Using Three Dimensional Hydrodynamic Modeling and Fish Swimming Energetics to Assess Culverts as Potential Physical Barriers to Upstream Fish Movement

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Overview of Presentation

- Aquatic barriers
- Factors affecting passage
- Assessment methods
- 3-D hydrodynamic method (and 1-D)
- Comparison to fish movement
- Future research directions
2.5 million aquatic barriers in U.S. by culverts, dams and canals (National Fish Passage Summit, 2006).

Estimated 1.4 million stream-road crossings in U.S. (U.S. Fish and Wildlife, National Fish Passage Program, unpublished data).

1,500 culverts on fish bearing streams within Montana’s National Forests: 47% barriers, 15% passable and 38% unclassified (Williams, 2007).
Physical Factors Influencing Fish Passage

- **High water velocity**
  - excessive turbulence
- **Shallow water depth**
- **Outlet drop**
  - pool depth/leap height ratio
  - jump location
  - air entrainment
- **Debris/sediment blockage**
Fish Locomotion

- Species and size
- Temperature
- Dissolved oxygen
- Motivation
- Gender
- Physical condition
- Disease
- Sexual maturity
Types of Barriers

- Total Barrier
- Partial Barrier
- Temporal Barrier
- No Barrier
### Assessment Techniques

<table>
<thead>
<tr>
<th>Direct Approach</th>
<th>Field experiments that measure fish movement directly and compare movement to flow conditions in a structure.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect Approach</td>
<td>Approximate movement potential using thresholds, modeling or comparisons between population characteristics measured upstream and downstream of a crossing.</td>
</tr>
</tbody>
</table>

#### Tagging studies:
- Mark-recapture, PIT tagging or others (e.g. radio telemetry)
- Visual observations
- Video camera

#### Regional screens:
- Based upon field and laboratory experiments
- Hydraulic modeling
- Comparisons between upstream and downstream fish population characteristics
### Assessment Techniques

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**Western Transportation Institute**

Montana State University College of Engineering
Upper Clearwater River Basin

Above Seeley Lake outlet
- 143 square miles
- 121 miles of stream
- Assessed 46 culverts
# Summary of Results for Sites Where Multiple Methods Were Applied

<table>
<thead>
<tr>
<th>Site Identification</th>
<th>FishXing Results</th>
<th>Direct Passage Results</th>
<th>Upstream vs. Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adult</td>
<td>Juvenile</td>
<td>Passage Indicator</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>B</td>
<td>-0.36</td>
</tr>
<tr>
<td>10</td>
<td>B</td>
<td>B</td>
<td>0.35</td>
</tr>
<tr>
<td>11</td>
<td>B</td>
<td>P</td>
<td>0.2</td>
</tr>
<tr>
<td>13</td>
<td>B</td>
<td>B</td>
<td>-1</td>
</tr>
<tr>
<td>19</td>
<td>B</td>
<td>B</td>
<td>0.13</td>
</tr>
<tr>
<td>20</td>
<td>B</td>
<td>B</td>
<td>0.03</td>
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<tr>
<td>23</td>
<td>P</td>
<td>P</td>
<td>-0.56</td>
</tr>
<tr>
<td>27</td>
<td>B</td>
<td>B</td>
<td>-0.19</td>
</tr>
<tr>
<td>28</td>
<td>B</td>
<td>B</td>
<td>-0.54</td>
</tr>
<tr>
<td>33</td>
<td>B</td>
<td>B</td>
<td>-0.85</td>
</tr>
<tr>
<td>35</td>
<td>B</td>
<td>B</td>
<td>-0.69</td>
</tr>
<tr>
<td>43</td>
<td>B</td>
<td>B</td>
<td>-0.22</td>
</tr>
</tbody>
</table>
Development and Testing of 3-D Method – Mulherin Creek

- Concrete Box Culvert
- Length ~ 37 ft
- Width ~ 12 ft
- Slope ~ 1.1%
- Outlet Drop ~ 1.5 ft

Main study culverts
Culverts in companion study
Direct Passage Measurement

- Visual observations
- PIT tagging w/ antennae
- Mark-Recapture
Hydrodynamic Model Development

CFD model development using ANSYS CFX platform.

**Boundary Conditions**
- Inlet: mass flow rate, turbulence intensity and length scale
- Outlet: static pressure (water depth)
- Culvert sides and floor: no-slip wall boundaries

**Initial Conditions**
- Inlet: grid of water velocities
- Outlet: water depth
- Velocities: 0 m/s
- VOF: step function
Model Validation

Observed

Predicted

Flow
Model Validation

$\hat{y} = \text{fit}$

$R^2_{mod} = 0.86, R^2_{fit} = 0.93$

$R^2_{mod} = 0.90, R^2_{fit} = 0.95$
**Barrier Assessment 1-D**

1. \( V_f - V_w = V_{\text{progress}} \)
2. \( \text{Time} = \frac{1}{V_{\text{progress}}} \)
3. If Total Time > 5 seconds, then fail, otherwise pass.

Flow

- 8.20 ft/s
- 8.62 ft/s
- 8.91 ft/s
- 9.02 ft/s
- 9.13 ft/s
- 9.22 ft/s
- 9.31 ft/s
- 9.38 ft/s
- 9.46 ft/s
- 9.53 ft/s
- 9.59 ft/s

Fish Movement
Barrier Assessment (3D)

- Estimate 3-D velocity field.
- Find minimum energy path for each starting point.
- Estimate passage using velocities along each path.
Energy Paths

June 29 Model

Flow
<table>
<thead>
<tr>
<th>Species</th>
<th>Burst Speed</th>
<th>Burst Speed Range</th>
<th>Size Range</th>
<th>Size Range</th>
<th>Time Range</th>
<th>Temperature Range</th>
<th>Source and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutthroat Trout</td>
<td>4.12</td>
<td></td>
<td></td>
<td></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>23 to 26</td>
<td>10 to 15</td>
<td></td>
<td>Paulik and Delacy (1957) as cited in Hoar and Randall, eds. (1978).</td>
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<tr>
<td>Rainbow Trout</td>
<td></td>
<td>5.36 to 8.17</td>
<td>61 to 81</td>
<td>24 to 32</td>
<td>1.5</td>
<td></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>5.6</td>
<td>0.08</td>
<td></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>5.6</td>
<td>0.04</td>
<td></td>
<td>Webb, as cited in Hoar and Randall, eds. (1978).</td>
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<tr>
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<td>2.72</td>
<td>0.83</td>
<td>-</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>5.33</td>
<td>1.62</td>
<td>-</td>
<td>10.3 to 28</td>
<td>4.1 to 11</td>
<td>1 to 20</td>
<td>Bainbridge (1960) as cited in Hunter and Mayor (1986).</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td>2.11**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hunter and Mayor (1986)</td>
</tr>
<tr>
<td>Rainbow Trout</td>
<td></td>
<td>3.28</td>
<td>-</td>
<td>61 to 81.3</td>
<td>24 to 32</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>
Four Different Assessments

1. 1-D flow model with Bell (1991) data.

2. 1-D flow model with Hunter and Mayor’s (1986) data.

3. 3-D flow model with Bell (1991) data.

4. 3-D flow model with Hunter and Mayor’s (1986) data.
Comparison of Predictions to Direct Observations

1. 1-D with Bell.
2. 1-D with Hunter and Mayor.
3. 3-D with Bell.
4. 3-D with Hunter and Mayor

• Documented Passage and Failed Attempt

• Documented Passage
Future Research

- Further validate 3-D hydrodynamic modeling for barrier assessment.
- Determine high end (burst) swimming speeds.
- Assessment should be in terms of probabilities, not yes/no.
- Marriage of aquatic ecology and hydraulics.
Acknowledgements

• Western Transportation Institute
• Montana Department of Transportation
• Montana Fish, Wildlife and Parks
• United States Forest Service
Select flow rate of interest.

Model velocity through culvert using ANSYS-CFX.

Export velocity field on plane 0.06 m above culvert bed from ANSYS-CFX to Microsoft Excel.

Calculate energy paths using Microsoft Excel with VBA code.

\[ E = \int_{0}^{s} |F| ds \]

\[ F = 0.5C_d \rho A_s (V - V_f)^2 \]
Energy Paths