater amount of passage through the culvert. The 3-D method also provided a more accurate picture of the

barrierity of the structure than the 1-D method when compared to field data of fish movements through the structure.

Both the 1-D and 3-D assessment methods are sensitive to the swimming abilities of the species of interest. There is very little data on burst swimming speeds for many species of fish; therefore, there is a need to collect more of this data (Haro et al., 2004). Much of the existing data was collected in the 60's and 70's, and it was typically collected for use in the design of fishways, not necessarily the assessment of barriers. Sprinting performance following methods used at the S.O. Conte Anadromous fish laboratory should be determined as existing data for most fish species is limited or non-existent (Haro et al., 2004).

When designing fishways, less aggressive swim speeds, like the sustained swimming ability are used (Clay, 1995). When evaluating barriers to passage, more aggressive speeds are incorporated into the analysis. This difference in swim speed is a very key distinction. In addition, recent research is showing that some fish species will select a distance-maximizing swimming strategy, while others will not (Castro-Santos, 2005). Therefore, more research related to fish swimming behavior and strategies is needed to allow better understanding of how fish may attempt passage.

Part of fish swim speed data is the time to fatigue. Knowing how long a fish can maintain a given speed is critical to predicting passage using a hydraulic approach regardless if it relies upon 1-D, 2-D or 3-D velocities. As an example, the 1-D hydraulic model presented herein uses 5 seconds as the time to fatigue for Yellowstone cutthroat trout using data from Bell (1991). FishXing uses a 10 second time to fatigue and the Bell (1991) data. Therefore, the 1-D approach herein estimates passage up to $0.85 \text{ m}^3/\text{s}$

compared to FishXing which estimates passage up to $1.5 \text{ m}^3/\text{s}$. The point is that data for the time to fatigue for Yellowstone cutthroat trout using burst swimming does not exist, nor does it exist for many fish species. Each of these modeling exercises are relying upon data from other species to derive a “best guess” of time to fatigue for cutthroat.

Even though the design of a new fishway and the assessment of the barrierity of an existing structure use similar information (swim-speed fatigue-time relationships for instance), each task is very different. There is a need to design the swimming method and experiments so that the data could be used for barrier assessments more easily.

Another interesting and important research question is how appropriate is the use of surrogate species when assessing barriers or designing fishways?

In terms of needs for improving the calculations of the hydraulic environment, there is a need to develop methods to approximate the temporal nature of an inlet velocity data set from a limited number of measurements. This task will be extremely challenging as there are many different controls on how water flows near structures, and those controls change with flow.

Although the investigation of jumping location and conditions at Culvert 1 did not show any significant relationships, there is a need to further investigate the effect of the outlet region conditions on passage success through culverts. Very little research has been done in this area to this date.

Additional validation of the 1-D and new 3-D barrier assessment methods would be very beneficial to those pursuing the assessment of barriers. There are millions of barriers in streams and rivers, many of which are temporal in nature. The 3-D method

could be used to evaluate the barrier status of other types of structures beyond road crossings, such as irrigation diversions.

CONCLUSIONS AND RECOMMENDATIONS

Fish passage through culverts is an important part of road and stream crossing design. Culverts can create barriers to the upstream and downstream movement of fish. The degree to which crossing structures act as barriers is an important research area. Common physical impediments to fish passage include excessive velocity, large outlet drops and insufficient water depth. This thesis explored the velocity factor of fish passage in great depth. In specific, several objectives were achieved during this research:

- (1) Velocity diversity in two culverts (one with baffles and one without) was quantified both spatially and temporally in 1-D and 3-D;
- (2) A 3-D CFD model of flow through Culvert 1 was developed and validated;
- (3) The extent that inlet velocity patterns created by upstream geometry propagate through the barrel of Culvert 1 was investigated;
- (4) The energy expenditure of trout passing through Culvert 1 at a range of flows was quantified;
- (5) The effect of flow rate, leap region and water temperature on leaping success into a culvert was explored; and
- (6) A new barrier assessment method that uses the 3-D velocity field and the minimum energy expenditure path was developed, compared to a 1-D assessment method and validated against field observations of fish movement.

Some of the more interesting results are worth repeating as this thesis is concluded. Velocity patterns were shown to be diverse in both the unbaffled and baffled culverts.

Even though the unbaffled culvert has a relatively simple geometry and a smooth floor, the velocity pattern through the structure is quite diverse.

A 3-D CFD model of culvert flow was found to predict the velocity pattern through the culvert on a plane 0.06 m above the culvert bed with good success. Comparisons between predicted and observed velocities yielded model correlation coefficients of r^2_{mod} of 0.86 for July 13, 2004 model ($Q = 1.44 \text{ m}^3/\text{s}$) and r^2_{mod} of 0.82 for August 9, 2004 model ($Q = 0.87 \text{ m}^3/\text{s}$).

Using the validated CFD model, the thesis explored the extent that velocity patterns created by stream geometry propagate through the structure by calculating three measures: the energy coefficient, momentum coefficient and MSE. Graphs of these three parameters throughout the length of the structure showed that all three parameters became relatively constant at approximately 5 to 6 m downstream of the culvert inlet, regardless of flow rate. Lower flows had greater values of all three parameters at the inlet than larger flows. These data suggest that, based on these measures, the velocity pattern created by the stream does not propagate through the entire structure. However, it creates a diverse velocity pattern that in turn creates a large range of energy paths through the structure.

Field observations of fish moving through the structure showed that all fish that were successful at passing through the structure used the minimum energy path to achieve passage. The maximum energy expenditure ranged from a minimum of 68.37 J on July 1, 2004 to a maximum of 72.60 J on July 29, 2004. The minimum energy expenditure ranged from 40.52 J on July 1, 2004 to a maximum of 41.61 J on June 29,

2004. The average energy expenditure ranged from a minimum of 40.74 J on June 28, 2004 to a maximum of 46.20 J on July 7, 2004.

Although field data seemed to show that fish preferred certain regions of the plunge pool to leap into the structure, statistical analyses did not show any significant affect of leap region, flow or water temperature on successful leaps into the structure.

The final part of the thesis developed a new barrier assessment method that uses the 3-D velocity field, the minimum energy path and fish swimming abilities to predict passage. This method was compared to a traditional method that uses the 1-D velocity field and fish swimming abilities to estimate passage. By comparing the passage thresholds for each method to actual observations of fish movement, the data showed that the 3-D method was most accurate.

Throughout the thesis, various recommendations were made to further the research of fish passage and assessment of barriers. Three main recommendations for future research seem most important. There is a need to further characterize fish swimming abilities. Many species do not have any data at all, and others have limited data. The research should explore swimming behavior of various species and life stages as well. More accurate swimming abilities and behavior information will greatly improve the predictive capacity of barrier assessments, the design of impassable barriers and the design of new crossings and retrofit structures.

A second recommendation for future research is to further characterize the 3-D nature of fish passage through a variety of hydraulic structures at a large range of flows. Combining fish swimming behavior with the advanced characterizations of velocity and turbulence will vastly improve our understanding.

A third recommendation is to test the 3-D assessment method across a range of different types of barriers and further validate its accuracy.

Throughout this thesis and the study performed in the Clearwater River Drainage, the approach combined ecology and engineering. This approach has proven extremely useful for analyzing fish passage. Figure 51 shows an hourglass that depicts an overall philosophy of ecology and engineering, two traditionally very disparate disciplines. The figure shows the “historic” viewpoints: ecologists take a big picture view of problems, while engineers typically piece things apart and focus on each detail within the big picture. The Clearwater River Drainage project used a big picture approach with a combination of engineering and ecology to investigate passage across a large basin. Based on the findings of the Clearwater research, a more detailed evaluation of a specific factor (velocity) was explored in Mulherin Creek. Both projects have yielded useful information that furthers the understanding of the complex physical and biological relationships within the fish passage arena. As future work is undertaken, the combined approaches of engineering and ecology should be nurtured as together they will provide a greater and richer understanding than either discipline can provide on its own.

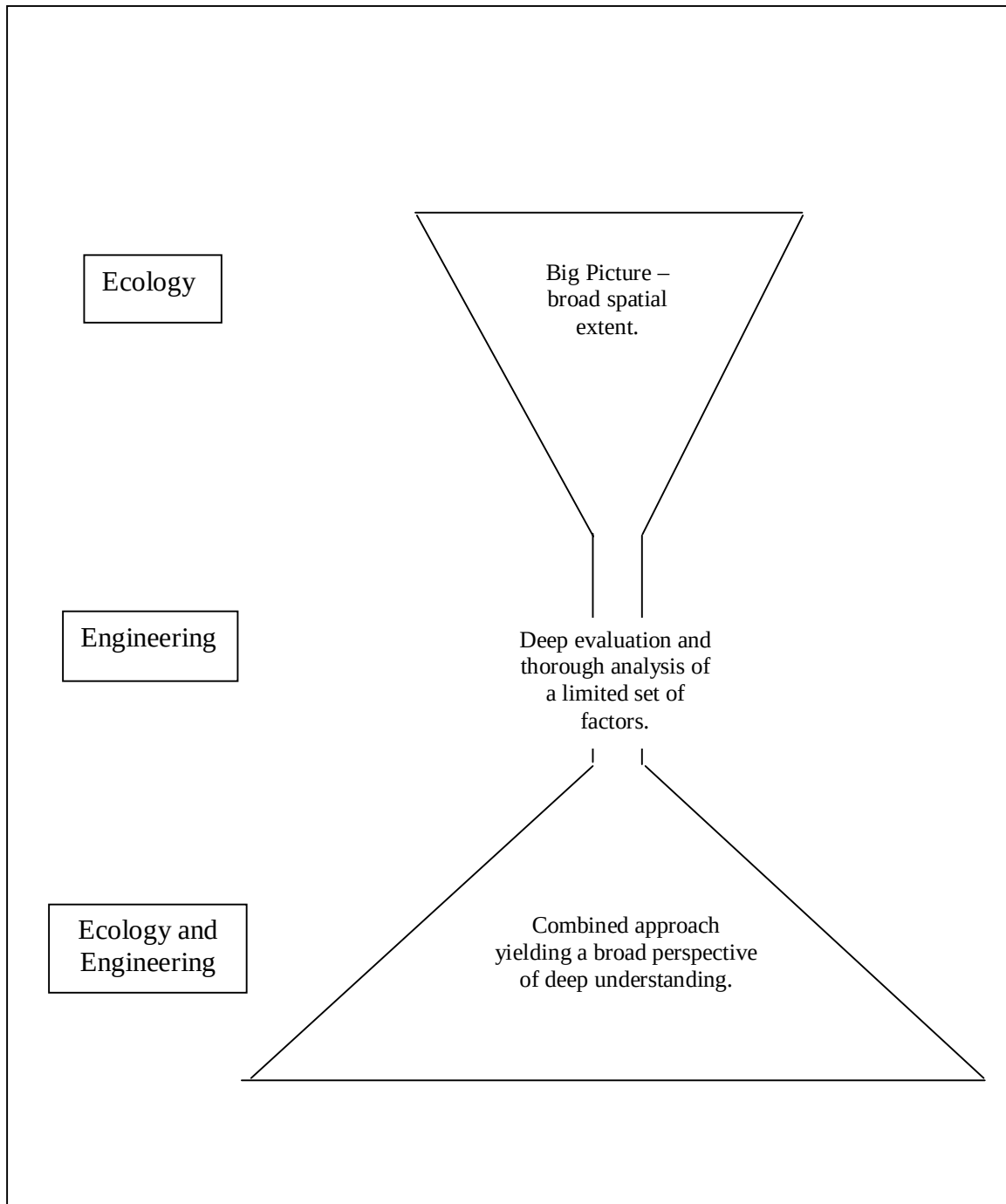


Figure 51. Diagram showing the engineering and ecology hourglass.

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APPENDICES

APPENDIX A

FIELD PHOTOS OF CULVERT 1 AND CULVERT 2



Inlet region of Culvert 1, looking downstream, flow rate estimated at 120 cfs.



Interior of Culvert 1, looking downstream, flow rate estimated at 120 cfs.



Outlet region of Culvert 1, looking upstream, flow rate estimated at 120 cfs.



Inlet region of Culvert 1, looking downstream, flow rate estimated at 28 cfs.



Interior of Culvert 1, looking downstream, flow rate estimated at 28 cfs.



Outlet region of Culvert 1, looking upstream, flow rate estimated at 28 cfs.



Inlet region of Culvert 1, looking downstream, flow rate estimated at 37.5 cfs.



Interior of Culvert 1, looking downstream, flow rate estimated at 37.5 cfs.



Outlet region of Culvert 1, looking upstream, flow rate estimated at 37.5 cfs.



Yellowstone cutthroat trout from Mulherin Creek.



Yellowstone cutthroat trout from Mulherin Creek.



Yellowstone cutthroat x rainbow trout from Mulherin Creek.



Inlet region of Culvert 2, looking downstream.



Outlet region of Culvert 2, looking upstream.

APPENDIX B

EXAMPLE OF ANSYS CFX MODEL INPUT CODE

CEL:

Option = Pure Substance

Thermodynamic State = Gas

PROPERTIES:

Option = General Material

Thermal Expansivity = 0.003356 [K⁻¹]

ABSORPTION COEFFICIENT:

Absorption Coefficient = 0.01 [m⁻¹]

Option = Value

END

DYNAMIC VISCOSITY:

Dynamic Viscosity = 1.831E-05 [kg m⁻¹ s⁻¹]

Option = Value

END

EQUATION OF STATE:

Density = 1.185 [kg m⁻³]

Molar Mass = 28.96 [kg kmol⁻¹]

Option = Value

END

REFRACTIVE INDEX:

Option = Value

Refractive Index = 1.0 [m m⁻¹]

END

SCATTERING COEFFICIENT:

Option = Value

Scattering Coefficient = 0.0 [m⁻¹]

END

SPECIFIC HEAT CAPACITY:

Option = Value

Reference Pressure = 1 [atm]

Reference Specific Enthalpy = 0. [J/kg]

Reference Specific Entropy = 0. [J/kg/K]

Reference Temperature = 25 [C]

Specific Heat Capacity = 1.0044E+03 [J kg⁻¹ K⁻¹]

Specific Heat Type = Constant Pressure

END

THERMAL CONDUCTIVITY:

Option = Value

Thermal Conductivity = 2.61E-02 [W m⁻¹ K⁻¹]

END

END

END

MATERIAL: Water

Material Description = Water (liquid)

Material Group = Water Data, Constant Property Liquids

Option = Pure Substance

Thermodynamic State = Liquid

PROPERTIES:

Option = General Material

Thermal Expansivity = 2.57E-04 [K⁻¹]

ABSORPTION COEFFICIENT:

Absorption Coefficient = 1.0 [m⁻¹]

Option = Value

```

END
DYNAMIC VISCOSITY:
  Dynamic Viscosity = 8.899E-4 [kg m^-1 s^-1]
  Option = Value
END
EQUATION OF STATE:
  Density = 997.0 [kg m^-3]
  Molar Mass = 18.02 [kg kmol^-1]
  Option = Value
END
REFRACTIVE INDEX:
  Option = Value
  Refractive Index = 1.0 [m m^-1]
END
SCATTERING COEFFICIENT:
  Option = Value
  Scattering Coefficient = 0.0 [m^-1]
END
SPECIFIC HEAT CAPACITY:
  Option = Value
  Reference Pressure = 1 [atm]
  Reference Specific Enthalpy = 0.0 [J/kg]
  Reference Specific Entropy = 0.0 [J/kg/K]
  Reference Temperature = 25 [C]
  Specific Heat Capacity = 4181.7 [J kg^-1 K^-1]
  Specific Heat Type = Constant Pressure
END
THERMAL CONDUCTIVITY:
  Option = Value
  Thermal Conductivity = 0.6069 [W m^-1 K^-1]
END
END
END
END
EXECUTION CONTROL:
  PARALLEL HOST LIBRARY:
    HOST DEFINITION: cemblank
    Remote Host Name = CE-MBLANK
    Installation Root = C:\Program Files\Ansys Inc\CFX\CFX-%v
    Host Architecture String = intel_p4.sse2_winnt5.1
  END
END
PARTITIONER STEP CONTROL:
  Multidomain Option = Independent Partitioning
  Runtime Priority = Standard
  MEMORY CONTROL:
    Memory Allocation Factor = 1.0
  END
  PARTITIONING TYPE:
    MeTiS Type = k-way
    Option = MeTiS

```

```

    Partition Size Rule = Automatic
END
END
RUN DEFINITION:
    Definition File = C:/CFX Stuff/nov.30.def
    Interpolate Initial Values = Off
    Run Mode = Full
END
SOLVER STEP CONTROL:
    Runtime Priority = Standard
EXECUTABLE SELECTION:
    Double Precision = Off
END
MEMORY CONTROL:
    Memory Allocation Factor = 1.0
END
PARALLEL ENVIRONMENT:
    Number of Processes = 1
    Start Method = Serial
END
END
END
FLOW:
DOMAIN: culvert 1
    Coord Frame = Coord 0
    Domain Type = Fluid
    Fluids List = Air at 25 C, Water
    Location = Assembly
BOUNDARY: inlet
    Boundary Type = INLET
    Location = inlet
BOUNDARY CONDITIONS:
    FLOW REGIME:
        Option = Subsonic
    END
    MASS AND MOMENTUM:
        Option = Cartesian Velocity Components
        U = July13Data.u(x,y,z)
        V = July13Data.v(x,y,z)
        W = July13Data.w(x,y,z)
    END
    TURBULENCE:
        Eddy Length Scale = uph
        Fractional Intensity = 0.05
        Option = Intensity and Length Scale
    END
END
FLUID: Air at 25 C
BOUNDARY CONDITIONS:
    VOLUME FRACTION:
        Option = Value

```

```

    Volume Fraction = upvofl
  END
END
FLUID: Water
BOUNDARY CONDITIONS:
  VOLUME FRACTION:
    Option = Value
    Volume Fraction = upvofh
  END
END
END
BOUNDARY: OULET
  Boundary Type = OUTLET
  Location = outlet
  BOUNDARY CONDITIONS:
    FLOW REGIME:
      Option = Subsonic
    END
    MASS AND MOMENTUM:
      Option = Average Static Pressure
      Relative Pressure = downpres
    END
    PRESSURE AVERAGING:
      Option = Average Over Whole Outlet
    END
  END
END
BOUNDARY: side 1
  Boundary Type = WALL
  Location = side 1
  BOUNDARY CONDITIONS:
    WALL INFLUENCE ON FLOW:
      Option = No Slip
    END
    WALL ROUGHNESS:
      Option = Rough Wall
      Roughness Height = 0.001 [foot]
    END
  END
END
BOUNDARY: side 2
  Boundary Type = WALL
  Location = side 2
  BOUNDARY CONDITIONS:
    WALL INFLUENCE ON FLOW:
      Option = No Slip
    END
    WALL ROUGHNESS:
      Option = Rough Wall

```

```

    Roughness Height = 0.001 [foot]
  END
END
BOUNDARY: side 3
  Boundary Type = WALL
  Location = side 3
  BOUNDARY CONDITIONS:
    WALL INFLUENCE ON FLOW:
      Option = No Slip
    END
    WALL ROUGHNESS:
      Option = Rough Wall
      Roughness Height = 0.001 [foot]
    END
  END
END
BOUNDARY: side 4
  Boundary Type = WALL
  Location = side 4
  BOUNDARY CONDITIONS:
    WALL INFLUENCE ON FLOW:
      Option = No Slip
    END
    WALL ROUGHNESS:
      Option = Rough Wall
      Roughness Height = 0.001 [foot]
    END
  END
END
BOUNDARY: bottom
  Boundary Type = WALL
  Location = bottom
  BOUNDARY CONDITIONS:
    WALL INFLUENCE ON FLOW:
      Option = No Slip
    END
    WALL ROUGHNESS:
      Option = Rough Wall
      Roughness Height = 0.001 [foot]
    END
  END
END
BOUNDARY: top
  Boundary Type = WALL
  Location = top
  BOUNDARY CONDITIONS:
    WALL INFLUENCE ON FLOW:
      Option = Free Slip
    END
  END
END

```

```

END
DOMAIN MODELS:
  BUOYANCY MODEL:
    Buoyancy Reference Density = 1.185 [kg m^-3]
    Gravity X Component = 0.0 [m s^-2]
    Gravity Y Component = -9.81 [m s^-2]
    Gravity Z Component = 0.0 [m s^-2]
    Option = Buoyant
  BUOYANCY REFERENCE LOCATION:
    Option = Automatic
  END
END
DOMAIN MOTION:
  Option = Stationary
END
REFERENCE PRESSURE:
  Reference Pressure = 0 [Pa]
END
END
FLUID: Air at 25 C
FLUID MODELS:
  FLUID BUOYANCY MODEL:
    Option = Density Difference
  END
  MORPHOLOGY:
    Option = Continuous Fluid
  END
END
FLUID: Water
FLUID MODELS:
  FLUID BUOYANCY MODEL:
    Option = Density Difference
  END
  MORPHOLOGY:
    Option = Continuous Fluid
  END
END
FLUID MODELS:
  COMBUSTION MODEL:
    Option = None
  END
  HEAT TRANSFER MODEL:
    Homogeneous Model = True
    Option = None
  END
  THERMAL RADIATION MODEL:
    Option = None
  END
  TURBULENCE MODEL:

```

```

Option = k epsilon
BUOYANCY TURBULENCE:
  Option = None
END
END
TURBULENT WALL FUNCTIONS:
  Option = Scalable
END
END
FLUID PAIR: Air at 25 C | Water
INTERPHASE TRANSFER MODEL:
  Option = None
END
MASS TRANSFER:
  Option = None
END
SURFACE TENSION MODEL:
  Option = None
END
END
MULTIPHASE MODELS:
  Homogeneous Model = On
FREE SURFACE MODEL:
  Option = Standard
END
END
INITIALISATION:
  Option = Automatic
FLUID: Air at 25 C
  INITIAL CONDITIONS:
    VOLUME FRACTION:
      Option = Automatic with Value
      Volume Fraction = upvofl
    END
  END
END
FLUID: Water
  INITIAL CONDITIONS:
    VOLUME FRACTION:
      Option = Automatic with Value
      Volume Fraction = upvofh
    END
  END
END
INITIAL CONDITIONS:
  Velocity Type = Cartesian
  CARTESIAN VELOCITY COMPONENTS:
    Option = Automatic with Value
    U = 0 [ft s^-1]
    V = 0 [ft s^-1]

```

```

    W = 0 [ft s-1]
END
EPSILON:
    Option = Automatic
END
K:
    Option = Automatic
END
STATIC PRESSURE:
    Option = Automatic with Value
    Relative Pressure = uppres
END
END
END
OUTPUT CONTROL:
RESULTS:
    File Compression Level = Default
    Option = Standard
END
END
SIMULATION TYPE:
    Option = Steady State
END
SOLUTION UNITS:
    Angle Units = [rad]
    Length Units = [m]
    Mass Units = [kg]
    Solid Angle Units = [sr]
    Temperature Units = [K]
    Time Units = [s]
END
SOLVER CONTROL:
ADVECTION SCHEME:
    Option = High Resolution
END
CONVERGENCE CONTROL:
    Maximum Number of Iterations = 200
    Physical Timescale = 0.1 [s]
    Timescale Control = Physical Timescale
END
CONVERGENCE CRITERIA:
    Residual Target = 1.E-4
    Residual Type = RMS
END
DYNAMIC MODEL CONTROL:
    Global Dynamic Model Control = On
END
END
COMMAND FILE:
    Version = 10.0

```

Results Version = 10.0
END

```

+-----+
|                                     |
|               Profile Data         |
|                                     |
+-----+

```

Inlet Velocity Data for Culvert 1 Collected with Pygmy,,,,,

,,,,,

,,,,,

[Name],,,,,

July13Data,,,,,

[Spatial Fields],,,,,

x,y,z,,

[Data],,,,,

x[ft], y[ft], z[ft], u[ft s⁻¹], v[ft s⁻¹], w[ft s⁻¹]

0,0.6,-5,1.76,0,0

0,0.4,-5,2.61,0,0

0,0.2,-5,2.83,0,0

0,0.05,-5,1.41,0,0

0,0.6,-4,4.96,0,0

0,0.4,-4,4.32,0,0

0,0.2,-4,1.73,0,0

0,0.05,-4,2.05,0,0

0,0.6,-3,2.49,0,0

0,0.4,-3,2.58,0,0

0,0.2,-3,2.87,0,0

0,0.05,-3,2.71,0,0

0,0.6,-2,3.05,0,0

0,0.4,-2,3.15,0,0

0,0.2,-2,2.68,0,0

0,0.05,-2,3.47,0,0

0,0.6,-1,3.44,0,0

0,0.4,-1,3.64,0,0

0,0.2,-1,2.8,0,0

0,0.05,-1,2.47,0,0

0,0.6,0,3.89,0,0

0,0.4,0,4.22,0,0

0,0.2,0,3.54,0,0

0,0.05,0,3.64,0,0

0,0.6,1,3.99,0,0

0,0.4,1,4.47,0,0

0,0.2,1,4.32,0,0

0,0.05,1,4.09,0,0

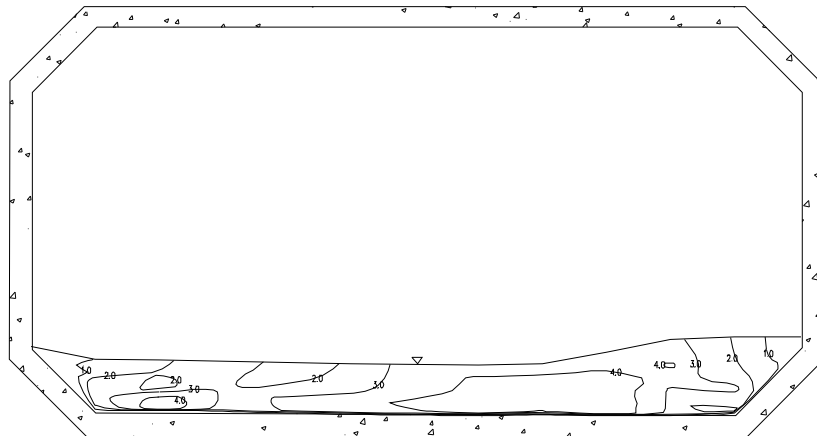
0,0.6,2,3.93,0,0
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0,0.05,2,4.18,0,0
0,0.8,3,5.01,0,0
0,0.6,3,5.01,0,0
0,0.4,3,4.86,0,0
0,0.2,3,4.76,0,0
0,0.05,3,3.38,0,0
0,1,4,2.83,0,0
0,0.8,4,2.93,0,0
0,0.6,4,2.95,0,0
0,0.4,4,3.38,0,0
0,0.2,4,4.03,0,0
0,0.05,4,3.7,0,0
0,1,5,3.15,0,0
0,0.8,5,2.76,0,0
0,0.6,5,3.12,0,0
0,0.4,5,2.49,0,0
0,0.2,5,2.17,0,0
0,0.05,5,2.02,0,0

APPENDIX C

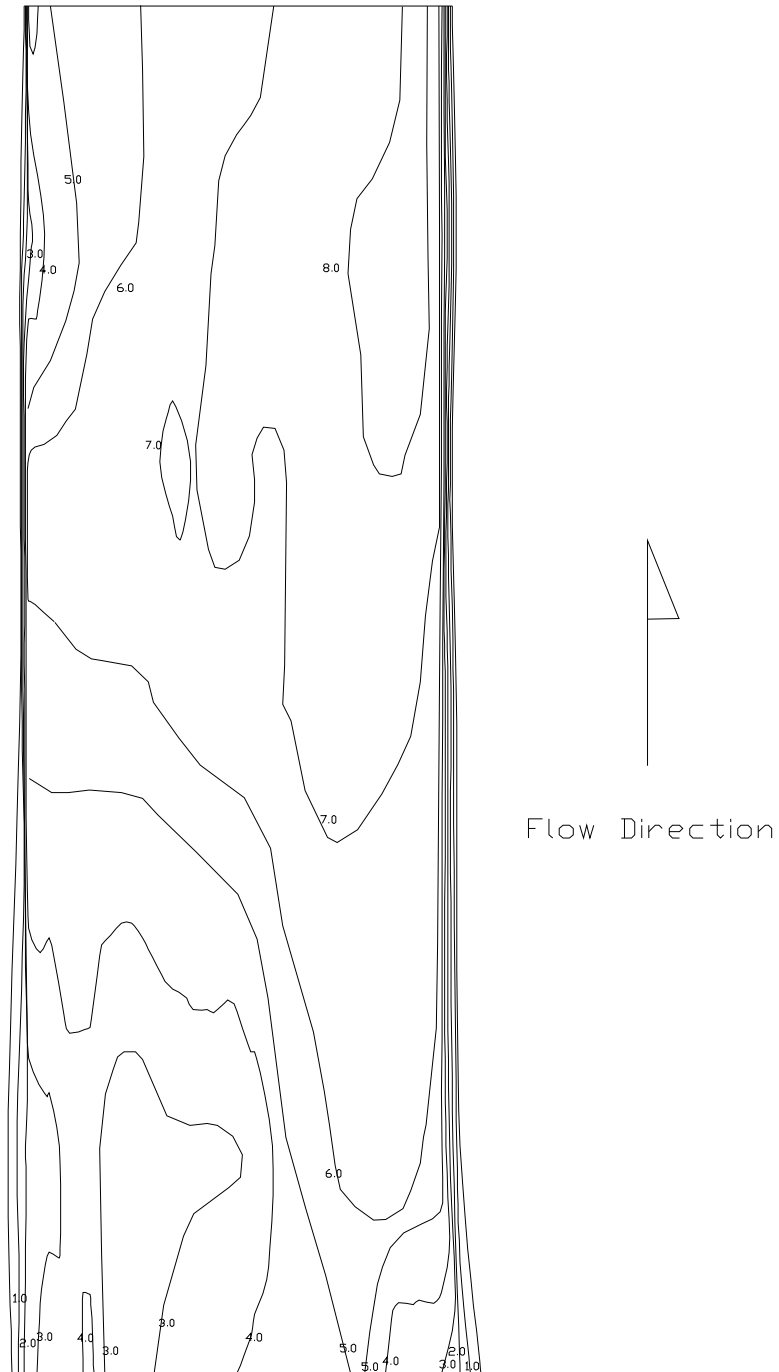
MAPS OF INLET AND PLAN VIEW VELOCITY PATTERNS IN CULVERTS



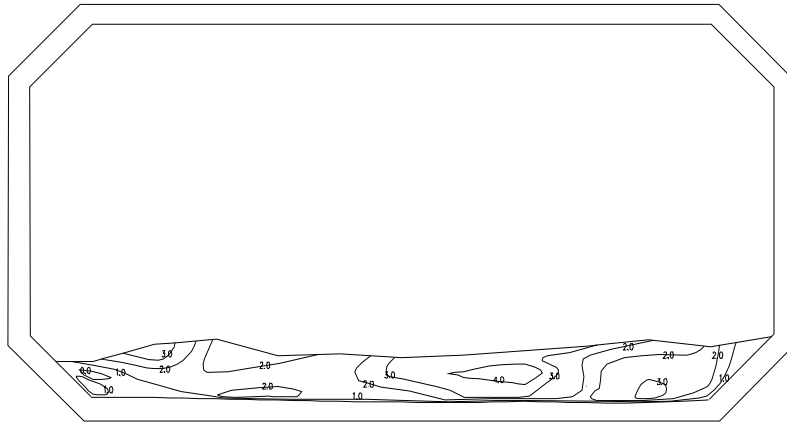
Culvert #1; May 26, 2004; Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 43.13 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = Pygmy Meter.



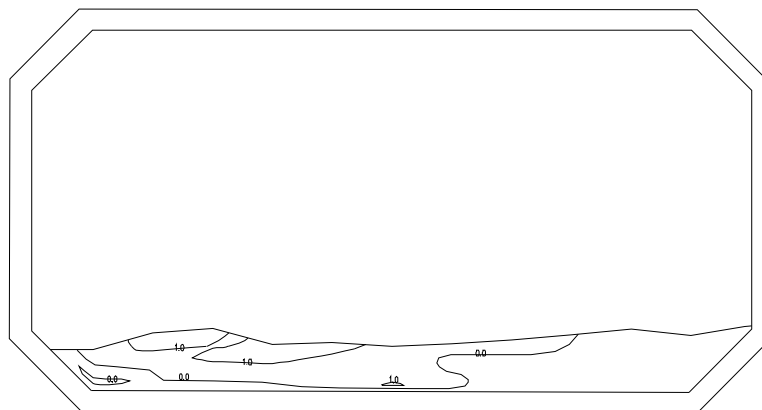
Culvert #1; July 13, 2004; Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 51.01 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = Pygmy Meter.



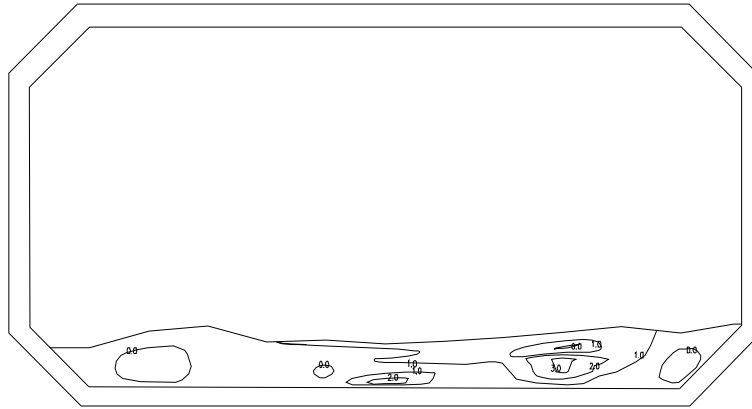
Culvert #1; July 13, 2004; Plan View of Velocity Contours;
 Measurements at 0.2 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 51.01 cfs; Culvert Width = 12.0 ft; Culvert Length = 36.7 ft;
 Instrument = Pygmy Meter.



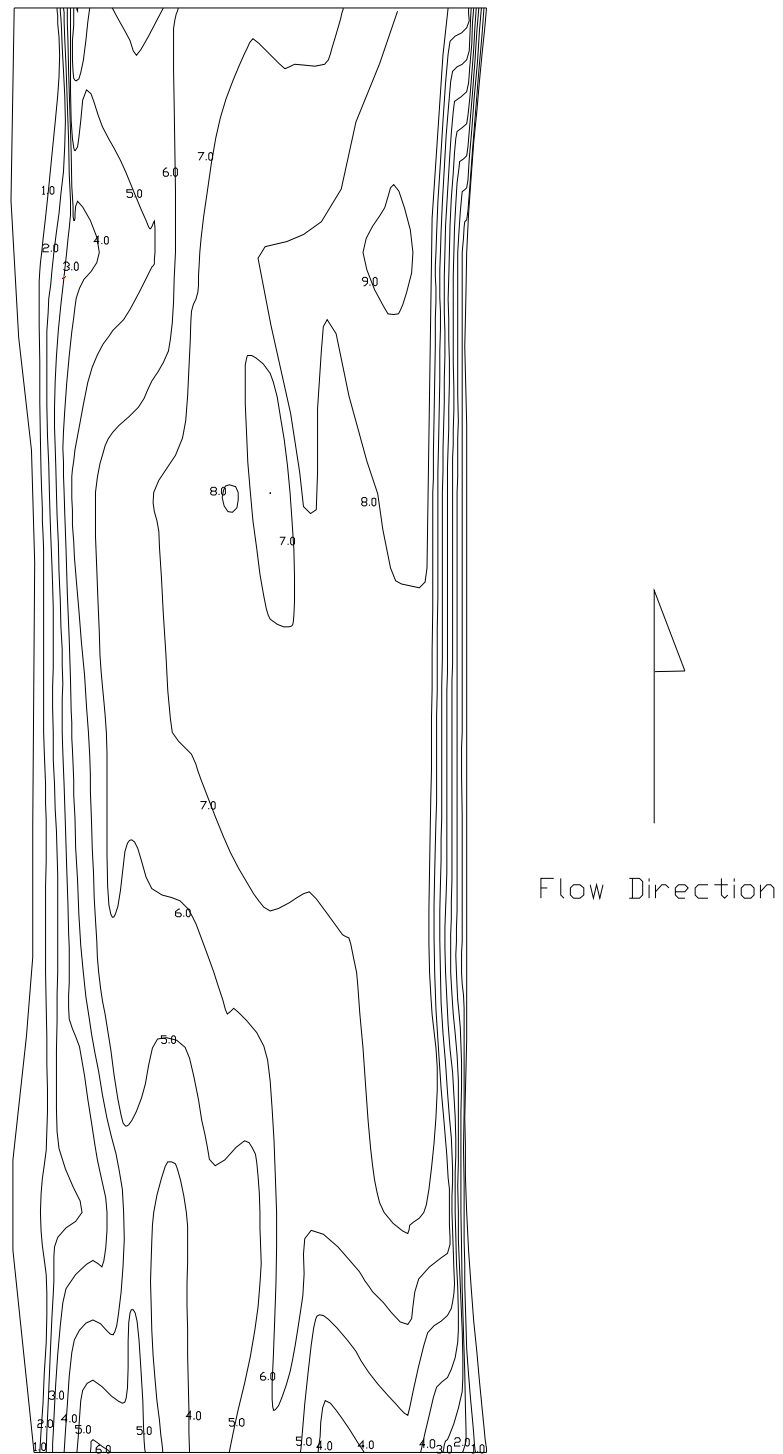
Culvert #1; July 21, 2004; X-Component Velocity Contours;



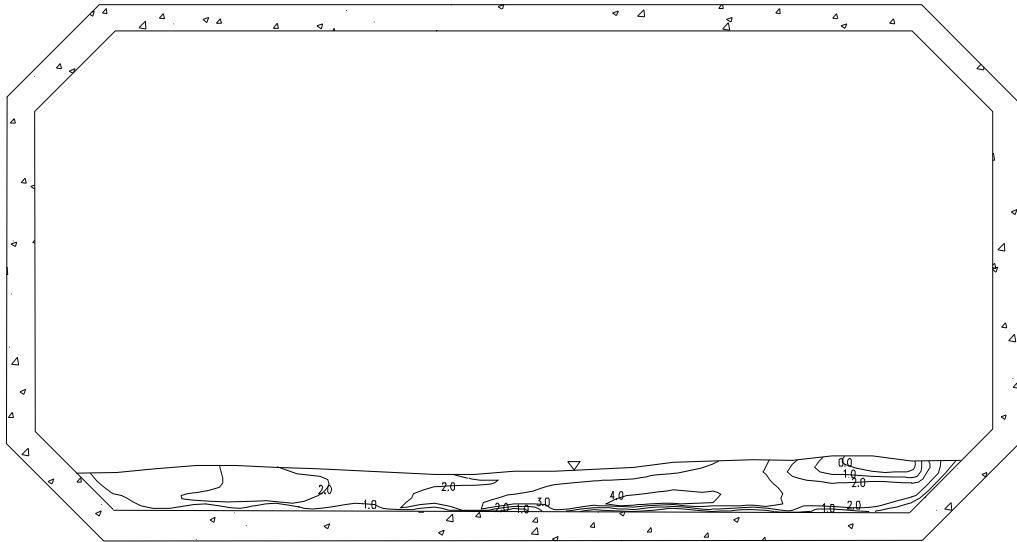
Culvert #1; July 21, 2004; Y-Component Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 42.14 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft.



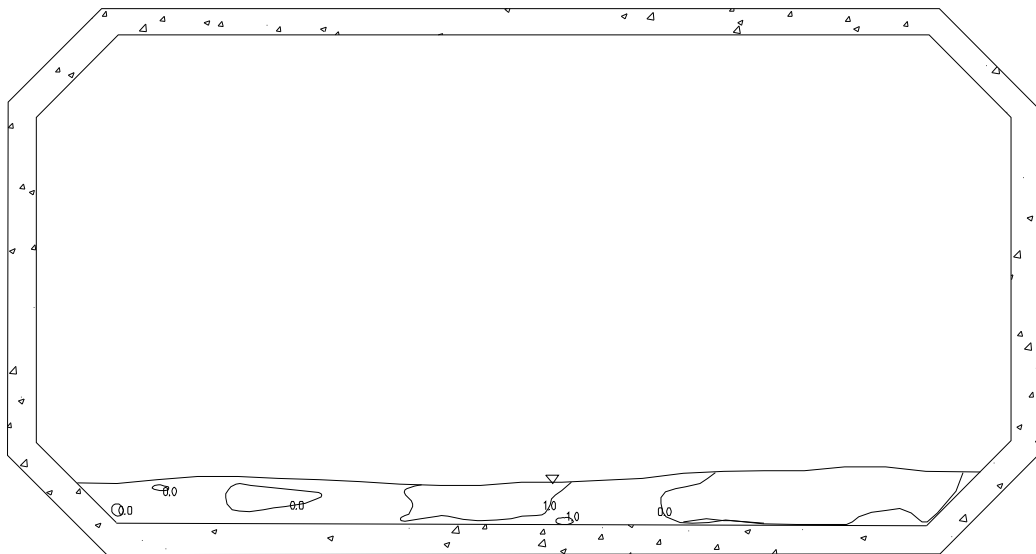
Culvert #1; July 21, 2004; Z-Component Velocity Contours;
Contour Interval = 1.0 ft/s; Discharge = 42.14 cfs; View Downstream;
Culvert Width = 12.0 ft; Culvert Height = 6.0 ft.



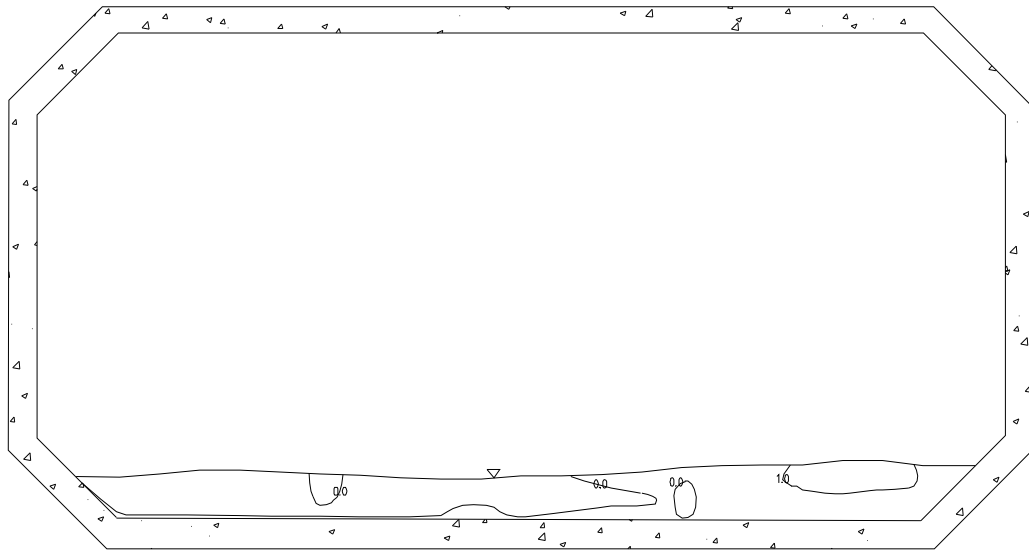
Culvert #1; June 30, 2004; Plan View of Velocity Contours;
 Measurements at 0.2 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 59.72 cfs; Culvert Width = 12.0 ft; Culvert Length = 36.7 ft;
 Instrument = Pygmy Meter.



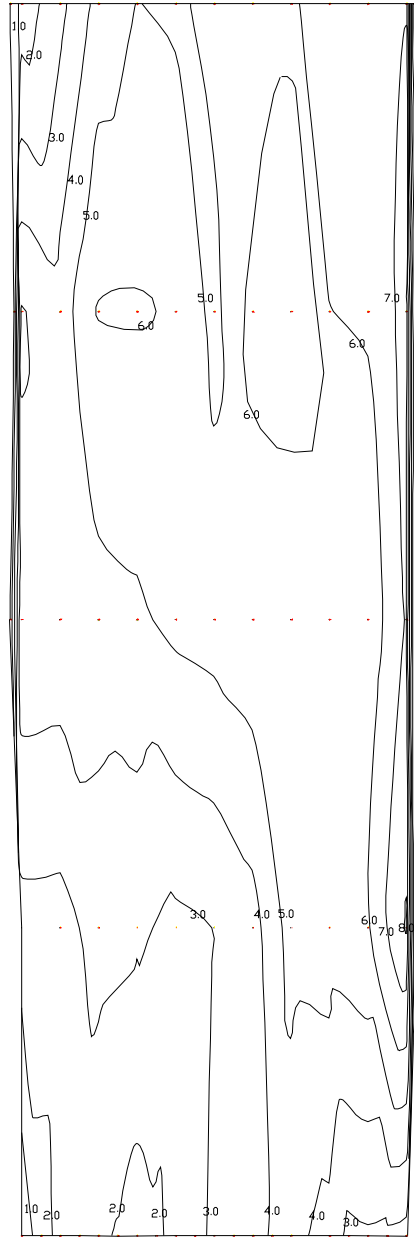
Culvert #1; August 8, 2004; X-Component Velocity Contours;
Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = ADV.



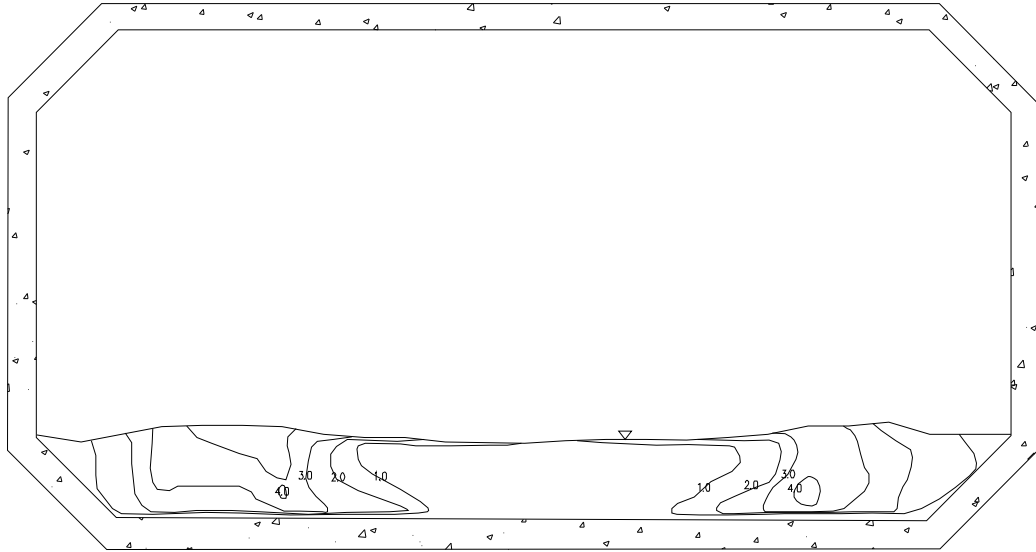
Culvert #1; August 8, 2004; Y-Component Velocity Contours;
Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = ADV.



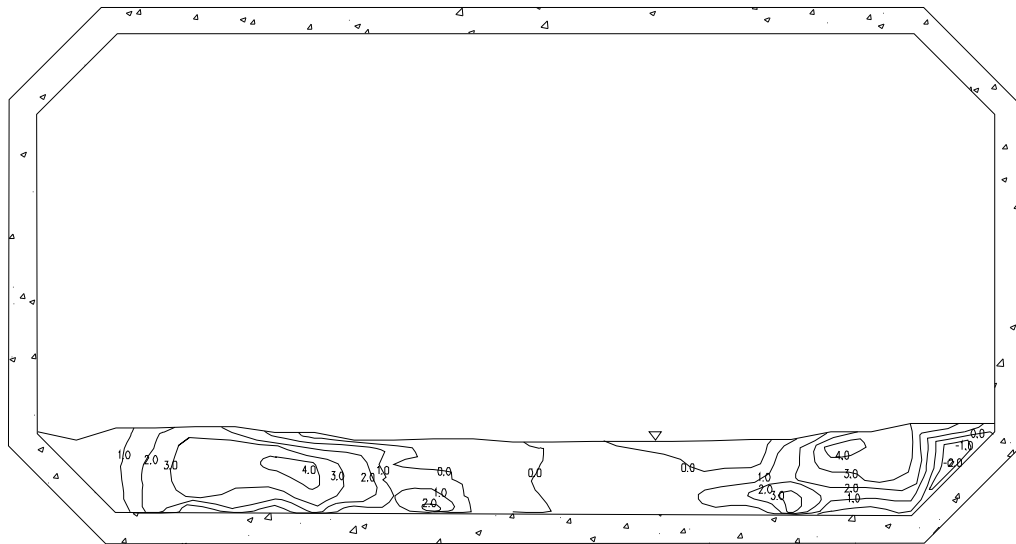
Culvert #1; August 8, 2004; Z-Component Velocity Contours;
Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = ADV.



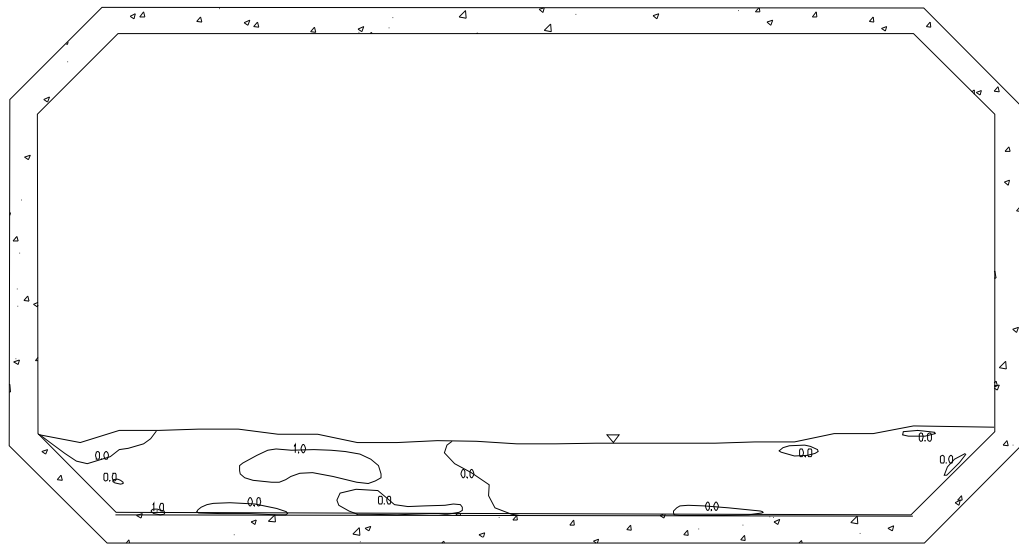
Culvert #1; August 9, 2004; Plan View of Velocity Contours;
 Measurements at 0.1 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 30.96 cfs; Culvert Width = 12.0 ft; Culvert Length = 36.7 ft;
 Instrument = Pygmy Meter.



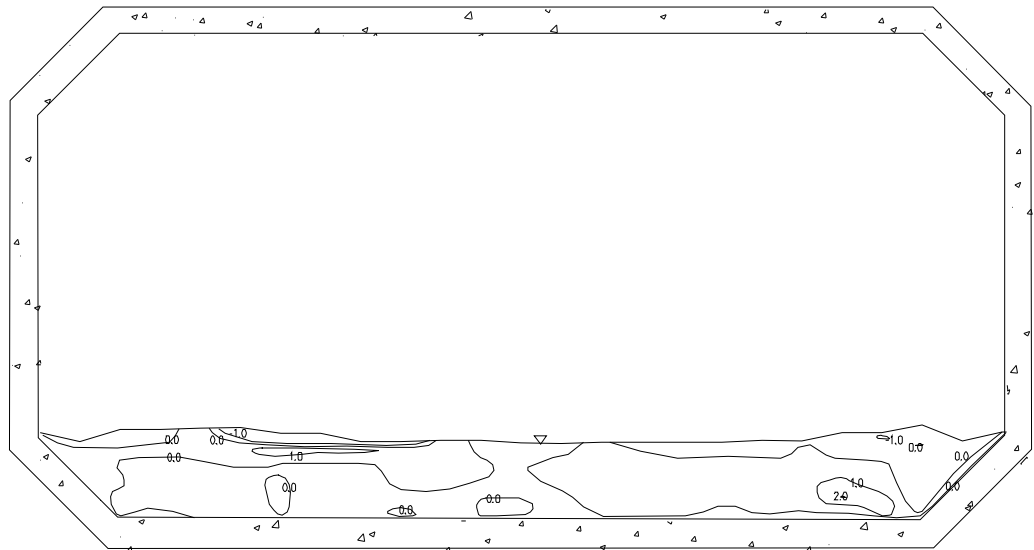
Culvert #2; Aug 2, 2004; X - Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = Pygmy Meter.



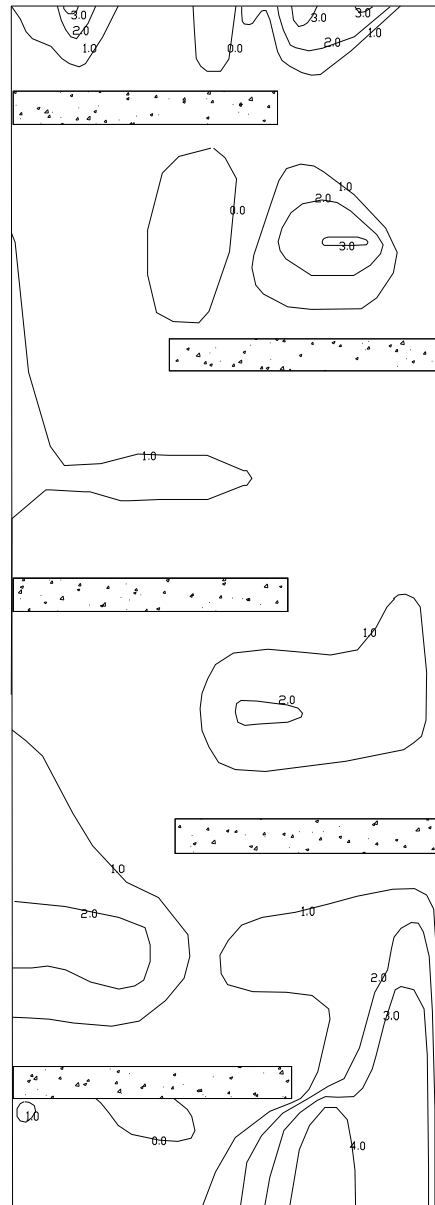
Culvert #2; August 3, 2004; X - Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = ADV.



Culvert #2; August 3, 2004; Y - Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = ADV.

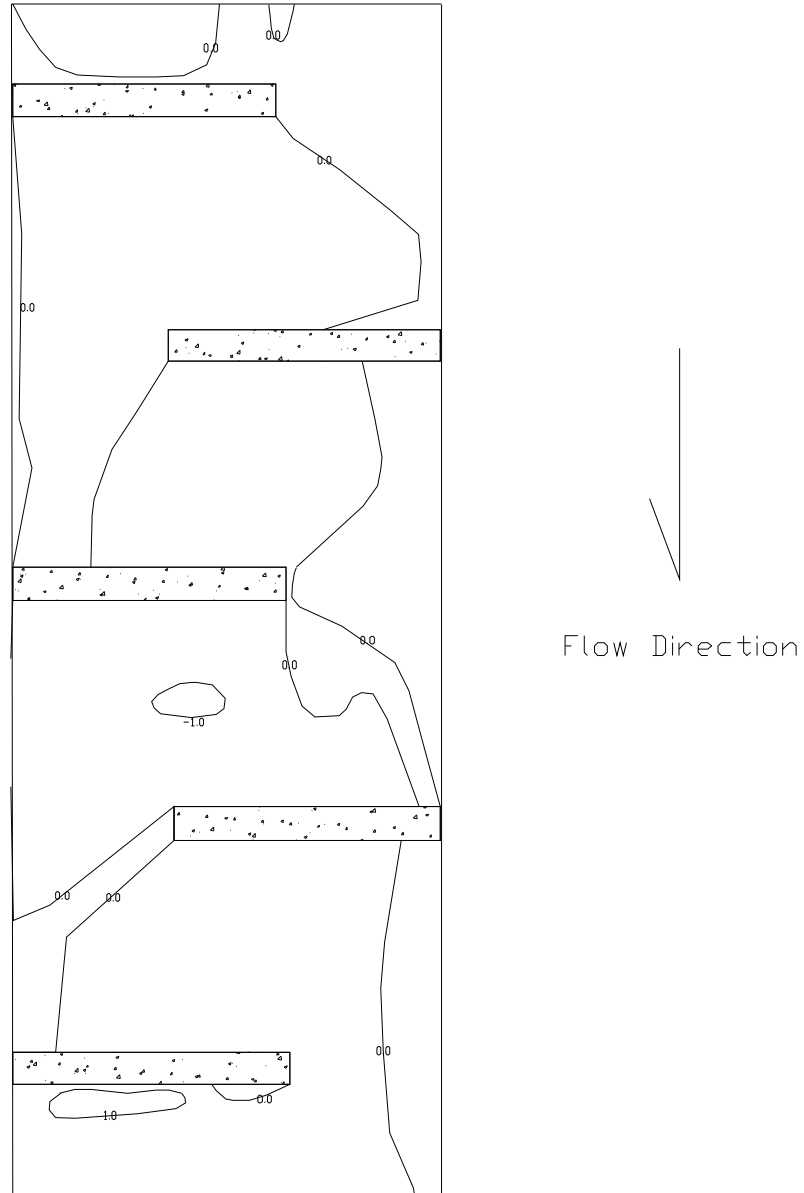


Culvert #2; August 3, 2004; Z - Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 30.16 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft.
 Instrument = ADV.

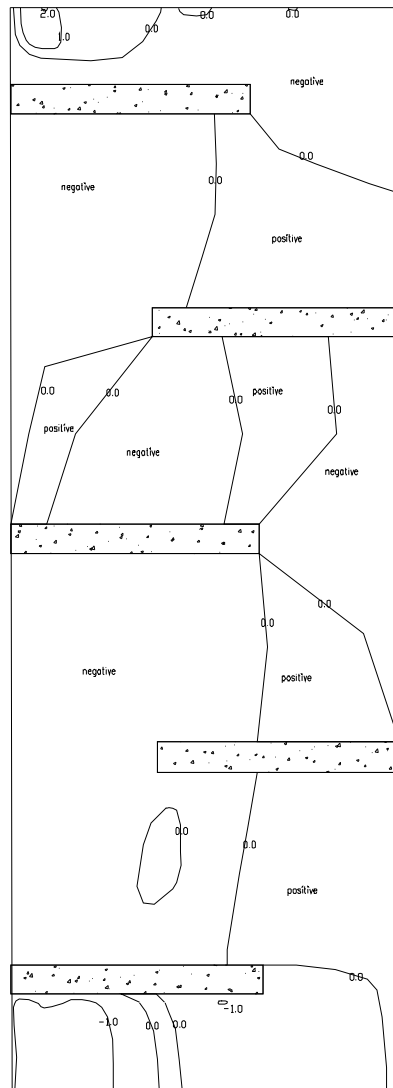


Flow Direction

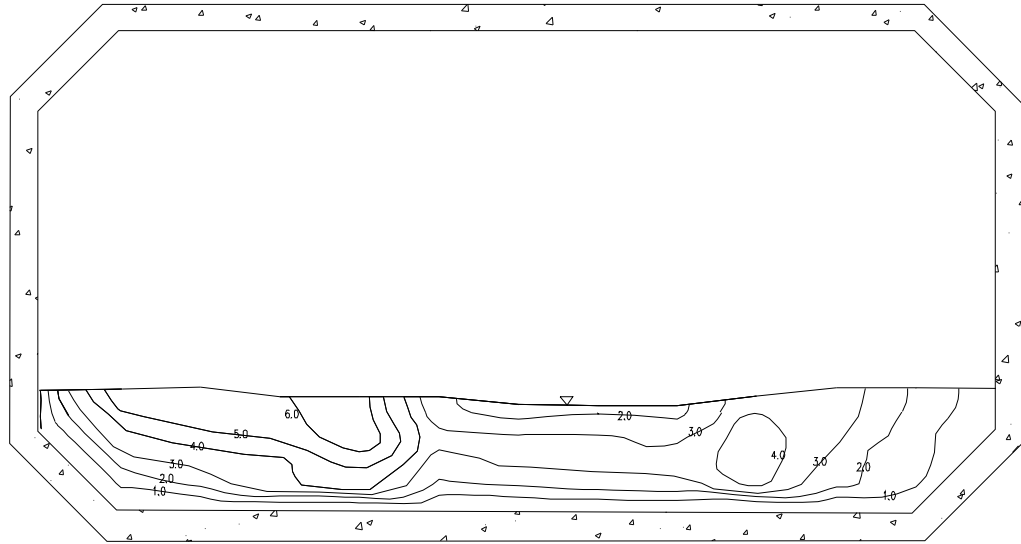
Culvert #2; August 4, 2004; Plan View of x - Velocity Contours;
 Measurements at 0.2 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 29.76 cfs; Culvert Width = 12.0 ft; Culvert Length = 30.48 ft;
 Instrument = ADV.



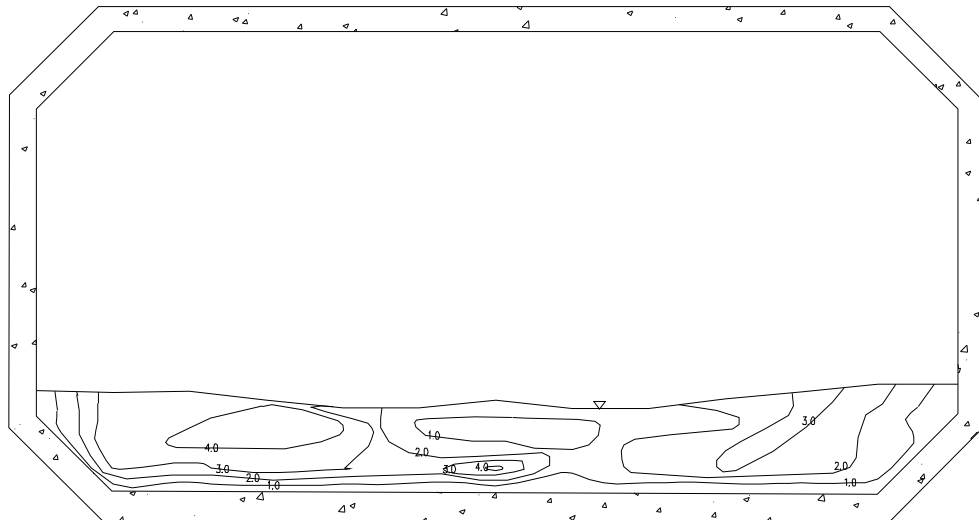
Culvert #2; August 4, 2004; Plan View of y - Velocity Contours;
 Measurements at 0.2 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 29.76 cfs; Culvert Width = 12.0 Ft; Culvert Length = 30.48 Ft;
 Instrument = ADV.



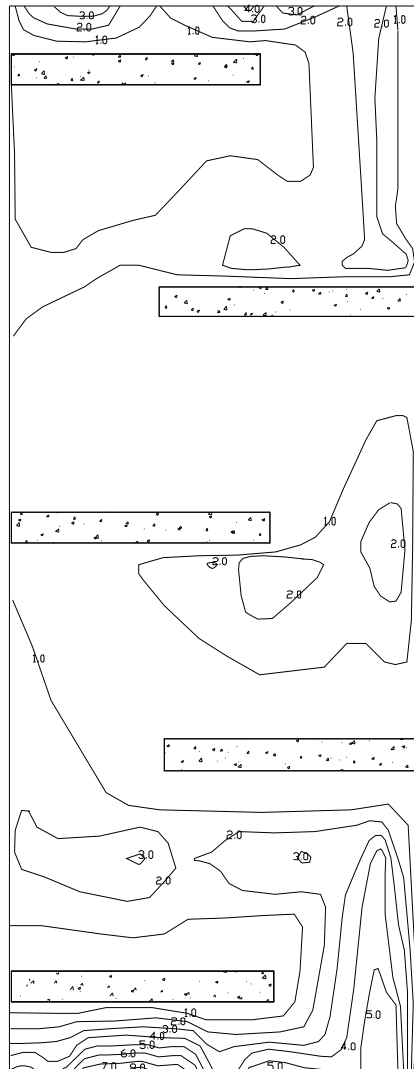
Culvert #2; August 4, 2004; Plan View of z - Velocity Contours;
 Measurements at 0.2 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 29.76 cfs; Culvert Width = 12.0 ft; Culvert Length = 30.48 ft;
 Instrument = ADV.



Culvert #2; July 2, 2004; X - Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 48.29 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = Pygmy Meter.



Culvert #2; July 16, 2004; X - Velocity Contours;
 Contour Interval = 1.0 ft/s; Discharge = 44.14 cfs; View Downstream;
 Culvert Width = 12.0 ft; Culvert Height = 6.0 ft. Instrument = Pygmy Meter.



Flow Direction

Culvert #2; July 16, 2004; Plan View of Velocity Contours;
 Measurements at 0.2 ft above Culvert Bed; Contour Interval = 1.0 ft/s;
 Discharge = 44.14 cfs; Culvert Width = 12.0 ft; Culvert Length = 30.48 ft;
 Instrument = Pygmy Meter.

APPENDIX D

VBA CODE FOR INLET VELOCITY PROPAGATION

File name: final velocity post process program

Revised: 1/20/27

Sub velocity_crunch()

'Revised last on January 20, 2007. Author: Matt Blank

'This subroutine will filter model cross section output data from ANSYS-CFX to remove
'redundant values, will set velocities to a grid, will check the data for continuity
'and adjust the velocities to account for continuity, and will calculate a range of
'hydraulic parameters for cross section data.

'Declare variables, vectors, arrays.

```
Dim a As String, b As String, c As String, d As String
Dim g As Double, l As Double, t As Double, w As Double, y As Double
Dim area_trap As Double, f As Double, numerator As Double
Dim i As Integer, j As Integer, kin As Double
Dim row As Integer, column As Integer, count As Integer, row_sample As Integer,
row_column As Integer
Dim old_data(10000, 5) As Double, pre_data(10000, 5) As Double, new_data(10000, 5)
As Double
Dim sample_point(52, 4) As Double, mult As Double, Re As Double
Dim x_dist As Double, y_dist As Double, min_dist As Double, real_dist As Double
Dim vel(10000, 5) As Double, area(10000, 5) As Double, alpha As Double
Dim area_total As Double, av_velocity As Double, sum_velocity As Double
Dim beta As Double, rmse As Double, inc_diff As Double, f_alpha As Double
Dim q_true As Double, q_pred As Double, q_ratio As Double, q_error As Double
Dim dq(100) As Double, q_diff As Double, q_percent(100) As Double,
q_correction(100) As Double
```

'Select unfiltered data in spreadsheet and read to program, read additional variables from
spreadsheet.

a = "Select the unfiltered data set."

b = "DATA FILTER"

mult = Worksheets("summary").Cells(3, 6).Value

w = Worksheets("summary").Cells(4, 6).Value

y = Worksheets("summary").Cells(2, 6).Value

g = Worksheets("summary").Cells(5, 6).Value

```

kin = Worksheets("summary").Cells(6, 6).Value

q_true = Worksheets("summary").Cells(8, 6).Value

Set dataf = Application.InputBox(a, b, , , , Type:=8)

row = dataf.Rows.count

column = dataf.Columns.count

'Read data into arrays.

For i = 1 To row

    For j = 1 To column

        old_data(i, j) = dataf.Cells(i, j)

    Next j

Next i

'Filter data set to remove points with volume fractions less than 0.5.

For i = 1 To row

    If old_data(i, 4) < 0.5 Then

        old_data(i, 4) = 0

    End If

Next i

'Read filtered data set into new array to get rid of rows with volume fractions less than 0.5.

count = 1

For i = 1 To row

    If old_data(i, 4) <> 0 Then

        pre_data(count, 1) = old_data(i, 1)

```

```

    pre_data(count, 2) = old_data(i, 2)

    pre_data(count, 3) = old_data(i, 3)

    pre_data(count, 4) = old_data(i, 4)

    count = count + 1

End If

Next i

'Filter data set to identify redundant data points.

count = 1

For i = 1 To row

    For j = count To row

        If pre_data(j + 1, 1) = pre_data(i, 1) And pre_data(j + 1, 2) = pre_data(i, 2) Then

            pre_data(j + 1, 1) = 999

        End If

    Next j

    count = count + 1

Next i

'Read filtered data into new array to get rid of redundant data points.

count = 1

For i = 1 To row

    If pre_data(i, 1) <> 999 Then

        new_data(count, 1) = pre_data(i, 1)

        new_data(count, 2) = pre_data(i, 2)

        new_data(count, 3) = pre_data(i, 3)

```

```

    new_data(count, 4) = pre_data(i, 4)

    count = count + 1

End If

Next i

'Write filtered data set to spreadsheet.

For i = 1 To column

    count = 0

    For j = 1 To row

        Worksheets("summary").Cells(4 + count, i + 23).Value = new_data(j, i)

        count = count + 1

    Next j

Next i

'Select locations for "sample points".

d = "Select the station, elevation and incremental areas for the sample points."

Set sample = Application.InputBox(d, b, , , , Type:=8)

row_sample = sample.Rows.count

row_column = sample.Columns.count

For i = 1 To row_sample

    For j = 1 To row_column

        sample_point(i, j) = sample.Cells(i, j)

    Next j

Next i

'Read data from sample_point array into area vector.

```

```
n = row_sample
```

```
For i = 1 To n
```

```
    area(i, 1) = sample_point(i, 3)
```

```
Next i
```

'Calculate minimum distance from ANSYS-CFX output data set points to "sample points" x, y.

'Set velocity at the x,y to equal nearest output velocity magnitude.

```
For i = 1 To row_sample
```

```
    min_dist = 15
```

```
    For j = 1 To row
```

```
        x_dist = Abs(sample_point(i, 1) - new_data(j, 1))
```

```
        y_dist = Abs(sample_point(i, 2) - new_data(j, 2))
```

```
        real_dist = Sqr((x_dist) ^ 2 + (y_dist) ^ 2)
```

```
        If real_dist < min_dist Then
```

```
            min_dist = real_dist
```

```
            sample_point(i, 3) = new_data(j, 3)
```

```
        End If
```

```
    Next j
```

```
Next i
```

'Read data from sample_point array into velocity vector.

```
For i = 1 To n
```

```
    vel(i, 1) = sample_point(i, 3)
```

```
Next i
```

'These velocities have not been adjusted for continuity.

'Write the pre-adjusted velocities to spreadsheet.

```
For i = 1 To row_column
```

```
    count = 0
```

```
    For j = 1 To row_sample
```

```
        Worksheets("summary").Cells(4 + count, i + 29).Value = sample_point(j, i)
```

```
    count = count + 1
```

```
    Next j
```

```
Next i
```

'Check continuity and adjust predicted velocities to maintain continuity.

```
q_error = 0
```

```
Do
```

```
    n = row_sample
```

```
    q_pred = 0
```

```
    For i = 1 To n
```

```
        q_pred = q_pred + area(i, 1) * vel(i, 1)
```

```
        dq(i) = area(i, 1) * vel(i, 1)
```

```
    Next i
```

```
    q_diff = Abs(q_pred - q_true)
```

'Case 1 is when the predicted flow is greater than the
'true flow. The true flow is estimated from the
'rating curves.

```
If q_pred > q_true Then
```

```
    For i = 1 To n
```

```
        q_percent(i) = dq(i) / q_pred
```

```
    Next i
```

```

For i = 1 To n

    
$$q\_correction(i) = dq(i) - q\_percent(i) * q\_diff$$


Next i

For i = 1 To n

    
$$vel(i, 1) = q\_correction(i) / area(i, 1)$$


Next i

Else

'Case 2 is when the predicted flow is less than the
'true flow. The true flow is estimated from the
'rating curves.

For i = 1 To n

    
$$q\_percent(i) = dq(i) / q\_pred$$


Next i

For i = 1 To n

    
$$q\_correction(i) = dq(i) + q\_percent(i) * q\_diff$$


Next i

For i = 1 To n

    
$$vel(i, 1) = q\_correction(i) / area(i, 1)$$


Next i

End If

q_pred = 0

For i = 1 To n

    
$$q\_pred = q\_pred + area(i, 1) * vel(i, 1)$$


Next i

```

```
q_error = Abs(q_true - q_pred)
```

```
If q_error < 0.01 Then Exit Do
```

```
Loop
```

'This section of the code calculates hydraulic parameters and
'writes them to the spreadsheet.

'Parameters include alpha, beta, froude, rmse, Re, adjusted froude,
'areas, average velocity, characteristic length.

'This loop calculates total area.

```
area_total = 0
```

```
For i = 1 To n
```

```
    area_total = area_total + area(i, 1)
```

```
Next i
```

'This loop calculates average velocity.

```
sum_velocity = 0
```

```
For i = 1 To n
```

```
    sum_velocity = sum_velocity + vel(i, 1) * area(i, 1)
```

```
Next i
```

```
av_velocity = sum_velocity / area_total
```

```
numerator = 0
```

'This loop calculates alpha.

```
For i = 1 To n
```

```
    numerator = numerator + (vel(i, 1) ^ 3) * area(i, 1)
```

```
Next i
```

```
alpha = numerator / ((av_velocity ^ 3) * area_total)
```

'Write alpha to worksheet.

Worksheets("summary").Cells(4, 22).Value = alpha

'This loop calculates beta.

numerator = 0

For i = 1 To n

numerator = numerator + (vel(i, 1) ^ 2) * area(i, 1)

Next i

beta = numerator / ((av_velocity ^ 2) * area_total)

'Write beta to worksheet.

Worksheets("summary").Cells(6, 22).Value = beta

'This loop calculates rmse.

inc_diff = 0

For i = 1 To n

inc_diff = inc_diff + ((vel(i, 1) - av_velocity) ^ 2)

Next i

rmse = Sqr((1 / n) * inc_diff)

'Write rmse to worksheet.

Worksheets("summary").Cells(8, 22).Value = rmse

'Calculate Froude number.

area_trap = w * y + y ^ 2

t = w + 2 * y

l = area_trap / t

f = av_velocity / Sqr(g * l)

'Calculate Froude number with alpha.

$f_alpha = av_velocity / \text{Sqr}((g * l) / alpha)$

'Calculate Reynolds number.

$Re = (av_velocity * l) / \mu$

'Write Froude, Froude with alpha, average velocity, characteristic length, Re and area to worksheet.

Worksheets("summary").Cells(10, 22).Value = f

Worksheets("summary").Cells(12, 22).Value = av_velocity

Worksheets("summary").Cells(14, 22).Value = l

Worksheets("summary").Cells(16, 22).Value = area_trap

Worksheets("summary").Cells(20, 22).Value = f_alpha

Worksheets("summary").Cells(18, 22).Value = Re

'Reset sample_point array velocities to the adjusted values.

For i = 1 To row_sample

 sample_point(i, 3) = vel(i, 1)

Next i

'Write values back to spreadsheet.

For i = 1 To row_column

 count = 0

 For j = 1 To row_sample

 Worksheets("summary").Cells(4 + count, i + 16).Value = sample_point(j, i)

 count = count + 1

 Next j

Next i

End Sub

APPENDIX E

VBA CODE FOR ESTIMATION OF ENERGY PATHS

Sub energypath()

'Written by Matt Blank.

'Updated on 2/1/08.

'This subroutine will take output data from ANSYS-CFX, remove
'redundant values and calculate the minimum, maximum and observed energy
expenditure and
'energy paths on a plane 0.06 meters above the culvert floor. The program calculates the
'energy expenditure for 10 possible starting points spaced evenly across the outlet of
'the culvert.

Dim a As String, b As String, c As String, d As String
Dim g As Double, l As Double, t As Double, w As Double, y As Double, countpath As
Integer
Dim i As Integer, j As Integer, k As Integer, row_sample As Integer, row_column As
Integer
Dim row As Integer, column As Integer, count As Integer, countrow As Integer,
countcolumn As Integer
Dim pre_data(12000, 5) As Double, new_data(12000, 5) As Double
Dim sample_point(500, 4) As Double, Re As Double, rev_sample(500, 4) As Double,
position(500, 2) As Double
Dim x_dist As Double, y_dist As Double, min_dist As Double, real_dist As Double
Dim vel(12000, 5) As Double, area(12000, 5) As Double, alpha As Double
Dim beta As Double, length As Double, visc As Double, h_density As Double, v_fish As
Double
Dim e_min As Double, e_max As Double, e_obs As Double, dels_straight As Double,
dels_angle As Double
Dim v_avg As Double, v_now As Double, v_left As Double, v_ahead As Double, v_right
As Double, v_min As Double
Dim v_max As Double, del_s As Double, vel_grad As Double, f As Double, e_inc As
Double, round_off As Double
Dim pathmax(500) As Double, e_max_sum(11), e_min_sum(11), pathmin(500) As
Double
Dim dis_emax(500) As Double, vel_emax(500) As Double, energy_emax(500) As
Double
Dim force_drag_emax(500) As Double, water_depth_emax(500) As Double
Dim dis_emin(500) As Double, vel_emin(500) As Double, energy_emin(500) As Double
Dim force_drag_emin(500) As Double, water_depth_emin(500) As Double,
count_output As Double
Dim time As Double, del_time As Double

'Select unfiltered velocity data in spreadsheet and read to program, read additional
variables from spreadsheet.

```

a = "Select the unfiltered data set."

b = "DATA FILTER"

Set dataf = Application.InputBox(a, b, , , , Type:=8)

row = dataf.Rows.count

column = dataf.Columns.count

'Read unfiltered velocity data into arrays.

For i = 1 To row

    For j = 1 To column

        new_data(i, j) = dataf.Cells(i, j)

    Next j

Next i

'Read values for variables from input sheet.

alpha = Worksheets("data input").Cells(5, 2).Value

beta = Worksheets("data input").Cells(6, 2).Value

length = Worksheets("data input").Cells(6, 6).Value

visc = Worksheets("data input").Cells(7, 2).Value

h_density = Worksheets("data input").Cells(4, 2).Value

v_fish = Worksheets("data input").Cells(4, 6).Value

dels_straight = 0.3048

dels_angle = 0.4309

'Select locations for "sample points".

d = "Select the x and z locations and an empty column for the sample points."

Set sample = Application.InputBox(d, b, , , , Type:=8)

```

```

row_sample = sample.Rows.count
row_column = sample.Columns.count

'Read sample point data into array.
For i = 1 To row_sample
    For j = 1 To row_column
        sample_point(i, j) = sample.Cells(i, j)
    Next j
Next i

'Calculate minimum distance from ANSYS-CFX output data set points to "sample
points" and set velocity
'equal to the velocity at the nearest data set point.
For i = 1 To row_sample
    min_dist = 15
    For j = 1 To row
        x_dist = Abs(sample_point(i, 1) - new_data(j, 1))
        y_dist = Abs(sample_point(i, 2) - new_data(j, 3))
        real_dist = Sqr((x_dist) ^ 2 + (y_dist) ^ 2)
        If real_dist < min_dist Then
            min_dist = real_dist
            sample_point(i, 4) = new_data(j, 4)
        End If
    Next j
Next i

'Write fitted values back to spreadsheet.

```

```

For i = 1 To row_column
    count = 0
    For j = 1 To row_sample
        Worksheets("data input").Cells(13 + count, i + 11).Value = sample_point(j, i)
        count = count + 1
    Next j
Next i

```

'Reverse rows of data stored in sample point array to align with movement of fish (upstream).

```

For i = 1 To row_column
    countrow = 0
    For j = 1 To row_sample
        rev_sample(row_sample - countrow, i) = sample_point(j, i)
        If countrow = row_sample Then
            GoTo 1
        End If
        countrow = countrow + 1
    Next j
1:
Next i

```

'Write reversed data back to spreadsheet.

```

For i = 1 To row_column
    count = 0

```

```

For j = 1 To row_sample

    Worksheets("data input").Cells(13 + count, i + 23).Value = rev_sample(j, i)

    count = count + 1

Next j

Next i

'Calculate the minimum and maximum energy path. This section of the program
calculates the energy expenditure
'of fish that enter the culvert at 10 different points that are equally spaced and cover the
entire width of the
'downstream end of the culvert. The range of energy paths are estimated based on these
starting points, then the
'maximum and minimum paths are identified.

i = 1

countpath = 1

'This section of the code calculates the maximum energy paths.

For k = 0 To 10

    e_max = 0

    j = k

    For i = 1 To row_sample Step 11

        pathmax(i) = j

        round_off = Round(rev_sample(i + j, 2), 2)

        If round_off = -1.52 Then

            GoTo 2

        End If

        If round_off > -1.52 And round_off < 1.52 Then

            GoTo 3

```

End If

If round_off = 1.52 Then

GoTo 4

End If

2: v_now = rev_sample(i + j, 4)

v_ahead = rev_sample(i + j + 11, 4)

v_left = rev_sample(i + j + 10, 4)

If v_ahead >= v_left Then

v_max = v_ahead

del_s = dels_straight

j = j

GoTo 5

Else

v_max = v_left * 0.7071

'0.7071 is equal to cos 45. The math in the previous line sets the velocity equal
'to the component along the direction the fish travels.

del_s = dels_angle

j = j - 1

GoTo 5

End If

3: v_now = rev_sample(i + j, 4)

v_left = rev_sample(i + j + 10, 4)

v_ahead = rev_sample(i + j + 11, 4)

v_right = rev_sample(i + j + 12, 4)

If $v_left > v_ahead$ And $v_left > v_right$ Then

$v_max = v_left * 0.7071$

$del_s = dels_angle$

$j = j - 1$

GoTo 5

End If

If $v_ahead > v_left$ And $v_ahead > v_right$ Then

$v_max = v_ahead$

$del_s = dels_straight$

$j = j$

GoTo 5

End If

If $v_right > v_left$ And $v_right > v_ahead$ Then

$v_max = v_right * 0.7071$

$del_s = dels_angle$

$j = j + 1$

GoTo 5

End If

4: $v_now = rev_sample(i + j, 4)$

$v_ahead = rev_sample(i + j + 11, 4)$

$v_right = rev_sample(i + j + 12, 4)$

If $v_ahead \geq v_right$ Then

$v_max = v_ahead$

```

del_s = dels_straight

j = j

GoTo 5

Else

v_max = v_right * 0.7071

del_s = dels_angle

j = j + 1

GoTo 5

End If

5:   v_avg = (v_now + v_max) / 2

      f = 0.020646 * h_density * (v_fish ^ 2) * (length ^ beta) * (((v_avg * length) /
visc) ^ -0.2)

      del_time = del_s / (v_fish - v_avg)

      e_inc = f * v_fish * del_time

      e_max = e_max + e_inc

'Store key variables into vectors: velocity, water depth, force, energy and cumulative path
distance.

dis_emax(i) = del_s

vel_emax(i) = v_now

water_depth_emax(i) = rev_sample(i, 3)

force_drag_emax(i) = f

energy_emax(i) = e_inc

Next i

```

e_max_sum(k + 1) = e_max

Worksheets("data input").Cells(3, 16 + countpath).Value = e_max_sum(k + 1)

countpath = countpath + 1

'Get rid of cells with zero.

count_emax = 0

For l = 1 To row_sample

 If pathmax(l) > 0 Or pathmax(l) < 0 Then

 pathmax(count_emax) = pathmax(l)

 End If

 If dis_emax(l) > 0 Or dis_emax(l) < 0 Then

 dis_emax(count_emax) = dis_emax(l)

 End If

 If vel_emax(l) > 0 Or vel_emax(l) < 0 Then

 vel_emax(count_emax) = vel_emax(l)

 End If

 If water_depth_emax(l) > 0 Or water_depth_emax(l) < 0 Then

 water_depth_emax(count_emax) = water_depth_emax(l)

 End If

 If force_drag_emax(l) > 0 Or force_drag_emax(l) < 0 Then

 force_drag_emax(count_emax) = force_drag_emax(l)

 End If

 If energy_emax(l) > 0 Or energy_emax(l) < 0 Then

 energy_emax(count_emax) = energy_emax(l)

```

        count_emax = count_emax + 1

    End If

Next l

count = 0

For l = 0 To count_emax

    Worksheets("max energy").Cells(4 + count, 2 + count_output).Value = dis_emax(l)

    Worksheets("max energy").Cells(4 + count, 3 + count_output).Value = vel_emax(l)

    Worksheets("max energy").Cells(4 + count, 4 + count_output).Value =
water_depth_emax(l)

    Worksheets("max energy").Cells(4 + count, 5 + count_output).Value =
force_drag_emax(l)

    Worksheets("max energy").Cells(4 + count, 6 + count_output).Value =
energy_emax(l)

    Worksheets("max energy").Cells(4 + count, 7 + count_output).Value = pathmax(l)

    count = count + 1

Next l

count_output = count_output + 10

For l = 0 To row_sample

    dis_emax(l) = 0

    vel_emax(l) = 0

    water_depth_emax(l) = 0

    force_drag_emax(l) = 0

    energy_emax(l) = 0

    pathmax(l) = 0

```

Next l

Next k

'This section of the code calculates the minimum energy path.

i = 1

countpath = 1

count_output = 0

For k = 0 To 10

 e_min = 0

 j = k

 For i = 1 To row_sample Step 11

 pathmin(i) = j

 round_off = Round(rev_sample(i + j, 2), 2)

 If round_off = -1.52 Then

 GoTo 6

 End If

 If round_off > -1.52 And round_off < 1.52 Then

 GoTo 7

 End If

 If round_off = 1.52 Then

 GoTo 8

 End If

6: v_now = rev_sample(i + j, 4)

 v_ahead = rev_sample(i + j + 11, 4)

```

v_left = rev_sample(i + j + 10, 4)

If v_ahead <= v_left Then

v_min = v_ahead

del_s = dels_straight

j = j

GoTo 9

Else

v_min = v_left * 0.7071

del_s = dels_angle

j = j - 1

GoTo 9

End If

7:  v_now = rev_sample(i + j, 4)

v_left = rev_sample(i + j + 10, 4)

v_ahead = rev_sample(i + j + 11, 4)

v_right = rev_sample(i + j + 12, 4)

If v_left < v_ahead And v_left < v_right Then

v_min = v_left * 0.7071

del_s = dels_angle

j = j - 1

GoTo 9

End If

If v_ahead < v_left And v_ahead < v_right Then

```

```

v_min = v_ahead

del_s = dels_straight

j = j

GoTo 9

End If

If v_right < v_left And v_right < v_ahead Then

v_min = v_right * 0.7071

del_s = dels_angle

j = j + 1

GoTo 9

End If

8:  v_now = rev_sample(i + j, 4)

v_ahead = rev_sample(i + j + 11, 4)

v_right = rev_sample(i + j + 12, 4)

If v_ahead <= v_right Then

v_min = v_ahead

del_s = dels_straight

j = j

GoTo 9

Else

v_min = v_right * 0.7071

del_s = dels_angle

j = j + 1

```

GoTo 9

End If

9: $v_avg = (v_now + v_min) / 2$

$f = 0.020646 * h_density * (v_fish ^ 2) * (length ^ beta) * (((v_avg * length) / visc) ^ - 0.2)$

$del_time = del_s / (v_fish - v_avg)$

$e_inc = f * v_fish * del_time$

$e_min = e_min + e_inc$

'Store key variables into vectors, velocity, water depth, force, energy and cumulative path distance.

$dis_emin(i) = del_s$

$vel_emin(i) = v_now$

$water_depth_emin(i) = rev_sample(i, 3)$

$force_drag_emin(i) = f$

$energy_emin(i) = e_inc$

Next i

$e_min_sum(k + 1) = e_min$

$Worksheets("data input").Cells(6, 16 + countpath).Value = e_min_sum(k + 1)$

$countpath = countpath + 1$

$count_emin = 0$

For l = 1 To row_sample

If $pathmin(l) > 0$ Or $pathmin(l) < 0$ Then

$pathmin(count_emin) = pathmin(l)$

End If

```

If dis_emin(l) > 0 Or dis_emin(l) < 0 Then
    dis_emin(count_emin) = dis_emin(l)
End If

If vel_emin(l) > 0 Or vel_emin(l) < 0 Then
    vel_emin(count_emin) = vel_emin(l)
End If

If water_depth_emin(l) > 0 Or water_depth_emin(l) < 0 Then
    water_depth_emin(count_emin) = water_depth_emin(l)
End If

If force_drag_emin(l) > 0 Or force_drag_emin(l) < 0 Then
    force_drag_emin(count_emin) = force_drag_emin(l)
End If

If energy_emin(l) > 0 Or energy_emin(l) < 0 Then
    energy_emin(count_emin) = energy_emin(l)
    count_emin = count_emin + 1
End If

Next l

count = 0

For l = 0 To count_emin
    Worksheets("min energy").Cells(4 + count, 2 + count_output).Value = dis_emin(l)
    Worksheets("min energy").Cells(4 + count, 3 + count_output).Value = vel_emin(l)
    Worksheets("min energy").Cells(4 + count, 4 + count_output).Value =
water_depth_emin(l)

```

```
Worksheets("min energy").Cells(4 + count, 5 + count_output).Value =  
force_drag_emin(l)
```

```
Worksheets("min energy").Cells(4 + count, 6 + count_output).Value =  
energy_emin(l)
```

```
Worksheets("min energy").Cells(4 + count, 7 + count_output).Value = pathmin(l)
```

```
count = count + 1
```

```
Next l
```

```
count_output = count_output + 10
```

```
For l = 0 To row_sample
```

```
dis_emin(l) = 0
```

```
vel_emin(l) = 0
```

```
water_depth_emin(l) = 0
```

```
force_drag_emin(l) = 0
```

```
energy_emin(l) = 0
```

```
Next l
```

```
Next k
```

```
End Sub
```

APPENDIX F

LOCATION OF LEAPING OBSERVATIONS

June 16, 2004 leaping observations at Culvert 1, Mulherin Creek
Approximate time: ????, Sample size: 1, Average Flow Rate: ????



Unsuccessful leap
into culvert.



Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 17, 2004 leaping observations at Culvert 1, Mulherin Creek
Approximate time: 15:00, Sample size: 3, Average flow rate: 1.73 m³/s



Unsuccessful leap into culvert.



Successful leap into, not successful passage through culvert.



Successful leap into, and passage through culvert.

June 23, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 12:40, Finish time: 13:23, Sample size: 3, Average flow rate: $1.33 \text{ m}^3/\text{s}$



Unsuccessful leap
into culvert.

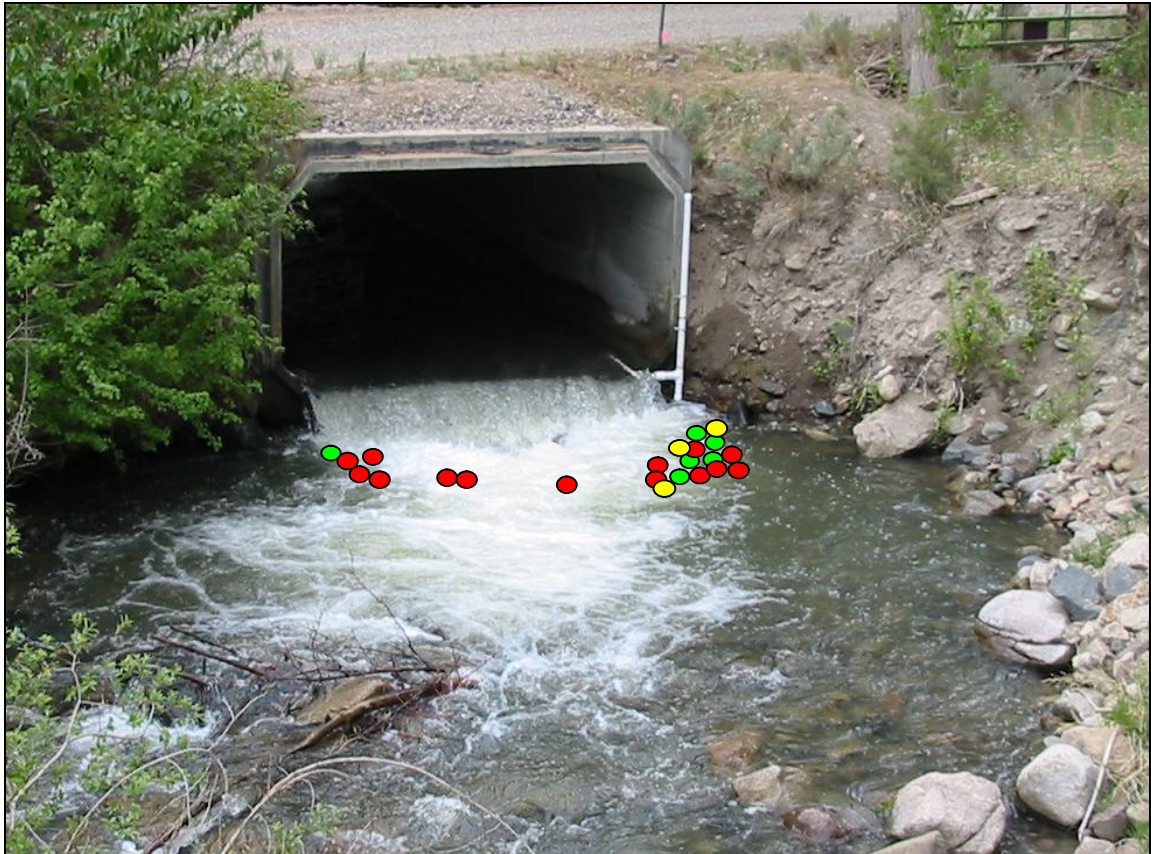


Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 24, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 13:20, Finish time: 17:20, Sample Size: 24, Average Flow Rate: $1.56 \text{ m}^3/\text{s}$



Unsuccessful leap
into culvert.



Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 25, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 13:30, Finish time: 17:00, Sample Size: 5, Average flow rate: $1.70 \text{ m}^3/\text{s}$



Unsuccessful leap
into culvert.



Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 26, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 13:45, Finish time: 14:30, Sample size: 1, Average flow rate: 1.70 m³/s



Unsuccessful leap
into culvert.

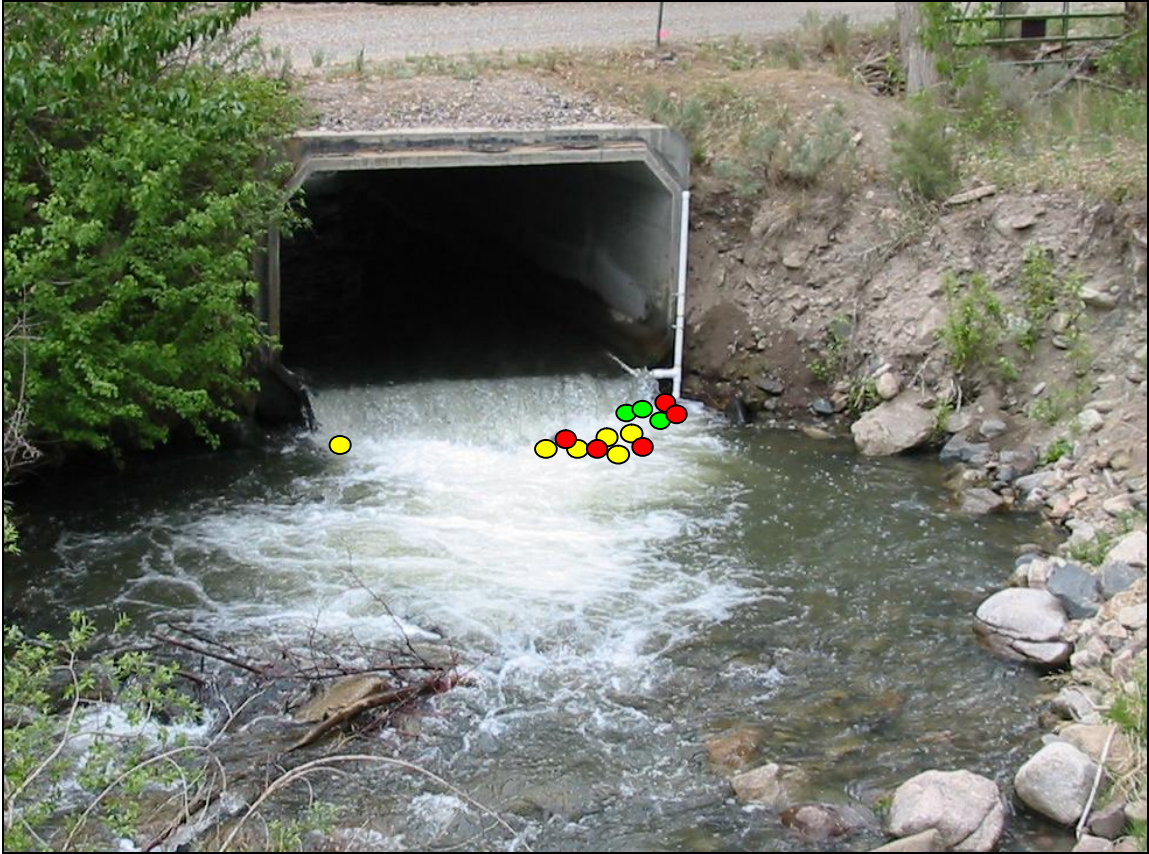


Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 28, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 13:00, Finish time: 16:15, Sample size: 14 , Average flow rate: 1.50 m³/s



Unsuccessful leap
into culvert.

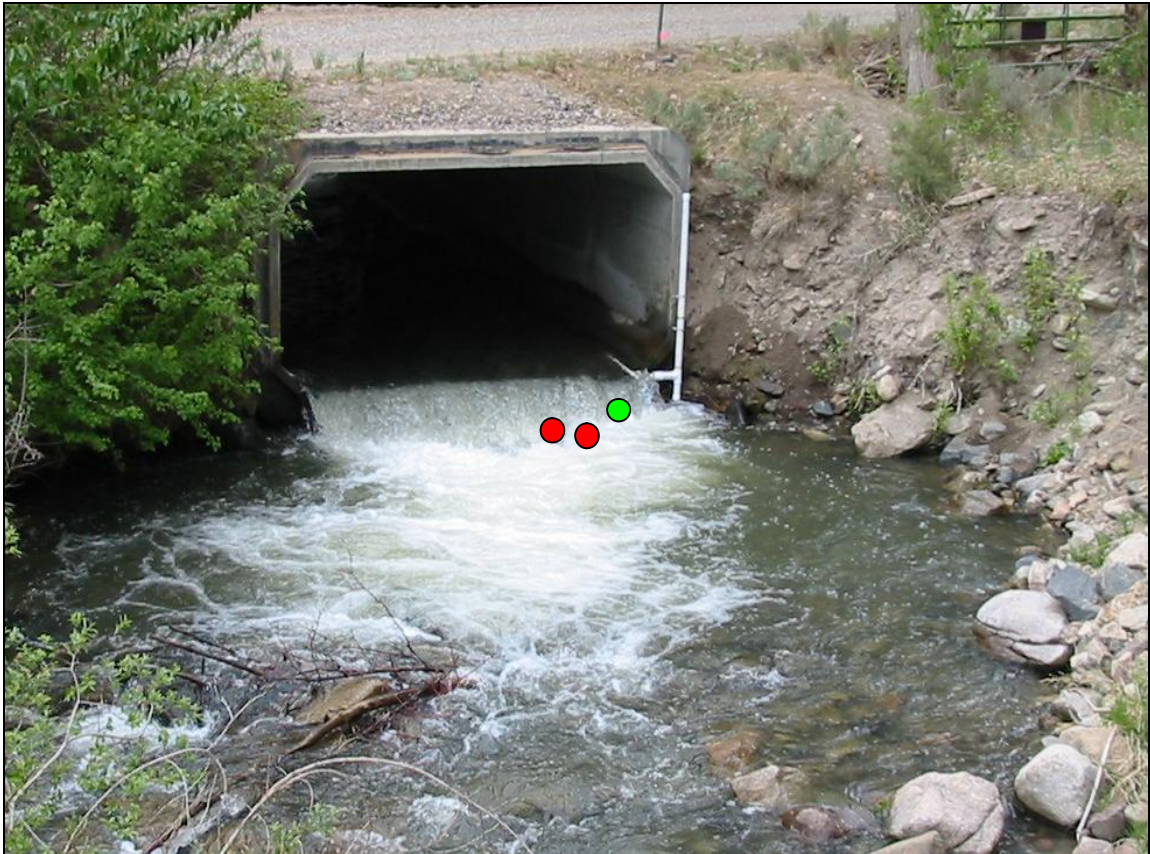


Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 29, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 16:00, Finish time: 16:45, Sample size: 3, Average flow rate: $1.89 \text{ m}^3/\text{s}$



Unsuccessful leap
into culvert.



Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

June 30, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 13:00, Finish time: 14:20, Sample size: 1, Average flow rate: $2.12 \text{ m}^3/\text{s}$



Unsuccessful leap
into culvert.

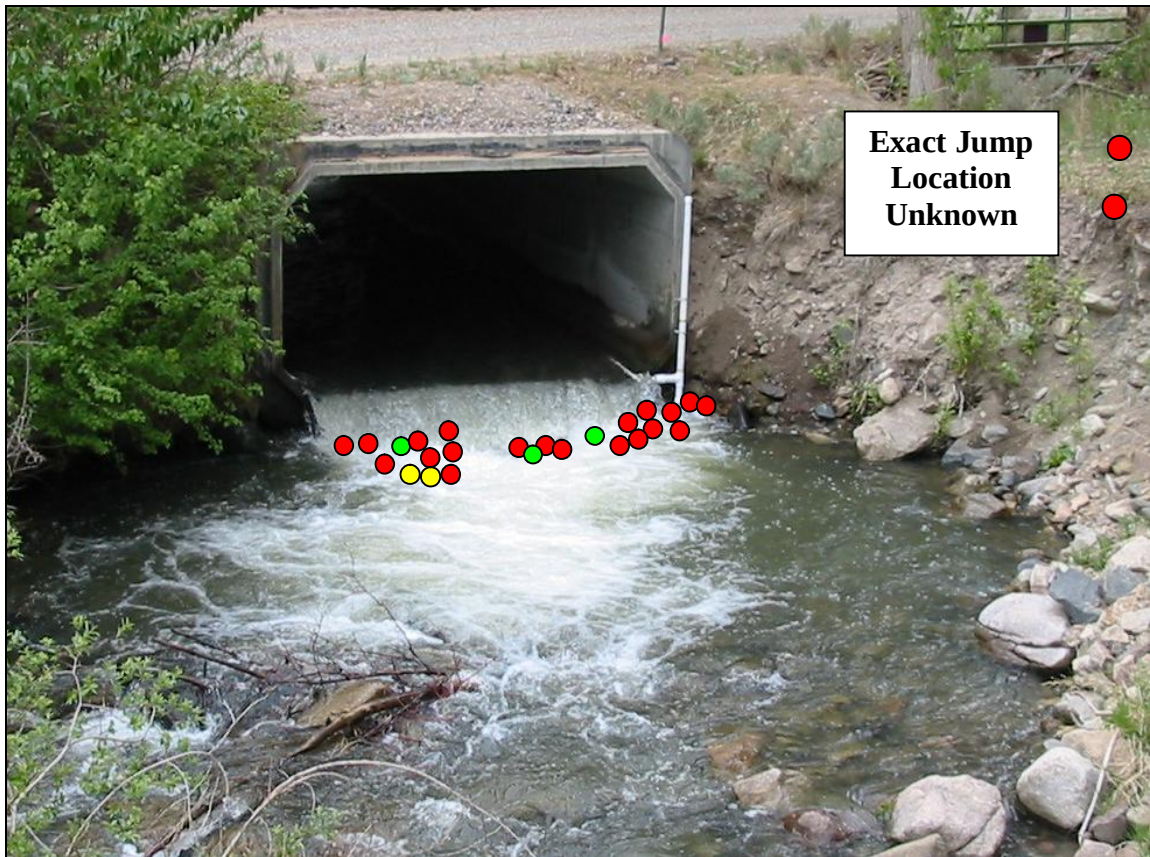


Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.

July 1, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 14:10, Finish time: 16:32, Sample size: 27, Average flow rate: $1.47 \text{ m}^3/\text{s}$



Unsuccessful leap into culvert.

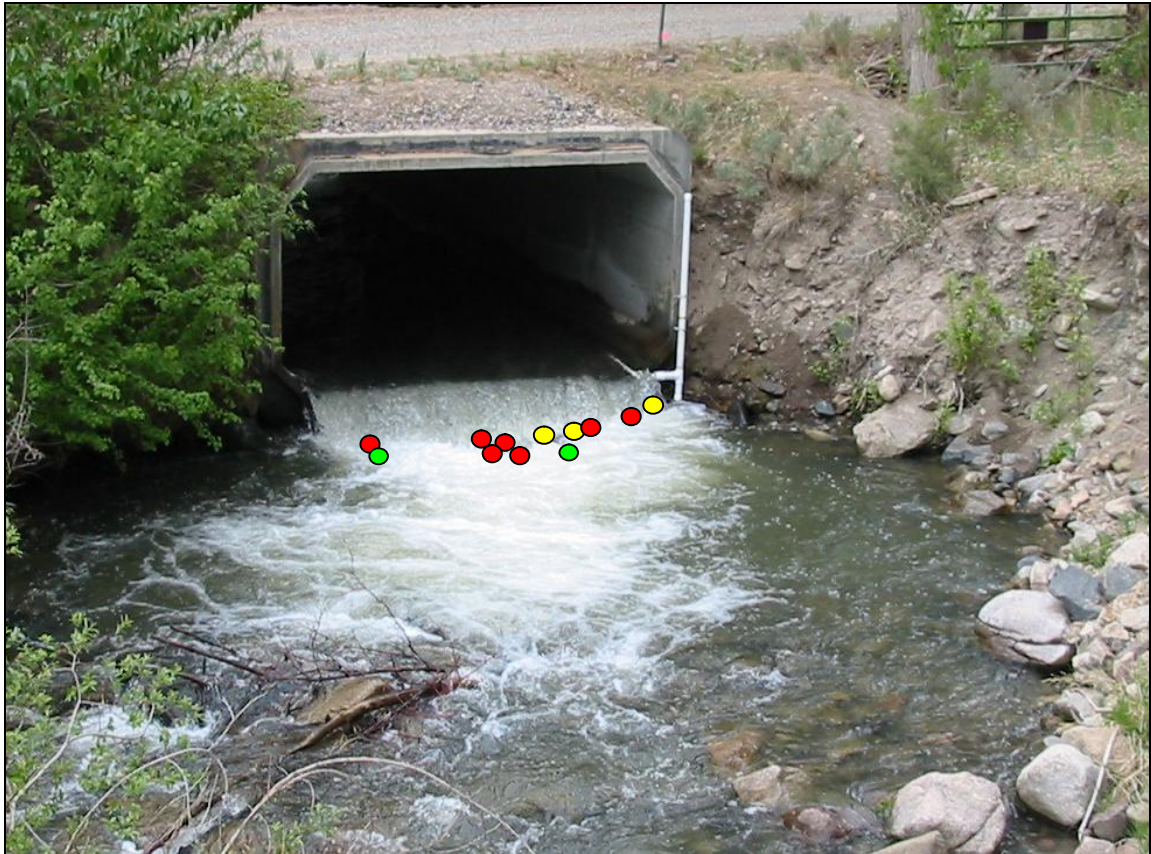


Successful leap into, not successful passage through culvert.



Successful leap into, and passage through culvert.

July 7, 2004 leaping observations at Culvert 1, Mulherin Creek
Start time: 14:45, Finish time: 16:38, Sample size: 12, Average flow rate: $1.59 \text{ m}^3/\text{s}$



Unsuccessful leap
into culvert.



Successful leap into,
not successful
passage through
culvert.



Successful leap into,
and passage through
culvert.