USING THREE DIMENSIONAL HYDRODYNAMIC MODELING AND FISH SWIMMING ENERGETICS TO ASSESS CULVERTS AS POTENTIAL PHYSICAL BARRIERS TO UPSTREAM FISH MOVEMENT

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Revised and re-submitted: October 14, 2008

Word Count: 5,510
Number of Tables: 3
Number of Figures: 4
Paper Number: 09-2917
Fish passage through culverts is an important consideration in road and stream crossing design. Although no comprehensive inventory of culverts on fish-bearing streams in the United States is available, there are an estimated 1.4 million stream-road crossings. The most common physical characteristics that create barriers to upstream fish passage include excessive water velocity, insufficient water depth and large outlet drop heights. Over the past decade, interest in the effect of culvert barriers on aquatic systems has grown; accordingly, various passage assessment techniques have been used to determine whether a structure is a barrier and under what flow conditions. Recent research has shown that determining the barrier status of a culvert is not trivial, and that different methods are often not congruent in their classification of barriers.

The purpose of this research was to test the use of 3-D hydrodynamic modeling to assess potential culvert barriers to upstream fish movement. The approach quantified the 3-D velocity field within the culvert barrel using computational fluid dynamics. A range of potential paths through the culvert were identified using an algorithm that estimates energy paths, and passage along the paths was assessed by combining the swim speed–fatigue time relationship with the 3-D velocity field. Results from the 3-D approach were compared to an approach that used the 1-D velocity field to estimate passability. Comparisons between estimated passage and measured passage showed the 3-D method more accurately predicted passage through the culvert compared to the 1-D method.
INTRODUCTION

Fish and aquatic organism passage through culverts is an important component of road and stream crossing design. Culverts represent a cost-effective means of conveying water underneath roadways and have been used as such for decades. If properly designed and maintained, culverts can provide an environment that passes fish and other aquatic organisms. On the other hand, they can inhibit or prevent 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 culverts on fish-bearing streams in the United States is available, there are an estimated 1.4 million stream–road crossings (USFWS). A report to the U.S. Congress in 2001 prepared by the United States General Accounting Office (USGAO) 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 2,600 of these culverts are barriers, and it would cost approximately $375 million to restore fish passage.

Examples of the number of culvert barriers from other parts of North America further highlight the problem. Sixty-one percent of culvert crossings in the Notikewin watershed and 74 percent of culvert crossings in the Swan river watershed, both in Alberta, likely impede fish movement (Tchir et al., 2004). In Whatcom County, WA, researchers assessed the passage status of culverts on 1,673 crossings and found 837 (50 percent) 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 percent) culverts probably allowed passage of all size classes of fish and 25 of 47 (53 percent) 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 percent are classified as barriers, 15 percent as passable, and 38 percent are unclassified (Williams, 2007).

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 (Votapka, 1991). Biological factors such as a fish’s swimming ability, motivation, and behavior play an equally important role in passage. With growing interest in the effect culvert barriers have on aquatic systems, various passage assessment techniques have been used to determine whether a structure is a barrier and, if so, under what flow conditions. Recent research has shown that determining the barrier status of a culvert is not trivial, and that different methods are often not congruent in their classification of barriers (Rajput 2003; Burford, 2005; and Coffman, 2005). Therefore, the purpose of this research was to test the use of 3-D (three-dimensional) hydrodynamic modeling combined with the swim speed–fatigue time relationship to assess a potential culvert barrier to upstream fish movement.

BACKGROUND

There are many different methods for analyzing the barrier status of culverts, each with distinct advantages and disadvantages. For this paper, these methods are categorized as either direct or 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 studies have been used to assess fish passage (Burford, 2005; Belford and Gould, 1989; Warren and Pardew, 1998). Other researchers analyzed fish movement through a range of flow conditions using passive integrated transponder (PIT) tags and antennae placed at the upstream and downstream ends of a culvert (Cahoon et al., 2007). 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 small 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 based 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 that are based on field and laboratory studies that compared physical characteristics to movement of fish.

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. 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 (Furniss et al., 2008). 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 estimate of the barrier status of culverts—i.e., more barriers to movement are predicted when compared to direct assessment results (Cahoon et al., 2005; Karle, 2005).

Another indirect approach is to use measures such as species presence or absence, relative abundance, relative length or species composition to evaluate fish passage. Typically, these approaches 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 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).

Assessing genetic differences between fish upstream and downstream of barriers is another method that has been used to identify whether a crossing is a barrier. 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).

One of the interesting findings from recent studies designed to assess barriers to fish is that different methods are not always congruent in their classification of a potential fish barrier. A basin-wide study designed to assess the effect of culvert barriers on trout populations in Montana found low congruency between a hydraulic assessment approach and observed fish movement data (Burford et al., in revision). Fish passage studies by Coffman (2005) and Rajput (2003) also show incongruency between different methods used to assess barriers to fish passage. Rajput found hydraulic model predictions and patterns of species loss to be congruent 71 percent of the time. Coffman 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 percent of the time. Model prediction improved after revising the predictive model parameters based on the data from the mark-recapture experiments.

There are several possible explanations for inconsistencies in assessing road crossings with 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 if 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.

One plausible explanation for why a hydraulic approach to assess passage has had varied success is that 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 (Behlke, 1991; Pearson et al., 2005 and others). Lab studies (Rajaratnam and Katopodis, 1990; Pearson et al., 2006 and others), field studies (Belford and Gould, 1989 and others) 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 velocity variation across a given cross section. 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 computational fluid dynamics (CFD) to predict 3-D flow fields and, subsequently, fish passage is a valid and useful endeavor.

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 for research to refine existing assessment methods and develop 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. A 1-D approach, similar to the one used in FishXing, was also developed to provide a comparison for the 3-D method. Both methods were compared to fish movement observations collected in a field setting.

Other studies have used CFD and fish energy expenditure concepts. Khan developed a hydrodynamic model of a vertical slot fishway to characterize the energy expenditure and drag forces along different flow paths (Khan, 2006). By comparing the predicted energy expenditure of various Pacific salmon species along selected flow paths through the fishway he identified those species capable of migrating through the fishway.
Lab studies of different fishways, and fish movements through them, led to development of 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. 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. 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.

METHODS

The current study combined field measurements of hydrologic and hydraulic conditions with fish movement data and hydraulic modeling. Field data were collected at Mulherin Creek, a tributary to the Yellowstone River with the confluence near Gardiner, MT (Figure 1). Data were collected from 2004 through 2006.

**Study Site Characteristics**

Mulherin Creek is a high gradient stream, with an average gradient from the headwaters to the mouth of 11.6 percent, and an average gradient between 2 percent and 5 percent 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 near 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 (*Oncorhynchus clarkia bouvieri*), 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 (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*).

Yellowstone cutthroat trout migrate from the Yellowstone River into Mulherin Creek to spawn. Typically, these fish move upstream for spawning on the falling limb of the spring runoff hydrograph when water temperatures exceed 12° to 14°C. The study focused on Yellowstone cutthroat trout because they are a native species and a species of special concern. In addition, interactions between Yellowstone cutthroat trout and invasive rainbow trout represent a common conservation issue for trout in much of the United States and Canada.
The study culvert was a concrete box culvert with chamfered corners. The culvert had a slope of 1.1 percent, length of 11.13 m, and an outlet drop that averaged 0.49 m during the course of the study.

**Field Data Collection**

A gaging station was constructed at the culvert to continuously record water depth for creation of a stage–discharge relationship and creation of hydrographs for all three years of the study. 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 Price AA or a Pygmy meter. Discharge
transects were established within the culvert and in a stable downstream reach of Mulherin Creek. A stage–discharge relationship was created following USGS protocols (USGS, 1982).

Hydraulic data including water depths and point velocities throughout the culvert barrel were collected to quantify the spatial patterns of depth and flow and to validate the hydraulic models. 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. Water velocity data sets (both 1-D and 3-D) were collected with a Pygmy meter (1-D) or an acoustic Doppler velocimeter (ADV). Velocity data sets were collected during most site visits. The frequency of the velocity data set collection was based on whether flow conditions at the culvert were different than previously recorded. Some data sets were collected at the same flow rate to provide replication of velocity measurements and hydraulic conditions within the structure.

Fish movement data were collected during the summer of 2004, 2005 and 2006 to better understand how fish moved through the study culvert, to validate the accuracy of the 1-D and 3-D passage assessment models, and to compare fish movements to a range of hydraulic conditions in the culvert. Three methods were used to collect fish movement data relative to a range of flows and times of year. The first method (2004 season) used a mark-recapture technique with fish traps and weirs placed both upstream and downstream of the culvert. A second method (2004 season) used visual observations of fish leaping and swimming through the culvert. These observations were made by a researcher sitting in a position downstream of the culvert. The viewing position and the wide, yet short length of the culvert allowed a full view through the entire culvert barrel. Markers were placed along the sides of the culvert barrel at regular intervals to aid in monitoring fish movement and progress through the culvert. Data including leap location, leap success or failure, and swimming path were recorded for each observation. A third method (2005 and 2006 season) used passive integrated transponder (PIT) tags placed within trout ascending Mulherin Creek. Antennae placed at the upstream and downstream ends of the culvert recorded movement of tagged fish attempting and ascending the culvert.

Passage Assessment

In this section, the specifics of the 1-D model are presented first, followed by details of the 3-D model. Each model was used to estimate passage through the 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 were identified as impassable, and flows less than the threshold were identified as passable. In addition, comparisons between the flow-rate thresholds predicted by the various models and observed fish movements were made and discussed.

Only passage relative to flow or velocities was assessed. 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 were included in the assessment.
1-D Fish Passage Assessment

The 1-D model uses gradually varied flow hydraulics to estimate the hydraulic conditions (water depth and velocity) in the structure. The hydraulic conditions are then compared to fish swimming abilities to estimate passability. One form of the gradually varied flow equation is shown below (Chow, 1959):

\[
\frac{dy}{dx} = \frac{S_o - S_f}{1 + \alpha \frac{d(V_{AVE}^2 / 2g)}{dy}}
\]

where \(\frac{dy}{dx}\) 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 \(V_{AVE}\) is the average velocity in the cross section of flow. This equation is a first-order differential equation that can be solved in a variety of ways.

A spreadsheet and VBA program were created to solve the gradually varied flow equation using the standard step method and to estimate water depths and average velocities through the culvert. 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 culvert had inlet control (critical depth at inlet) and was supercritical throughout. 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 in this method 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 (Furniss, 2008).

The velocity of a fish swimming relative to a fixed frame of reference is:

\[
V_{GRD} = \frac{dx}{dt} = V_w + V_f
\]

where \(V_{GRD}\) is the absolute velocity of the fish with respect to the ground; \(V_w\) is the water velocity component parallel to the direction of fish swimming; and \(V_f\) is the swimming velocity of the fish. 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:

\[
t = \frac{x}{V_w + V_f}
\]
The approach to estimate passage divided the culvert into sections that were 0.3 m long in the x-direction, the same interval that velocities were calculated using the gradually varied flow equation. Equation 3 was solved for the time it takes the fish to swim each 0.3 m section of the culvert, where the water velocity \( V_w \) across each section was assumed to be constant and the fish was assumed to swim at a constant speed. The total time to pass the culvert was then calculated by summing the time it takes to pass each 0.3 m increment. This total time was 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 was greater than the time to fatigue, then the culvert was 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 was less than the time to fatigue, then the culvert was identified as passable at that flow rate.

3-D Fish Passage Assessment

The 3-D approach was similar to the 1-D approach with a few key modifications. First and most importantly, the 3-D velocity field was used to estimate passage rather than the average 1-D velocity field. ANSYS-CFX was used to estimate the 3-D velocity field for the flow of interest. Modern day computing power has progressed to the point where simple flow models constructed using ANSYS-CFX or similar software can be run on personal computers. Simulation times will vary depending on computer capabilities; for this study the computational time was approximately 24 hours per run. Second, possible paths a fish could take through the culvert were identified based on dividing the outlet of the culvert into ten equally spaced areas. Third, the minimum energy path starting from each of these sections was calculated using the following relationship and algorithm. The energy expended \( (E_f) \) by a fish to pass through the culvert can be expressed as follows:

\[
E_f = \int_0^t P_f dt \quad (4)
\]

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.

\[
E_f = \sum_{i=1}^{n} P_f t_i \quad (5)
\]

The time it takes for a fish to swim an increment of the path length is estimated using the following equation:
where $\Delta x$ is the increment of path length. 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 ($V_f$). This relationship assumes the buoyant force, gravity force and virtual mass force are negligible.

$$P_f = F_D V_f$$

(7)

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

$$F_D = 0.5 \rho C_d \left[ |V'_w| + |V'_f| \right]^2 A_s$$

(8)

where $\rho$ is water density, $C_d$ is the drag coefficient and $A_s$ is the wetted surface area of a fish.

The energy expenditure algorithm used 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 vectors at each grid point were 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 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 (Figure 2). The path with the lowest velocity was identified as the minimum energy path. The program selected the grid point with the lowest velocity of the three potential paths. The position of the fish was moved to that grid point, and the procedure was repeated until the fish had ascended the entire structure. Only continued upstream progress was allowed in the decision of potential paths through the structure.

Last, the velocities along the minimum energy path were 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 follow the minimum energy path to pass the culvert. This assumption was based on visual observations of trout swimming through the culvert.

**Fish Swimming Abilities**

Both methods for determining passage rely on knowledge of 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 was based on visual observations of fish attempting passage through the culvert. In addition, the burst speed was assumed to be constant.

Table 1 provides a summary of burst speed data for cutthroat trout and rainbow trout. The swimming speeds for rainbow trout were included because there was only one
reference (to the author’s knowledge) for burst speeds of cutthroat trout (Bell, 1991) and rainbows are often used as a surrogate species for cutthroat trout.

Figure 2. The decision process for estimating energy expenditure using the VBA program. The path shown with bold arrows was the maximum energy expenditure; and the path shown with the thin arrows was the minimum energy expenditure. The starting point was arbitrary. Water velocities are in m/s.

The 1-D and 3-D assessment methods used 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 1. 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.

Time to fatigue for fish varies (Hoar and Randall, eds., 1978; Hunter and Mayor, 1986). Table 1 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.
Table 1. Summary of burst swimming speeds for cutthroat trout and rainbow trout.

<table>
<thead>
<tr>
<th>Species</th>
<th>Burst Speed</th>
<th>Burst Speed Range</th>
<th>Size Range</th>
<th>Time Range</th>
<th>Source and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutthroat Trout</td>
<td>4.1</td>
<td>1.8 to 4.1</td>
<td>-</td>
<td>-</td>
<td>Bell (1991).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>-</td>
<td>1.86 to 2.26</td>
<td>58 to 67</td>
<td>10 to 15</td>
<td>Paulik and Delacy (1957) as cited in Hoar and Randall, eds. (1978).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>-</td>
<td>5.36 to 8.17</td>
<td>61 to 81</td>
<td>1.5</td>
<td>Weaver (1963) as cited in Hoar and Randall, eds. (1978).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>-</td>
<td>0.3 to 2.5</td>
<td>14.3</td>
<td>0.08</td>
<td>Webb, as cited in Hoar and Randall, eds. (1978).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>-</td>
<td>0.3 to 1.8</td>
<td>14.3</td>
<td>0.04</td>
<td>Webb, as cited in Hoar and Randall, eds. (1978).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>0.83</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Jones et al. (1974) as listed in FishXing Swimming Speed table.</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>1.49 ⭐</td>
<td>-</td>
<td>10.3 to 28</td>
<td>1 to 20</td>
<td>Bainbridge (1960) as cited in Hunter and Mayor (1986).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>1.87 ⭐</td>
<td>-</td>
<td>10.3 to 81.3</td>
<td>1 to 20</td>
<td>Bainbridge (1960), Weaver (1963) and Beamish (1978) as cited in Hunter and Mayor (1986).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>3.09 ⭐</td>
<td>-</td>
<td>61 to 81.3</td>
<td>1.6 to 12.5</td>
<td>Weaver (1963) and Beamish (1978) as cited in Hunter and Mayor (1986).</td>
</tr>
</tbody>
</table>

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.

Both the 1-D and the 3-D assessment methods were used to estimate passage 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.

RESULTS AND DISCUSSION

Results for the 1-D and 3-D assessment methods are summarized in Figure 3 for the hydrograph measured in 2004. Similar results were found for the 2005 and 2006 hydrographs. This figure shows the amount of time that passage was predicted relative to the flow rate measured in Mulherin Creek at the culvert location. The figure includes passage assessment results for four hydraulic methods and observed passage (n = 21) and failed attempts (n = 16). Multiple fish passed or failed to pass during the same date and flow; therefore, the number of fish observations shown in the graph are less than the actual observations themselves (e.g. some symbols overlap). 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 the 1-D model and swim data in Bell (1991) for cutthroat trout, flow rates less than 0.85 \( m^3/s \) were passable, and flow rates greater than 0.85 \( m^3/s \) were impassable.

2) Using the 1-D model and Hunter and Mayor’s (1986) data for rainbow trout, there was no passage at any flow rate because the average velocities were too great at all measured flow rates.

3) Using the 3-D model and swim data in Bell (1991) for cutthroat trout, flow rates less than 2.1 \( m^3/s \) were passable, and flow rates greater than 2.1 \( m^3/s \) were impassable.

4) Using the 3-D model and Hunter and Mayor’s (1986) data for rainbow trout, flow rates less than 1.1 \( m^3/s \) were passable, and flow rates greater than 1.1 \( m^3/s \) were impassable.

Figure 3. Estimated passage thresholds for 2004 using all four assessment methods. Data from fish movement experiments is included for comparison. Flow rates greater than the thresholds were impassable based on the method, and flow rates less than the thresholds were passable based on the method.
Another way of expressing these results is the percent of time (based on the measured hydrograph compared to the estimated flow passage thresholds) that was estimated as passable to Yellowstone cutthroat trout. Table 2 summarizes this information for water years 2004, 2005, 2006, and all years combined.

Table 2. Summary of fish passage assessment method results.

<table>
<thead>
<tr>
<th>Method</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>All Years Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-D with Bell</td>
<td>57%</td>
<td>49%</td>
<td>37%</td>
<td>49%</td>
</tr>
<tr>
<td>1-D with Hunter and Mayor</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>3-D with Bell</td>
<td>93%</td>
<td>84%</td>
<td>75%</td>
<td>85%</td>
</tr>
<tr>
<td>3-D with Hunter and Mayor</td>
<td>67%</td>
<td>62%</td>
<td>46%</td>
<td>60%</td>
</tr>
</tbody>
</table>

The 3-D assessment method estimated a greater amount of passage time because the method used a more accurate and realistic calculation of the flow field. A lower velocity region on the river left side of the culvert developed due to the skew of the culvert with the upstream channel (Figure 4). This lower velocity region allowed fish to swim upstream against velocities that were less than the average velocity in the culvert barrel; therefore, they were able to pass upstream at flow rates with high average velocities. The 1-D method compared passage to the average velocity only and therefore estimated 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. A total of 16 failed attempts at passage were recorded that same year. PIT tagging results from Solcz (1997) documented 6 successful passes and two failed attempts during 2005 and 2006 combined. Table 3 compares the passage assessment flow rate thresholds to the flow rates where passage was observed and where failures to pass were documented.

Table 3 shows the most accurate method for estimating passage was the 3-D model with swim speed information from Bell (1991). All other methods identified the culvert as a barrier even though observations showed fish movement through the culvert. Paths that fish used to successfully and unsuccessfully negotiate the culvert were documented based on visual observations. Fish that used the lower velocity region within the culvert (e.g. the minimum energy path) were successful in negotiating the culvert. In contrast, fish that attempted passage by using other paths which were against higher velocities were unsuccessful and washed back out of the culvert barrel.
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 showed this relationship (Cahoon et al., 2007). 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).

Table 3. Summary of passage assessment and observations of fish movement in the culvert for all three years.

<table>
<thead>
<tr>
<th>Number of Fish Observed Passing</th>
<th>Number of Observed Failures to Passing</th>
<th>Measured Flow Rate (m³/s)</th>
<th>1-D with Bell</th>
<th>1-D with Hunter and Mayor</th>
<th>3-D with Bell</th>
<th>3-D with Hunter and Mayor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.11</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.23</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.27</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.30</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.40</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1.47</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1.50</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>1.55</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1.58</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1.62</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1.64</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.70</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1.81</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.90</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>2.12</td>
<td>Not Passable</td>
<td>Not Passable</td>
<td>Passable</td>
<td>Not Passable</td>
</tr>
</tbody>
</table>

There are advantages and disadvantages to each of these methods. The 1-D method requires less data and less computational effort to describe the flow field. However, it proved to be less accurate at estimating passage 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. In our study, the study culvert represented a typical temporal barrier to passage.

SUMMARY AND FUTURE RESEARCH NEEDS

This paper presented the use of 3-D hydrodynamic modeling to assess the velocity field through a culvert and to estimate fish passage. A comparison of a 1-D method to the 3-D method showed that the 3-D method predicted a larger range of passable flows through the culvert. The 3-D method also provided a more accurate picture of passage through the structure than the 1-D method when compared to field data of fish.
movements through the structure. However, some fish did fail to pass the culvert at flows less than the passage threshold predicted by the 3-D method.

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 or sprint swimming speeds and time to fatigue 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 1960s and 1970s, and it was typically collected for use in the design of fishways, not necessarily the assessment of barriers. Sprinting performance should be determined following methods used at the Silvio O. Conte Anadromous Fish Research Laboratory, as existing data for many fish species is limited or non-existent (Castro-Santos, 2005).

Less aggressive swim speeds, like the sustained swimming ability, are used when designing fishways (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.

As a final recommendation, more evaluation and validation of 3-D hydrodynamic modeling as a tool for assessing barriers is needed to refine the technique and further determine its effectiveness for assessing potential culvert barriers.
ACKNOWLEDGMENTS

We’d like to thank the Montana Department of Transportation and the Western Transportation Institute for providing funding for the work presented in this paper. We’d also like to thank the following individuals for their efforts in supporting or facilitating this project: Bob Gresswell, Andy Solcz, Jesse Patton, and Pat Byorth.

REFERENCES CITED


