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GIS Modelling of Fish Habitat and Road Crossings for the Prioritization of Culvert Assessment and Remediation

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Background

Roads throughout British Columbia invariably cross streams and rivers on a frequent basis, requiring installation of a crossing structure during road construction. Although open-bottom structures (OBS), such as bridges and some larger culverts, typically retain or emulate natural stream channel morphology and fish habitat, smaller closed-bottom structures (CBS), such as corrugated metal pipes, often do not. The change to stream morphology created by installation of a CBS often creates a barrier to fish passage through factors such as:

- high velocities and turbulence from concentrated flow;
- outlet drop heights;
- plunge pool condition;
- ice or debris blockage;
- lack of resting pools downstream or upstream; and
- culvert alignment relative to the stream channel (Furniss et al. 1991; Forest Practices Board 2009).

Extensive research and investigation of this issue in British Columbia has shown that most closed-bottom, round pipe culverts have at least one (if not all) of these problems present (Forest Practices Board 2009; B.C. Ministry of Environment 2010).

History

Barriers to fish passage associated with culverts have long been an identified problem in many areas of North America (Wightman and Taylor 1976; Dane 1978; Saremba 1984). As early as 1976, the Province of British Columbia recognized that more needed to be done to study culverts and the capability of fish to move through them (Wightman and Taylor 1976). To address this problem, the Province has provided training and guidance on proper installation of CBS and funded programs such as Forest Renewal BC and the Forest Investment Account to remediate culverts that block fish passage (B.C. Ministry of Forests 2002; B.C. Ministry of Environment 2009). The surrounding jurisdictions of Alberta, Alaska, Washington, and Oregon have also been engaged in similar efforts over the past decades (Furniss et al. 1991; Conroy 1997; McCleary and Hassan 2008; Park et al. 2008).

Despite the work done to date in British Columbia, recent evaluations carried out through various programs and agencies (e.g., Forest Renewal BC, Forest Investment Account, B.C. Ministry of Forests, Mines and Lands, B.C. Ministry of Environment, and the federal Department of Fisheries and Oceans) have found that culvert-associated barriers to fish passage are still a significant problem. Many studies have shown that 60–90% of road/stream crossings with CBS likely impede fish passage (Harper and Quigley 2000; Avison Management Services 2006; B.C. Ministry of Environment 2010). The Forest Practices Board (2009) found that 90% of the CBS located in important and critical habitat presented a risk to fish passage. This result is not inconsistent with

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findings in adjacent jurisdictions such as Alberta, Washington, Oregon, and Alaska (Beechie et al. 1994; Conroy 1997; Park et al. 2008). Habitat fragmentation caused by poorly installed culverts has also been identified as one of the greatest concerns related to recovery of coastal cutthroat stocks in the Lower Mainland of British Columbia (Slaney 2005).

In 2007, the Fish Passage Technical Working Group, with membership from the B.C. Ministry of Forests, Mines and Lands, the B.C. Ministry of Environment, and the Department of Fisheries and Oceans, was established to address this problem and to guide the allocation of the Forest Investment Account's fish-passage funding through its Land Based Investment Program. Funding is available for assessment of fish passage status of all culverts on forestry roads, and for remediation of fish-barrier culverts on Crown land forestry roads constructed prior to enactment of the *Forest Practices Code of British Columbia Act* (1995). Stream crossings of public highways, railways, and other resource roads are ineligible for this funding.

To help plan its efforts and to maximize the return in fish habitat restored per dollar invested, the Working Group undertook a series of geographic information system (GIS) analyses. First, the total potential number of culverted stream crossings in British Columbia was quantified. Second, to help guide assessments, a fish habitat model was generated, and all potential culverted stream crossings were indexed by the relative amount of upstream fish habitat. Finally (and still in progress), field data from assessed and remediated culverts are being added to the GIS database to refine the fish habitat model and track progress of habitat restoration. To keep the analysis manageable and standard throughout the province, only complete spatial databases held by the Province were used as inputs. The analysis did not incorporate road data from licensees or other agencies. Metadata records for all input layers are provided at the end of this article.

GIS Analysis: Phase I – Potential Number of Culverted Stream Crossings

The first phase of the analysis simply asked: "How many potential culverted stream crossings are there in the province?"

Methodology: Phase I

To generate this estimate, road data from the Digital Road Atlas (DRA) and Forest Tenure Roads (FTEN) (replaced in 2010 by the Forest Tenure Road Segment Lines database) were intersected with Stream Network data from the Freshwater Atlas (FWA). Every intersection of a single line stream with a road was considered a potential culvert location. Double line streams (watercourses large enough to have a left bank and right bank mapped during air photo interpretation) were excluded as these were assumed to be serviced by a span structure such as a bridge. As discussed, properly designed and installed OBS, which maintain channel width and retain the natural streambed profile, do not usually represent a barrier to upstream fish passage.

Results: Phase I

A total of 434 960 crossings were modelled as likely having some type of culvert. This translates into an estimated provincial average of 0.78 crossings per kilometre of road (as of 2009) (Table 1).

This estimate comes with several caveats. First, road construction is ongoing and additional culverts continue to be installed. Second, stream extents are generally overestimated in dry interior areas and underestimated in coastal areas. Third, the FTEN road data used are the best source available for Crown land forestry roads; however, as these data record

Table 1. Summary of potential culverted stream crossings broken down by road type and forest region

Road type	Forest Region			Total
	Coast	Northern Interior	Southern Interior	
Forest service road				
No. of crossings	10 153	13 608	26 257	50 018
Length (km)	8504	15 965	30 723	55 192
Crossings per km	1.2	0.9	0.9	0.9
Road permit				
No. of crossings	44 930	37 875	48 794	131 599
Length (km)	41 752	49 793	72 856	164 401
Crossings per km	1.1	0.8	0.7	0.8
Public roads, highways				
No. of crossings	7258	7982	16 910	32 150
Length (km)	25 974	15 508	25 004	66 486
Crossings per km	0.3	0.5	0.7	0.5
Non-status roads				
No. of crossings	42 358	79 112	99 723	221 193
Length (km)[a]	21 662	110 345	139 225	271 232
Crossings per km[a]	2.0	0.7	0.7	0.8
TOTAL				
No. of crossings[a]	104 699	138 577	191 684	434 960
Length (km)[a]	97 892	191 611	267 807	557 310
Crossings per km	1.1	0.7	0.7	0.78

[a] Estimated.

tenure rather than actual construction, road extents may be overestimated as some roads in the database have not actually been built. Finally, bridges will be present on many single line streams, and many crossing sites will be serviced by OBS, such as pipe arches or wooden box culverts. The use of these types of structures varies regionally and temporally. The exact type of structure in place at any given crossing is not known until the crossing has had an on-site assessment performed. Likewise, without detailed field inspections, the condition of a crossing and its ability to pass fish is unknown. Culvert inspections are a significant component of the current Working Group's efforts. Proponents have been awarded Forest Investment Account (FIA) funding to perform these assessments since 2008. The protocol for these assessments is outlined in the *Field Assessment for Fish Passage Determination of Closed Bottomed Structures* (B.C. Ministry of Environment 2009)

GIS Analysis: Phase II – Crossings and Fish Habitat

Knowing the number of potential crossing sites with culverts was informative, but the Working Group needed to understand how many of these sites were likely to be on streams that support fish, which we define simply as "fish habitat." Although poorly installed culverts can be detrimental on any stream (stability, sediment production, barrier to non-fish species, etc.), those not located on fish-bearing streams are outside this project's scope. As no comprehensive aquatic fish habitat data were available, the team needed to create a provincial model of potential fish habitat—something not previously attempted at a scale suitable for forestry planning. The release of the Freshwater Atlas, a hierarchically coded and topologically connected stream network at 1:20 000 (Gray 2009), has made this possible.

The body of research on watershed-scale fish-habitat modelling, often for specific species, has grown steadily for the past decade (Porter et al. 2000; Latterell et al. 2003; Steel et al. 2004; O'Hanley and Tomberlin 2005; Fransen et al. 2006; McCleary and Hassan 2008; Kocovsky et al. 2009). To predict habitat suitability, this modelling typically employs landscape indicators, such as geology, stream morphology, elevation, and climate. While manageable at a reach or watershed level, this type of intensive modelling is not yet possible on a provincial scale in British Columbia. Required data either do not exist at the appropriate scale or are not provincially comprehensive. Also, landscape, species, and habitat variables are so diverse provincially that creation of several geographically distinct models would be required. As such, we developed a basic model adequate for provincial planning, and with the potential to be locally refined with additional inputs.

Methodology: Phase II

As with Phase I, to keep the analysis manageable and standard throughout the province, only provincially comprehensive spatial databases held by the Province were used as inputs. These inputs were:

- Freshwater Atlas Stream Network;
- modelled stream gradient (from TRIM contours);
- historical fish observation points; and
- obstacles or obstructions to fish passage (i.e., dams, waterfalls).

In simple terms, everything downstream of a known fish observation point was considered viable fish habitat. Moving upstream from a known fish observation site, stream segments were considered fish-bearing until either an obstruction (waterfall, dam, etc.) or a sustained channel gradient of more than 25% was encountered.

Building stream gradient segments

Streams are typically subdivided and classified as reaches—a section of stream that is relatively uniform in character, gradient, width, morphology, and discharge. As gradient has been widely used to identify streams too steep for use by anadromous fish, and is the only one of these variables easily derived from provincially comprehensive spatial data, streams were segmented and classified as "stream gradient segments" rather than as reaches.

Stream gradient segments were created by splitting the FWA Stream Network lines at each intersection with a 20 m contour line (TRIM Contour Lines), thereby creating a highly segmented stream line. The length of these individual segments served as a useful surrogate for slope. In areas of low slope, a larger distance occurs between contours and, as a result, longer segments were generated. Conversely, steeper slopes generated short line segments. A rolling nearest neighbour analysis was employed, whereby the length of each segment was compared to that of its immediate neighbours. Where the difference in the lengths of two adjacent stream segments was greater than the standard deviation of the lengths of all the segments making up the given stream, a significant change in slope is deemed to occur. Breaks in the stream at contour lines were removed except at these identified points, creating the stream gradient segments. Slope of individual stream gradient segments was then calculated using their length and endpoint elevations. This measure of slope was then available as an input to the fish habitat model (see Figures 1 and 2).

Fish habitat model

Fish habitat was modelled using fish observations and fish passage barriers. Fish observations were taken from the Land and Resource Data Warehouse layer "Known Fish Observations." As the name implies, these are sites where fish have been sampled in the field.

Barriers were taken from three sources. First, the Stream Gradient Segments previously derived were considered barriers at a given slope thereshold. Typically, grades exceeding 20% are considered a barrier for anadramous species (B.C. Ministry of Forests 1998). Nevertheless, some species (e.g., Bull Trout and Dolly Varden/Cutthroat) can utilize reaches with a sustained slope of 25–30% (Cannings

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and Ptolemy 1998). Considering these values, Stream Gradient Segments with slopes greater than 25% were considered barriers. The second barrier source was all features identified as *dam* or *falls* from the “Freshwater Atlas Obstructions” layer. The final source for barriers was all *dams*, *weirs*, and *falls* (greater than 5 m high) from the “Provincial Obstacles to Fish Passage” layer. The obstacle and obstruction layers include features derived from air photo interpretation and collected through various field fisheries surveys.

To model fish habitat, all streams segments downstream of a known Fish Observation Point (*n* = 160 000) were considered fish-bearing, and classified as “Fish Habitat – Observed.” Then, starting at the bottom/mouth(s) of the watershed group and working up the Freshwater Atlas Stream Network, streams were classified as fish-bearing until encountering a barrier feature. Segments upstream of any known fish observation but downstream of any barrier feature are classified as “Fish Habitat – Inferred.” Stream segments upstream of barrier features are classified as “Non-Fish Habitat” (See Figure 2).

For convenience, processing was broken down by individual watershed group *(n* = 246). Side channels of the stream network were included in the overall model, but barriers on the side channels (which account for 2% of the stream network by length) were not considered as the stream network is too complex to effectively model fish passage through multiple channels of the same stream.

With the habitat model complete, it was overlaid with the potential culverted stream crossings derived in Phase I to determine how many crossings are on each type of modelled fish habitat.

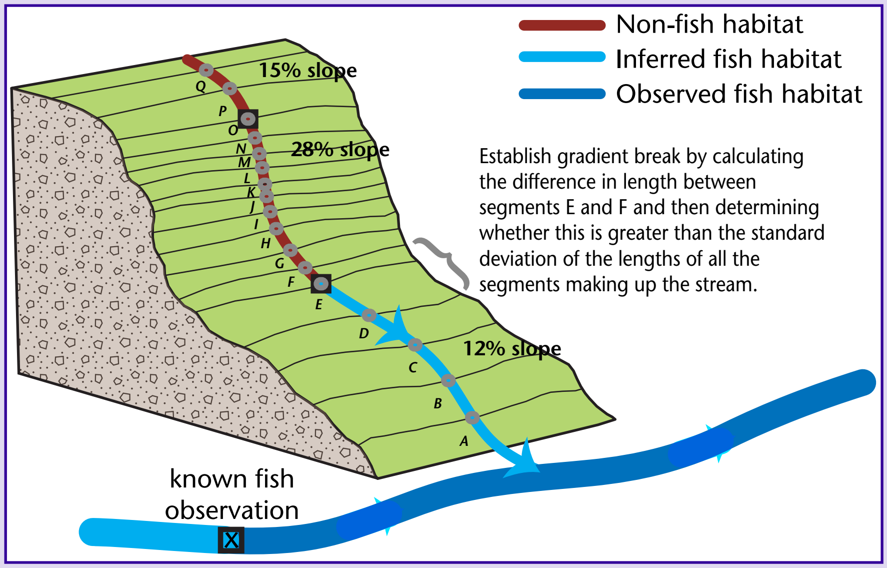

Figure 1. Method used to determine gradient breaks and habitat designation.

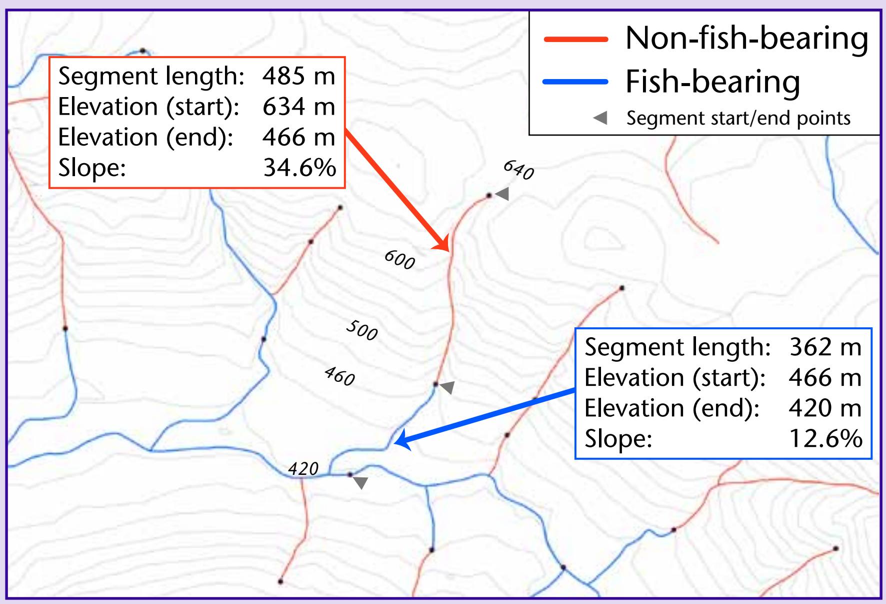

Figure 2. Example of stream segment breaking based on channel gradient. Difference in length of these two adjacent segments (defined by contour crossings) is greater than the standard deviation of all the segment lengths in that stream and therefore a break is generated. The gradient of the stream segment below the break is x% (fish-bearing), whereas above the break it is x% (non-fish-bearing).

Results: Phase II

By classifying the potential culverted stream-crossing locations derived in Phase I by modelled fish habitat, 112 539 (or 25.9%) sites are removed from further analysis. Barring further region- or site-specific inputs by users, these sites are unlikely to bear fish. Table 2, a summary of road/stream crossings on modelled fish habitat, is aiding regional planning for resource allocation. A detailed breakdown of road/stream crossings on modelled fish habitat (by watershed group) is provided at: ***http://goo.gl/z4ukh***

Table 2. Summary of road/stream crossings on modelled fish habitat broken down by road type and forest region

Road type	Forest Region			Total
	Coast	Northern Interior	Southern Interior	
Forest service roads				
Fish habitat (Observed)	414	1023	1730	3167
Fish habitat (Inferred)	5286	11 790	17 522	34 598
Non-fish habitat	4453	795	7005	12 253
Road permit				
Fish habitat (Observed)	1084	1541	1481	4106
Fish habitat (Inferred)	20 931	32 263	32 319	85 513
Non-fish habitat	22 915	4071	14 994	41 980
Public roads, highways				
Fish habitat (Observed)	1563	613	1846	4022
Fish habitat (Inferred)	5107	7097	12 989	25 193
Non-fish habitat	588	272	2075	2935
Non-status roads				
Fish habitat (Observed)	1580	2377	5141	9098
Fish habitat (Inferred)	18 477	69 860	68 388	156 725
Non-fish habitat	22 301	6875	26 194	55 370
Total				
Fish habitat (Observed)	4641	5554	10 198	20 393
Fish habitat (Inferred)	49 801	121 010	131 218	302 029
Non-fish habitat	50 257	12 013	50 268	112 538
TOTAL	104 699	138 577	191 684	434 960

GIS Analysis: Phase III – Prioritize Road/Stream Crossings for Assessment and Remediation

As generated, the road/stream crossing data set is a useful tool for quantifying the magnitude of potential barriers to fish passage at various levels; however, with over 300 000 potential barriers on modelled fish habitat, further analysis is required to prioritize the crossings for assessment and remediation. To this end, an index was derived to identify crossings that will generate the greatest increase in accessible fish habitat, should a problem culvert be repaired at the site. The index identifies the sites where we can get our best return on investment for our limited restoration funding.

Although crossing priority indexes have recognized limitations (O'Hanley and Tomberlin 2005), these tools are commonly used in nearby jurisdictions (e.g., Washington, California, Oregon [Hotchkiss and Frei 2007]) and are relatively simple to implement. As we know virtually nothing about the condition of most crossings in the province, an indexing system that accounts for spatial arrangement of sites is adequate to direct site assessments. The index can be updated when assessments are complete and repairs planned.

Methodology: Phase III

To generate the Habitat Gained Index (HGI), the road/stream crossings were linearly referenced along the stream network. Given the relative position of all crossings on the stream network, it is possible to use the attributes within the stream network (i.e., watershed code, blue line key, downstream route measure) to determine what is located upstream or downstream of any given crossing. Several functions were built to query the stream database and calculate the following two variables for each crossing point.

- ***Downstream Crossings:*** The total number of crossings downstream; assuming all crossings in the database are barriers to fish passage, this is the number of crossings that would require remediation before fish could reach the crossing under consideration.
- ***Upstream Fish Habitat Uncrossed:*** The total length of modelled fish habitat (known and inferred) upstream of the crossing (on all tributaries) but below any further crossings; assuming that fish can reach this crossing (all the downstream crossings are passable to fish) and this crossing is a barrier to fish passage, this is how much additional fish habitat would become available if the crossing is remediated.

Although each is valuable on its own, to prioritize assessments and remediation work these variables are most useful when combined to create the HGI. The HGI is generated by dividing *Upstream Fish Habitat Uncrossed* by *Downstream Crossings*. This index is an attempt to rank crossings based on the best return on investment associated with repairing a given culvert. Culverts with a great deal of habitat upstream and a small number of downstream culverts (possibly requiring repair to realize this gain) have the highest HGI values. Conversely, crossings in the upper reaches of a watershed with only a few hundred metres of habitat upstream and many crossings downstream have low scores and should be near the bottom of the priority list. In practice, when planning assessments, if two adjacent valleys have similar road networks but the field season program has only enough time/money to focus on one, then the assessment team will need to decide where best to apply

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their efforts. Therefore, before conducting field work, the team should consider the following factors for both valleys to help determine assessment priorities.

- Total number of culverts
- Total length of fish habitat
- Overall quality of fish habitat and fish species/diversity (fish value)
- Average HGI for all of the culverts in the valley
- Future access plans for the road networks (i.e., deactivation, upgrade)

After the decision is made and the assessments are complete, the HGI is easily updated and these factors (along with projected repair cost for each structure) can be revisited to determine subsequent repair and replacement priorities.

Results: Phase III and Ongoing Work

Potential culvert locations on modelled fish habitat with associated HGI values were provided to contractors conducting field assessments in the 2010 season and were confirmed as a valuable planning tool.

As field assessments become available, Phase III work will continue. Assessment data will be incorporated with the modelled fish habitat to indicate the proportion of crossings that are fish barriers and to further refine the estimates of modelled fish habitat that has been isolated as a result of failed crossings. As restorations of failed crossings are completed, the amount of fish habitat restored is measured by fisheries biologists at each site. This field data will then be compared with modelled *Upstream Habitat Uncrossed* values to help gauge the relative accuracy of the fish habitat model.

The goals of ongoing work are to better understand the size and scope of fish passage problems in the province; to continue refining and improving the decision-support tools available for determining restoration priorities; and to track the amount of fish habitat restored and made available through remediations.

Summary

Fish habitat fragmentation by poorly designed, installed, and maintained culverts on resource roads throughout British Columbia is a significant issue. The various agencies involved are committed to reducing this impact, and the GIS analysis and modelling work carried out by the Fish Passage Technical Working Group is helping in this effort. Since 2008, $7.5 million in Forest Investment Account funding through the Land Based Investment Program has been spent on assessment and remediation of CBS and our work has helped direct this investment. Ongoing refinement of the GIS analysis will improve efficiency of further investments. Possible refinements include:

- improving the fish habitat model by incorporating additional variables, such as basin size and precipitation;
- adding an areal measure of upstream fish habitat to the HGI (i.e., incorporating lakes); and
- updating the HGI as assessments and repairs are conducted.

This will enable better decisions and ensure funding is used to address the highest priority sites.

Access to the modelling data is currently available to parties involved with culvert fish passage projects through the primary author.

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Ongoing refinement of the GIS analysis will improve efficiency of further investments, enabling better decisions and ensuring funding is used to address the highest priority sites.

Metadata Links

Digital Road Atlas (DRA) – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=45674&recordSet=ISO19115***

Forest Tenure Road Segment Lines (FTEN Roads) – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=51944&recordSet=ISO19115***

Freshwater Atlas: Obstructions – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?from=search&edit=true&showall=showall&recordSet=ISO19115&recordUID=50645***

Freshwater Atlas: Stream Network – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=50648&recordSet=ISO19115***

Known Fish Observations – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?from=search&edit=true&showall=showall&recordSet=ISO19115&recordUID=43471***

Provincial Obstacles to Fish Passage – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?from=search&edit=true&showall=showall&recordSet=ISO19115&recordUID=50219***

TRIM Contour lines – ***https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=4089&recordSet=ISO19115***

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