Background

- Historically culverts have been designed to convey flood stages underneath transportation corridors.
- Such traditional approaches have not considered adverse impacts of such structures to the fluvial environment, particularly to aquatic species.
- An immediate consequence is that the installation of culverts may difficult or prevent the migration of fish species to spawning sites, as well other aquatic species.
- Results in decrease of fish population, among other environmental impacts, with economical consequences.

Problem is recognized by the research community and different mitigation strategies have been developed, including:

- Stream simulation culverts – reproduce stream characteristics within culvert
- Bottomless culverts
- Internal baffles
- Elimination of perched outlets

Such mitigation techniques are effective in mitigating culvert impacts, but a pertinent question is to determine where they are most needed.

Culverts placed at a certain watershed should have different impacts to local species, and the knowledge of which ones cause more impacts is very desirable.

Mitigation strategies to improve aquatic species mobility – Stream simulation

Stream simulation ...

- is a method of designing crossing structures (usually culverts), with the aim of creating within the structure a channel as similar as possible to the natural channel in both structure and function. The premise is that the simulated channel should present no more of an obstacle to aquatic animals than the adjacent natural channel." USFS 2008

Unlike hydraulic design

- Does not target a specific fish species as far as target water depth, water velocity, crossing length criteria, etc.
- Channel inside culvert should mimic stream (meets bankfull width of reference stream, without offsets, same roughness)
Before and after stream simulation

Stream simulation roadmap: Design and construction main steps

- **Initial assessment** to compile watershed-scale information, determine crossing objectives, and initial reconnaissance
- **Site assessment** follows, aiming to survey project area and determine the reference reach (key step)
- **Stream simulation** design will create/size a crossing structure mimicking the reference reach
- **Final design** focuses on structural part, as well road approaches
- **Construction/operation phases** must ensure detailed “as-built” documentation, monitor performance of crossing and maintain crossing as needed

Limitations and potential challenges

- **Stream simulation cannot recreate**
  - Natural light
  - Cohesive soils
  - Embedded wood
  - In-stream debris jam
- **Stream simulation is more challenging when**
  - Unstable (laterally or vertically)
  - Undergoing rapid meander shift or bank erosion
  - Severely incised below the crossing
  - Severely aggraded above crossing
  - Subject to debris flows, hillslope erosion events, etc.
  - Large sediment inputs upstream
  - Steeper than 6 percent
  - Made up of intermittent bedrock exposures in the streambed

Hydraulic improvements in culverts aiming at fishing passage

- A **less-holistic** approach is to intervene in culverts to ensure that flow conditions do not prevent passage of fish and/or other aquatic species
- This involves the use of
  - Baffles inside culverts
  - Prevention/elimination of perched outlets
  - Use of bottomless culverts
- The latter one is often applied as part of a Stream Simulation intervention

Culvert baffles

- The idea of using culvert baffles is to reduce flow velocity within the culvert, and create pool zones where fish could rest during the process of culvert crossing
- May be built in concrete, wood, plastic, etc. with a variety of geometries

Prevention/elimination of perched outlets

- Erosive processes downstream from a culvert can lead to significant sediment removal, preventing fish and other aquatic species passage
- Identification of erosive processes are needed in design phases of culverts
- Maintenance of culvert structures should also indicate unforeseen erosive processes, and erosion control measures will be needed
Bottomless culverts

- Embed culverts with the material that is found in the natural stream, anchoring the culvert in position
- Consider the vertical adjustment profile lines expected in the lifetime of the project

Available hydraulic tools

- Current tools to perform Culvert design and analysis with focus in fish movement are limited
  - One such model is USFS FishXing 3.0, freely available
- Hydraulic analysis of culverts assuming steady gradually varied flow
- Analyst inputs culvert geometry data, a relevant flow rate that is to be considered in the studies, and the code perform an analysis of that specific flow condition (or range of flow conditions) to fish species of interest
- Other culvert models do not consider fish movement in their formulation – hydraulic design is the focus
  - FHWA HY-8
  - USACE HEC-RAS 4.1
- The latter has the advantage to simulate the entire river system

Challenges related to intervention costs

- It will be often the case that there are more needed interventions in roadway-stream crossings than available
- How to prioritize the process of culvert improvement and replacement to mitigate issues with fish mobility
- How to incorporate time in the analysis?
  - One problem that we have is that in many cases varying degrees of hindrance in the passage of aquatic species
  - As flow varies in a watershed, depths and velocities should be varying in culverts. Mobility difficulties vary over time

Limitations of current culvert models in the assessment of culverts as fish movement barriers

- Inability to incorporate flow unsteadiness in the analysis
  - Current models performs analysis of fixed flow rates considered relevant (e.g. 7-day low flows), not an extended period simulations
- Culverts are simulated as stand-alone structures
  - Except by HEC-RAS model, other alternatives do not perform modeling of the entire river stream, in which the culvert is an element. Interactions between constrictions (e.g. backwater effects) becomes harder
- Flow velocities within culvert barrels are non-uniform
  - Culvert models generally obtain an cross-sectionally average velocity \( V = \frac{Q}{A} \), which may not be the velocity fish experience close to the conduit bottom and walls

Research at Auburn University in this topic

- Created a tool to perform an analysis of an entire watershed indicating culverts causing most impacts to fish species
- Shift focus from a snapshot modeling of the culvert into an extended period analysis, incorporating stream’s flow unsteadiness
- Reconstruct cross sectional velocity distribution based on average velocity data using results by Ead et al. (2000)
- Implemented as a post-processing tool of HEC-RAS, using that model hydraulic engine to simulate streams and culverts
- Fish species data obtained from FishXing 3.0 installation

Vision: shifting focus from individual culverts into group of culverts within watershed

- Source: http://www.fs.fed.us/r10/tongass/districts/pow/projects_plans/fish/n_thorne_eis.shtml
- Source: http://hydrology.pnnl.gov/projects/watershed.asp
Methodology

- Use HEC-RAS 4.1 to compute unsteady flow applying the Saint-Venant equation and a 4-point implicit scheme
  \[
  \frac{dA}{dt} + \frac{dQ}{dx} - \frac{Q}{T} = 0
  \]
  \[
  \frac{dQ}{dt} + \frac{dQ}{dx} + \rho A \left( \frac{Q^2}{2} + h_f \right) = 0
  \]
- Reconstruct of velocity distribution using Ead et al. (2000) data
  - Calculates velocity at a given point in the cross section
  - Empirical corrections to account for changes in shear velocity, variations of the bed shear stress away from the centerline and for deviations from the log-law (circular culverts, depth/diameter<50%)
  - Velocities evaluated at discrete points in a rectangular grid

Application

- Modified a HEC-RAS culvert project (Spring Creek) to incorporate a unsteady 48-h long flow hydrograph
  - Double-barrel, D=1.83 m, concrete culvert (n=0.013)
  - 957-m long stream simulated, slope 0.80%, n=0.040
  - Hydrograph has a 25-year return period peak, and a second smaller rain event. Between these events, no flow for 10 hours
  - Assess the adequacy of fish passage conditions considering minimum flow depth and flow velocities, comparing with fish dimensions and swimming capability
  - Compare the analysis using the average velocity as the relevant fish velocity, and also using velocity reconstruction for varying cross sectional resolutions (from 1,000 to 10,000 cells)
Results of American Shad mobility

Table 1: Summary of the results obtained with the proposed model simulating Spring Creek for the 48-h long unsteady hydrograph

<table>
<thead>
<tr>
<th>Simulation Condition</th>
<th>% of time with excessive velocity</th>
<th>% of time with low depth</th>
<th>% of time with unknown conditions</th>
<th>% of time with adequate fish passage conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Cross-sectionally averaged velocity</td>
<td>29.2</td>
<td>26.0</td>
<td>0</td>
<td>44.8</td>
</tr>
<tr>
<td>2 - Varying cross-section velocity 1,000 grid</td>
<td>5.7</td>
<td>26.0</td>
<td>9.9</td>
<td>58.3</td>
</tr>
<tr>
<td>3 - Varying cross-section velocity 5,000 grid</td>
<td>4.6</td>
<td>26.0</td>
<td>9.9</td>
<td>59.4</td>
</tr>
<tr>
<td>4 - Varying cross-section velocity 10,000 grid</td>
<td>4.6</td>
<td>26.0</td>
<td>9.9</td>
<td>59.4</td>
</tr>
</tbody>
</table>

Result discussion

- Significant differences when reconstructed velocity profiles are used
- Fish passage is adequate for about 60% of the time, instead of 45% obtained with average velocity
- Flow reconstruction is not possible for about 10% of the simulation time as depth exceeds 50% of the culvert diameter – hence “unknown conditions”
- 5,000-cell discretization are not different from 10,000-cell results, indicating a good balance between computational effort and accuracy
- However, the best discretization will generally be dependent on fish and culvert dimensions

Future work – research interests

- Expand velocity maps to include a broader depth range in the analysis, as well as critical discharge conditions
- Use experimental data as well as CFD simulation
- Include hydrological software (e.g. HEC-HMS) to be able to supply watershed hydrographs for the culvert analysis
- Consider perched discharge conditions in model
- Improvements on the post-processing tool
- Field work validation of the approach

Further questions

- Could a tool such as this one indicate which culverts would cause greater impacts to fish movement within a watershed?
- Useful information for a short-term planning
- How a tool such as this one under development could devise an optimized order of culvert replacements?

Final considerations

- Environmental regulations are increasingly stringent
- A healthy and restored environment is extremely valuable to all in our society today and in future years
- Culverts can be very impactful to aquatic species migration
- Intervention strategies that have been proposed in the past years can be effective in mitigating culvert impacts
- We hope that more attention will be directed to this topic, and that more environmentally-friendly hydraulic structures are implemented in the future

Thank you!
Questions?
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