The Vermont Culvert Aquatic Organism Passage Screening Tool

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1.0 Introduction

The Vermont DEC River Management Program, Department of Fish and Wildlife, and others have collected stream crossing structure data across Vermont streams using the Bridge and Culvert Assessment (Appendix A) in the Vermont Stream Geomorphic Assessment (Appendix G in VTANR, 2007). Currently the publicly accessible database contains information on approximately 3,400 culverts. The Department of Fish and Wildlife uses information collected in the Bridge and Culvert Assessment to identify stream crossing structures which may impact aquatic organism passage (AOP). This project builds upon the existing screen to create a more comprehensive *Vermont Culvert Aquatic Organism Passage Screening Tool*.

The screening tool was developed based on a review of the scientific literature of AOP at crossing structures, existing fish passage culvert screening tools, current design guidelines, and the previously collected Vermont culvert data. After reviewing the existing literature (Appendix B), information was synthesized into a variable list for consideration for the AOP screening tool (Appendix C). The lack of definitive biological data about fish swimming and leaping ability and the wide range of hydraulic conditions present at culverts required the use of professional judgment to synthesize existing methods and decide which variables to include in the screen and how to score each based on the biology of fish and other aquatic organisms most common in Vermont. The screening tool presented here will benefit from periodic updates as more data are collected and the scoring of structures is tracked in relationship to instream populations.

The *Vermont Culvert AOP Screening Tool* consists of a three components:

1. *AOP Coarse Screen;*
2. *AOP Retrofit Potential Screen; and*
3. *AOP Habitat Connectivity Potential Screen.*

The *AOP Coarse Screen* characterizes the expected level of AOP based on a set of physical measures of the culvert and adjacent stream during low flow conditions. This first level of screen is useful at the watershed and subwatershed scales to observe regional conditions and to begin to identify structures having the most impact on species of interest. The *AOP Coarse Screen* is similar in format to other coarse screens commonly used in the United States (e.g., Taylor and Love, 2002; Clarkin et al., 2005).

The *AOP Retrofit Potential Screen* identifies the likelihood of improving passage via structural changes at a culvert. This screen is useful at the subwatershed and local catchment scales to begin to target structures for further analysis and management. The *AOP Retrofit Potential Screen* is based on the biological traits of the fish and aquatic organisms in Vermont. This screen indicates the potential passability for strong, moderate, and weak swimmers and leapers.

The *AOP Habitat Connectivity Potential Screen* indicates the amount of habitat that would be re-connected if passage were to be improved at a structure. This screen is best applied at the subwatershed and local catchment scales to realize the potential gains in habitat due to changes at a specific structure or set of structures.

The use of the three components as a collective set will provide the most information to assist management decisions, yet each component of the screening tool may be used individually as needed. It is important to understand that these tools provide a cursory analysis of AOP and that more detailed biological, hydrological and structural assessments are necessary to determine if a given structure is a worthwhile candidate for enhancement or replacement.

The following report summarizes the development and initial use of the *Vermont Culvert AOP Screening Tool*. Each screen is defined along with the reasoning for inclusion of selected variables. The results of a pilot study to test the screening tool are presented.

The screening tool for a database of culverts assessed around the State of Vermont, a description of the screening tool, and variable analyses are contained in the spreadsheet 'VT AOP Screen.xls' (Appendix D). The spreadsheet 'AOP_GC pilot study.xls' contains the screening tool for the pilot study watersheds, a description of the screening tool, and the new *Vermont Culvert Geomorphic Compatibility Screening Tool* (VTDEC, 2008) (Appendix E).

At the time of this project, a parallel effort was underway by the Vermont Department of Environmental Conservation to create a screening tool to explore the geomorphic compatibility between culverts and streams based on dominant channel form and processes. When used together, the *Vermont Culvert AOP Screening Tool* and *Geomorphic Compatibility Screening Tool* (VTDEC, 2008) will offer a comprehensive view of how a culvert influences both the physical and biological aspects of a stream.

2.0 Description of the *AOP Coarse Screen*

2.1 AOP Coarse Screen Categories

The *AOP Coarse Screen* is a broad screen to determine the likely level of passage at a culvert under low flow conditions. Based on previously collected structure assessment data, the screen classifies structures into the following categories (Table 2-1):

- *Full AOP for all aquatic organisms* (green),
- *Reduced AOP for all aquatic organisms* (gray),
- *No AOP for all aquatic organisms except adult salmonids* (orange), or
- *No AOP for all aquatic organisms including adult salmonids* (red).

Table 2-1

The AOP Coarse Screen

VT Aquatic Organism Passage Coarse Screen	**Full AOP**	**Reduced AOP**	**No AOP**			
Updated 2/25/2008	**for all aquatic organisms**	**for all aquatic organisms**	**for all aquatic organisms except adult salmonids**		**for all aquatic organisms including adult salmonids**	
AOP Function Variables / Values	**Green (if all are true)**	**Gray (if any are true)**	**Orange**		**Red**	
Culvert outlet invert type	at grade **OR** backwatered	cascade	free fall **AND**		free fall **AND**	
Outlet drop (ft)	= 0		> 0 , < 1 ft **OR**		≥ 1 ft **OR**	
Downstream pool present			= yes	(= yes **AND**	= no **OR**	(= yes **AND**
Downstream pool entrance depth / outlet drop			n/m	≥ 1)	n/a	< 1) **OR**
Water depth in culvert at outlet (ft)					< 0.3 ft	
Number of culverts at crossing	1	> 1				
Structure opening partially obstructed	= none	≠ none				
Sediment throughout structure	yes	no				

Notes:

Assessment completed during low flows.

Outlet drop = invert of structure to water surface.

Pool present variable is used alone if pool depths are not measured.

n/m = not measured.

n/a = not applicable.

The coarse screen identifies potentially problematic structures. Further analysis using the *AOP Retrofit Potential Screen* and the *AOP Habitat Connectivity Potential Screen* should be conducted along with subsequent field work prior to moving forward towards implementation. Additional field measurements and assessments will be necessary to confirm and expand upon findings to support management decisions and design and may include:

- aquatic community assessment;
- aquatic habitat assessment;
- stream channel profile, tailwater and cross section assessment;
- hydraulic modeling (e.g., FishXing);
- natural barrier assessment; or
- construction constraints (access, utility crossings, etc.).

Structures classified as having *Full AOP* (i.e., green) are functionally no different than the upstream and downstream natural stream channel. For this most conservative of culvert conditions where all fish and salamanders are likely to be able to pass through there must be no outlet drop and the culvert outlet invert must be either at grade or backwatered with natural channel bottom sediment throughout the structure. No obstructions can be present at the structure opening, as they are considered to limit some AOP. Structures with multiple openings create complex hydraulic patterns and are prone to blockage that typically reduces AOP so only one culvert can be present for this category.

The classification of *Reduced AOP* (i.e., gray) is assigned to structures that likely limit AOP for some species or life stages due to limited depth or high velocities. Culverts classified in this category could potentially pass strong and moderate swimming fish under some flow conditions as they either have at grade, backwatered, or cascade outlet types. Culverts that have outlet inverts classified as cascade, obstructions, more than one pipe, or lack sediment throughout the structure are classified as having *Reduced AOP*.

All structures classified as *No AOP* (i.e., orange or red culverts) have a freefall outlet and a measurable outlet drop. The outlet drop associated with *No AOP except adult salmonids* (i.e., orange) is 0-1 feet, based on the strong swimming and leaping abilities of these species generally reported in the literature (e.g., Bates and Kirn, 2008). Presence of a plunge pool downstream of a freefall outlet would increase the likelihood of passage (e.g., Kondratieff and Myrick, 2006; e.g., FHWA, 2007). If a downstream plunge pool is present and data is not available for the pool entrance water depth by the culvert than the structure is classified as *No AOP except for adult salmonids* since there is a chance these species can jump into the culvert. If the water depth at the culvert outlet has been measured and is equal to or larger than the outlet drop (i.e., pool entrance depth / outlet drop ≥ 1), then salmonids are likely to access the culvert at times. Note that water depth at the entrance to the downstream pool and maximum pool depth are new variables being added to the Bridge and Culvert Assessment for the 2008 field season so these data do not exist at this time. However, the AOP screens presented here have been set up to work with and without these variables so that both existing and new structure data can be analyzed simultaneously with the best available data.

The *No AOP for all aquatic organisms including adult salmonids* (i.e., red) category identifies poor AOP conditions where a freefall outlet invert either has an outlet drop height greater than 1 foot, no downstream plunge pool present, or a downstream plunge pool with an entrance depth less than the outlet drop height (i.e., outlet pool depth / outlet drop < 1). A structure is also placed in this category if the water depth at the culvert outlet is less than 0.3 feet.

2.2 AOP Coarse Screen Variables

The following assessment variables are used in the *AOP Coarse Screen* (Table 2-1):

- Culvert outlet invert type;
- Outlet drop (ft);
- Downstream pool present;
- Downstream pool entrance depth / outlet drop;
- Water depth in culvert at outlet (ft);
- Number of culverts at crossing;
- Structure opening partially obstructed; and
- Sediment throughout structure.

The variables are either currently collected during the Vermont Bridge and Culvert Assessment (Appendix G in VTANR, 2007) or have been proposed for future inclusion in the assessment as they are measured rapidly with minimal equipment. The requirement for simple field measurements eliminated the inclusion of culvert slope, water velocity in the culvert, and residual pool depth that were considered for inclusion in the screens. The variables used in the coarse screen are described here.

2.2.1 Culvert Outlet Invert Type, Outlet Drop, and Leaping Ability

Many stream crossing structures have perched outlets, creating a drop from the outlet to the water surface, either from initial poor design or incompatibilities with stream processes as the channel evolves since the time of culvert installation. The inability of an aquatic organism to jump up and into a perched structure often limits passage. Researchers have attempted to document fish swimming and leaping jumping ability, yet knowledge of this information typically remains uncertain. Bates and Kirn (2008) have compiled a summary of fish biology traits for common Vermont species that guided various aspects of this project such as setting thresholds used in the *AOP Retrofit Potential Screen*.

Jumping ability is related to fish size (Adams et al., 2000). Coffman (2005) found a 2-foot barrier height to limit the movement of salmonids, using a conservative approach. There was less than a 1% chance that minnows could pass waterfall barriers greater than 1.2 feet. Oregon's culvert assessment protocol (Robison et al., 1999) uses a drop between the culvert downstream invert and residual pool surface of 2 feet as a block for all but strong swimmers such as adult pacific salmon and a 4 foot drop as a total fish block.

The structure outlet condition is described by the culvert outlet invert type variable, classifying the structure as at grade, backwatered, cascade, or freefall. Backwatered has been added to the screen because increased water depth and lower velocity will likely improve AOP. At grade indicates that there is no outlet drop. Freefall indicates that there is a measurable outlet drop exists. Cascade indicates an exit where flow cascades downstream over rocks. These structures may be passable under some flow conditions, but can also compromise fish passage due to the potential for physical abrasion on the rocks. The outlet drop height is measured as the distance from the outlet invert to the water surface.

2.2.2 Downstream Pool Presence and Entrance Depth Required for Jumping

The presence and depth of a plunge pool, used to initiate motion to jump a barrier, directly influences fish jumping ability (e.g., Stockard and Harris, 2005; Nedeau, 2006). A shallow plunge pool of 0.33 feet allowed brook trout to jump no greater than 1.43 feet, while a deeper plunge pool of 1.6 ft allowed jumps of 2.4 feet (Kondratieff and Myrick, 2006). Brandt et al. (2005) found that fish could not ascend waterfalls higher than 16 cm (0.5 feet) with 8 cm (0.26 ft) plunge pools and waterfalls higher than 22 cm (0.75 feet) with 10 cm (0.33 ft) plunge pools. The Oregon design guidelines (Robison et al., 1999) suggest that a plunge pool should be 1.5 to 2 times deeper than the required hump height.

Plunge pool presence immediately downstream of a structure, the water depth where flow from the structure enters the downstream pool, and the maximum pool water depth have been added to the Vermont Bridge and Culvert Assessment (Appendix G in VTANR, 2007) to describe the jumping environment downstream of culverts. If pool depths are not measured, then the *AOP Coarse Screen* considers pool presence alone to separate the two levels of most limited category, *No AOP* (i.e., orange and red). If downstream pool entrance depth is measured, then the ratio of downstream pool entrance depth to outlet drop is used to separate the levels of limited passage. The ratio of downstream pool entrance depth to outlet drop is common in existing AOP research and guidelines (e.g., Stuart, 1962; WDFW, 2000; Clarkin et al., 2005).

2.2.3 Water Depth

Many culverts limit AOP due to inadequate water depths during normal and low flows that do not allow natural fish swimming mechanics. Minimum depth recommendations are typically based on the size of fish, such as 2.5 times the height of tail (ADF&G, 2001), 0.8-1.0 feet for adult salmonids (Bates et al., 2003), and 1.5 times body thickness (MEDOT, 2004). Bates and Kirn (2008) have assembled low flow depth recommendations for Vermont fish species based on 1.5 times maximum body depth. Water depth is measured in the culvert at the outlet during the field assessment. A water depth minimum of 0.3 feet is used in this coarse screen.

2.2.4 Number of Culverts at Crossing

The presence of more than one culvert at a crossing decreases the likelihood of natural stream processes continuing in and around the structure (VTDEC, 2008), and thus the number of culverts at a crossing is recorded during the assessment. Multiple openings are prone to obstruction due to areas of low velocity between structures. Hydraulics around multiple openings can be unusually turbulent during higher flow, and one or more of the pipes often has limited depth during lower flows.

2.2.5 Obstruction of Culvert Opening

AOP may be reduced by physical obstructions resulting from sediment, wood debris, or deformation (Bates et al., 2003). The presence of any obstruction at the upstream structure end is recorded during the assessment. AOP can be substantially limited in culverts with partial obstructions due to reduced cross sectional area causing local velocity increases or vertical barriers.

2.2.6 Natural Channel Bottom

Natural channel sediments roughen the bed and create low-velocity resting locations for aquatic organisms. For a culvert to function as natural habitat, sediment must be maintained throughout the structure length. The absence or presence of sediment throughout the structure is noted during the assessment. Current design guidelines typically now call for culverts that have a natural channel bottom (e.g., Bates and Kirn, 2008). Due to the common presence of reduced cross section flow area in culverts as compared to the nearby stream channel (i.e., the width of the culvert is smaller than the bankfull width of the channel), many culverts have excessively high water velocities that can scour bed sediments, transporting them downstream. In fact, the ability of a pipe to self-clean has been a central design goal or the culvert will fill in and not function properly. With the increased desire to achieve AOP along with conveyance objectives, design recommendations for culverts now include a prescribed natural bed and dynamic equilibrium so that a balance is achieved between incoming, stored, and transported sediment over the range of flow (i.e., natural stream simulation).

2.3 AOP Coarse Screen Initial Testing

The screening tool was developed and initally tested using the bridge and culvert assessment data obtained from the Vermont Department of Fish and Wildlife (B&C database thru 2005.xls). This database contained 465 records collected between June 2004 and October 2005. All bridge and arch data were previously removed for this analysis. In addition, channel's having width < 7.12 feet, which is analogous to drainage area < 0.25 square miles based on Vermont regional hydraulic geometry curves (Appendix J of VTANR, 2007), were removed from the database due to the limited potential for fish populations in these small catchments.

The culvert *AOP Coarse Screen* scores are not distributed evenly across the four potential categories. Only six structures (1.3%) met the criteria for *Full AOP* (i.e., green), while 197 or 42% of assessed culverts had *No AOP* (i.e., red) (Figure 2-1). AOP is limited at 44 culverts where only adult salmonids have the potential to pass (i.e., orange). Just under half of the assessed culverts were categorized as having *Reduced AOP* (i.e., gray). These results represent a small portion of the total number of stream crossings in the state of Vermont, but clearly show that current culvert design and maintenance does not adequately account for AOP.

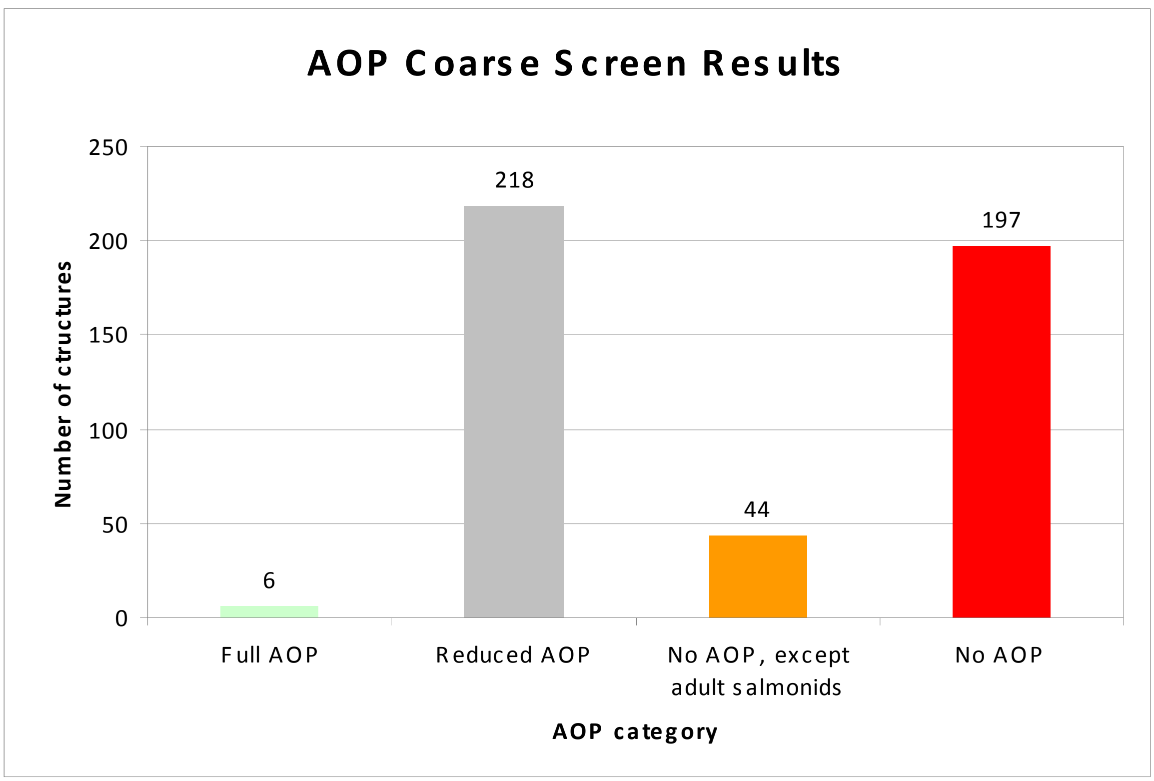


FIGURE 2-1: Results of the *AOP Coarse Screen* for Assessed Vermont Culverts

3.0 Description of the *AOP Retrofit Potential Screen*

3.1 AOP Retrofit Potential Screen Categories

The primary constraints for AOP at a given structure are generally driven by the magnitude of the culvert's length, outlet drop and constriction (% bankfull width). The *AOP Retrofit Potential Screen* estimates the potential to improve AOP at a culvert with *Reduced AOP* or *No AOP* (i.e., coarse screen category gray, orange or red). For each assessed culvert, a retrofit potential category of low (L), medium (M), or high (H) (Table 3-1A) is assigned for each of strong, moderate, and weak swimming / leaping ability groups (Table 3-1B). A high retrofit potential indicates that the culvert is more likely to be improved, while moderate and low retrofit potential indicate increasing challenges for AOP enhancements at the structure. Each structure is assigned a 3-letter retrofit potential category corresponding to the retrofit potential for the strong, moderate and weak swimming groups (i.e., strong-moderate-weak, LLL, MLL, MML, MMM, HML, HMM, HHM, HHH).

The retrofit potential category is assigned based on calculation of a retrofit potential score (RPS) and consideration of thresholds that have been set to guide retrofit potential. The RPS maximum is 15 and is calculated by the sum of three scores (0 - 5) that quantify the percent of the channel bankfull width the structure occupies, non-backwatered structure length, and outlet drop height (Table 3-1C). The higher the variable scores it is assumed the more likely AOP is currently good or easily improved.

The variable threshold values automatically rank the structure as low (L) if any single variable scores exceptionally low that would limit retrofit potential, and assure a high (H) rank is only assigned if each of the three variable scores is high. As with the RPS, the thresholds are dependent on swimming and leaping ability (Table 3-1A). Thresholds were included to control for circumstances where the actual retrofit potential was deemed to not be represented accurately by the RPS alone. For example, a culvert having width ≥ 120% of the channel bankfull width (%BFW score = 5), no outlet drop (Od score = 5), and a non-backwatered length of 500 feet (length score = 0) would be assigned a retrofit potential category of medium or higher for all organisms (HMM) based on RPS = 10 alone, but the very long length would make the culvert difficult to retrofit. A threshold was set that assigns a retrofit category of low (L) for strong swimmers if the non-backwatered structure length is ≥ 200 feet, and a category of low is assigned to moderate and weak swimmers if the non-backwatered length is ≥ 100 feet. The example with the long culvert length is thus categorized as having low retrofit potential for all organisms (LLL).

Table 3-1

The AOP Retrofit Potential Screen.

A) RPS Ranges and Variable Thresholds for Screen

	Strong Swimmers/Leapers	***Moderate Swimmers/Leapers***	***Weak Swimmers/Leapers***
Low	%BFW < 30 **OR** [($L_{NBW} \geq 200$) **OR** ($L \geq 200$ **AND** $D < 1$)] **OR** $Od \geq 2.5$ **OR** $0 \leq RPS < 5$	%BFW < 50 **OR** [($L_{NBW} \geq 100$) **OR** ($L \geq 100$ **AND** $D < 1$)] **OR** $Od \geq 1.5$ **OR** $0 \leq RPS < 5$	%BFW < 75 **OR** [($L_{NBW} \geq 100$) **OR** ($L \geq 100$ **AND** $D < 1$)] **OR** $Od \geq 1.0$ **OR** $0 \leq RPS < 5$
Medium	$5 \leq RPS < 9$	$5 \leq RPS < 10$	$5 \leq RPS < 12$
High	%BFW ≥ 75 **AND** [($L_{NBW} < 100$) OR ($L < 100$)] **AND** $Od < 1.5$ **AND** $RPS \geq 9$	%BFW ≥ 75 **AND** [($L_{NBW} < 100$) OR ($L < 100$)] **AND** $Od < 1.0$ **AND** $RPS \geq 10$	%BFW ≥ 100 **AND** [($L_{NBW} < 100$) OR ($L < 100$)] **AND** $Od < 0.5$ **AND** $RPS \geq 12$

B) Aquatic Organism Groups Based on Swimming/Leaping Ability

Strong Swimmers/Leapers	***Moderate Swimmers/Leapers***	***Weak Swimmers/Leapers***
adult trout	juvenile trout	rainbow smelt
adult salmon	suckers	sculpin
American eel	shad	minnows
	lamprey	bass and sunfish
		pike, pickerel
		darters, perch, walleye
		stickleback
		aquatic salamanders

C) RPS Variable Scoring

Percent structure width of channel width		***Non-backwatered structure length (ft)*** [†]		***Outlet drop height (ft)***	
Score	*Values*	*Score*	*Values*	*Score*	*Values*
0	%BFW < 30	0	$L_{NBW} \geq 300$	0	$Od \geq 2.5$
1	30 ≤ %BFW < 50	1	$200 \leq L_{NBW} < 300$	1	$2.0 \leq Od < 2.5$
2	50 ≤ %BFW < 75	2	$100 \leq L_{NBW} < 200$	2	$1.5 \leq Od < 2.0$
3	75 ≤ %BFW < 100	3	$40 \leq L_{NBW} < 100$	3	$1.0 \leq Od < 1.5$
4	100 ≤ %BFW < 120	4	$25 \leq L_{NBW} < 40$	4	$0.5 \leq Od < 1.0$
5	%BFW ≥ 120	5	$L_{NBW} < 25$	5	$Od < 0.5$

Notes

%BFW = (culvert width/channel width)*100; L_{NBW} = non-backwatered structure length (ft); L = culvert length (ft); D = water depth in culvert at outlet (ft); Od = outlet drop height (ft); RPS = sum of scores for %BFW, L, and Od.

[†]Use culvert length (L) if non-backwatered length (L_{NBW}) not measured.

3.2 AOP Retrofit Potential Screen Variables

The variables included in the *AOP Retrofit Potential Screen* are:

- %BFW = structure width / channel bankfull width (%);
- L_{NBW} = non-backwatered culvert length (ft);
- L = culvert length (ft);
- D = water depth in culvert at outlet (ft);
- Od = outlet drop height (ft); and
- Retrofit Potential Score (RPS) = sum of scores for %BFW, L, and Od (Table 3-1).

3.2.1 Percent Bankfull Width

Percent bankfull width (%BFW) is included in the screening tool to track changes in structure width relative to the stream channel. %BFW is a surrogate for changes in cross sectional flow area, velocity, sediment transport, and debris transport. Ideally, a culvert would not constrict the channel (i.e., %BFW ≥ 100%) and would have natural flows to support full AOP. Narrow widths relative to the channel lead to high culvert velocity that typically limits AOP, and the ability to retrofit a structure. Constrictions can also lead to excessive degradation downstream due to channel incision that can create a cascade or free fall outlet invert type and limit AOP.

%BFW is commonly included in existing screening tools and guidelines. The Massachusetts stream crossing design standards require a structure width to be 1.2 * bankfull width (120%) (MARSCP, 2006) and Maine design standards specify that new structures should be 100% (MEDOT, 2004). Oregon's culvert assessment classifies culverts with a width less than 2 bankfull widths (200%) a partial block only allowing adult strong swimmers to pass and 0.5 times bankfull width (50%) as a total block (Robison et al., 1999).

The scoring system for %BFW is based primarily on common design guidelines, and the shape of the distribution of the %BFW variable in the Vermont culvert data (Figure 3-1). In general, AOP retrofit potential increases with culvert width. A score of 5 was set at %BFW ≥ 120% (Table 3-2), which has recently been included in Massachusetts design standards for new structures (MARSCP, 2006). This desirable standard is typically adequate for fish passage, and is likely associated with normal hydraulics and sediment/debris transport.

A score of 4 was set for culverts with 100 ≤ %BFW < 120. These structures do not constrict flows up to the bankfull storm event. This is the current design recommendation for several states (e.g., Bates and Kirn, 2008). A score of 3 was assigned when 75 ≤ %BFW < 100, as this is a range of values commonly found in transportation-based assessments and design standards.

Values of %BFW < 75% are rarely cited as they are undesirable, often leading to culvert maintenance challenges and fish blocks. The distribution of %BFW values for existing Vermont culvert data were examined to determine thresholds to differentiate between scores of 0, 1, and 2. The data show that 50% of the structures have %BFW of less than 48.9% and 10% of the structures have %BFW less than 31.3% (Table 3-2). These percentiles were used as a guide to set a score of 2 for 50 ≤ %BFW < 75, a score of 1 for 30 ≤ %BFW < 50, and a score of 0 for %BFW < 30. The majority of the assessed Vermont culverts score a 0, 1 or 2 indicating the presence of many undersized culverts and widespread reduced AOP (Figure 3-1).

The %BFW scoring used here is the same as that proposed for the geomorphic compatibility screening tool (VTDEC, 2008).

TABLE 3-2
The Distribution of % Bankfull Width in Assessed Vermont Culverts

Percentile	Percent Bankfull Width
MAX	118.9
90 %	81.4
75 %	63.6
50 %	48.9
25 %	37.5
10 %	31.3
MIN	25.0

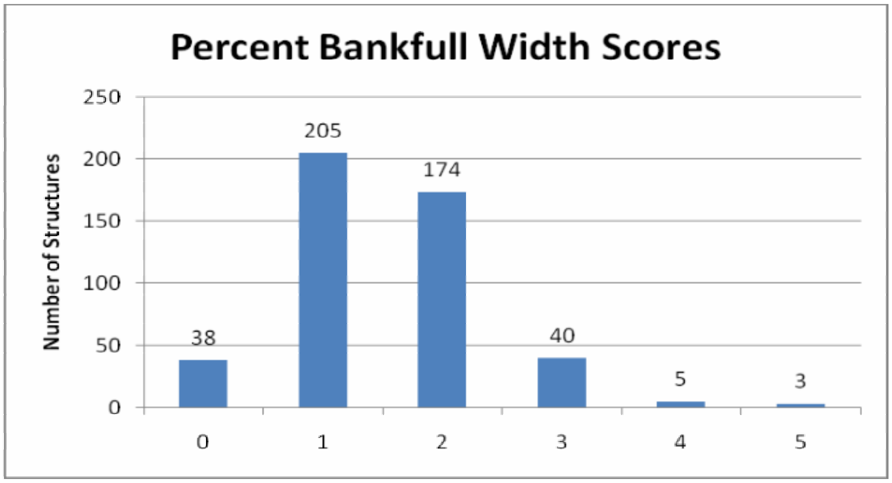


FIGURE 3-1
The Distribution of % Bankfull Width Scores for Assessed Vermont Culverts

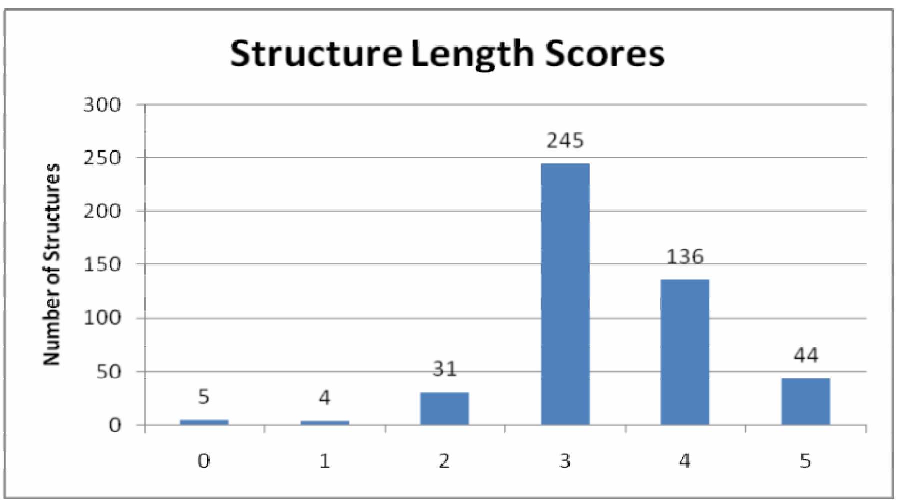


FIGURE 3-2
The Distribution of Structure Length Scores for Assessed Vermont Culverts (non-backwatered length not measured)

3.2.2 Culvert length

Longer culverts are typically more difficult to retrofit than shorter culverts due to unnatural hydraulics and high project costs due to the potential presence of substantial overlaying infrastructure such as large roadways and structures. Long pipes require holding areas along their length with low water velocities for AOP as most fish cannot maintain high swimming speeds over long distances (FHWA, 2007).

Backwatered portions of culverts are often fish passable due to increased water depth, reduced water velocities, and smooth flow. The remaining non-backwatered length of pipe is thus the retrofit target to improve AOP. For example, a 200-foot long culvert that is half backwatered becomes a 100-foot AOP retrofit project. Backwatered culvert length will be a new addition to the VT Bridge and Culvert Assessment (Appendix G in VTANR, 2007) for the 2008 field season. Non-backwatered length will be determined by subtracting the backwatered length from the structure length, to identify the remaining portion of the culvert in need of retrofit. Non-backwatered length (L_{NBW}) is used in the *AOP Retrofit Potential Screen.* If these data are not available for a culvert, which they are not for any structure at this time, the screen has been set up to utilize the combination of structure length and water depth in the pipe at the culvert outlet instead. A water depth of < 1 foot is assumed to represent a non-backwatered culvert and a thus a low retrofit potential for a long pipe.

Culvert length variable scores have been assigned to typical length categories used in fish biology research on maximum velocities for passage over a particular culvert length (summarized in Bates and Kirn, 2008) (Table 3-1). For example, culverts with over 300 feet not backwatered are scored a 0 as they would likely be difficult to retrofit, while those with less than 25 feet not backwatered are scored a 5 as they would be relatively easy to improve AOP. Design guidelines (e.g., Robison et al., 1999) were also reviewed to set length cutoffs, such as thresholds for low retrofit potential of $\geq$ 200 feet for strong swimmers and $\geq$ 100 feet for moderate and weak swimmers.

Just over half of the structures in the study database are between 40 and 100 feet long (score 3) (Figure 3-2). Data indicate that 40% of the culverts are shorter than 40 feet long (score 4 or 5), while 9% are longer than 100 feet (score 0, 1, or 2). It appears that culvert length may not to be a factor that regularly limits retrofit potential due to the abundance of moderate and short structure lengths.

3.2.3 Water depth at culvert outlet

As previously discussed, shallow water depth can limit AOP through a culvert. Lower water depths lead to more difficulty retrofitting a culvert. A water depth threshold of 1 foot is used to represent potentially backwatered culverts that may be passable. Below a 1-foot depth, retrofit potential is reduced for longer pipes.

3.2.4 Outlet drop height

Outlet drop height scores were set based on jump height literature previously discussed in this report (Table 3-1C). The studies show a range of maximum jump heights with individuals jumping up to 2.4 feet (Adams et al., 2000; Coffman, 2005; Kondratieff and Myrick, 2006; Nedeau, 2006; Bates and Kirn, 2008). A maximum drop that may be passable by adult salmonids was taken to be 2.5 feet (score of 0). Scores were then set in half-foot increments to encompass a range of common jumping abilities. A large portion of adult salmonids are likely to pass a drop of 1.0 to 1.5 feet (score 3). The score of 4 was set at 0.5-1.0 feet, which was found to block fish only when there was a downstream pool depth of less than 8 cm (0.26 feet) (Kondratieff and Myrick, 2006).

Almost half of the assessed culverts have an outlet drop height of < 0.5 feet, while approximately 20% have drops > 2.5 feet (Figure 3-3). All of the other structures are relatively evenly distributed across scores 1 to 4.

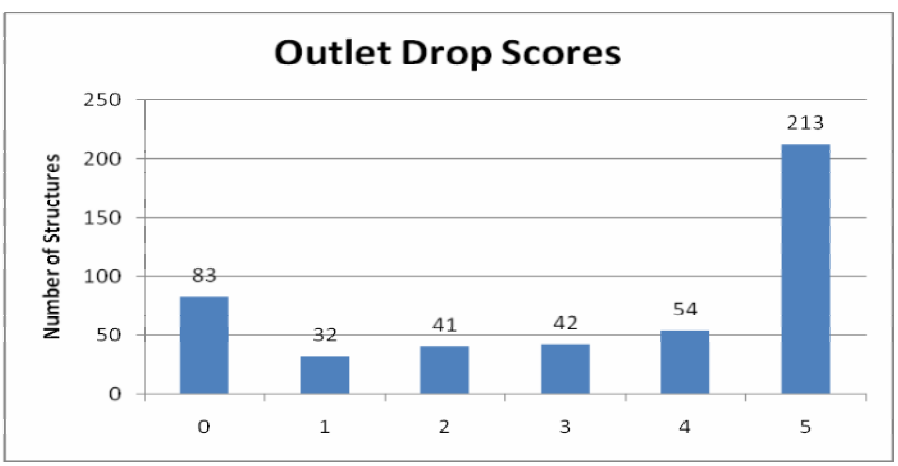


FIGURE 3-3
The Distribution of Outlet Drop Scores for Assessed Vermont Culverts

3.3 AOP Retrofit Potential Screen Initial Testing

3.3.1 RPS Scoring

The total retrofit potential score (RPS), which is the sum of the individual scores for percent bankfull width, (non-backwatered) structure length, and outlet drop height, ranged between 2 and 13 (Figure 3-4). The distribution of scores is skewed with the score of 10 being most common.

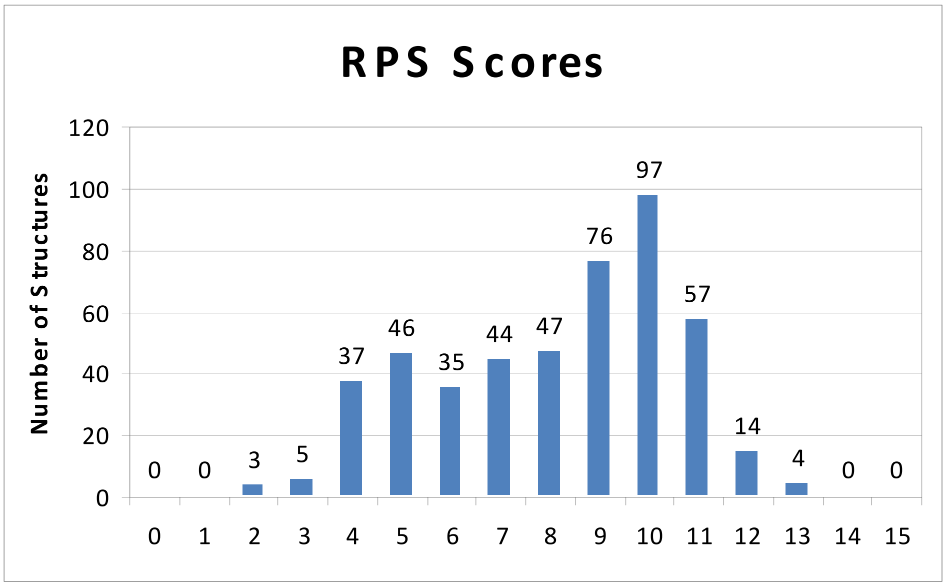


FIGURE 3-4
The Distribution of RPS Scores for Assessed Vermont Culverts

3.3.2 *AOP Retrofit Potential Screen* Results

The *AOP Retrofit Potential Screen* indicates that few structures have a high retrofit potential (Table 3-3). For example, just 4 structures have a high chance of being retrofitted to achieve full AOP for the weakest swimmers and leapers (xxH). The outlook is poor for the weak swimmers with 92% of culverts having a low retrofit potential for this group (xxL). Strong swimmers and leapers such as adult salmonids are in better shape, with 7% of assessed culverts having a high retrofit potential (Hxx) and 67% having a moderate potential to improve AOP (Mxx).

It is instructive to investigate the results of both the *AOP Coarse Screen* and the *Retrofit Potential Screen* together to begin to formulate potential management strategies (Table 3-3). For example, 3 gray and 1 red structure have the potential to be retrofit for *Full AOP*. On the other hand, 66 red structures have a very limited retrofit potential and thus may not be initial choices for management. Fish populations, habitat quality, the amount of potential habitat reconnected, and other factors must also be considered.

TABLE 3-3
***AOP Retrofit Potential Screen* Results for**
Assessed Vermont Culverts

		Coarse Screen		
Retrofit Potential	**Total**	**Gray**	**Orange**	**Red**
LLL	*119*	48	5	66
MLL	*202*	92	20	90
MML	*104*	58	16	30
MMM	*1*	1	0	0
HML	*4*	0	0	4
HHM	*25*	16	3	6
HHH	*4*	3	0	1
Total	*459*	218	44	197

4.0 Description of the *AOP Habitat Connectivity Potential Screen*

4.1 The AOP Habitat Connectivity Potential Screen Approach

The *AOP Habitat Connectivity Potential Screen* is the third and final component of the *VT Culvert AOP Screening Tool.* This component is a GIS-based analysis to calculate the potential full network and mainstem stream lengths reconnected with AOP improvements at culverts. The habitat connectivity potential screen can be used at three spatial scales – the subwatershed, basin and state. The full database of culverts can be analyzed for upstream full network and mainstem distance to the next barrier or stream source. This level of information will be updated annually as the culvert database increases in size with more assessments and answer general questions about stream fragmentation. At the basin scale, upstream network and mainstem distances are quickly generated. This scale of data allows for querying to locate potential habitat bottlenecks due to fragmentation and the beginning stages of project location. The option to manually input the order of several culverts of interest allows for calculation of downstream distances. At the subwatershed scale, both upstream and downstream distances are typically calculated to generate subwatershed and town maps of the possible benefits to AOP improvements. The subwatershed mapping allows smaller scale decision making to focus on areas where the potential benefits are greatest.

ArcMap (ESRI, 2006) and the RivEx Vector River Network Tool (Hornby, 2008) are used to find distances and results are transferred to Excel for basic calculations and data organization. Step-by-step instructions are provided (Appendix F). Some of the initial GIS file preparation has been completed to facilitate running the large state-wide culvert database. An Excel Spreadsheet (*VT AOP Connectivity Screen.xls)* has been setup to store results from GIS components of this analysis and perform calculations for the *AOP Habitat Connectivity Potential Screen* (Appendix G).

The values of the screening variables can be conveniently viewed on a local catchment GIS map along with the retrofit potential category. GIS maps containing screen results are useful for locating structures along the drainage network and examining the density of blockages. If a whole stream branch could be reconnected to aquatic habitat through the replacement of one structure it should take precendence over a structure reconnecting only a small amount of habitat. Although they may not lead to immediate replacement, the results of the screen could illistrate the relative importance of specific structres in relationship to habitat connecitvity.

Gathering of existing data and field assessment is recommended to locate additional natural (e.g. waterfalls) or manmade (e.g. other culverts, dams, instream ponds) AOP blocks that have not been previously identified. Biological and habitat assessments such as the ANR rapid habitat assessment (VTANR, 2007) will also be important to develop better informed management recommendations.

4.2 The AOP Habitat Connectivity Potential Screen Initial Testing

The *AOP Habitat Connectivity Potential Screen* was performed on the entire culvert database to facilitate GIS mapping and investigation at the state scale. After setting up the barrier analysis for 30 minutes, the full data set took 42 hours to process the approximate 3,000 structures. Due to the length of time to run this analysis to generate upstream full network and mainstem distances, it is anticipated that the full state analysis will be run one or two times each year to input additional assessed culverts.

5.0 ***Vermont Culvert AOP Screening Tool*** Pilot Study

5.1 Introduction

A pilot study was conducted to test each of the three components of the new *Vermont Culvert AOP Screening Tool*. The publicly accessible Vermont Stream Geomorphic Assessment Data Management System was accessed to download structure information for the White River and Ottauquechee River watersheds. These watersheds were chosen for inclusion in the pilot study based on high potential spawning habitats for fish migrating up the Connecticut River. Bridges and arches were removed from the database. Small drainage basins with drainage areas less than 0.25 square miles were removed from the study due to lower significance for fisheries. The White River watershed contains 326 assessed culverts and the Ottauquechee River watershed contains 179 assessed culverts.

5.2 White River Watershed

The White River watershed coarse screen results identified only 4 assessed structures with *Full AOP* and 135 with *No AOP including adult salmonids* (Figure 5-1). Almost half of the structures were classified in the intermediate category of *Reduced AOP*. These coarse screen results indicate a great need for AOP improvement in the White River Watershed.

The *AOP Retrofit Potential Screen* was run for structures assigned *Reduced AOP* or *No AOP* by the coarse screen, finding no assessed structures with high retrofit potential for all species (Table 5-1). Only 12 structures were classified in the HHM group which could be further examined for improvements to AOP. 30% of structures were considered to have Low retrofit potential for all ability groups.

GIS maps of the screen results are useful to look at collections of culverts in specific watershed areas to understand habitat connectivity. For example, a map of culvert AOP in the White River watershed (Figure 5-2) appears to show a general abundance of *No AOP for all species* (red) structures in the lower watershed. A close-up view of a subwatershed such as the headwaters of the Second Branch (Figure 5-3) reveals that there are two *Reduced AOP* (grey) and one *No AOP except adult salmon* (orange) structures on the mainstem, all with medium retrofit potential for strong swimmers, that could be explored to return AOP to the upper reaches. In the lower western section of the watershed a cluster of *No AOP* (red) structures suggests that multiple blocks would need to be addressed to provide access to the upstream habitat. The location map can help prioritize limited retrofit and replacement funds.

The close-up map also reveals the limited number of structures in the subwatershed that have been assessed relative to the number of apparent crossings where the stream and road layers cross.

The *AOP Habitat Connectivity Potential Screen* took 20 minutes to run to get upstream network and mainstem distances for the assessed structures in the White River basin. The mean upstream full network length that could be re-connected was 2.5 miles, with a maximum of 31 miles. The mean mainstem length that could be re-connected was 1 mile, with a maximum of 10 miles.

Zooming in to analyze the re-connectivity potential in the headwaters of the Second Branch of the White River the analysis took 45 minutes to determine both up and downstream distances for the full network and mainstem river (see data table in Figure 5-3). Mean upstream distances were 6.5 miles for the full network and 1.5 miles for the mainstem (Table 5-2). Mean downstream distances were 15 miles for the full network and 6 for the mainstem. Exploring habitat connectivity potential was useful at the catchment scale to help identify the improvements for possible future projects.

TABLE 5-1
White River Watershed *AOP Retrofit Potential Screen*
Results for the Pilot Study

		Coarse Screen		
Retrofit Potential	**Total**	**Gray**	**Orange**	**Red**
LLL	*93*	40	4	49
MLL	*152*	70	15	67
MML	*62*	35	11	16
MMM	*2*	2	0	0
HML	*1*	0	0	1
HHM	*12*	10	0	2
HHH	*0*	0	0	0
Total	*322*	157	30	135

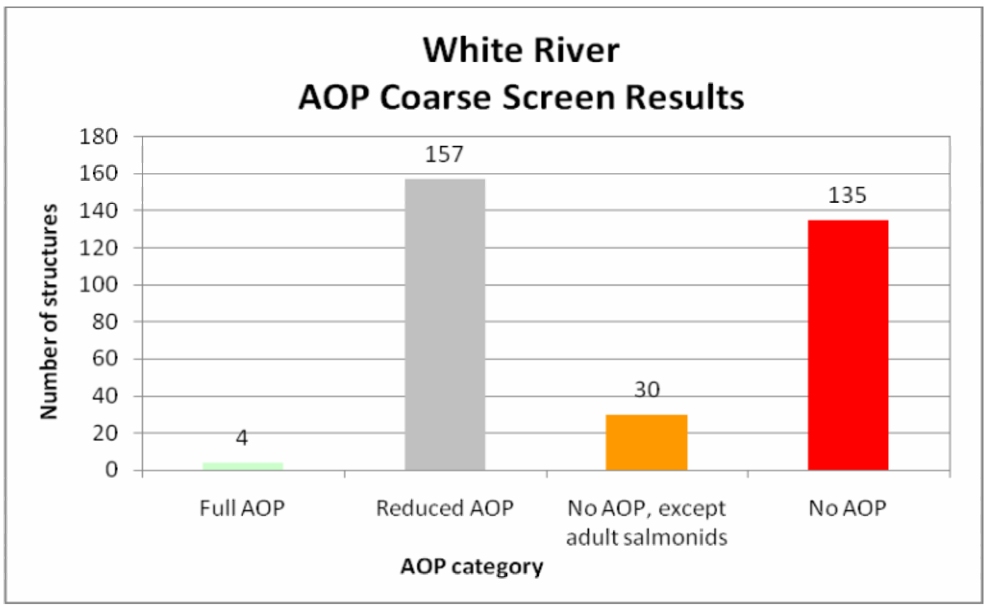


FIGURE 5-1
Pilot study results of the *AOP Coarse Screen* for the White River Watershed

TABLE 5-2
Results of the *AOP Habitat Connectivity Potential Screen*
for the Headwaters of the Second Branch (Miles Potentially Reconnected)

(miles)	Upstream Network	Upstream Mainstem	Downstream Network	Downstream Mainstem
MEAN	6.5	1.5	14.7	5.9
MIN	0.6	0.0	0.6	0.4
MAX	30.0	10.5	30.0	10.5

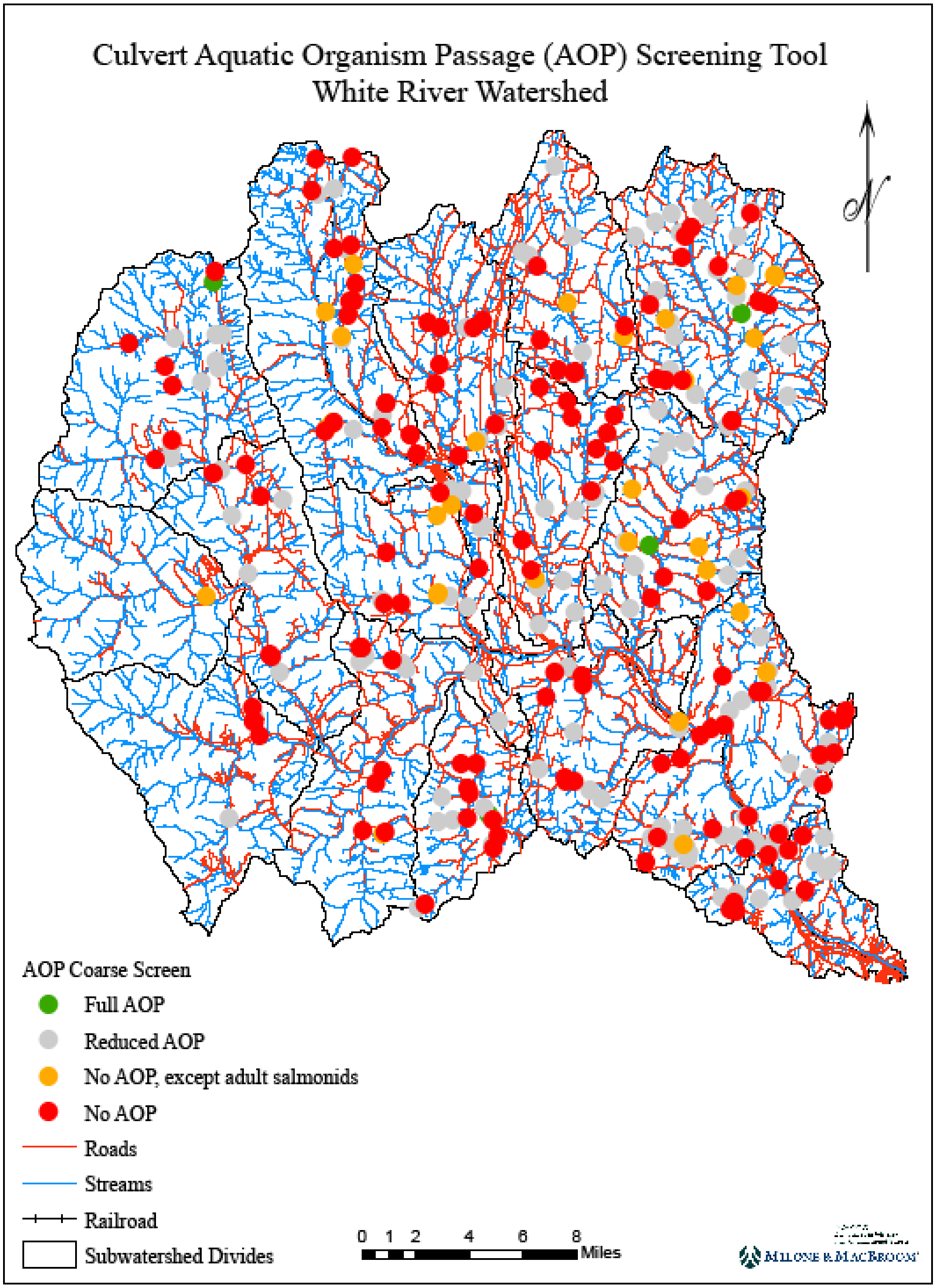
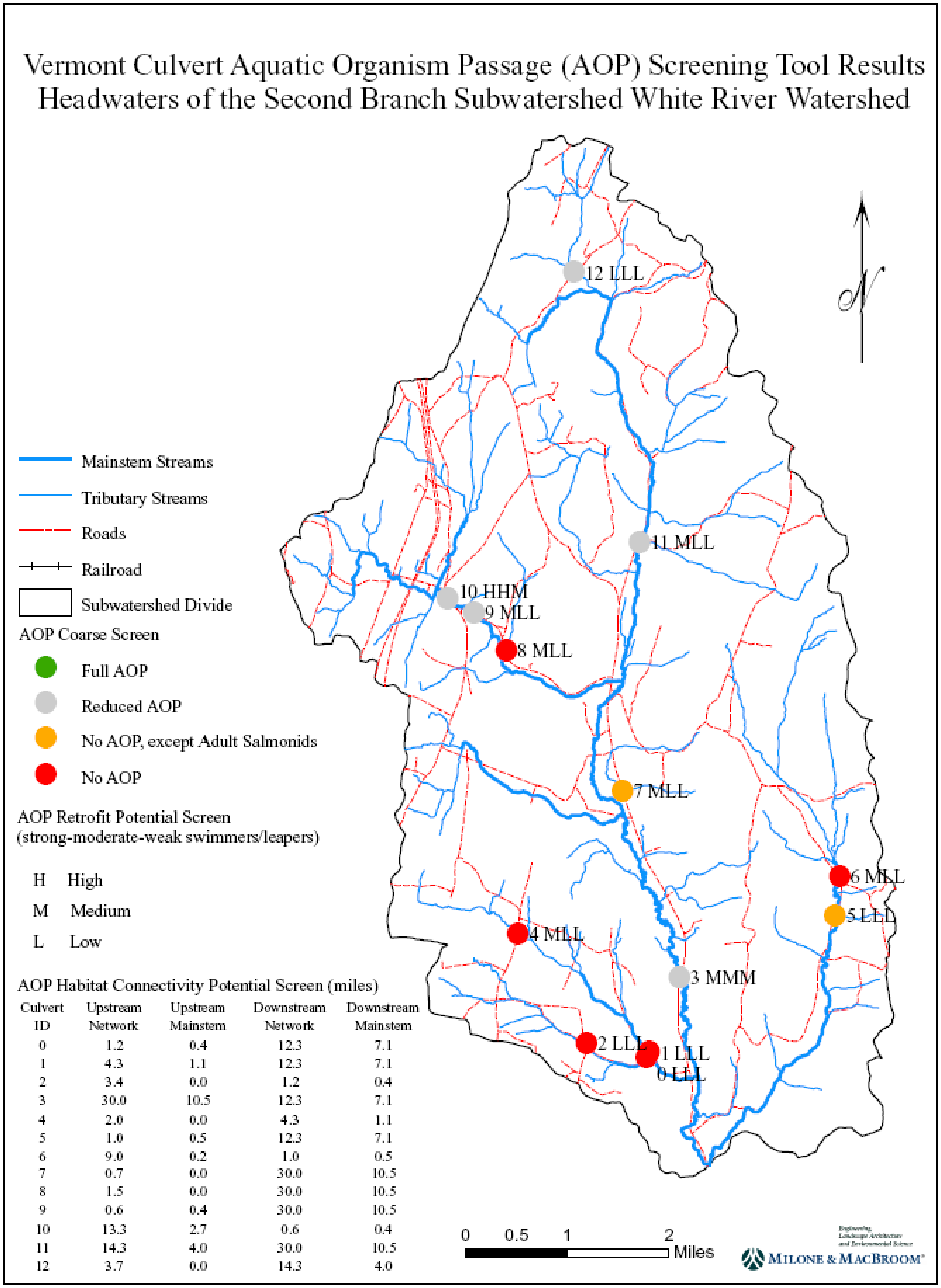


FIGURE 5-2
Culvert Aquatic Organism Passage in the White River Watershed



Culvert ID	Upstream Network	Upstream Mainstem	Downstream Network	Downstream Mainstem
0	1.2	0.4	12.3	7.1
1	4.3	1.1	12.3	7.1
2	3.4	0.0	1.2	0.4
3	30.0	10.5	12.3	7.1
4	2.0	0.0	4.3	1.1
5	1.0	0.5	12.3	7.1
6	9.0	0.2	1.0	0.5
7	0.7	0.0	30.0	10.5
8	1.5	0.0	30.0	10.5
9	0.6	0.4	30.0	10.5
10	13.3	2.7	0.6	0.4
11	14.3	4.0	30.0	10.5
12	3.7	0.0	14.3	4.0

FIGURE 5-3
Culvert Aquatic Organism Passage in the Headwaters of the Second Branch Subwatershed

5.3 Ottauquechee River Watershed

In the Ottauquechee River watershed, only 13 structures received a *Full AOP* rating, but more than half had *No AOP* (Figure 5-2). The *Reduced AOP* category contained 40% of structures. Only two structures were identified as having a high retrofit potential for all species ability groups, while 29% were found to have low potential for all groups (Table 5-3).

A map of the assessed structures and *AOP Coarse Screen* results in the Ottauquechee River watershed (Figure 5-3) shows the *No AOP* structures to be spread throughout all of the subwatersheds. A closeup map of the Broad Brook subwatershed (Figure 5-4) shows a cluster *No AOP* structues at the west side of the watershed. On the closeup map it is apparent that many structures have not yet been assessed.

The habitat connectivity screen took 22 minutes to run for the 10 assessed structures. The mean full network upstream connection protential is 2.5 miles, while that for the mainstem only is 0.5 miles. The maximum full netork connectin disance is 83 miles while that on the mainstem is 24 miles. Mean connectivity potential length for the Broad Brook catchment ranges from 0.5 on the mainstem to 13.2 on the downstream netowrk (Table 5-4, and Figure 5-6).

TABLE 5-3
Ottauquechee River Watershed *AOP Retrofit Potential Screen* Results for the Pilot Study

		Coarse Screen		
Retrofit Potential	**Total**	**Gray**	**Orange**	**Red**
LLL	*50*	19	0	31
MLL	*93*	38	1	54
MML	*18*	11	0	7
MMM	*0*	0	0	0
HML	*0*	0	0	0
HHM	*3*	1	0	2
HHH	*2*	2	0	0
Total	*166*	71	1	94

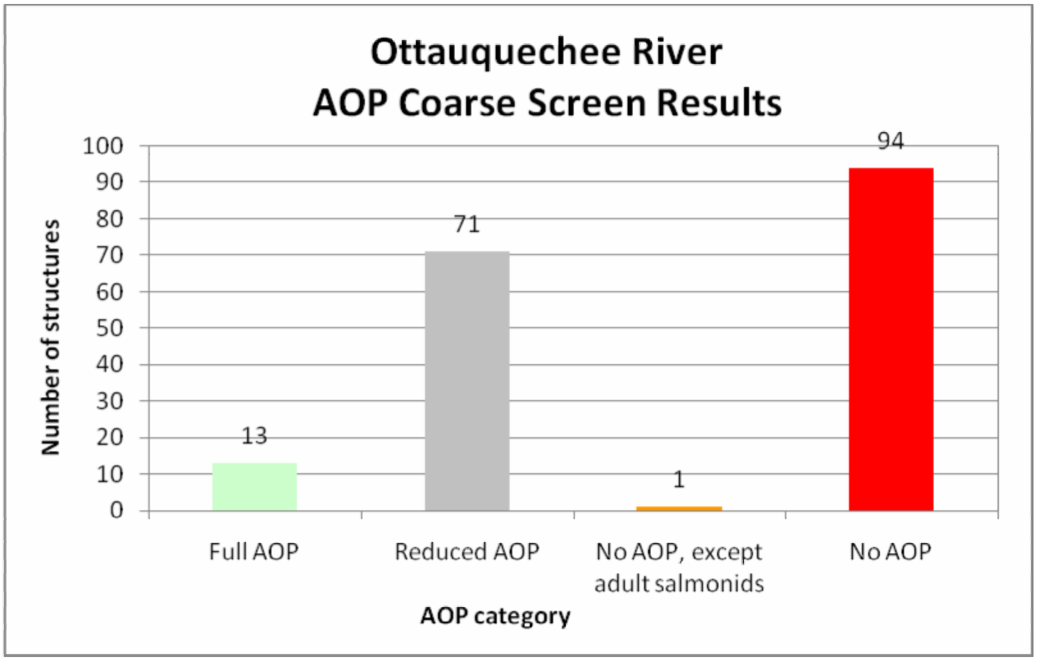


FIGURE 5-4
Pilot study results of the *AOP Coarse Screen* for the Ottauquechee River Watershed

TABLE 5-4
Results of the *AOP Habitat Connectivity Potential Screen* for Broad Brook (Miles Potentially Reconnected)

(miles)	Upstream Network	Upstream Mainstem	Downstream Network	Downstream Mainstem
MEAN	3.2	0.5	13.2	2.8
MIN	0.0	0.0	0.0	0.0
MAX	18.0	2.9	33.2	8.0

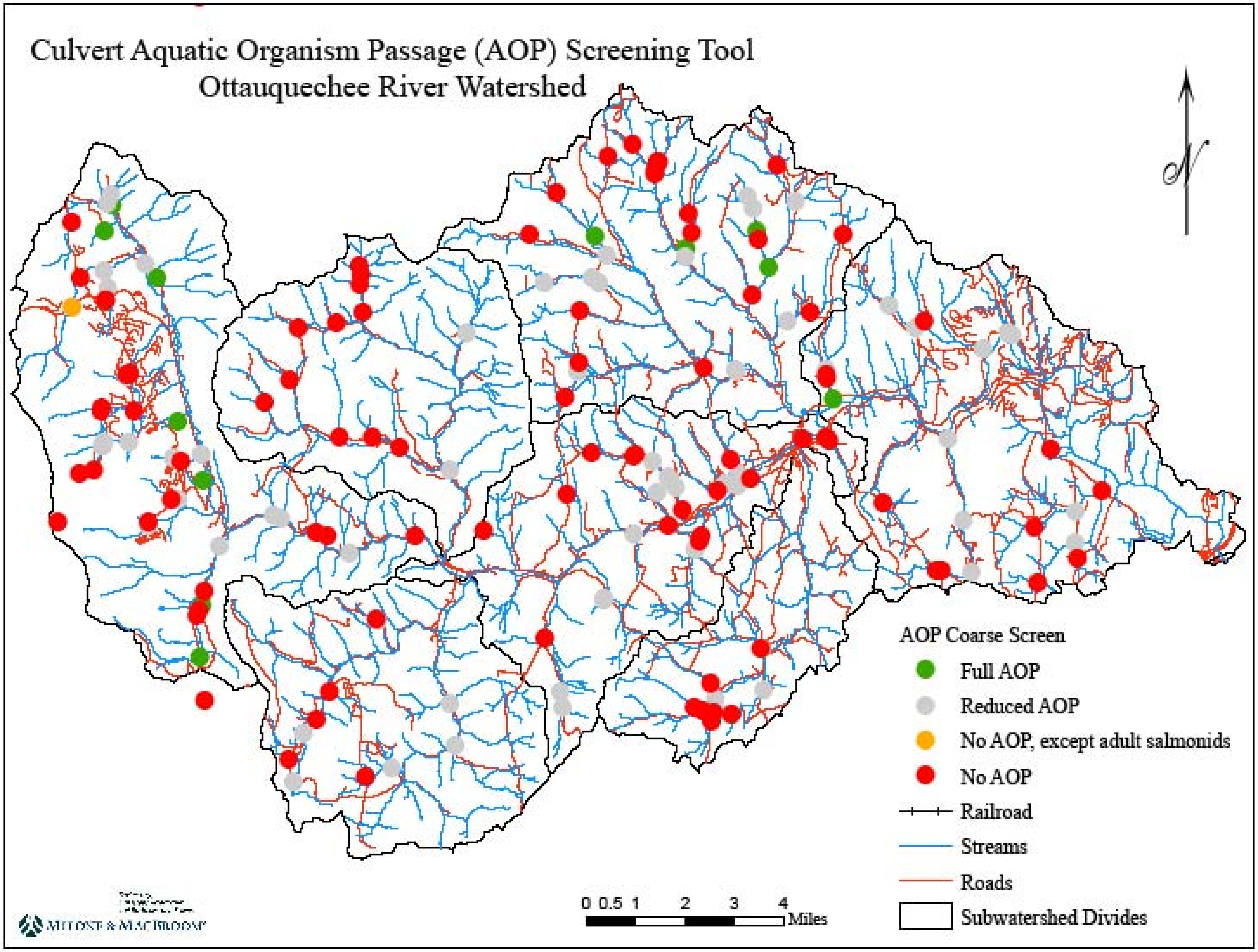


FIGURE 5-5
Culvert Aquatic Organism Passage in the Ottauquechee River Watershed

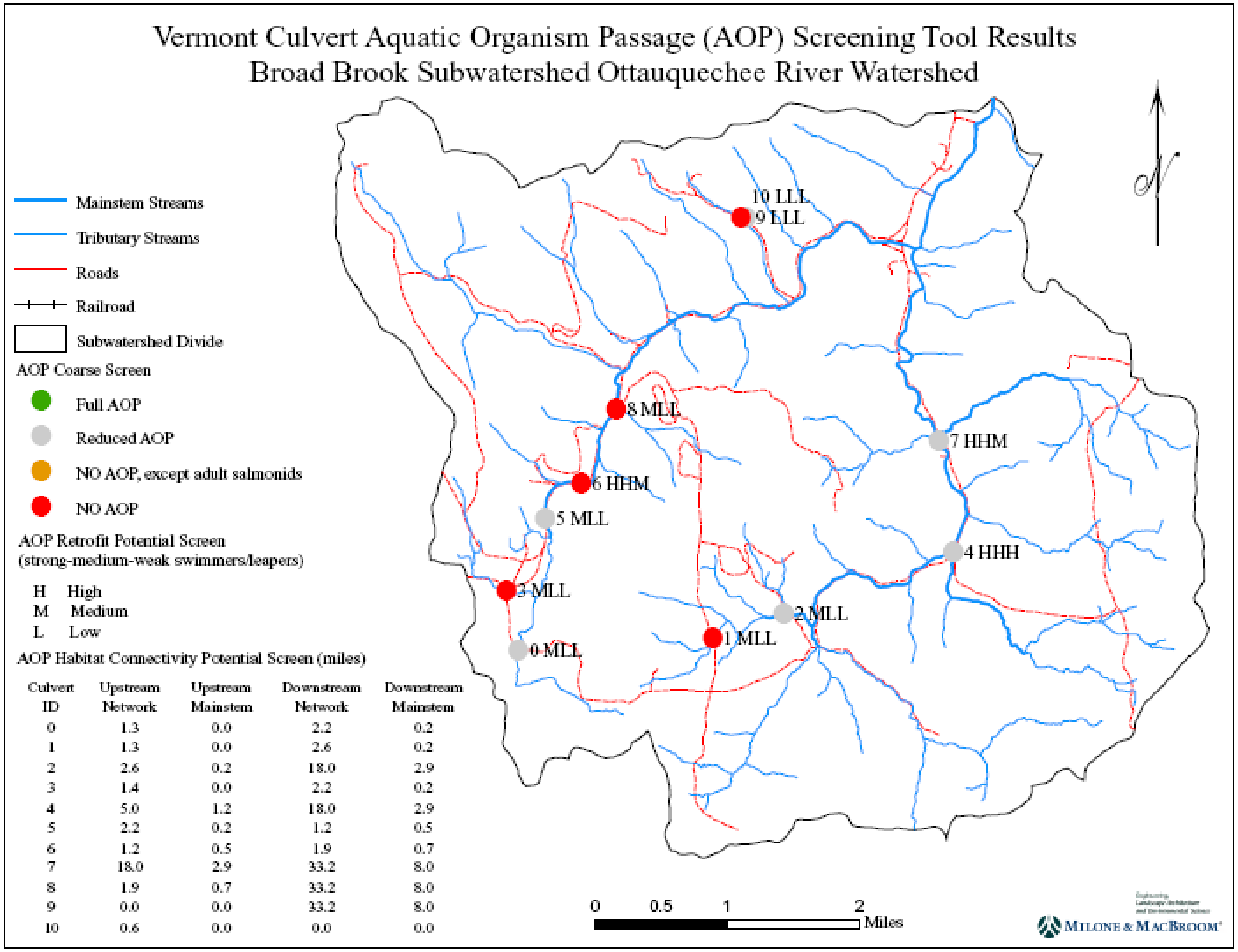


FIGURE 5-6
Culvert Aquatic Organism Passage in the Broad Brook Subwatershed

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Appendix A – Vermont Culvert Assessment

Culvert Assessment - Geomorphic & Habitat Parameters

Field Map # _____

SGA Structure ID				Local ID	
Observer(s) / Organization(s)				Date	
Town				Phase 1 Project	
Location				Longitude (E/W)	
Reach VTID				Latitude (N/S)	
Road Name				Road Type	**paved gravel trail railroad**
Stream Name				High Flow Stage	**yes no**
Culvert Length	(ft.)	Structure Material	**concrete** **plastic corrugated** **plastic smooth** **tank** **steel corrugated** **stone** **aluminum corrugated** **other** **mixed**	Channel Width **curve measured**	(ft.)
Culvert Height	(ft.)			# of culverts at crossing	
Culvert Width	(ft.)			Overflow pipe(s)	**yes no**
				Structure skewed to roadway	**yes no**

Geomorphic and Fish Passage Data

General

Floodplain filled by roadway approaches: **entirely partially not significant**

Structure located at a significant break in valley slope: **yes no unsure**

Culvert slope as compared with the channel slope is: **higher lower same**

Upstream

Is structure opening partially obstructed by (circle all that apply): **wood debris sediment deformation none**

Steep riffle present immediately upstream of structure: **yes no**

If channel avulses, stream will: **cross road follow road unsure**

Estimated distance avulsion would follow road: __________ (feet)

Angle of stream flow approaching structure: **sharp bend mild bend naturally straight channelized straight**

Downstream

Water depth in culvert (at outlet): ___________ (0.0 feet)

Culvert outlet invert: **at grade cascade free fall**

Outlet drop (invert to water surface): ___________ (0.0 feet)

Pool present immediately downstream of structure: **yes no**

Pool depth at point of streamflow entry: ___________ (0.0 feet)

Maximum pool depth: ___________ (0.0 feet or >4feet)

Downstream bank heights are substantially higher than upstream bank heights: **yes no**

Geomorphic and Fish Passage Data	UPSTREAM	DOWNSTREAM	IN STRUCTURE
Dominant bed material at structure	1 2 3 4 5 UK bedrock present: yes no	1 2 3 4 5 UK bedrock present: yes no	0 1 2 3 4 5 UK material throughout: yes no
Sediment deposit types	none delta side point mid-channel	none delta side point mid-channel	none delta side point mid-channel
Elevation of sediment deposits is greater than or equal to ½ bankfull elevation:	yes no	yes no	yes no
Bank erosion	high low none	high low none	
Hard bank armoring	intact failing none unknown	intact failing none unknown	
Streambed scour causing undermining around/under structure (circle all that apply)	none culvert footer wing walls	none culvert footer wing walls	
Beaver dam near structure Distance from structure to dam	yes no distance: __________ ft.	yes no distance: __________ ft.	

Bed Material Codes
- 0-none
- 1-bedrock
- 2-boulder
- 3-cobble
- 4-gravel
- 5-sand
- UK-unknown

Wildlife Data (left/right bank determined facing downstream)	LEFT	RIGHT	LEFT	RIGHT
Dominant vegetation type				
Does a band of shrub/forest vegetation that is at least 50' wide start within 25' of structure and extend 500' or more up/downstream?	yes no	yes no	yes no	yes no

Vegetation Type Codes
- C-coniferous forest
- D-deciduous forest
- M-mixed forest
- S-shrub/sapling
- H-herbaceous/grass
- B-bare
- R-road embankment

Road-killed wildlife within ¼ mile of structure? (circle none or list species)	species: none

Wildlife sign and species observed near (up/downstream) and inside structure (circle none or list species and sign types)	Outside Structure		Inside Structure	
	species (none)	sign	species (none)	sign

Spatial data collected w/GPS: yes no Photos taken: yes no Please fill out photo log below	**Comments:**

Roll and Frame #	Photo View	Description of Features in Photo

Appendix B – Annotated Bibliography

Massachusetts River and Stream Crossing Standards (MARSCP, 2006)

Three goals include aquatic organism passage, river/stream continuity (i.e., maintenance of appropriate substrate and hydraulic characteristics, and wildlife passage. Employs "stream simulation" approach for design since swimming speeds and passage requirements are not well known. This approach is also best for maintaining essential ecological processes. Stream simulation focuses on maintaining a natural substrate through the structure and not constricting the flow. The goal is to create a structure that is invisible to the stream.

Channel type
Long profile
Likely variability of stream over structures life
Stream potential for adjustment
Headcutting
Culverts should be embedded: ≥2 feet for box and others with smooth walls, ≥1 foot for corrugated arches, and ≥1 foot and at least 25% for corrugated round pipes.
W = 1.2 * bankfull width
Natural bottom substrate
Consistent water depths and velocities in structure as in stream
Openness ration (cross sectional area / length) >0.25 m

General screening recommendations: Assess habitat quality in river or stream and surrounding areas, upstream and downstream conditions, number of other crossings, large discontinuities, and barriers affecting the system. Use watershed approach.

Things to avoid/mitigate:
Inlet and outlet drops
Contractions that produce turbulence
Tailwater armoring
Tailwater scour pools
Passage barriers

Check for grade controls to keep bed stable
Avoid HDPP or plastic pipes due to low friction and high velocities

New Hampshire Stream Crossing Guidelines (Draft - Not for Release) (NHDFG, 2007)

Goals of geomorphic compatibility and aquatic organism passage

"Methods have been developed, and are continuing to be refined and adapted, for evaluating culverts and other crossing structures for their impacts on animal passage and other ecosystem processes. Along with these assessments there needs to be a process for prioritizing problem crossings for remediation. The process should take into account **habitat quality in the river or stream and surrounding areas, upstream and downstream conditions, as well as the number of other crossings, discontinuities (channelized or piped sections), and barriers affecting the system**. It is important to use a watershed-based approach to river and stream restoration in order to maximize positive outcomes and avoid unintended consequences. Although a watershed approach to stream crossing replacement is preferred, it is understood that limited funding forces most stream crossing structure replacement to occur as the need arises, however this in no way lessens the dramatic ecosystem impacts resulting from these culverts. Each individual stream crossing replacement should be evaluated as an opportunity to improve the overall connectivity of a watershed."

Maine Fish Passage Policy & Design Guide (MEDOT, 2004)

Goals of replicating the natural stream while passing suitable flows and fish.

Consider resource inventory data (species, size, seasonal passage needs), future streamflow conditions when and the presence of suitable upstream habitat when screening for projects.

Explore physical and hydraulic barriers.

Effective passage when: ()=defaults
Pass peak flow (50yr)
Does not exceed specified flow velocity (2fps)
Maintains minimum depth (8”) and
Maintains channel gradient (see channel).

Species specifics are preferred if known.

Use max. sustained speed for target species during their periods of movement through the culvert.

Use 1.5 x body width for required flow depth. Base flow depth on low flow channel geometry up and downstream of structure.

Use monthly median flows during key movement times.

New structures at bankfull width.

Note pipe cross sectional area and roughness.

WA uses 1.2 bankfull width for structures plus 2’ at the flow line. Too large for Maine.

****DRAFT Design of Fish Passage at Bridges and Culverts (HEC-26) (FHWA, 2007)*

This draft manual is an excellent overview of design methods for bridges and culverts, and covers most of the important related topics including screening for structure/stream restoration to improve both aquatic organism passage and geomorphic compatibility. The document draws on several of the central existing guidelines and approaches on the topic to form a federal summary document. References are included within for facts primarily taken from other publications.

Geomorphic response of channel to undersized culvert (adapted from Bates 2006): Downstream erosion of bed and banks, downstream channel incision, disconnected floodplains, direct habitat loss and degradation.

Minimum depth requirements: 2.5 times height of caudal fin (AK fish and game 2001), 0.8-1.0 ft for adult trout/salmon (Bates 2003 (WA guidelines)), 1.5 times body thickness (MEDOT 2004)

AOP for weakest swimmer/age of concerned species group, including timing of fish migration.

Jump pool required to gain momentum (added to VT 2007). Drop height:pool depth ~1:1.25 requirement (Stuart 1962). Oregon uses 1.5 times jump height or a minimum of 2 ft for jump-pool depth.

Some interesting points on roughness. Is this assessed? Wonder if could include a field determination to explore the potential for simple retrofit. Are large roughness elements present?

Inlet conditions are the last main barrier for AOP. Especially important for long structures. Could open up options for basic retrofits using wingwalls to improve transition (Behlke et al. 1991)

Turbulence important. WA and ME specify an energy dissipation factor □QS/A and give criteria. Useful for screen?

Excessive length reduces tolerable velocities unless resting areas are introduced.

Long barriers: drop, turbulence, velocity (boundary layer, max point, average), debris, length, depth.

In the review of the inventory methods tailwater and headwater controls are included. These are critical as they constitute both key pool habitat near the structure and grade control for channel stability. May want to expand details of this to get distance to first us/ds control and relative elevation to culvert inverts if possible.

CA (Taylor and Love 2003) have method for taking gray in green gray red scheme to further split indeterminants. They use the degree of “barrierity”, portion of time or degree to which a crossing disrupts fish passage. Good for prioritization for AOP. Determine if the structure is a temporal, partial, or complete block.

Coarse filter – determine transparency of structure, is it same as natural channel?
Regional screen – determine status when coarse filter does not work. Species-specific in local region. (see Taylor and Love 2003 for example in flow chart form) Also see Clarkin et al. 2003 for a template of a screen at different levels that could help us refine the VT approach.

Are aprons included in assessment?

Prioritization is not necessarily for ranking the order structures are addressed, but allowing information to come up with an efficient plan.

AOP considerations – invasives, upstream habitat, grade control, acceptable delay collectively at all structures

CA – screen based on points awarded for species diversity, extent of barrier, habitat value, risk of failure, and current conditions.

OR – five categories to help identify need of replacement. 1-block stream with target restoration species to 5-non-fsih bearing stream with moderate to high risk of failure (Robison et al., 1999)

WA – priority index (PI) ranking. Barrier severity, production potential, blocked habitat, condition of fish stock, projected cost, species value.

See USFS Inventory summary (Clarkin et al, 2003) for prioritization schemes. Template presented as guide.

Look at upper and lower flow thresholds, timing, allowable delay,

Culverts limit range of ecological solutions. Closer to restoring valley and floodplain natural processes more options exist for aop (Gubernick 2006 (steam simulation meeting)).

Channel influence and structure and structure influence on channel.

Subcritical flow throughout structure key.

Culvert alignment important as angles induce scour.

Design approaches:
No impedance – aop remains natural as structure spans channel and floodplain;

Geomorphic Simulation – recreate or maintain natural geomorphology (slope, width, substrate, and bedform) which should lead to natural passage. Some criteria include slope within 25% of channel (Barnard 2003), width is 1.3 bankfull width, applied only to coarse beds thus far.

Hydraulic simulation – embedded culverts, natural or mixed bed material, natural large roughness materials, to create good aop hydraulics. Width is ~ bankfull width.

Hydraulic design – depths and velocities to pass fish. Tough as this information is approximate.

Other possible variables. Bed and bank material. Wetted width. OHW.

(Note: Did not do a detailed review of the design approaches as the focus here is screening and prioritization.)

Preliminary Assessment and Rating of Stream Channel Stability near Bridges (Johnson, 2005)

Change definition of acceptable lateral channel migration in vicinity of crossings. These are fixed points and movement is bad. Consider in screening in some way.

Excellent scores for stability indicators:
1. Watershed and floodplain activity and characteristics – stable, forested, undisturbed watershed
2. Flow habit – perennial stream with no flashy behavior
3. Channel pattern – Straight (nonengineered) to meandering with low radius of curvature; primary suspended load
4. Entrenchment/channel confinement – Active floodplain exists at top of banks; no sign of undercutting infrastructure; no levees
5. Bed material; Fs=approximate portion of sand in bed – Assorted sizes tightly packed overlapping, and possibly imbricated; most material >4mm; Fs<20%
6. Bar development – For S<0.02 and w/y>12, bars are mature, narrow relative to stream width at low flow, well vegetated, and composed of coarse gravel to cobbles; for S>0.02 and w/y <12, no bars are evident
7. Obstructions, including bedrock outcrops, armor layer, LWD jams, grade control, bridge bed paving, revetments, dikes or vanes, riprap – rare or not present
8. Bank soil texture and coherence – clay and silty clay; cohesive material
9. Bank slope angle (where 90 degrees is vertical) – bank slopes <3H:1V (18deg) for noncohesive or unconsolidated materials to <1:1 (45 deg) in clays on both sides
10. Vegetative or engineered bank protection – Wide band of woody vegetation with at least 90% density and cover; primarily hard wood, leafy, deciduous trees with mature, healthy, and diverse vegetation located on bank; woody vegetation orientated vertically; in absence of vegetation, both banks are lined or heavily armored
11. Bank cutting – Little or none evident; infrequent raw banks, insignificant percentage of total bank
12. Mass wasting or bank failure – No or little evidence of potential or very small amounts of mass wasting; uniform channel width over entire reach
13. Upstream distance to bridge from meander impact point and alignment – More than 35 m; bridge is well aligned with river flow

Note stratification by three groups of channel types:

A. riffle-pool, place-bed, dune-ripple, and engineered channels
B. cascade, step-pool channels
C. braided channels

Aggradation at Bridges (Johnson et al., 2001)

Increase sediment supply causes aggradation to migrate downstream, while a reduction in transport capacity leads to deposition to move upstream. Morphology evolves in both cases

Backwatering and aggradation common problems at structures such as bridges and culverts.

Rapid Assessment of Channel Stability in Vicinity of Road Crossing (Johnson et al., 1999)

Power > 35 W/m2 and bankfull Q are unstable due to erosion

Pfankuch (1978) stability assessment with changes made. See more recent paper on rapid assessment at bridges.

Stream Assessment for Multicell Culvert Use (Johnson and Brown, 2000)

Use CEMs to assess likely channel stability around structures. II or III require stabilization for culvert use or bridge.

Investigate bank condition in terms of stability and armoring

Debris potential in flood plain

Multi-cell, meaning in-channel and overflow good design for conveyance and fish passage during normal flows.

Interesting design flow charts to help design decisions.

Movements of Nonnative Brook Trout in Relation to Stream Channel Slope (Adams et al., 2000)

Summer upstream movement dominant in summer in mountains in ID

Brook trout passed…
S=13%, distance >67m
S=22%, distance >14m
And 1.2 m high falls

Fish can move up steep slope and vertical walls will stop them.

<95 mm fish did not move much

Changes in Distribution of Nonnative Brook Trout in an Idaho Drainage over Two Decades (Adams et al., 2002)

1971 to 1996 adult ranges expanded at least 0.5 km upstream in some stream, and upstream invasion (1.2-2.4 km) occurred in 3 of 8 streams.

1993 and 1997 no changes in upstream distribution limits over that shorter time interval. Certainly no upstream invasion.

How high can brook trout jump? A laboratory evaluation of brook trout jumping performance (Kondratieff and Myrick, 2006)

Brook trout jumping a function of vertical height, plunge pool depth, fish total length, and fin conditions

10-15-cm brook trout could jump a 63.5-cm-high waterfall, equivalent to 4.7 times their body length, from a 50-cm-deep plunge pool, which was 3.7 times their body length. At this size, 10-30 cm was where bulk of fish could pass as long as jump pool depth >10cm.

15-20 cm TL:10-40 cm height where most passage took place with >=10cm pool

+20 cm TL: 10-40 cm height where most passage took place with pool depth >= 10cm

bulk of passage took place where jump pool had depth of 20-30 cm

Larger size-classes were capable of jumping 73.5-cm waterfalls, or 2.9-4.0 times their body length, provided the plunge pools were at least 40 cm deep (> 1.6 times their body lengths).

Shallow plunge pools (10 cm) prevented brook trout from all size-classes front jumping waterfalls 43.5 cm or more in height

Small fish were capable of jumping a greater number of body lengths over vertical obstacles than large fish

Fish Passage Evaluation at Stream Crossings
Part IX of the California Salmonid Stream Habitat Restoration Manual (Taylor and Love, 2002)

Barrier Category	Definition	Potential Impacts
Temporal	Impassable to all fish at certain flow conditions (based on run timing and flow conditions).	Delay in movement beyond the barrier for some period of time.
Partial	Impassable to some fish species, during part or all life stages at all flows.	Exclusion of certain species during their life stages from portions of a watershed.
Total	Impassable to all fish at all flows.	Exclusion of all species from portions of a watershed.

Characteristics of stream crossings with poor fish passage include:
• Crossings that constrict the natural channel width
• Crossings with hardened bottoms lacking diverse stream substrate
• Paved crossing invert set above the channel bottom
• Crossings not in alignment with stream channel
• Crossings requiring baffles or weirs inside to meet hydraulic criteria
• Channel bed and banks showing signs of instability upstream or downstream
• Crossings with projecting culvert inlets
• Crossings with trash rack installed at culvert inlet.
Such characteristics cause these typical types of passage problems (Figure IX-1):
• Excessive water velocities within a culvert
• Excessive drop at the outlet, resulting in a too high entry leap, or too shallow of a jump pool below a crossing
• Lack of water depth within culvert or over crossing
• Excessive water velocity or turbulence at a culvert inlet
• Debris accumulation at a culvert inlet or within a culvert barrel.

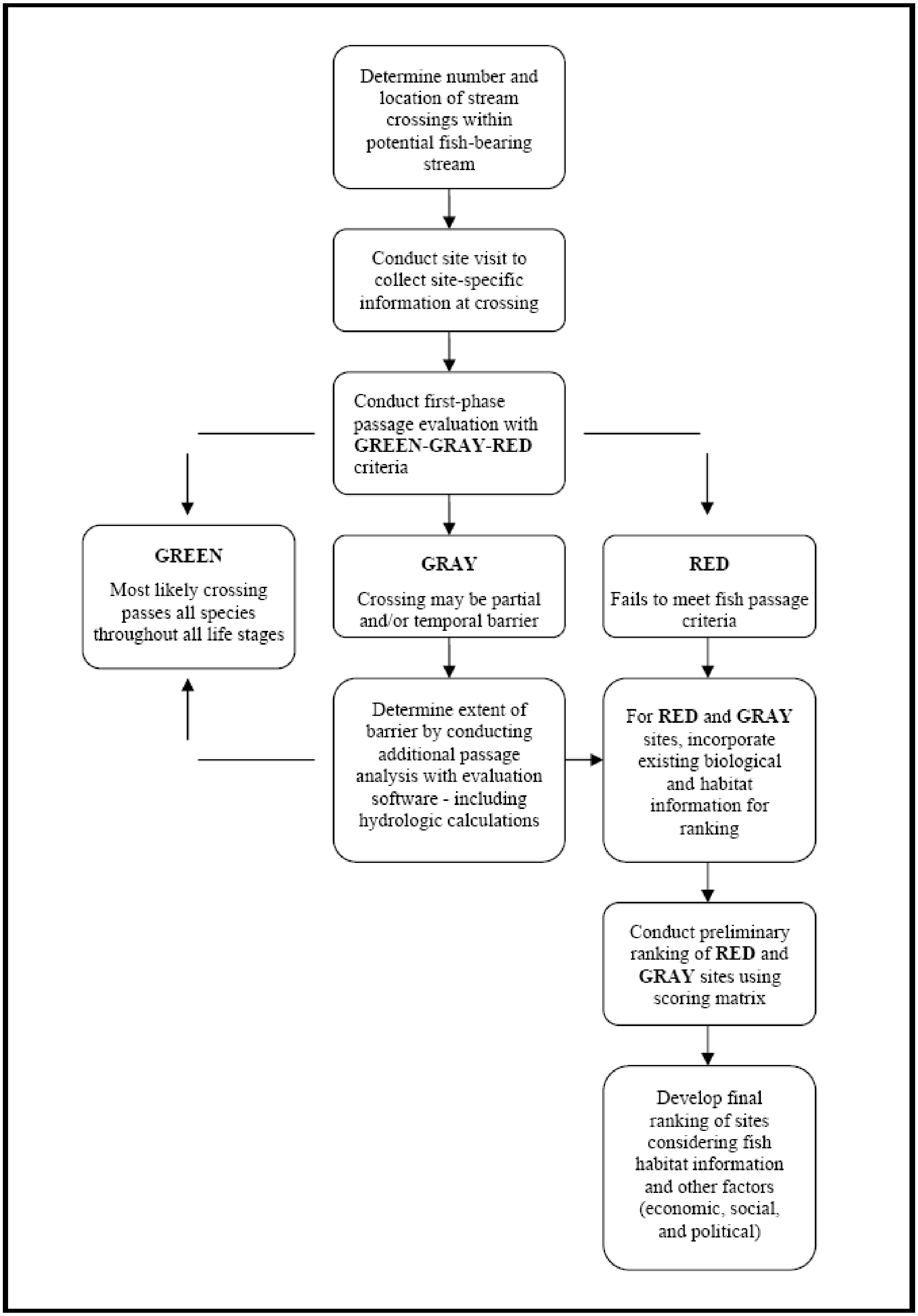
Active channel width v bankfull channel width

Record head- and tailwater control depths

Stream Crossing Information
Inlet Type: Check the box that best describes inlet configuration (Figure IX-9).
Projecting: Culvert barrel projects upstream out of the road fill.
Headwall: Culvert barrel is flush with road prism, often set within a vertical concrete or wooden headwall.
Wingwall: Concrete walls that extend out from the culvert inlet in an upstream direction. In a downstream direction, wingwalls taper towards the inlet and usually increase a crossings flow capacity
Mitered: Culvert inlet is cut on an angle similar to angle of the road prism, increasing the size

of the opening and the flow capacity.
Flared: Flared inlet secured to culvert in increase capacity.

Tailwater Control: Defined as the channel feature which influences the water surface immediately downstream of the crossing. Check the box that best describes the tailwater control.



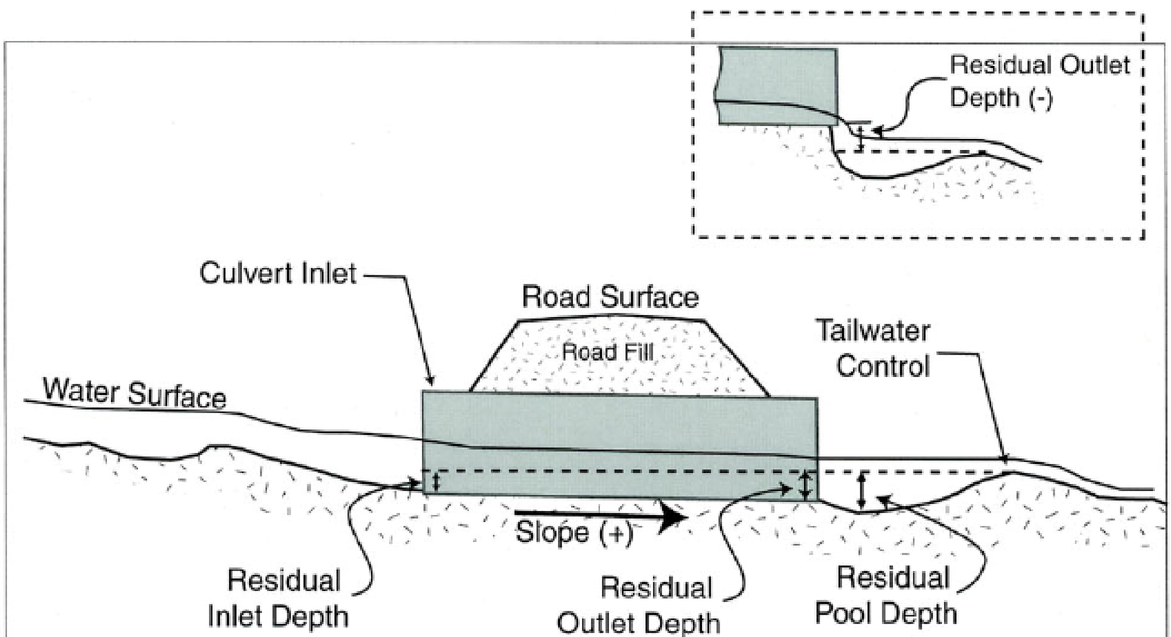
CA EVAL protolcs

GREEN: Condition assumed adequate for passage of all salmonid life stages or throughout all salmonid life stages.

• **GRAY:** Condition may not be adequate for all salmonid species at all their life stages. *FishXing* is used to determine the extent of barriers for each salmonid life stage.

• **RED:** Condition fails to meet DFG and NOAA passage criteria (Appendix IX-A and Appendix IX-B) at all flows for strongest swimming species presumed present. Analysis of habitat quantity and quality upstream of the barrier is necessary to assess the priority of this crossing for treatment.

Some stream crossings have characteristics which may hinder fish passage, yet they are not recognized in the filtering process, such as breaks in-slope, inlet and outlet aprons, crushed inlets, or damage to the crossing invert. For crossings meeting the GREEN criteria, a review of the inventory data and field notes is necessary to ensure no unique passage problems exist before classifying the stream crossings as "passable".



Residual Pool Depth = (Elev $_{\text{Tailwater Control}}$ - Elev $_{\text{Pool Bottom}}$)

Residual Outlet Depth = (Elev $_{\text{Tailwater Control}}$ - Elev $_{\text{Culvert Outlet}}$) (If Residual Outlet Depth is less than zero it is referred to as the Residual Outlet Drop)

Residual Inlet Depth = (Elev $_{\text{Tailwater Control}}$ - Elev $_{\text{Culvert Inlet}}$)

Figure IX-16. Measurements used in filtering criteria.

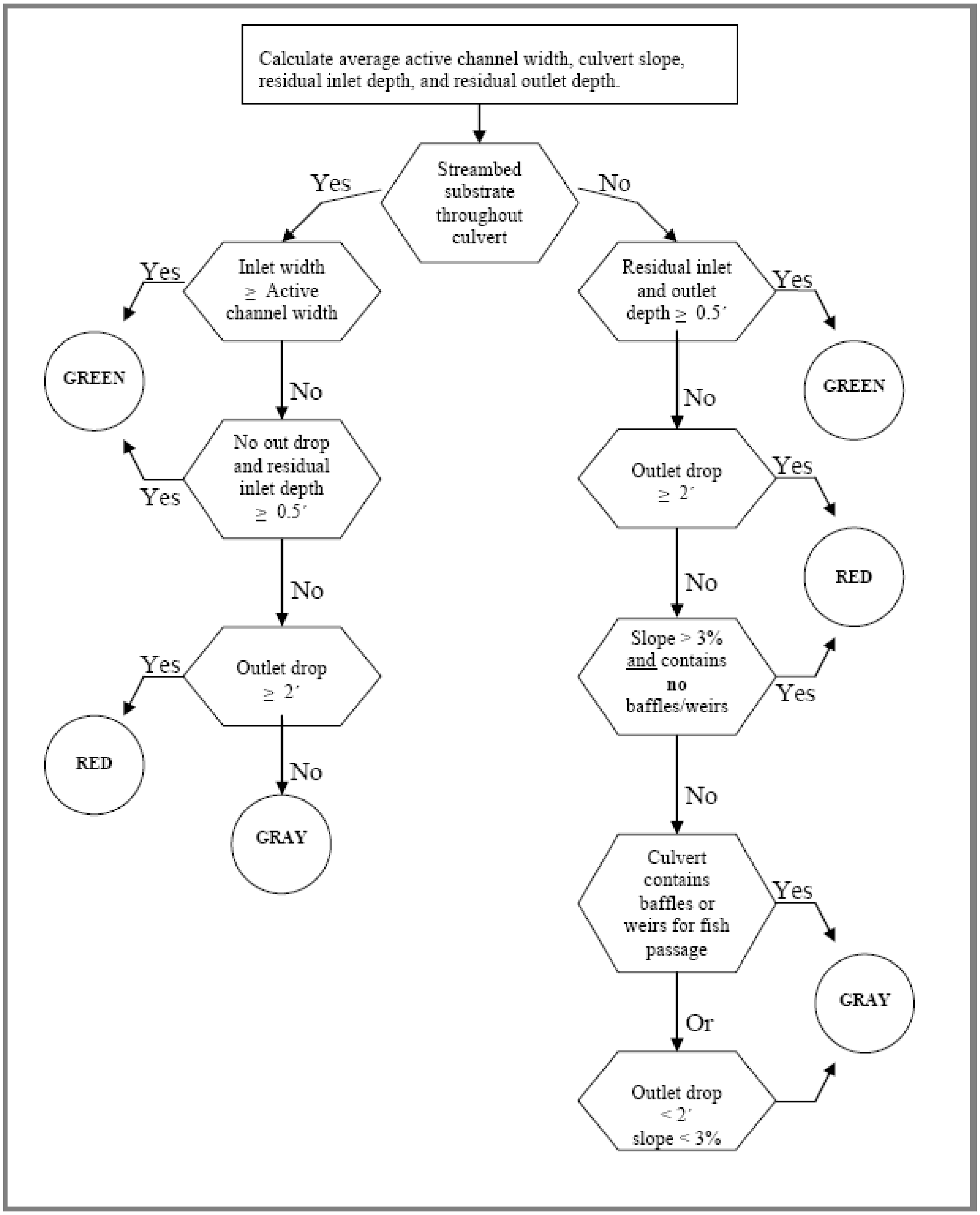


Figure IX-17. GREEN-GRAY-RED first-phase passage evaluation filter.

Resident trout >6”: min water depth 0.5 feet, max swim speed 4.0 ft/sec, exhaustion time 30 minutes, max burst speed 5.0 ft/sec, exhaustion time 5.0 sec, max leaping speed 6.0 ft/sec

Ranking of gray and red structures for restoration follows:

1. fish diversity in stream
2. barrier extent
3. habitat value, quality x quantity above crossing
4. size, risk of failure
5. current condition

other considerations

a. other crossings present
b. observed fish
c. amount of road fill
d. cost to remediate
e. opportunity

For each stream crossing that was placed in the GRAY category, conduct a separate passage analysis for all salmonids and their life stages.

Flow capacity estimates at HW/D = 1 for standard metal circular, metal pipe-arch, and concrete box culverts, and compare to hgr calcs of peak flows.

place each crossing into one of six categories:

• Flow capacity equal to or greater than the 100-year flow
• Between the 50-year and 100-year flows
• Between the 25-year and 50-year flows
• Between the 10-year and 25-year flows
• Between the 5-year and 10-year flows
• Less than the 5-year flow.

Compare Q. Adult non-anadromous salmonids upper passage flow 5% (20 year flood) exceedance, lower passage flow 90% (1.1 year flood) or 2 cfs.

treatment options follow WA and OR, not reviewed here, same with guidelines…

slope, slope x length, and velocity for cyprinids

Road crossings with outlet drops < 10 cm, slope < 2.0%, and slope x length values < 25 experienced the greatest movement illustrating the importance of those culvert characteristics in determining fish passage.

Species groupings

- Salmonidae (Group A)
- Cyprinidae, and young-of-year Salmonidae (Group B)
- Percidae (except *Stizostedion sp*., and *Perca flavescens*), and Cottidae (Group C).

culvert features

- Outlet drop and outlet perch (jump barrier)
- Culvert slope (velocity barrier)
- Culvert slope x length (exhaustion barrier)
- Presence of natural stream substrate in culvert (depth barrier)
- Relationship of tailwater control elevation to culvert inlet elevation (depth and velocity barrier).

Many fish, especially smaller ones did not move through culverts in summer. Some in fall.

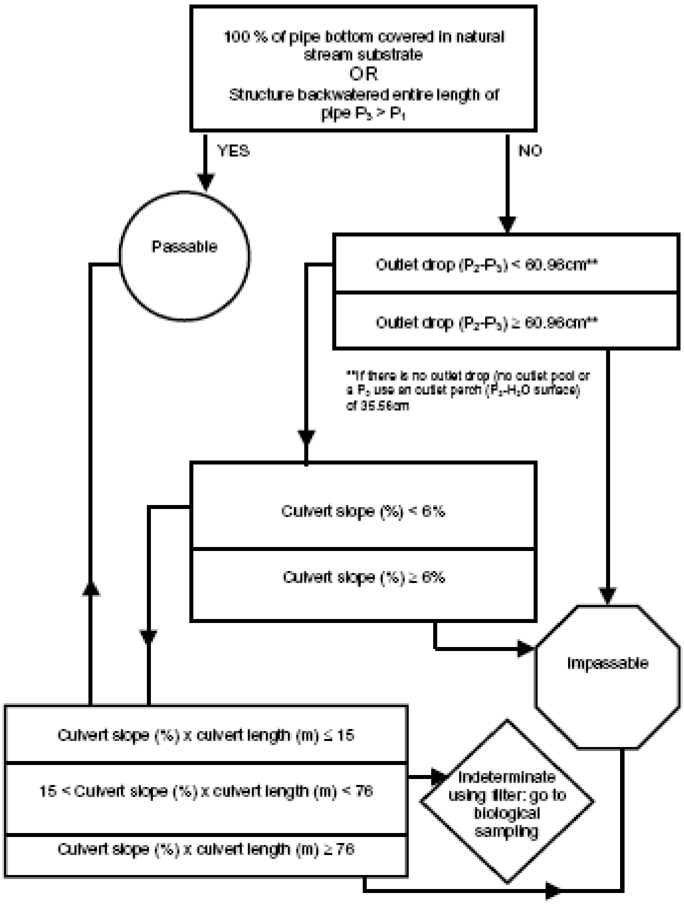


Figure 1.2. Upstream fish passage predictive model A for Salmonidae. See Figure 1.1 for profile of survey points used in fish passage predictive model. P_x = elevation measurements.

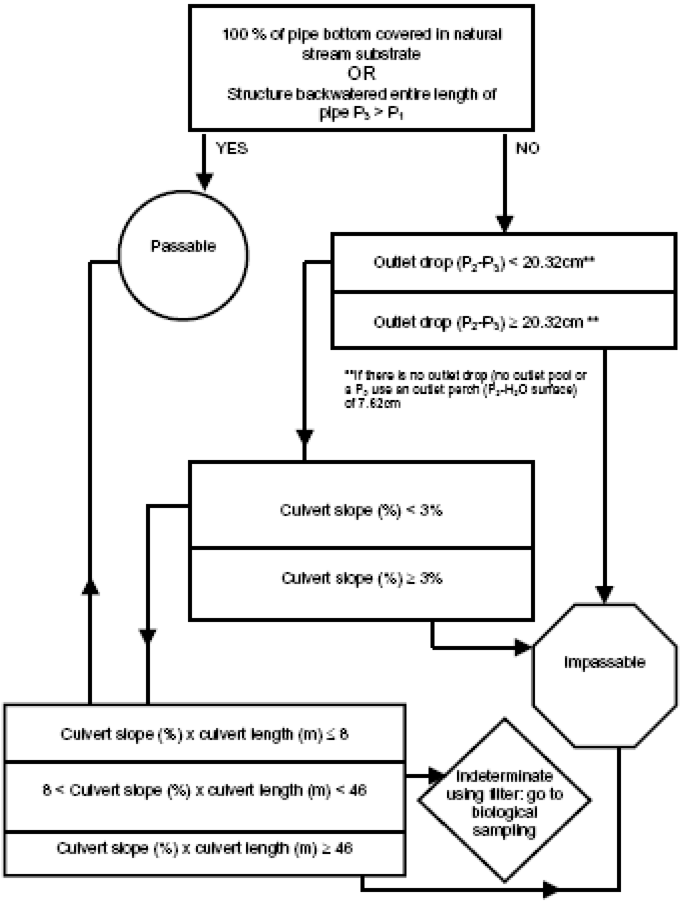


Figure 1.3. Upstream fish passage predictive model B for Cyprinidae and young-of-year Salmonidae. See Figure 1.1 for profile of survey points used in fish passage coarse filter. P_x = elevation measurements.

Design of Road Culverts for Fish Passage (WA) (Bates et al., 2003)

This principle is paraphrased from the State of Washington (1999):
a. Maintain and restore the freedom of rivers and streams to move and change, especially during floods.
b. Allow time for natural regenerative processes to occur and provide recovery of river and stream integrity.
c. Protect the natural diversity of species and restore the natural diversity of habitats within river channels and riparian zones.
d. Support and foster habitat connectivity.
e. Tailor actions locally and to the whole watershed in the proper sequence of time and place. Match the system's potential and long-term human commitment

There are five common conditions at culverts that create migration barriers:
• excess drop at the culvert outlet,
• high velocity within the culvert barrel,
• inadequate depth within the culvert barrel,
• turbulence within the culvert, and
• debris and sediment accumulation at the culvert inlet or internally.

A **no-slope** culvert is defined by the following characteristics:
• width equal to or greater than the average channel bed width at the elevation the culvert meets the streambed,
• a flat gradient,
• the downstream invert is countersunk below the channel bed by a minimum of 20 percent of the culvert diameter or rise,
• the upstream invert is countersunk below the channel bed by a maximum of 40 percent of the culvert diameter or rise,
• the possibility of upstream headcut has been taken into account, and
• there is adequate flood capacity.

Generally, the **Hydraulic Design** Option might be applied in the following situations:
• new, replacement and retrofit culvert installations;
• low to moderate culvert slope without baffles;
• moderate culvert slope with baffles (as retrofit); and
• target species have been identified for passage.

Stream simulation is a design method used to create or maintain natural stream processes in a culvert. Stream simulation is based on the principle that, if fish can migrate through the natural channel, they can also migrate through a man-made channel that simulates the stream channel.

Geomorphologic Impacts of Culvert Replacement and Removal (OR) (Castro, 2003)

Incision key problem for channel (CEM)

(1) high velocities, (2) shallow flow depths, (3) length of run with no resting areas, or (4) excessive jump height.

Look for offset in channel profile up and downstream of structure to see if incision is taking place downstream

Nice list of potential influences of removing structure.

1. Headcut migration upstream and subsequent deepening of the stream channel.
2. Relatively high channel banks that may exceed critical height resulting in mass failure (bank erosion).
3. Addition of fine sediment to the stream system due to erosion of the channel boundary.
4. Disconnection of floodplains from active stream channels.
5. Prematurely dewatered or disconnected backwater habitat.
6. Locally increased channel slope and loss of pool habitat.
7. Drainage of shallow aquifers which affects riparian vegetation.
8. Meander cut-offs due to knickpoint migration across a meander neck caused by an increased elevation drop between the old floodplain and active channel bed.
9. Deposition of large masses of sediment causing localized channel braiding and instability of the streambanks.

Fish Habitat Manual: Guidelines and Procedures for Watercourse Crossings in Alberta (TRANS, 2001)

Mostly design guidelines so not too much for prioritization

provide an inventory of available habitats and to show the locations of important fish habitat, such as migration routes, spawning, rearing and overwintering habitats.

The required data for characterizing the fish habitat potential is listed
below:
Species;
Life stage (adult, juvenile);
Timing of movements/migrations (start and end date); and
Reason for movements (spawning, foraging, cover, overwintering, etc.).

design and permitting aspects for Alberta, Canada reviewed briefly and no new additional information for screening tool.

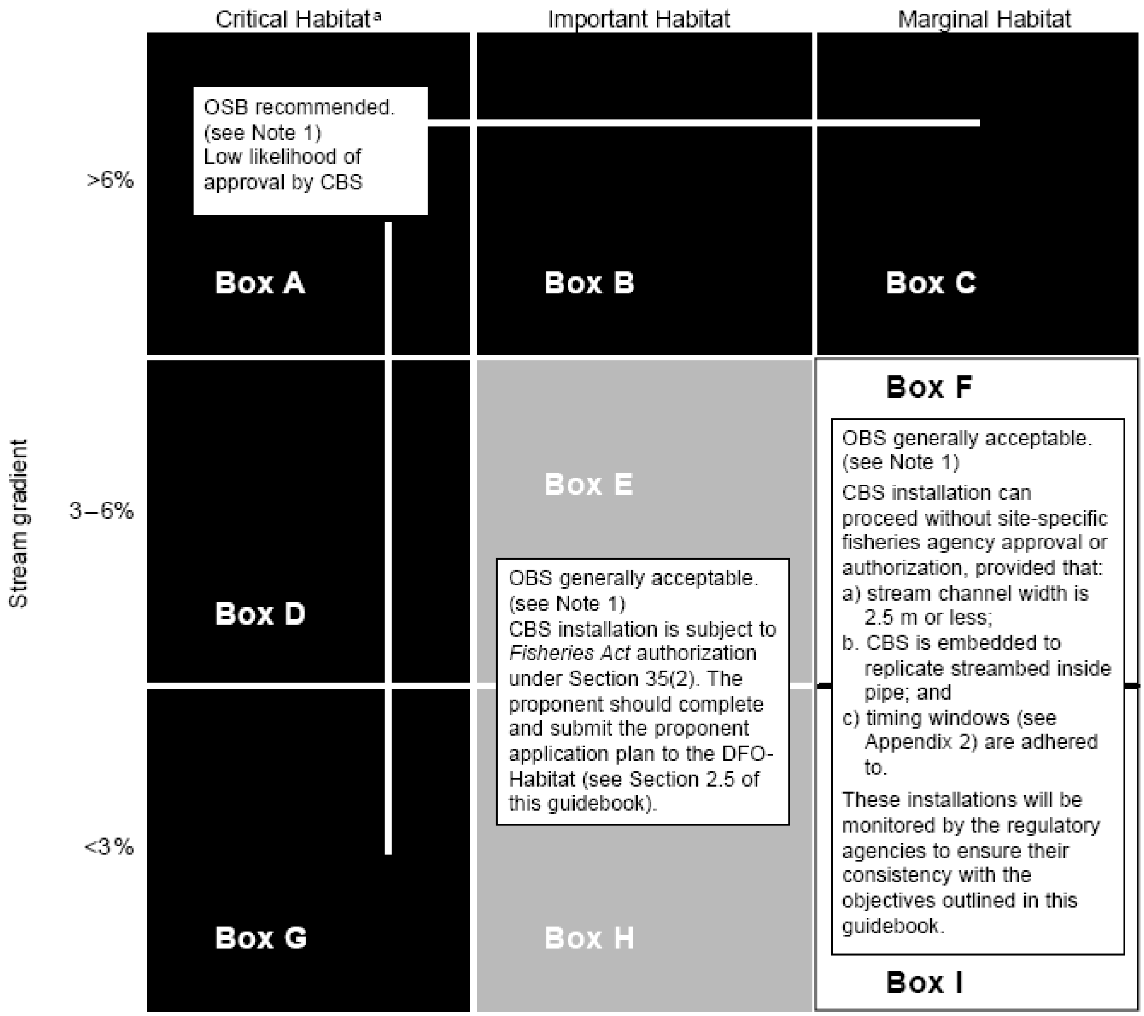
Fish-stream crossing guidebook, Forest Practices Code of British Columbia (BCMF, 2002)

Specifically, the guidebook provides users with technical, statutory reference, and process guidance for selecting and designing fish-stream1 crossings on forest roads (as well as mineral and petroleum access roads) that should (1) avoid harming fish and fish habitat, and (2) provide fish passage at stream crossing sites.

	Habitat at Crossing Site		
	Critical	**Important**	**Marginal**
Definition	Habitat that is critical in sustaining a subsistence, commercial, or recreational fishery, or species at risk (red- and blue-listed and COSEWIC list) because of its relative rareness, productivity, and sensitivity.[a]	Habitat that is used by fish for feeding, growth, and migration, but is not deemed to be critical. This category of habitat usually contains a large amount of similar habitat that is readily available to the stock.	Habitat that has low productive capacity and contributes marginally to fish production.
Indicators[b]	• The presence of high-value spawning or rearing habitat (e.g., locations with an abundance of suitably sized spawning gravels, deep pools, undercut banks, or stable debris, which are critical to the fish population present)	• Important migration corridors • The presence of suitable spawning habitat • Habitat with moderate rearing potential for the fish species present	• The absence of suitable spawning habitat, and habitat with low rearing potential (e.g., locations with a distinct absence of deep pools, undercut banks, or stable debris, and with little or no suitably sized spawning gravels for the fish species present)

a See www.gov.bc.ca/wlap/ or http://www.cosewicgc.ca/cosewic.

b The indicators provided here are highly generalized and require regional interpretation. Those involved in conducting habitat assessments should contact the regional office of DFO-Habitat and the Ministry of Water, Land and Air Protection.



a See Figure 1 for habitat definitions and examples. OBS — open bottom structure, CBS — closed bottom stucture.

Figure 2. Decision-making matrix for selecting type of new installation acceptable for fish-stream crossings.

For circular culverts, the embedment should make up at least 40% of the culvert diameter or 0.6 m, whichever is greater. For pipe-arch or box culverts, embedment depth should be at least 20% of the vertical rise of the arch.

Downstream weir:
An instream weir (see Figure 10) should be established within one and a half to two channel widths downstream of the culvert outlet, particularly for streams greater than 3% gradient, to retain substrate within the culvert and to prevent the formation of a plunge pool. The residual pool depth formed by this downstream weir should be less than 0.3 m.

Generalized study of hydraulics of culvert fishways (Ead et al., 2002)

From the first part of the paper dealing with the increased depths provided by the baffle systems, it was observed that almost all the baffle systems worked effectively, so long as the longitudinal spacing was less than the pipe diameter. Taller baffles provided larger depths and smaller mean velocities

It was found that for the relative height of the baffles h/D in the practical range of 0.1–0.15, spacing of the baffles should be limited to a maximum of one diameter of the culvert. Even though, from the hydraulics perspective, these baffle systems performed reasonably well in the range of parameters recommended, the weir and slotted weir baffle systems
are possibly the best choices, because these systems are simple and equally effective.

Turbulent open-channel flow in circular corrugated culverts (Ead et al., 2000)

Look at pipe corrugations

D~24 in

Edge velocities low for fish

Design and Construction of Aquatic Organism Passage at Road-Stream Crossings: Ecological Considerations in the Design of River and Stream Crossings (Jackson, 2003)

Survival of individual animals, facilitation of reproduction, and the maintenance of population continuity are important functions of movement at a population level.

Stream simulation

Over the short term, depending on a species' life history characteristics, the minimum viable population size ranges from 50 to 200 or more individuals (Franklin 1980, Soulé 1980). For long-term viability, estimates of minimum population size range from 500 to 5,000 or more individuals. Given the narrow, linear configuration of streams and rivers, animal movements are critical for maintaining populations large enough to remain viable.

Absence of bank-edge areas. Passage by weak-swimming organisms can be inhibited or prevented by the absence of bank-edge areas within crossing structures.

Improving Stream Crossings for Fish Passage (NMFS/CA) (Lang et al., 2004)

NMFS / California – nice study of hydrology and fish movement

Improve culvert design
Cause of failures
New standards for CA

Problems – shallow jump pools or cascades over riprap

Tier 1 sites have migratory fish
Tier 2 sites do not, and thus only hydraulics used here

Full hydrology study to gage streams and understand structure capacity

Fish used low velocity regions of culverts and channel

Flow duration and peaks regulated fish movement, clear differences annually

3 cfs low flow passage recommendation

used residual pool depths to investigate tailwater

Monitoring the Effectiveness of Culvert Fish Passage Restoration (Stockard and Harris, 2005)

The objectives for restoring fish passage for juvenile and adult salmonids are to promote migration and increase accessibility to available habitat by:

- Increasing pool depth before jumps to allow fish to accelerate for a leap attempt
- Reducing jump heights to within the range of jumping ability
- Reducing stream velocities to within salmonid swimming abilities
- Increasing flow capacity to accommodate 100-year flood events and associated debris in order to prevent future obstructions
- Maintaining or restoring bedload transport by preventing sediment buildup at the inlet or outlet
- Focusing low flows so that they are similar in depth to the natural channel

Table 1. Monitoring Questions, Parameters, Effectiveness, Criteria and Field Methods.

MONITORING QUESTION	EFFECTIVENESS CRITERIA[1]	PARAMETERS	FIELD METHODS
1. Is the project still functioning as designed?		Fish passage restoration project is within DFG passage guidelines.	
a. Is there still a sufficient jump pool depth for targeted species and life stages?	Residual pool depth at downstream outlet (if culvert outlet is perched or has entry leap).	If there is a jump, pool depth is appropriate for leap height. (Not required for no entry leap)	Field Method 1: Thalweg Profile Through Culverts plus water depths
b. Are leap heights still within jumping ability for targeted species and life stages?	Leap height (residual pool water surface elevation to passage outlet.)	Leap height is below critical heights for targeted species and life stage. (Not applicable for no entry leap.)	Field Method 1: Thalweg Profile Through Culverts.
c. Is stream velocity in critical flow areas still within the swimming ability of the target species and life stages?	Stream velocity	Stream velocity is equal to or less than swimming ability of target species and lifestage.	Field Method 3: Stream Velocity/Discharge Measurements[1]
d. Is upstream inlet of the passage area/ structure still at grade or below the channel bed?	Bed elevation at inlet and inlet elevation	Difference between natural channel bed and inlet is 0.	Field Method 1: Thalweg Profile Through Culverts
e. Is the passage area/ structure still at grade?	Slope	Passage structure is at specific designed slope or the slope relative to the natural channel.	Field Method 1: Thalweg Profile Through Culverts
f. Can sediment bed load still pass through the restored area?	Slope (top riffle to opening), active channel width, hydraulic capacity	Passage inlet shows no signs of clogging or deposition.	Field Method 1: Thalweg Profile Through Culverts, Field Method 2: Cross-section Surveys

MONITORING QUESTION	EFFECTIVENESS CRITERIA1	PARAMETERS	FIELD METHODS
g. Can the structure pass 100-year flows and debris?	Hydraulic capacity	Passage passes 100-year flows and watershed products.[2]	Field Method 2: Cross-section Surveys
h. Does the passage project shows signs of imminent failure?	Structural integrity	Structure shows no signs of collapsing.	Field Method 1: Thalweg Profile Through Culverts, Field Method 2: Cross-section Surveys
2 Have channel or bank adjustments impaired the function of the passageway?	Slope, head-cutting, sediment deposition	Channel adjustments have not impaired passage or habitat values.	Field Method 1: Thalweg Profile Through Culverts
3. Did the project have adverse effects on upstream or downstream habitat?	Bank erosion, channel incision / head-cutting, debris accumulation or sediment deposition.	Passage project has not adversely affected up and downstream habitat.	Field Method 1: Thalweg Profile Through Culverts. Field Method 2: Cross-section Surveys
4. Is upstream habitat still suitable for the targeted fish species and life stages?	Habitat types and quality in upstream reaches.	Area is still suitable for targeted species and life stages.	Habitat Monitoring See *Monitoring the Effectiveness of Instream Habitat Restoration*

this monitoring may be useful for screening in field.

Partial barrier may be passable for adults, but not juvenile salmonids. Temporal barriers limit access at specified flow regimes.

Design information taken from California manual outlined above

Guidelines for Salmonid Passage at Stream Crossings (NMFS, 2001)

This document provides guidelines for design of stream crossings to aid upstream and downstream passage of migrating salmonids.

The following alternatives and structure types should be considered in order of preference:
1. *Nothing* - Road realignment to avoid crossing the stream
2. *Bridge* - spanning the stream to allow for long term dynamic channel stabilty
3. *Streambed simulation strategies* - bottomless arch, embedded culvert design, or ford
4. *Non-embedded culvert* - this is often referred to as a hydraulic design, associated with more traditional culvert design approaches limited to low slopes for fish passage
5. *Baffled culvert, or structure designed with a fishway* - for steeper slopes

Active Channel Design Method
size a culvert sufficiently large and embedded deep enough into the channel to allow the natural movement of bedload and formation of a stable bed inside the culvert.

Stream Simulation Design Method
mimic the natural stream processes within a culvert.

Hydraulic Design Method
matches the hydraulic performance of a culvert with the swimming abilities of a target species and age class of fish.

Retrofit options too
Baffles, multiple openings, fishways, etc…

Scientific Basis of Road-Stream Crossing Assessments in the Ashuelot River Watershed (Nedeau, 2006)

Nice review of NE fish biology.

Use passage of weakest swimmer as conservative approach

Endorses MA standards

1. All culverts must be embedded
2. All crossings are to be at least 1.2x the bankfull width of the stream
3. Natural substrate must be used
4. Water depth and velocity within the crossing must match conditions upstream and downstream
5. Crossings must have a minimum openness ratio

Use ecological assessment to prioritize changes for greatest improvement

Fragmentation based on # of structures

Problems: undersized, shallow, perched, low openness ratio (x-section area:length)

Lead to water depth, flow velocity, flow heterogeneity, substrate conditions, retention and transport of materials (e.g., sediment and coarse particulate organic matter), and dry-land passage.

Review shows 4% key slope above which special designs are needed.

Brandt et al. (2005) found that waterfall height and fish size strongly affected jumping performance of YOY (young of the year) brook trout. Plunge pool depth and waterfall width affected jumping performance to a lesser extent. The only combinations of height and plunge pool depth that fish did not ascend (among waterfall heights of 2-24 cm and plunge pool depths of 8-18 cm) were waterfalls higher than 16 cm with 8 cm plunge pools, and waterfalls higher than 22 cm with 10 cm plunge pools. Probabilities of fish jumping the waterfall increased with the size of the fish.

a shallow plunge pool greatly reduces the height that brook trout can jump. There is evidence of brook trout ascending taller waterfalls

Adams et al. (2000) documented large brook trout ascending a 1.5 m complex falls, and smaller brook trout ascending a 0.7 m nearly vertical falls.

According to their analysis, there was only a 0.04% chance that minnows could pass waterfall barriers greater than 35 cm. Larger minnows could jump highest.

it appears that culvert flow rates should be kept below 0.30-0.40 m/s to allow successful passage of the majority of mature individuals of migratory species."
Belford and Gould (1989): Studied ability of four trout species to swim

Broad Characterization of Swimming Ability

Weak Swimmers

Small benthic species (e.g., sculpins, darters, burbot)

Early life stages (age-0 and juvenile) of larger benthic and pelagic species

Weak-Marginal Swimmers

Small pelagic species (e.g., sunfish, dace, shiners)

Medium benthic species (e.g., creek chubsucker, bullhead)

Juveniles of large benthic and pelagic species

Marginal-Strong Swimmers

Large pelagic and benthic species (e.g., fallfish, creek chub, suckers, perch, bass, pickerel)

Strong Swimmers

Large pelagic species (e.g., salmon, trout, shad, alewife)

Table 2. Northeastern stream fish grouped by taxonomic affinity and athletic performance. Species marked with an asterisk (*) collectively comprise the majority of fish biomass in most 0-4 order streams.

Group	Species
Group A Salmonidae	Brook Trout*
	Rainbow Trout*
	Atlantic Salmon*
	Brown Trout*
Group B Large Cyprinidae + Catostomidae	White Sucker*
	Creek Chub*
	Fallfish*
	Longnose Sucker*
	Lake Chub
	Creek Chubsucker
Group C Small Cyprinidae	Blacknose Dace*
	Longnose Dace*
	Common Shiner*
	Spottail Shiner
	Redbelly Dace
	Finescale Dace
	Silvery Minnow
	Bridle Shiner
	Golden Shiner
	Pearl Dace
Group D Benthic Non-Minnows	Slimy Sculpin*
	Tesselated Darter*
	Burbot
Group E Bass, Pickerel, and Perch	Chain Pickerel
	Yellow Perch
	Largemouth Bass
	Smallmouth Bass
	Rock Bass
Group F Sunfish	Bluegill
	Pumpkinseed Sunfish
	Banded Sunfish
	Redbreasted Sunfish
Group G Catfishes	Brown Bullhead
	Yellow Bullhead
Group H Eels and Lampreys	American eel
	Sea Lamprey
	Brook Lamprey
Group I Alosidae	River Herring
	American shad

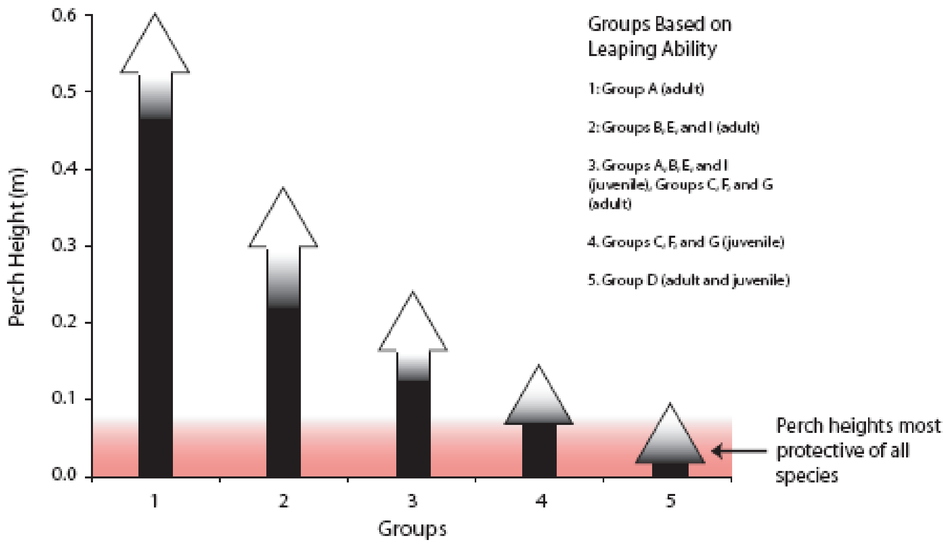


Figure 2. Perch height thresholds for species groups. The gradient from black to white indicates uncertainty and variability within the groups. The perch height protective of most species is indicated in red. Table 2 lists species groups.

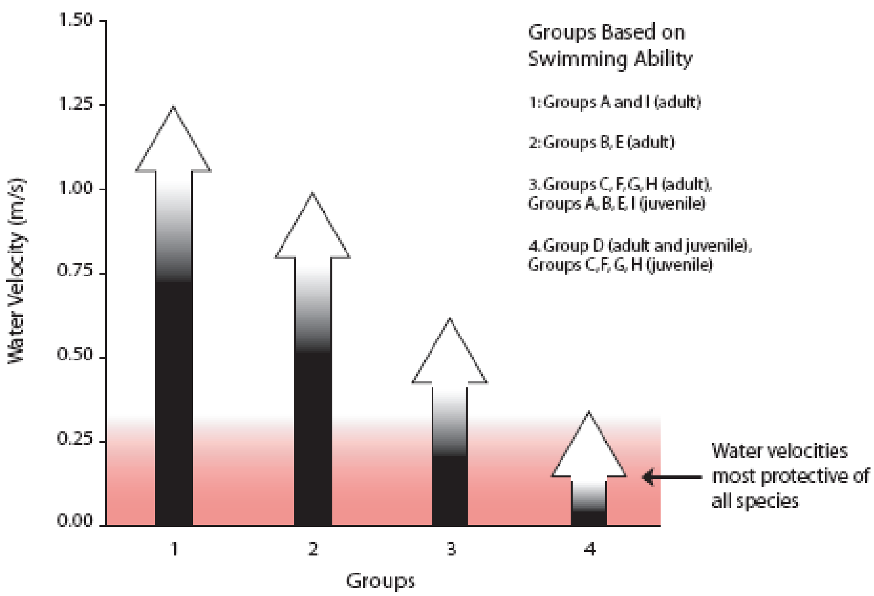


Figure 3. Water velocity thresholds for species groups to swim through a 30-m smooth culvert. The gradient from black to white indicates uncertainty and variability within the groups. The water velocity protective of most species is indicated in red. Table 2 lists species groups.

Coffman (2005) provided a general recommendation that has much broader application than the specific models that he developed: "Generally, culverts providing the greatest advantage for fish moving upstream were those with little to no outlet drop (<10 cm), gentle slopes (<2.0%), and low slope x length (< 25) values."

Research on stream crossings and fish movement by the Etowah HCP (2005) concluded that culverts should be designed so that average water velocities at low flows do not exceed 0.3 m/s, and under no circumstances should non-embedded or perched culverts (box culverts or pipe culverts) be used.

Reasons movement needed; breeding, access to thermal refuge, drought refuge, predation, segregation, feeding,

A parallel effort could rank road-stream crossings according to engineering specifications and physical measurements, and provide a "worst of the worst" list comprised of crossings that are severely perched, grossly undersized, or fail during floods. Upgrading or replacing these structures might meet economic objectives and restore physical habitat, but may do little to further the ecological goals that the Ashuelot River Continuity Project is based on. It would be instructive to compare scores/ranks derived from ecological vs. physical ranking processes to see how congruent they are. A reasonable compromise between physical measurements and ecological concerns would be to target those stream crossings that rank high in both categories.

DRAFT Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont (Bates and Kirn, 2008)

A 2004 inventory of 207 culverts in the White River watershed rated 47% of the structures as barriers to passage of aquatic organisms during summer low flow conditions while the remaining 53% of structures inventoried were rated as potential barriers. None of these structures were rated entirely "passable" (Alexander and Hammond 2004).

Studies in Michigan and Vermont have documented daily movement of adult brown trout, which leave daytime resting areas and travel upstream or downstream overnight, sometimes over a mile or more, presumably to forage, and then return to daytime home sites (Diana, 2004; Kenneth Cox, VDFW, personal communication).

Gowan and Fausch (1996) documented brook trout summer seasonal movements of over a mile and shorter distances traveled regularly by resident brook trout. Movement occurs even in high gradient streams, as evidenced by Adams et al. (2000) who observed upstream movement of brook trout in slopes as high as 22%.

Peterson and Fausch (2003) observed peak movement of brook trout in the summer and fall, with nearly 80% of recaptured fish moving upstream and up to 2km away within a summer.

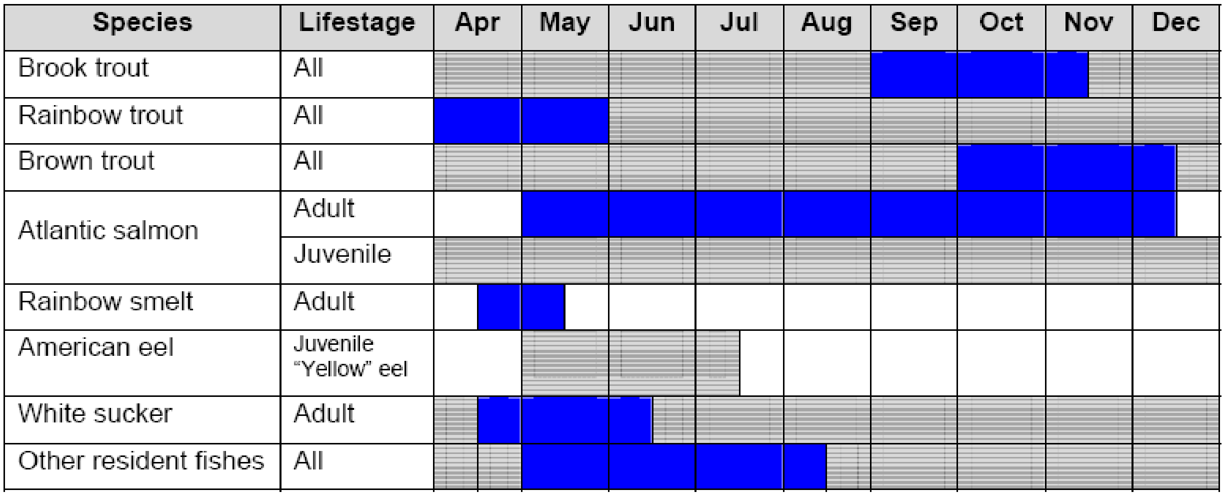
Many crossings may provide "partial" or "temporal" passage, i.e. passage for specific species or size classes, or under certain flow conditions. In addition to excluding weaker swimming species and lifestages, significant migration delays may occur for other species (Lang et al.2004), leaving fish vulnerable to predation, disease and overcrowding and potentially affecting reproductive success.

Species most commonly influences in VT - salmonids (trout and salmon), cyprinids (minnows), catastomids (suckers), osmerids (smelt), and cottids (sculpin). Aquatic salamanders associated with these habitats may include spring, two-lined and dusky salamanders.

Vertical adjustment range, the range of elevations the channel might experience through the reach in the lifetime of the new culvert. This is a key to setting the elevation of the culvert. See Section 3.3.1-Channel vertical adjustment range.

Review of headcut issues that negatively influence habitat. Aggradation problematic too.

• Low-slope option
• Stream simulation option
• Hydraulic option



Spring and Fall Spawning - High Passage Flow criteria defined

Low fish passage design flow

Maximum cross-section-averaged water velocities at the high fish passage design flow are shown in Table 6-1 for a variety of Vermont species.

• **Maximum outlet drops** for several Vermont fish species are shown in Table 7-3**.** While the avoidance of an outlet perch should be the goal of all designs, it is recognized that retrofit applications may not be able to always eliminate the drop.

• **Minimum water depth** in the culvert at the low fish passage design flow is shown in Table 7-4 for several Vermont species.

Table 7-2. Maximum velocity criteria for several Vermont fish species.

Species/Lifestage	Maximum Velocity (fps)				Reference
	Culverts <40'	Culverts 40-100'	Culverts 100-200'	Culverts >200'	
Brook trout –adult (>6") Brook trout –juvenile	2.6 1.0	2.4 0.8	2.2 0.7	1.9 0.7	Peake et. al. 1997
Brown trout – adult (>8") Brown trout – juvenile	4.5 1.7	4.3 1.7	4.1 1.7	4.1 1.7	Peake et. al. 1997
Rainbow trout – adult (>8") Rainbow trout – juvenile	4.3 1.7	3.6 1.7	3.4 1.7	3.2 1.7	Belford and Gould 1989, NA:Peake et. al. 1997 (BNT)
Steelhead trout – adult (>10") Steelhead trout – juvenile	6.0 1.7	5.0 1.7	4.0 1.7	3.0 1.7	NA: use WDFW Steelhead NA:Peake et. al. 1997 (BNT)
Atlantic salmon – adult Atlantic salmon – juvenile	6.0 2.1	5.0 2.0	4.0 1.9	3.0 1.8	NA: use WDFW Steelhead Peake et. al. 1997
Rainbow smelt	NA				NA
Longnose and White sucker – adult (10"+)	1.3				Jones et. al. 1974
Smallmouth bass-adult (>10")	3.0				Peake 2004
Minnows (Cyprinids) Darters (Percids) Sculpin (Cottids)	1.0				Warren and Pardew 1998 Jones et. al. 1974

Table 7-3. Maximum outlet drop criteria for retrofit applications for passage of several Vermont fish species.

Species/Lifestage	Maximum Outlet Drop (inches)*	Reference
Brook, brown, rainbow trout - adult	8	Kondratieff and Myrick 2006 Coffman 2005
Brook, brown, rainbow trout – juveniles;	4	Coffman 2005
Steelhead trout – adult	12	WDFW
Atlantic salmon – adult	12	NA: use WDFW steelhead criteria
Atlantic salmon – juvenile	4	NA: use trout juvenile criteria
Rainbow smelt	NA	
Longnose and White Sucker	NA	
Smallmouth bass	NA	
Darters (Percids) Sculpin (Cottids)	0	Coffman 2005

* Outlet drop is the vertical dimension from normal water level in the culvert to water level downstream.

* Pool Depth/Outlet Drop ratio > 1.25 (Stuart 1962)

NA = information not available

Table 7-4. Body depth/total length ratios and low flow depth recommendations for several Vermont fish species.

Species	Body Depth/Total Length ratio	Target Length (inches)	Target Low Flow Depth (1.5 x maximum body depth in inches)	Reference
Brook trout – juvenile Brook trout – adult	0.28	3-5 6-10	2.1 4.2	Scott and Crossman 1973
Brown trout – juvenile Brown trout – adult	0.24	3-5 6-21	1.8 7.5	Scott and Crossman 1973
Rainbow trout – juvenile Rainbow trout – adult	0.22	3-5 6-18	1.7 6.0	http://stream.fs.fed.us/fishxing/
Steelhead trout – juvenile Steelhead trout – adult	0.22	3-8 14-26	3.3 8.6	NA: use rainbow trout
Atlantic salmon – juvenile Atlantic salmon – adult (anadromous) Atlantic salmon – adult (landlocked)	0.22	3-8 14-30 24-36	3.3 9.9 11.9	Scott and Crossman 1973
Rainbow smelt	0.14	4-8	1.7	Scott and Crossman 1973
White sucker	0.20	3-14	4.2	Scott and Crossman 1973
Longnose sucker	0.18	3-10	2.7	Scott and Crossman 1973
Smallmouth bass	0.28	3-18	7.6	Scott and Crossman 1973
Minnows (Cyprinids) Darters (Percids) Sculpin (Cottids)	0.16-0.26	3-5	2	Scott and Crossman 1973
Fallfish	0.21	3-12	3.8	Scott and Crossman 1973

energy dissipation factor (EDF).

Verify the largest bed particle size is less than one quarter the culvert bed width.

Scott Jackson at The University of Massachusetts at Amherst (UMASS). Thirty-one barriers were categorized as Priority 1 for restoration, 128 as Priority 2, 172 as Priority 3 and 275 as Priority 4. Prioritization was based solely on habitat, but network lengths were calculated to illustrate the degree of aquatic habitat fragmentation in the watershed.

In aggregate, road crossings on tributary streams represent a serious fragmenting feature in the Westfield watershed.

The algorithm assigns points for each answer on the road-stream crossing field form and calculates a total score from 0-10 (Figure 3). These numeric scores were translated to categories: severe, moderate, or minor barrier, meets general standards, or meets optimal standards.

Reaches were assessed algorithmically based on their spatial relationship with previously defined areas of importance (data developed by various state and federal agencies that represent an assessment of biological diversity or health). Based on the outcome of the algorithm, each reach was assigned a standard that every road crossing on that reach *should* meet. **Class A** standards were applied in areas where crossings might adversely impact Living Waters Core habitats or special BioMap Core habitats (designated for vertebrate animals). **Class B** standards were applied in areas designated as high quality ecosystems because they fell within Areas of Critical Environmental Concern (ACEC), BioMap cores, known anadromous fish runs, streams that supported coldwater fisheries, or were designated as either federal or state wild and scenic corridors. Streams that do not fall within any of the above areas **(Class C)** should at least meet general standards to allow passage of fish species and maintain some stream continuity.

Applying a length-of-network, drainage area, or unique habitat filter to project selection, DSI dam would be chosen over Coles Brook. However, restoration of Coles Brook has significant ecological merit (that dam fragments exemplary aquatic habitat, increases the temperature of an otherwise coldwater stream, and the impoundment drowned a large shrub swamp). Opportunity and feasibility also play an important role.

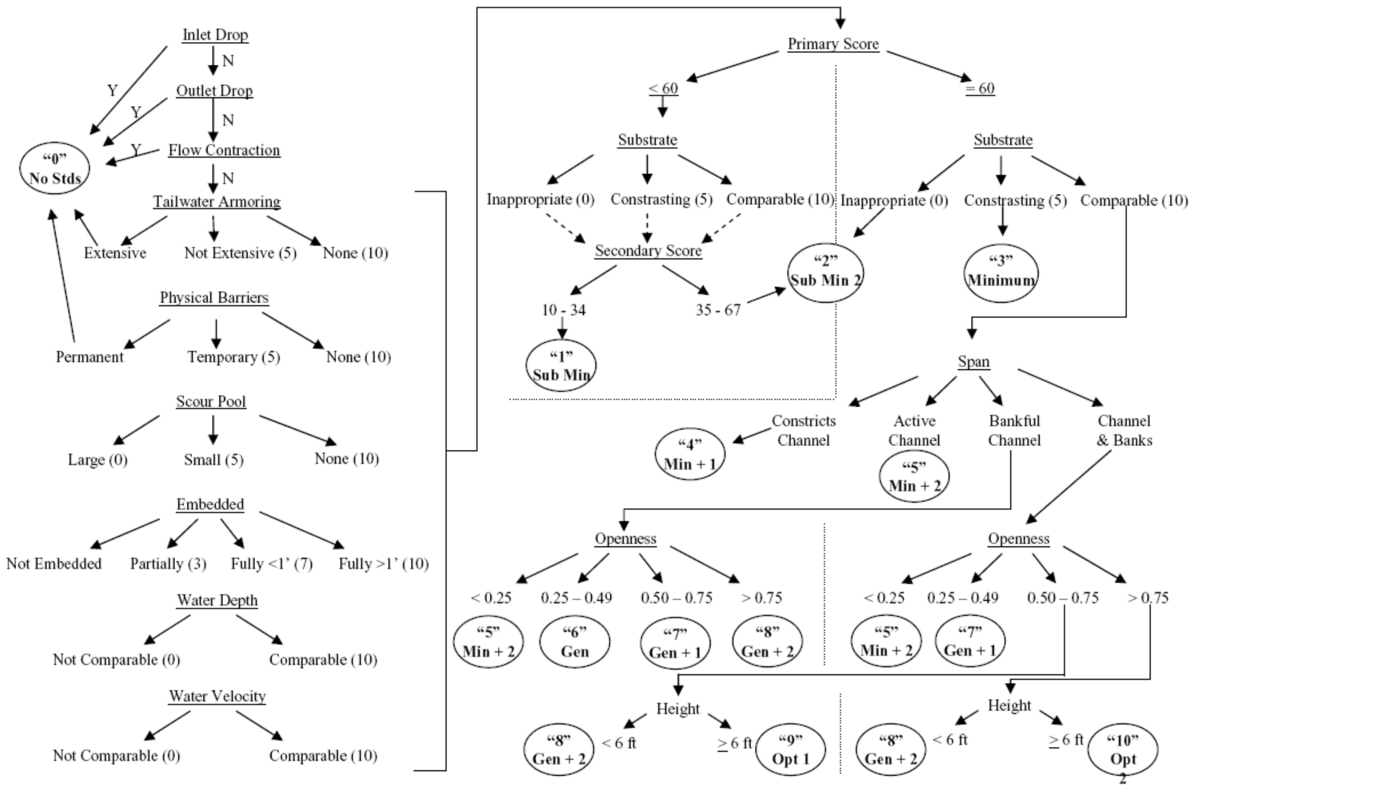


Figure 3. Scoring flowchart for road-stream crossings based on 2006 Massachusetts River and Stream Crossing Standards.

Merge MA reach habitat prioritization based on above scoring, and tnc watershed priority based on criteria below. To get restoration priorities on map on next page.

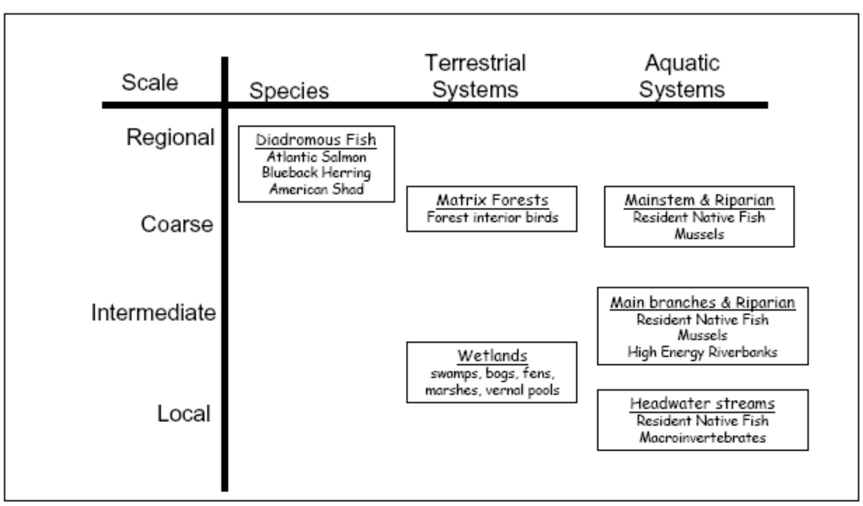
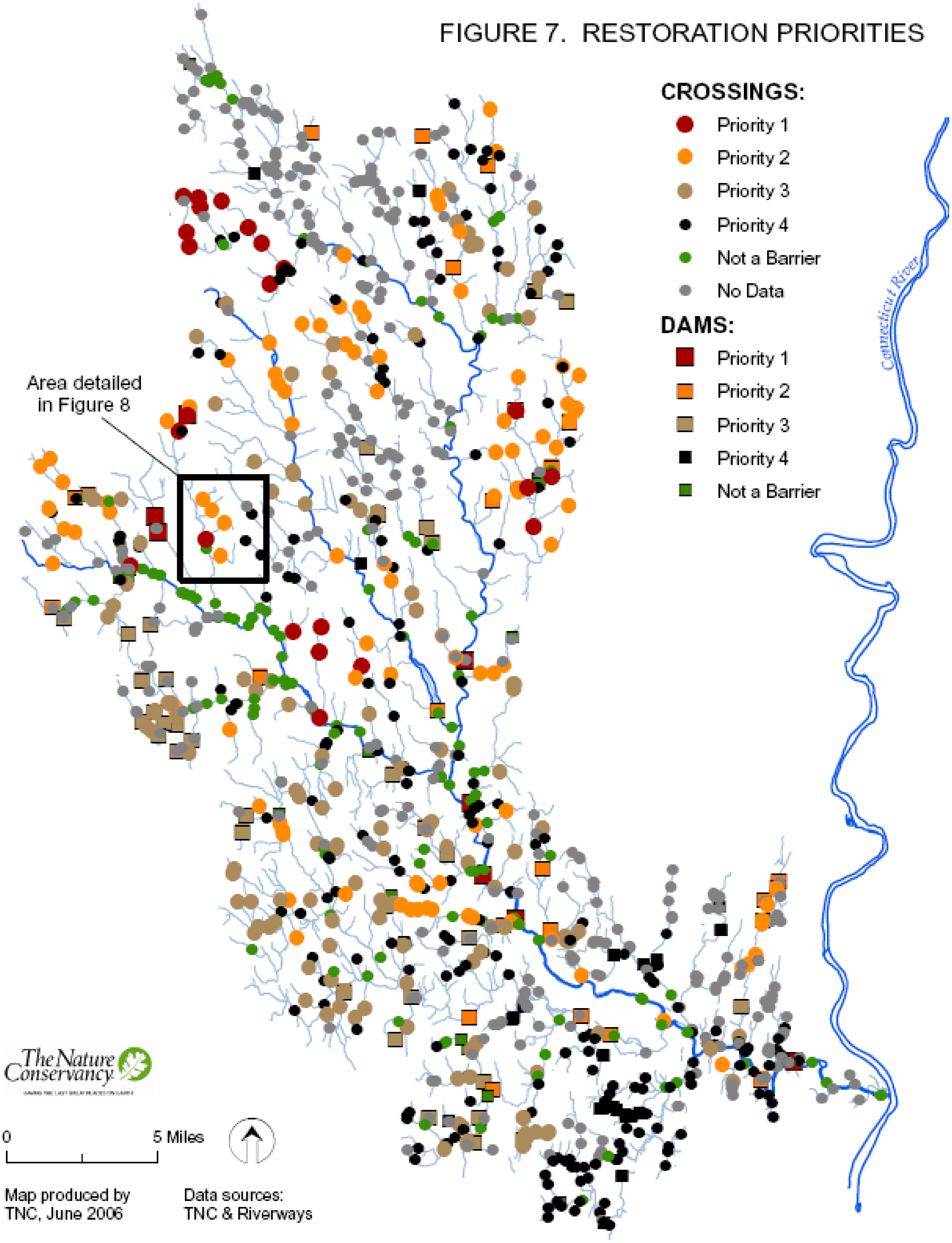


FIGURE 7. RESTORATION PRIORITIES



Memorandum of Agreement between Alaska Department of Fish and Game and Alaska Department of Transportation and Public Facilities for the Design, Permitting, and Construction of Culverts for Fish Passage (ADF&G, 2001)

Design flood is 2-yr for 2 day duration for mainland and 40% of this for southeast and coast

2.5 D min water depth (D is height of caudal fin)

3 tiers 1 natural, 3 most unnatural, and requiring most engineering design
stream simulation (tier 1)
fish pass h and h (tier 2)
hydraulics (tier 3)

outlet flow control via tailwater ideal for aop. Grayling showed most white muscle fatigue battling exit turbulence so need to increase depth to keep outlet flow subcritical.

3% or larger slope use baffles

overflow culverts in stream with narrow channel and wide floodplain

avoid debris racks or interceptors

consider watershed land use change leading to increased flow and sediment

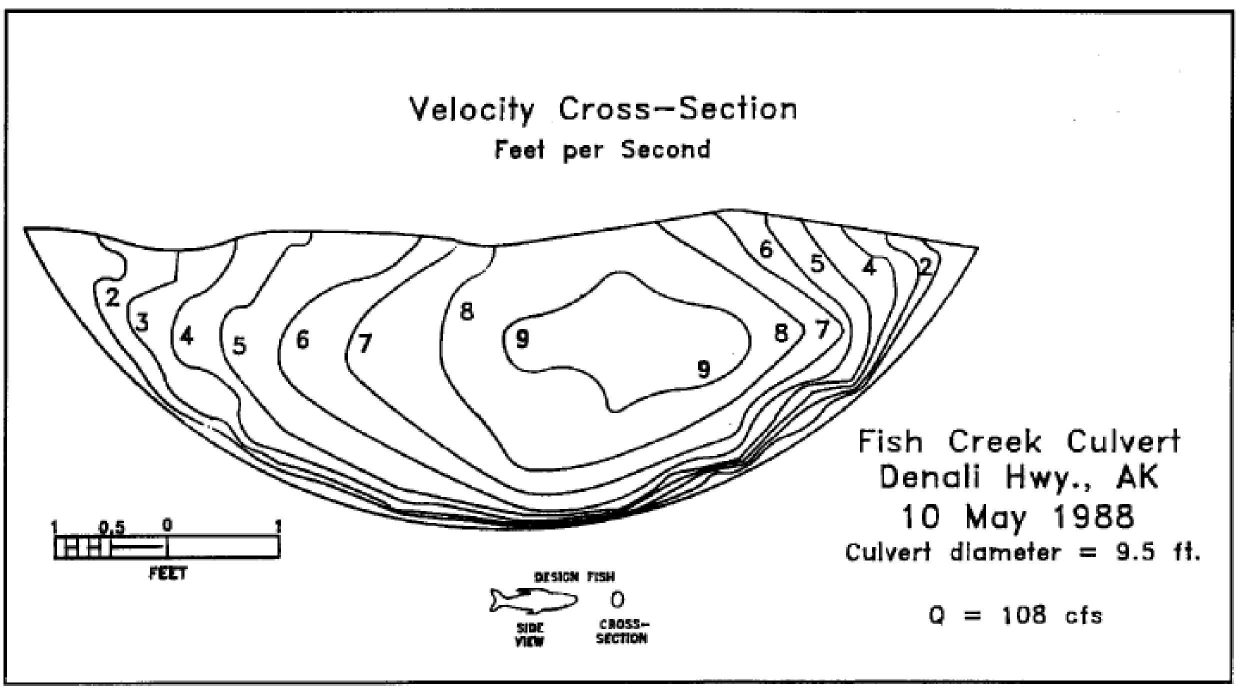
Fundamentals of Culvert Design for Weak Swimming Fish (Behlke et al., 1991)

Arctic Grayling
Long Nose Sucker
Northern Pike
Stickleback
Whitefish
Burbot
Sheefish
Smelt
Sculpin
Dolly Varden/Arctic Char
Upstream migrant salmon fry

2 day delay for grayling ok, truncate mean annual spring flood for design flow

seems like outlet hydraulics key first step, then length and presence of resting, and then last inlet hydraulics channalge.

Look at tailwater control. Sediment filling this location? Outlet pool depth key. Recommends gabion or log weirs to control tailwater, or series of them. bedload collectors, baffles



circular culverts d=0.3 D of pipe gives best swimming area for passage.
Elliptical culverts tend to work better for aop

Contraction zone at inlet? Deceleration in barrel

5 fps for weak swimmers in barrel

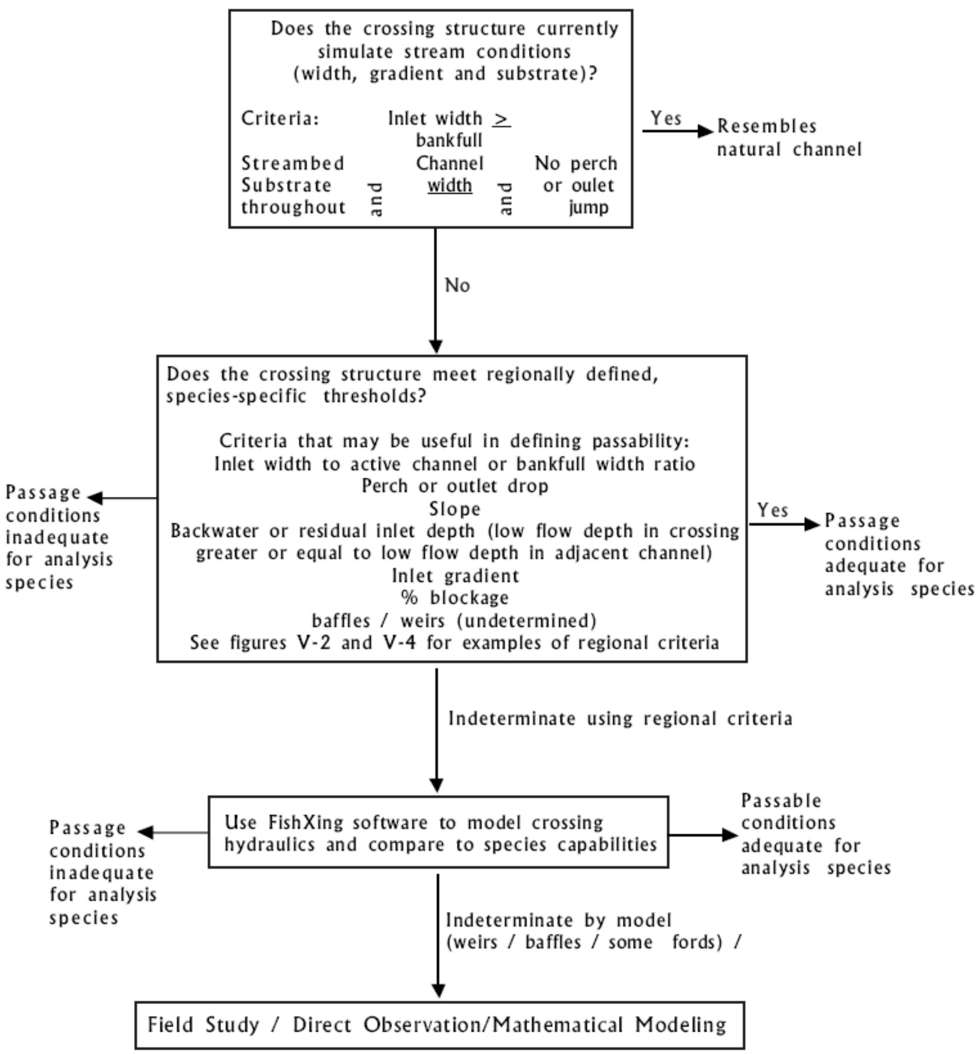
Table IV-1. Discharges and velocities at various critical depths for a range of circular culvert diameters.

Culvert Diameter (ft)	Critical Depth (ft)	Q at Critical Depth (ft^3/sec)	Average Cross-Sectional Velocity of Flow (ft/sec)
3	1	10.0	4.9
	2	37.8	7.6
6	1	14.6	4.7
	2	56.5	6.9
	3	123.1	8.7
	4	213.8	10.7
8	1	17.0	4.7
	2	66.4	6.8
	3	145.7	8.5
	4	252.8	10.1
	5	387.4	11.7
10	1	19.1	4.7
	2	75.0	6.7
	3	165.4	8.3
	4	288.1	9.8
	5	441.6	11.2
12	1	21.0	4.7
	2	82.8	6.7
	3	183.0	8.3
	4	319.8	9.7
	5	491.4	11.0
14	1	22.8	4.7
	2	89.8	6.7
	3	199.1	8.2
	4	348.8	9.6
16	1	24.4	4.7
	2	96.4	6.6
	3	214.1	8.2

NATIONAL INVENTORY AND ASSESSMENT PROCEDURE—For Identifying Barriers to Aquatic Organism Passage at Road-Stream Crossings (USFS) (Clarkin et al., 2005)

1Establish the watershed context
2Collaboratively establish criteria for regional screens
3Conduct the field inventory
4Determine barrier category: natural channel resemblance or species-specific crossing category
5 Map barrier locations and overlay on habitat-quality maps to set priorities for restoring connectivity

Figure V-1. Passage assessment process



passage assessment

coarse screen – simulate natural channel in terms of substrate throughout, bankfull width, perch/jump absent, transport all debris and sediment,

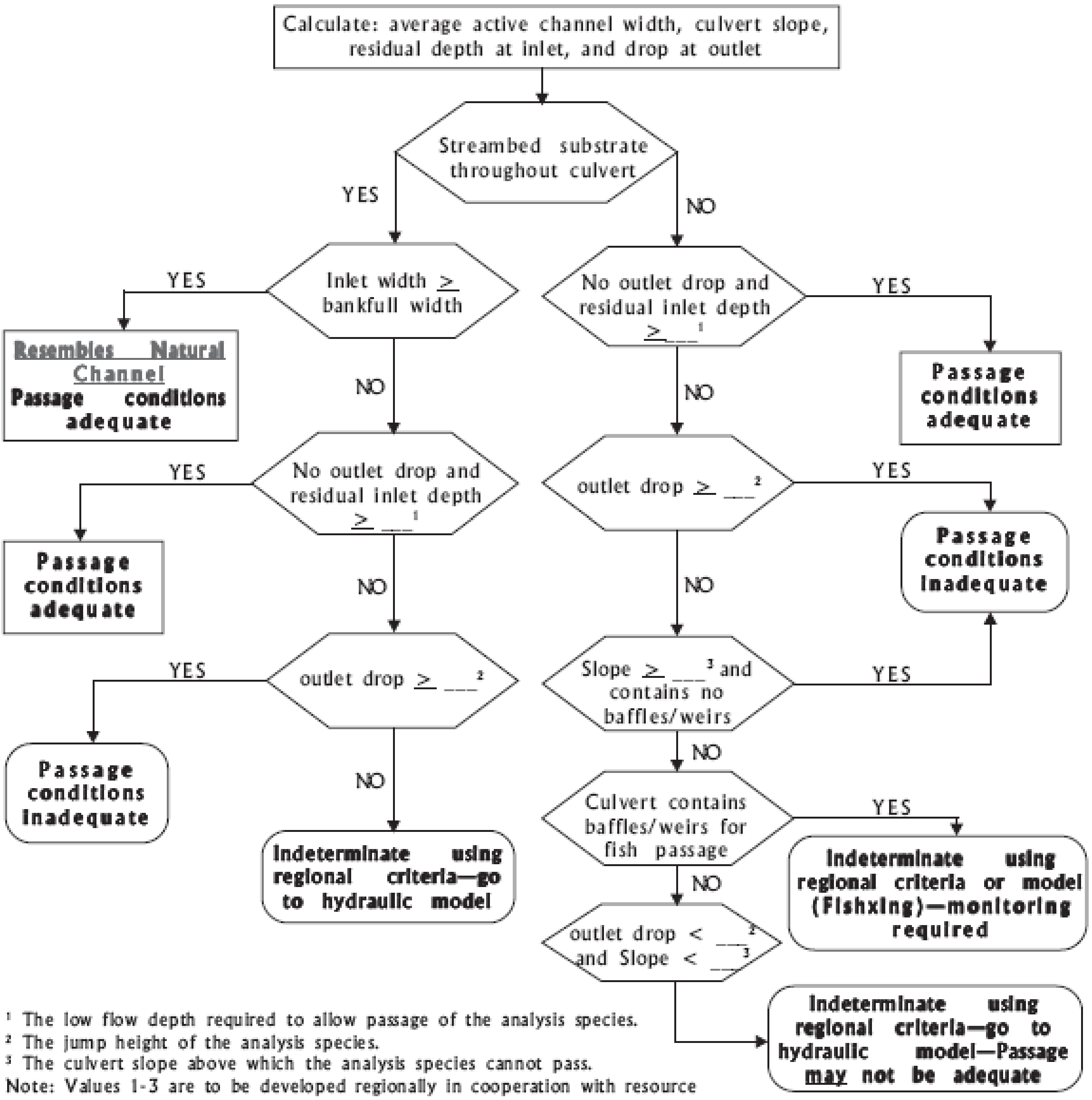
In the field, evidence of similarity in embedded structures that have been in place for several years is: lack of bedload or debris accumulation upstream of the structure (caused by the structure), lack of downstream scour, and low flow depths similar to those in the natural channel. Upstream of the structure, look for unusual bank erosion, and for finer bed material and lower slopes than in adjacent sections (evidence of aggradation). Downstream, look for abrupt slope changes and larger bed material (evidence of degradation). Keep in mind that nearby tributaries can modify streambed particle sizes as well. Also keep in mind the age of the structure. If it is new, the channel may still be adjusting to installation, so determining whether the crossing will function like the adjacent natural channel may not be possible.

Regional screen - Regional analysis species criteria are thresholds that reflect the species, life stage, or species group's ability to swim through or leap into crossing structures.

The screening procedure should quickly classify crossings into one of four categories:
• Crossing resembles adjacent channel: passage assumed for aquatic species
• Meets criteria: passage conditions are adequate for the analysis species for which the screen is designed
• Fails criteria: passage conditions are inadequate for the analysis species for which the screen is designed
• Indeterminate barrier category: requires hydraulic or other analysis.

These barrier categories are species specific, so it is possible for a crossing to be in more than one category (eg. adequate for adults, indeterminate for juveniles).

APPENDIX B Fill-in-the-Blank Regional Screen, California model



1 The low flow depth required to allow passage of the analysis species.
2 The jump height of the analysis species.
3 The culvert slope above which the analysis species cannot pass.
Note: Values 1-3 are to be developed regionally in cooperation with resource management

Passage inadequate: Crossing does not meet the criteria for the analysis species for which the screen is designed.
Indeterminate barrier category: for analysis species using the screen.

Example Only

Figure V-3. Alaska fish-passage evaluation criteria (juvenile coho) USDA Forest Service Region 10				
	Structure	Green[1]	Gray[2]	Red[3]
1	Bottomless pipe arch or countersunk pipe arch, substrate 100% coverage and invert depth greater than 20% of culvert rise.	Installed at channel grade (+/- 1%), culvert span to bedwidth ratio of 0.9 to 1.0, no blockage.	Installed at channel grade (+/- 1%), culvert span to bedwidth ratio of 0.5 to 0.9, less than or equal to 10% blockage.	Not installed at channel grade (+/- 1%), culvert span to bedwidth ratio less than 0.5, greater than 10% blockage.
2	Countersunk pipe arches (1x3 corrugation and larger). Substrate less than 100% coverage or invert depth less than 20% of culvert rise.	Grade less than 0.5%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75.	Grade between 0.5 to 2.0%, less than 4" perch, less than or equal to 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 2.0%, greater than 4" perch, greater than 10% blockage, culvert span to bedwidth ratio less than 0.5.
3	Circular CMP 48 inch span and smaller, spiral corrugations, regardless of substrate coverage.	Culvert gradient less than 0.5%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75	Culvert gradient 0.5 to 1.0%, perch less than 4 inches, less than or equal to 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Culvert gradient greater than 1.0%, perch greater than 4 inches, blockage greater than 10%, span to bedwidth ratio less than 0.5.
4	Circular CMPs with annular corrugations larger than 1x3 and 1x3 spiral corrugations (>48" span), substrate less than 100% coverage or invert depth less than 20% culvert rise.	Grade less than 0.5%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75.	Grade between 0.5 to 2.0%, less than 4" perch, less than or equal to 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 2.0%, greater than 4" perch, greater than 10% blockage, culvert span to bedwidth ratio less than 0.5.
5	Circular CMPs with 1x3 or smaller annular corrugations (all spans) and 1x3 spiral corrugations (>48" span), 100% substrate coverage and substrate depth greater than 20% of culvert rise.	Grade less than 1%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75	Grade 1.0 to 3.0%, perch less than 4 inches, less than or equal to 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Culvert gradient greater than 3.0%, perch greater than 4 inches, blockage greater than 10%, culvert span to bedwidth ratio less than 0.5.
6	Circular CMPs with 2x6 annular corrugations (all spans), 100% substrate coverage and substrate depth greater than 20% of culvert rise.	Grade less than 2.0%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75	Grade 2.0 to 4.0%, less than 4" perch, less than or equal to 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 4.0%, greater than 4 inch perch, greater than 10% blockage, culvert span to bedwidth ratio less than 0.5.
7	Baffled or multiple structure installations		All	
8	Log stringer or modular bridge	No encroachment on bedwidth.	Encroachment on bedwidth (either streambank).	Structural collapse.

Note: Larger corrugations increase roughness allowing for fish passage at steeper culvert gradients.

[1]Green – Conditions at the crossing are assumed adequate for fish passage
[2]Gray – Conditions at the crossing may not be adequate for fish passage, additional analysis required.
[3]Red – Conditions at the crossing are assumed to be not adequate for fish passage, additional fieldwork and analysis required.

after regional screen, move on to hydraulics if more information needed on aop.

Then, prioritize for restoration

Watershed context
Reduce chance of invasive movement

Scheme for prioritization – quantity and quality of habitat cut off, species status, risk of structural failure, presence of nearby other barriers, access and habitat use, biodiversity of natives, known barriers, social and economic factors

APPENDIX A EXAMPLE SCHEME FOR SETTING PRIORITIES— MODIFIED FROM THE CALIFORNIA METHOD

This ranking method is slightly generalized from a draft developed for California by Taylor and Love (2002); it is shown here with their permission. The original was devised primarily for coastal watersheds with potential habitat for anadromous salmonids. Some terminology has been modified to be consistent with this document, the emphasis on anadromous fish has been eliminated, and the extent-of-barrier variable has been simplified (2, below).

The ranking method assigns scores for the following parameters at each barrier crossing.

1. Species diversity

For each road crossing, add up ESA-listing status scores for each species known to be within the stream reach (now or historically). Score: Endangered = 3 points; Threatened = 2 points; not listed = 1 point Consult your local State Fish and Wildlife agency, USFWS, or NMFS for species distribution and listing status.

2. Extent of Barrier

For each species and lifestage of concern at the crossing, determine whether it is a total or partial (passable at some flows) barrier. Add the scores to get a total barrier extent score. Score: Total barrier for a species and lifestage= 2 points; partial barrier for a species and lifestage=1 point.

3. Habitat quantity

Score length in feet or meters above the road crossing to the limit of distribution of the analysis species. Score: We suggest starting at some agreed on minimum (such as, 500 ft); and assign 0.5 points for each size class unit (example: 0 points for <500 ft; 1 point for 1,000 ft; 2 points for 2,000 ft; and 5.5 points for 5,500 ft).

4. Habitat quality

Assign a habitat-quality score after reviewing available habitat information as follows.

- **Score: 1.0 = Excellent**. Relatively undeveloped, "pristine" watershed conditions. Habitat features include dense riparian zones with mix of mature native species, frequent pools, high-quality spawning areas, high water quality, near natural water temperature regimes, complex in-channel habitat, channel floodplain relatively intact. High likelihood of no future human development. Presence of one or more migration barriers is obviously the watershed's limiting factor.
- **0.75 = Good**. Habitat is fairly intact, but human activities have altered the watershed, and that activity is likely to continue. Habitat still includes dense riparian zones of native species, frequent pools, spawning

gravels, good water quality, near- natural water temperature regimes, complex in-channel habitat, floodplain relatively intact. Presence of one or more migration barriers is most likely one of the watershed's primary limiting factors.

- **0.5 = Fair**. Human activities have altered the watershed. Expect continued or increased human activity that will continue to affect watershed processes and features. Habitat effects include riparian zone present that lacks mature vegetation and has non-native species, infrequent pools, sedimentation evident in spawning areas (pool tails and riffle crests). Water quality and water temperature regimes have been altered to the point that they periodically exceed stressful levels for analysis species. There is sparse in-channel complex habitat, floodplain intact or slightly modified. Presence of one or more migration barrier is probably one of the watershed's limiting factors (out of several factors).

- **0.25 = Poor**. Human activities have significantly altered the watershed with high likelihood of continued (or increased) activities, with apparent effects to watershed processes. Habitat effects include intact riparian zones absent or severely degraded, little or no pool formations, excessive sedimentation evident in spawning areas (pool tails and riffle crests), water-quality problems are stressful to lethal to analysis species, lack of in-channel habitat, floodplain severely modified with levees, riprap, and residential or commercial development. Other limiting factors in watershed most likely have higher priority for restoration than remediation of migration barriers.

5. Total habitat score

Multiply the scores for habitat quality and habitat quantity for each blocked species of concern. Add all the species together to get the total score.

6. Sizing (risk of failure)

Score each culvert according to the size of flow it was designed to accommodate. **Score**: sized for at least a 100-year flow at headwater/depth = 1, low risk = **1**; sized for at least a 50-year flow = **2**; sized for at least a 25-year flow = **3**; sized for less than a 25-year flow = **4**; sized for less than a 10-year flow = **5**.

7. Current condition

for each culvert, assign one of the following values. **Score**: good condition = **1**; fair (problems exist but are not likely to cause culvert to fail) = **2**; poor (problems could cause failure) = **3**.

For each road crossing, enter the scores into a spreadsheet and compute the total. Then, sort the list by "total score" to determine a first-cut ranking. Other sorts can be done to isolate certain kinds of crossing problems. For example, sites that have poor habitat quality may be sorted separately so that ranking at these sites can focus on culvert sizing and risk failure.

Additional Ranking Considerations

The results of the ranking matrix provide a rough, first-cut prioritized list of crossings requiring treatment. Other important factors will be considered when you decide the exact scheduling of remediation efforts.

On a site-specific basis, some or all of the following factors should be considered in refining the first-cut ranking.

1. Amount of road fill. At structures that are undersized or in poor condition, consider the volume of fill material in the road prism potentially deliverable to the stream channel if the culvert were to fail. Also consider diversion potential.

2. Presence or absence of other road crossings. Multiple roads under a variety of management or ownership may cross a single stream. Then, close communication with other road managers is important. If multiple culverts are migration barriers, a coordinated effort is required to identify and treat them in a logical sequence.

3. Presence of aquatic organisms attempting to migrate past a barrier. In Northern California, several crossings were ranked higher because of the annual presence of adult salmonids below total barriers. After treatments, the upstream habitat was immediately recolonized the following winter.

4. Remediation project cost. You should examine the range of treatment options and associated costs when determining the order in which to proceed and what should be implemented at specific sites. Where federally listed fish species are present, costs must also be weighed against the consequences of failing to comply with the ESA by not providing unimpeded passage.

Other limiting factors. Other limiting factors besides migration barriers often exist in a watershed and limit production of aquatic species. On a watershed or sub-basin scale, restoration decisions must be made after carefully reviewing potential limiting factors, the source of the effects, range of restoration options available, and what restoration activities are actually feasible.

Fish Passage Barrier and Surface Water Diversion Screening Assessment and Prioritization Manual (WDFW, 2000)

ID potential habitat gain. Accessible from downstream for anadromous or a lot of good habitat for residents? Significant means at least 200 m of good habitat with no other blocks so resident fish are there and likely trying to pass upstream. Gains for anadromous are upstream to next barrier. Gains for residents is the smaller portion of the reaches adjacent to the culvert until the next barrier or natural block. Example, 600 m downstream and 2200 m upstream, use 600 m restoration potential for prioritization.

Assessment guided if stream is fish-bearing – w>2-3', priority habitat to state, specific delineations on state maps, documented Salmonid use.

Assessment variables that could be added to vtbanc– river distance from stream mouth (to 0.01 miles), fish use, apron, plunge pool depth, length, and OHW, maintenance needed?, % passability field judgement, downstream control cross section,

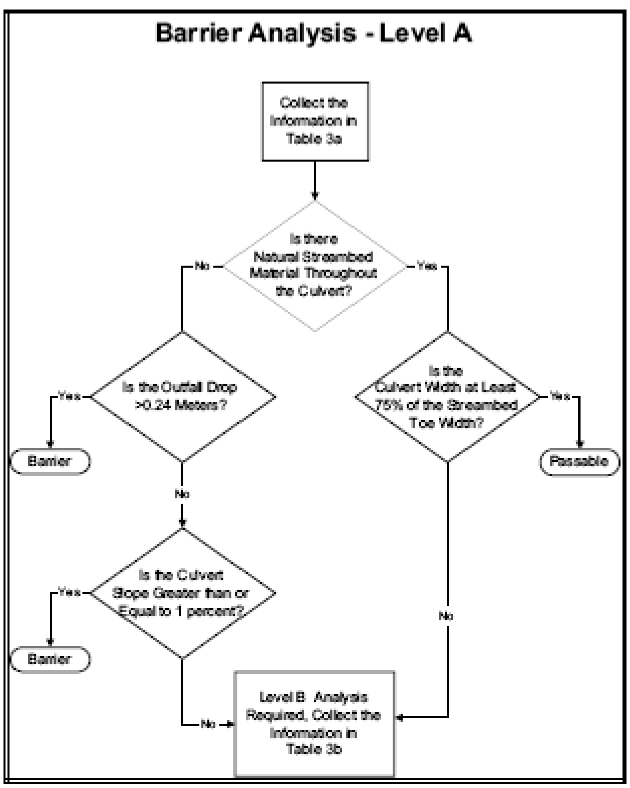


Figure 4. Flow chart of the Level A culvert analysis.

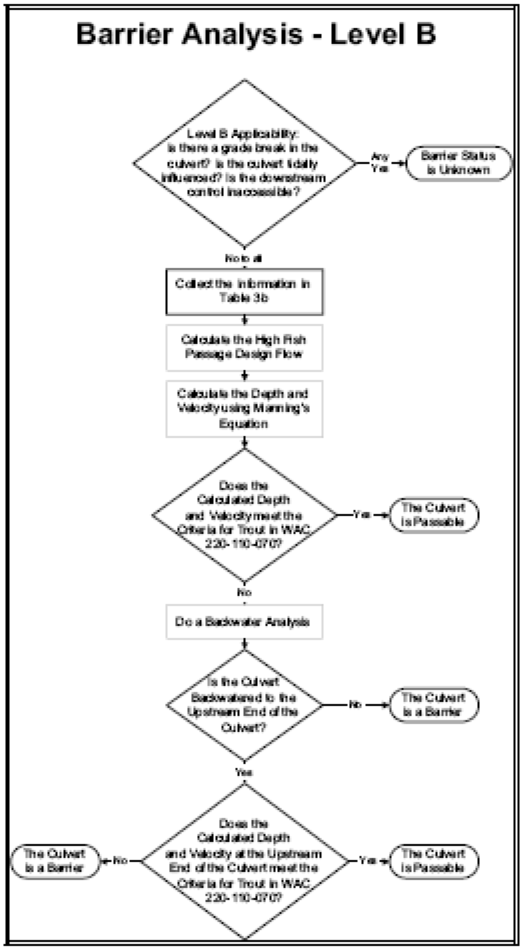


Figure 5. Flow chart of the Level B culvert analysis.

track downstream location to see next barrier. Structures can be fixed so keep going until you hit a waterfall >3.7 m tall or a stream with slope >20% for 160 meters. (anadromous #s)

use habitat score as a multiplier of habitat area to get H (potential habitat gain) in priority index.

Use 2 habitat quality modifiers that weigh the productivity for spawning and rearing.

Spawning area determined by substrate type

Input spreadsheet available

Adjusted production area based on competition

Expanded threshold determination used to create sample habitat and then extrapolated in watershed over reach

Table 11. Criteria used to assign Habitat Quality Modifiers to rearing and spawning habitat.

HABITAT QUALITY MODIFIER (HQM)			
HABITAT CONDITION	**HQM VALUE**	**REARING HABITAT CRITERIA[2]**	**SPAWNING HABITAT CRITERIA**
GOOD TO EXCELLENT	1	Rearing habitat is stable and in a normal productive state with all components functional	Spawning gravel patches have ≤16% fine particle sizes that are <0.85mm in diameter
FAIR	2/3	Rearing habitat shows moderate/widespread signs of instability and/or disturbance known to reduce productive capability (one or more habitat components missing or significantly reduced presence)	Spawning gravel patches/riffles show moderate/widespread signs of instability (scour/filling) and/or >16% and ≤21% fine particle sizes <0.85mm in diameter
POOR	1/3	Rearing habitat shows signs of major/widespread disturbance likely to cause major reductions in its production capabilities (two or more habitat components missing or severely reduced presence)	Spawning gravel patches/riffles show major/widespread signs of instability (scour/filling) and/or >21% and ≤26% fine particle sizes <0.85mm in diameter
NO VALUE	0	Rearing habitat severely disturbed so that production capabilities are with out value to salmonids at this time	Spawning gravel patches with >26% fine particle sizes <0.85mm in diameter

threshold determination to identify if a significant habitat reach exists (>200 m), with no natural barrier, not including culvert tubes, and within smaller fixable structure since larger infrastructure is often no correctable.

Slope analysis not likely very critical for brook trout

$$PI ' \sum_{all\ species} \sqrt[4]{[(BPH)\ x\ MDC\ ]}$$

Where:

PI = Fish Passage Priority Index

- Relative project benefit considering cost.

- The PI is actually the sum ($\sum_{\text{all species}}$) of individual PI values, one of which is calculated for each species present in a stream (*e.g.*, PI_{coho} is added to PI_{chum} to obtain $PI_{all\ species}$).

- The quadratic root in the equation is used because it provides a more manageable number and represents a geometric mean of factors used.

B = Proportion of passage improvement

- Proportion of fish run expected to gain access due to the project (passability after project minus passability before project); gives greater weight to projects providing a greater margin of improvement in passage.

- Barriers are assumed to be partial and have a value of 0.67. Modifications to this approach can be applied with advanced levels of expertise.

P = Annual adult equivalent production potential per m^2

- Estimated number of adult salmonids that can potentially be produced by each m^2 of habitat annually.

- The values (adults/m^2) are species specific; chinook salmon = 0.016, chum salmon = 1.25, coho salmon = 0.05, pink salmon = 1.25, sockeye salmon = 3.00, steelhead =

0.0021, bull trout/Dolly Varden = 0.0007, searun cutthroat trout = 0.037, resident cutthroat/rainbow trout = 0.04, brook trout = 0.04, and brown trout = 0.0019.

H = Habitat gain in m^2

- Measured/calculated from physical survey; gives greater weight to projects which will make greater amounts of habitat available.

- Spawning area values used for species complexes normally limited by spawning habitat (sockeye, chum, and pink salmon) and rearing area values used for species complexes normally limited by rearing habitat [(coho salmon, searun cutthroat, chinook salmon, and steelhead) and (resident cutthroat/rainbow trout and bull trout/Dolly Varden) and (brook and brown trout)].

- When more than one species within a species complex is present H is modified to reflect sympatric interactions among species with similar freshwater life histories. The result is a reduction of single species habitat area values when competing species coexist.

M = Mobility Modifier

- Accounts for benefits to each fish stock for increased mobility (access to habitat being evaluated); gives greater weight to projects that increase productivity of species that are highly mobile and subject to geographically diverse recreational and commercial fisheries by providing access to habitat currently limiting productivity.

  2 = Highly mobile stock subject to geographically diverse recreational and commercial fisheries (anadromous species).

  1 = Moderately mobile stock subject to local recreational fisheries (resident species).

  0 = Increased mobility of stock would have negative or undesirable impacts on productivity or would be contrary to fish management policy. By default, exotic salmonid species such as brook trout and brown trout are assigned a 0 value unless they are the only salmonid species present in the system.

D = Species Condition Modifier

- Representation of status of species present; gives greater weight to less healthy species as listed in the *Washington State Salmon and Steelhead Stock Inventory (SASSI)* report (WDF *et al.* 1993) and *Washington Salmonid Stock Inventory, Bull Trout/Dolly Varden* (WDFW 1997). In the absence of a SASSI assignment, stock condition should be estimated using the best available information.

  3 = Condition of species considered critical.

Oregon Road/Stream Crossing Restoration Guide (Robison et al., 1999)

Table 1: Barriers to fish passage and their potential impacts.

Barrier Category	Definition	Potential Impacts
Total	Impassable to all fish at all times	1) Exclusion of fish entirely or from portions of a watershed 2) Isolation of fish populations upstream of barrier
Partial	Impassable to some fish at all times	1) Exclusion of certain fish species or ages entirely or from portions of a watershed 2) Isolation of certain fish species or ages upstream of barrier
Temporary	Impassable to all fish some of the times	1) Delay of movement beyond the barrier for some period of time

Table 2: Biological factors related to fish passage criteria. Certain ODFW regulatory criteria differ for culvert length (L), fish species (S) and age of fish (A, adult or juvenile).

Fish Passage Criteria and Related Biological Factors	
General Regulatory Criteria	Biological Factors
Water velocity in culvert (L, S, A)	Swimming Speed
Water Depth in culvert (S, A)	Submergence (sufficient depth for swimming)
Design flow criteria (S, A)	Delays, dispersion
Height between culvert outlet and water surface (S, A)	Jumping ability
Timing of in-stream work (S)	Emergence (silting in of redds) Migration - delays or reduction of adult spawners

In order to make a culvert compatible for fish passage three provisions must occur:
1. Manage water velocities in culvert
2. Prevent drops in and around culvert
3. Provide adequate water depth

There are seven steps in restoring fish passage at road/stream crossings in a basin or land ownership:
1. Find and prioritize problem road/stream crossings
2. Get information about stream and other conditions at crossings to be restored
3. Decide if installation can be repaired or improved or must be replaced
4. Decide on design strategy based on information collected
5. Prepare a design

6. Install new road/stream crossing structure
7. Monitor and Maintain road/stream crossing structure.

Criteria used in deciding if a culvert had a fish passage “problem” in ODFW- Oregon Department of Transportation state and county road/stream crossing surveys included a slope greater than 1% and an outlet jump greater than one foot if only adult passage was considered and six inches if juvenile passage was also considered. If a jump occurred the pool needed to be 1.5 – 2.0 deeper than the height of the jump. Another concern that put culverts into the problem category were inlet deposits and drops at the inlet which was termed “diving flow.”

Partial block = juvenile block at some time

For bare (non embedded) culverts:

slope should not exceed 0.5%.

The outlet drop should be no more than 2 foot from the culvert outlet lip to the residual pool water elevation.

To control constricting of flow at the inlet, the culvert diameter or span should be at least 2 the width of the natural bankfull channel.

The culvert should be less than 100 feet long.

There is outlet backwatering such that the water depth even at baseflows is 12 inches deep.

For embedded culverts:

simulated natural channel. The material should in most places be a foot or more deep.

There should be no outlet drop.

The culvert width should

also at least 90% of the average bankfull channel width to prevent channel constriction,

Complete block = adult block at some time

For bare (non embedded) culverts:

Culvert slope should not exceed 4% unless there is backwatering or unless the culvert is less than 50 feet long.

The outlet drop should be no more than 4 feet from the culvert outlet lip to the residual pool water elevation.

The culvert should be less than 200 feet long.

For embedded culverts:

simulated natural channel inside

There should be minimal outlet drop

The inlet should have tapering streambed material into it not a sudden drop at the inlet. The culvert width should also be at least 1/2 the bankfull channel width

According to ODFW guidance an acceptable level of risk of failure is that the fill should remain structurally stable up to a 100 year peak flow by design.

ODF in contrast, specifies that culverts
and bridges should pass the 50 year peak flow to the top of the culvert (not to structural integrity of the fill) or to 3 feet below the bridge bottom.
Type 1: Culverts that ℑblockE fish passage (see previous section) to potential coho salmon habitat or have high crossing failure risk to downstream coho salmon habitat within two stream miles downstream.

Type 2: Culverts that ℑimpedeE fish passage to potential coho habitat or have moderate risk of fill failure that could affect downstream coho salmon habitat within stream miles downstream of crossing.

Type 3: Culverts that block or impede fish passage to potential steelhead or sea run cutthroat trout habitat or have high to moderate risk of fill failure that could affect steelhead or sea run cutthroat habitat within two stream miles downstream of crossing.

Type 4: Culverts that block or impede fish passage of any gamefish (generally resident rainbow or cutthroat trout define upstream extent of fish) or crossings that have a high risk of fill failure that can affect resident fish habitat within two stream miles downstream of the crossing.

Type 5: Culverts on non-fish bearing streams that have a moderate to high risk of failure.

1. Get required information on all culverts using a survey protocol (see section 7)
2. With the survey information calculate whether the culvert has characteristics that would cause it to be classed as a blockage or impediment to fish passage or a moderate or high failure risk. Also determine what the fish use (or potential fish use) is upstream and downstream (up to two stream miles) from the crossing.
3. With the fish passage, failure risk, and fish use classifications assign each culvert a priority type as defined above.
4. Sort the database based on classification into the five types.
5. Based on information such as the actual potential habitat blocked (in terms of stream miles and quality) to further prioritize crossings within each type. Examine the highest priority ones in each type to see if it can be ranked above some of those in a higher priority type. This step should be done in consultation with the local fish biologist and possibly forest practices forester and other local expertise.
6. After doing all this rank all the culverts examined.

After setting this scheme up, it must be stressed that prioritizing and then targeting crossings for repair and replacement is extremely complex with dozens of technical and social factors to consider. It may be that there is a lower priority culvert that has a landowner that is willing to fix it at his or her cost. Obviously even though this is a lower priority, it still represents an excellent opportunity. However, if a local entity like a watershed council is given a lump sum of money, this scheme can be useful in determining which culverts to fix in what order and can be used as a base to add the other less quantifiable factors concerning crossing priorities to be built upon it.

Table 5. Field and map based estimates of fish presence from ODF rule guidance.

Type of Barrier		Physical Survey		Map Analysis
		Salmon & Steelhead	Resident Trout	
Falls & Chutes		8'+	4'+	Any waterfall marked on a map.
		2'+ require a jump pool 1.25 times the fall or chute height.		
Channel Steepness	With Pools	30' or more @ 20%+	20' or more @ 20%+	20%+
	W/O Pools	30' or more @ 12%+	20' or more @ 12%+	
Lack of Livable Space		No pools approximately 12" or more in depth during spring spawning.		60 Acres or Less (Coast 80 Acres or Less (South Coast) 100 Acres or Less (Interior) 300 Acres or Less (Siskiyou) 350 Acres or Less (Blue Mountain and East Cascade)

listed culvert was rated as HIGH, MEDIUM or LOW priority for repair by ODFW field staff most familiar with fish populations and habitat in each stream. The ratings indicated in the database are generally based on:

< the number and status of species present;

< population size and condition; and

< the estimated quantity and quality of habitat blocked.

No effort was made to include factors such as estimated cost of repair, proportion of passage improvement or estimated increase in production; there were too many unknowns associated with these elements.

In most cases, staff were sufficiently familiar with the relevant

Fish Passage Through Road Culverts (Gardner, 2006)

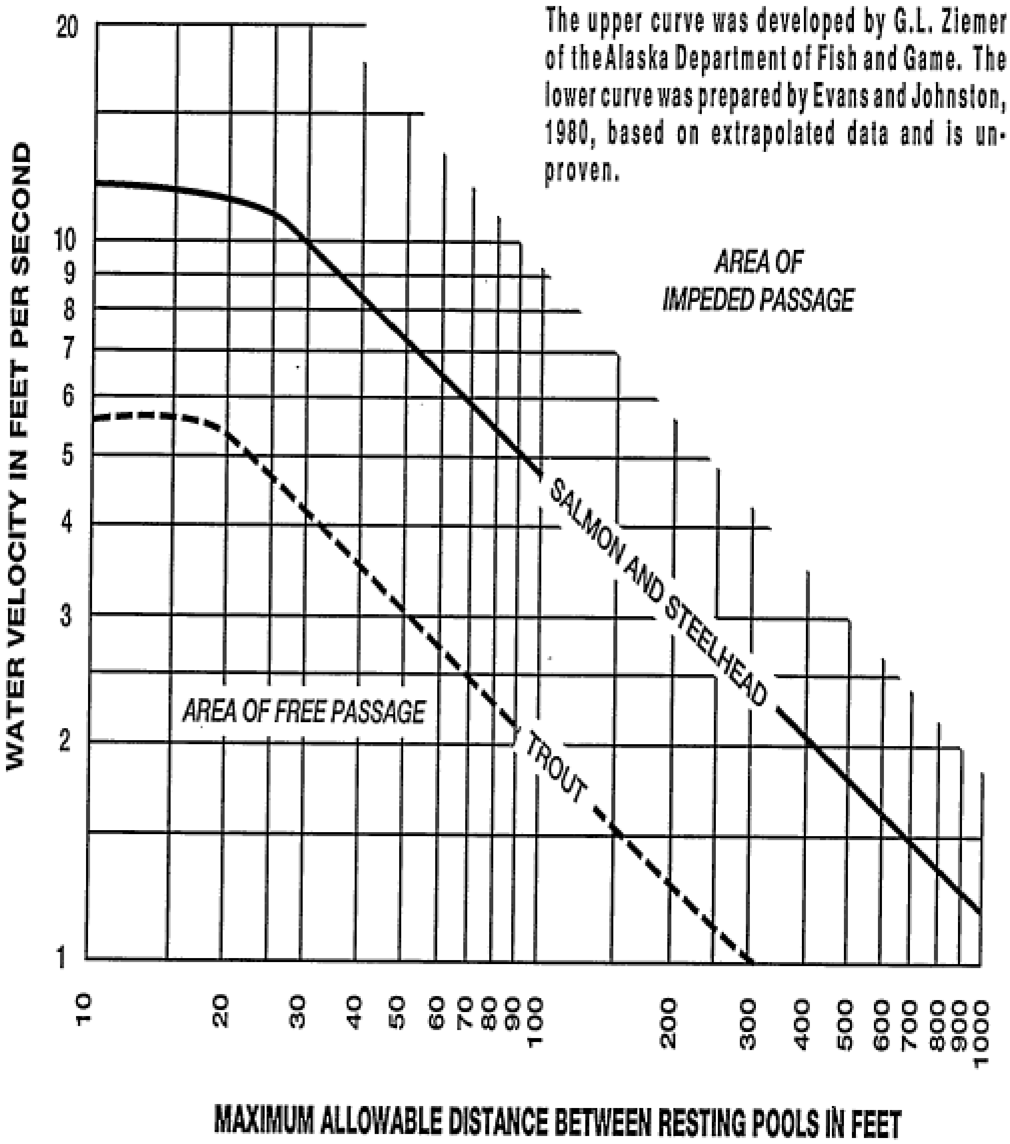
To develop a regional screen, a list of species must be selected. “The ideal crossing is one that passes all aquatic organisms and terrestrial species that require stream or streamside zones to move (Clarkin et al. 2003).”

Used clarkin et al. screening algorithm

Flume experiments to get length v critical velocities

Fish passage through culverts *(Baker and Votapka, 1990)*

Good information on fish biology and passage



Inlet control occurs when the culvert barrel is capable of conveying more flow than the inlet of the culvert will accept. When a culvert is flowing under inlet control, the capacity of the culvert is controlled by four factors:

1. Depth of headwater.
2. Cross-sectional area.
3. Inlet edge configuration.
4. Barrel shape.

Under outlet control flow, factors at the culvert outlet or immediately downstream are determining the flow capacity of the culvert. The capacity is determined by the following eight factors:

1. Depth of headwater.
2. Cross-sectional area.
3. Inlet edge configuration.
4. Barrel shape.
5. Culvert slope.
6. Culvert length.
7. Culvert roughness.
8. Depth of tailwater.

Fish Passage Conservation Practice Standard (Code 396) (NRCS, 2006)

Planning and Evaluation
Evaluate sites for variations in stage and discharge, tidal influence, hydraulics, geomorphic impacts, sediment transport and continuity, and organic debris movement.

Design passage features to account for the known range of variation resulting from this evaluation.

Minimize any foreseeable channel plan or profile shifts resulting from the modification or removal of a passage barrier.

Plan and locate passage for compatibility with local site conditions and stream geomorphology, to the extent possible.

Avoid locating fishway entrances and exits in areas that will obstruct function, increase harassment or predation, or result in excessive operation and maintenance requirements.

(OR/WA BLM, 2005)

Prioritization Variables

District Priority
Stream Name
Culvert Location (UTM, Lat/Long)
List the Anadromous Species Benefited…
List the Resident Species Benefited…
List Other Salmonid Species that would be benefited…
Miles of Habitat Upstream of Culvert for each Species
Quality of Habitat Upstream of Culvert for each Species (Good, Fair, Poor)
Number of Downstream Barriers
Coordination/ Partnerships - Indicate if local partners involved with prioritization. Y/N
Cost Estimate ($ x 1000)
Comments

Instructions:

District Priority: Highest priority are those culverts that if replaced would have the greatest positive impact to salmonids.
Stream Name: Give local name.
Culvert Location: Provide the UTM (indicate NAD 27 or 83) or Lat/Long (Deg, Min, Sec) of the culvert.
List Anadromous Species Benefited: Coho Salmon = CO, Chinook Salmon = CH, Steelhead = ST, Cutthroat Trout = CT
List Resident Species Benefited: Cutthroat Trout = CT, Rainbow Trout = RBT, Bull Trout = BT
Other Salmonid Species: List any other salmonid species that would benefit from the culvert replacement.
Miles of Habitat Upstream of Culvert for each Species: Show to the nearest quarter mile the amount of spawning, rearing and/or migration habitat upstream of the culvert for each species.
Quality of Habitat Upstream of Culvert for each Species: Indicate the quality of spawning, rearing or migration habitat upstream of the culvert for each species. Use Good, Fair, or Poor descriptors.
Number of Downstream Barriers: Include natural and man-made barriers to upstream juvenile movements.
Coordination/ Partnerships: Indicate if local partners (other federal, state, or local agencies or watershed councils) were involved with the district prioritization of this culvert.

Cost Estimate: Include all costs (planning, design and implementation) associated with replacing the culvert. These data will not be used to prioritize the culvert but will assist in developing a strategy for additional funding.
Comments: Add any additional information you feel is needed to justify the culvert's priority ranking. Also include NEPA, ESA, and design status.

Appendix C – ANR Culvert Screening – List of Additional Variable to Consider for Prioritization

Variable	Reference(s)	Notes
openness ratio	*(MARSCP, 2006), (Bowden, 2006)*	(cross sectional area / length) >0.25 m
grade controls present	*(MARSCP, 2006), (BCMF, 2002)*	
local habitat quality and quantity	*(MARSCP, 2006), (Stockard and Harris, 2005), (Nedeau, 2006), (Clarkin et al., 2005), (WDFW, 2000), (Mirati, 1999), (OR/WA BLM, 2005)*	quality x quantity above crossing (Taylor and Love 2003),(WDFW, 2000), WA uses at least 200 m up and downstream, with potential for residents being smaller of up and downstream lengths to be recovered.
number of crossings and discontinuities (fragmentation)	*(MARSCP, 2006), (Nedeau, 2006), (Clarkin et al., 2005), (WDFW, 2000), (OR/WA BLM, 2005)*	a discontinuity is a piped or channelized section
Jump, or plunge, pool present	*(FHWA, 2007), (Kondratieff and Myrick, 2006), (Stockard and Harris, 2005), (Nedeau, 2006), (Clarkin et al., 2005), (WDFW, 2000), (Robison et al., 1999)*	added to SGA appendix G in 2007, OR - pool needs to be 1.5-2 feet deeper than jump height.
Drop height:pool depth, or pool depth	*(FHWA, 2007), (Kondratieff and Myrick, 2006), (Taylor and Love 2003), (Stockard and Harris, 2005), (Nedeau, 2006), (Clarkin et al., 2005), (WDFW, 2000)*	~1:1.25 requirement (Stuart 1962). Oregon uses 1:1.5 or a minimum of 2 ft for jump-pool depth.depth of 20-30cm passable, see additional jump results for brook trout in second reference. Third reference discusses different pool depths. May want to use RPD to avoid influences of changing wse.
residual inlet and outlet depth	*(Taylor and Love 2003), (BCMF, 2002), (Lang et al., 2004), (Stockard and Harris, 2005), (Behlke et al., 1991), (Clarkin et al., 2005), (Baker and Votapka, 1990)*	used in CA green-gray-red screen, rpd <0.3 m
structure roughness	*(FHWA, 2007)*	could be place to tie into fish swimming speed via manning's equation in initial screen. Focus on weakest of group moving during period of interest.

baffles present	*(Ead et al., 2002), (Ead et al., 2000), (Clarkin et al., 2005)*	It was found that for the relative height of the baffles h/D in the practical range of 0.1–0.15, spacing of the baffles should be limited to a maximum of one diameter of the culvert.
turbulence	*(FHWA, 2007)*	WA and OR use energy dissipation factor criteria, EDF = γQS/A, EDF(ft-lb/ft3/sec) γ = unit weight of water (lb/ft3) Q = fish-passage design flow (ft3/sec) S = dimensionless slope of the culvert (ft/ft) A = cross-sectional flow area at the fish-passage design flow in square feet. (For baffled installations flow area is taken between baffles, and for roughened channels large roughness elements are excluded.)
headwater and tailwater controls	*(FHWA, 2007), (Taylor and Love 2003), (Coffman, 2005), (Robison et al., 1999)*	may want more detials on these as cirtical to both geomorphic compatibility and aop
degree of "barrierity"	*(FHWA, 2007), (Taylor and Love 2003) , (Bates and Kirn, 2008)*	portion of time or degree to which a crossing disrupts fish passage, used to further refine grays.
wing walls, head walls or projecting culvert inlets, aprons and edge configuration	*(FHWA, 2007), (Taylor and Love 2003) , (WDFW, 2000), (Baker and Votapka, 1990)*	
CEM stage	*(Johnson and Brown, 2000), (Castro, 2003)*	II or III require stabilization for culvert use or bridge.
culvert slope, slope x length	*(Taylor and Love 2003, (Coffman, 2005), (Stockard and Harris, 2005), (Nedeau, 2006), (Clarkin et al., 2005), (Robison et al., 1999)*	used in their green-gray-red screen
cost to remediate and opportunity	*(Taylor and Love 2003), (Bowden, 2006), (Clarkin et al., 2005), (Robison et al., 1999), (OR/WA BLM, 2005)*	
outlet drop and perch	*(Coffman, 2005)*	

fish population size and diversity	*(Jackson, 2003), (Franklin 1980, Soulé 1980), (Clarkin et al., 2005), (Robison et al., 1999), (Mirati, 1999), (OR/WA BLM, 2005)*	For long-term viability, estimates of minimum population size range from 500 to 5,000 or more individuals. In OR fish presence based on matrix of suitable habitat.
tailwater armoring, exposed riprap over cascades	*(Lang et al., 2004) ,(Bowden, 2006)*	
fish swimming/jumping ability	*(Nedeau, 2006), (Bates and Kirn, 2008), (Robison et al., 1999)*	4 classes according to Belford and Gould (1989), grouped for new england species
combined aop and geomorph rankings	*(Nedeau, 2006)*	A reasonable compromise between physical measurements and ecological concerns would be to target those stream crossings that rank high in both categories.
proximity to important ecological area	*(Bowden, 2006), (ADF&G, 2001)*	see scoring flow charts for structure prioritization, AK based on naturalness of channel
presence of resting locations	*(Behlke et al., 1991)*	
river distance to stream mouth	*(WDFW, 2000)*	
% passability estimate	*(WDFW, 2000)*	
access to spawning and rearing habitat	*(WDFW, 2000)*	
water marks in culvert to estimate depth	*(Robison et al., 1999)*	

Appendix D – Guide to the Worksheets in VT AOP Screen.xls

Aop results table – Summary table with results of both AOP Coarse Screen and AOP Retrofit Potential Screens for the project study database.

Retrofit Rank – Exploration of results of retrofit potential screen during trials, specifically used to explore inclusion of both Length of Culvert not Backwatered and Water Depth values on the overall screen scores.

Retrofit Potential Comp – Description of retrofit potential variables and setup.

Retrofit Potential Comp (rearr) – Description of retrofit potential variables and setup organized in a printer friendly format.

2008 Coarse Screen – A table summarizing each variable included in the screening tool and the scoring breakdown.

2008 AOP Analysis – Contains the Vermont Assessed Structures data, *Vermont Aquatic Organism Passage Screening Tool* begins in Column AN with screen summary information at the bottom of the screening columns.

ExploredScreenOption2 – This screening format was explored as a means of incorporating multiple variables in a final screen score.

OutletDrop – Data analysis on Drop Heigth variable and trials for segregating structures based soley on drop height.

ExploredScreenOption1 – Early experiment of a reorganized screen tool format, based on jump height and an additional score comprised of other variables.

Histograms – Initial variable data analysis on continous data types.

Bar Charts – Initial variable data analysis on catagorical data.

Inlet Obstructions Query Results – All structures with obstructions are listed here by structure ID.

Appendix E – Guide to the Worksheets in AOP_GC pilot study.xls

White GC – The *Vermont Culvert Geomorphic Compatibility Screening Tool* has been applied to the White River Basin culvert data.

Ottauquechee GC – The *Vermont Culvert Geomorphic Compatibility Screening Tool* has been applied to the Ottauquechee River Basin culvert data.

GC Screen - The *Vermont Culvert Geomorphic Compatibility Screening Tool* is defined in tables describing scoring catagories and variable scoring breakdown, corresponding to Tables 2-1 and 2-2 in this report.

White AOP_RF – The *Vermont Culvert Aquatic Organism Passage (AOP) and Retrofit Potential Screening Tools* have been applied to the White River Basin culvert data.

Ottauquechee AOP_RF – The *Vermont Culvert Aquatic Organism Passage (AOP) and Retrofit Potential Screening Tools* have been applied to the Ottauquechee River Basin culvert data.

AOP_RF screen – Describes the *Vermont Culvert Aquatic Organism Passage (AOP) and Retrofit Potential Screening Tools* variables and scoring breakdown.

White Reduced - This worksheet contains the White River Basin culvert data used in the pilot study. It was reduced in size by removal of all bridges and arches, removal of structures with no channel dimensions, and identified small watersheds (DA < 0.25 mi^2) for further removal from the AOP_RF screening tool analysis.

Ottauquechee Reduced - This worksheet contains the Ottauquechee River Basin culvert data used in the pilot study. It was reduced in size by removal of all bridges and arches, removal of structures with no channel dimensions, and identified small watersheds (DA < 0.25 mi^2) for further removal from the AOP_RF screening tool analysis.

White DMS – All culvert data obtained from the Data Management System for the Ottauquechee River Basin streams.

Ottauquechee DMS – All culvert data obtained from the Data Management System for the White River Basin streams.

Variable List DMS – Variable name code, data type, and full variable name for all variables included in the data lists obtained from the Data Management System.

Appendix F – Instructions for the *AOP Habitat Connectivity Potential Screen*

Data Requirements

Stream Centerline Shapefile – A stream centerline layer must be used. This layer must have correct connections between stream segments, with direction of flow designated. Connectivity must be verified as correct and can be done using the RiveEx software. Preprocessing has been completed in each of the following stream layers:

VHDCartoRivex_Statewide.shp – Stream layer for the whole state with preprocessing of the stream layer already completed for use in RivEx.

VHDCartoMainstem_Statewide.shp – Mainstem stream layer for the whole state with preprocessing of the stream layer already completed for use in RivEx. This layer assumes that stream segments with a Strahler order of 3 or greater is considered to be mainstem.

VHDCartoRivex_ToClip.shp – A copy of the Statewide stream network to be used for smaller scale analysis by clipping to a watershed boundary.

VHDcartoMainstem_ToClip.shp - A copy of the Statewide mainstem stream network to be used for smaller scale analysis by clipping to a watershed boundary.

Barrier Shapefile – A shapefile must be provided with locations of barriers, or culverts, to be analised. Instructions for creation of this layer are included in the following instructions.

Watershed Clip Shapefile – To perform small scale sub-watershed level analysis a watershed layer must be provided to serve as a clip boundary. WBD12VT_POLY.shp. provides a HUC-12 size watershed boundary.

STATEWIDE CULVERT DATABASE ANALYSIS PROCESS

Calculate Upstream Reconnection Distance for the Statewide Database

Setup Map

Open RivEx map *RivEX_Tool_Vermont.mxd* in ArcMap 9.x

This map has been setup specifically for the whole statewide database to run, with preprocessing of the stream layer already completed. The stream layer VHDCartoRivex_Statewide.shp should be loaded already.

Create the culvert shapefile

The large culvert database must be prepared before input to GIS for analysis. An Excel or text file must be created with columns for at least Latitude, Longitude, and an identification number for linking the culverts to the larger dataset after analysis. All culverts in list must have location information. Delete all culverts from spreadsheet that do not have latitude and longitude information before adding this data to GIS. It is convenient to have additional data in this table for viewing results in GIS in map form, such as culvert characteristics and results of other screening tools. You may want to just modify the DMS culvert database to just remove culverts without location information, leaving all available culvert information in the table.

In GIS Tools Menu / Add X Y Data / Browse to Excel/text File containing culvert data / Specify LAT and LONG / SELECT… Select a Predefined Coordinate System – Geographic Coordinate Systems – World – WGS 1984.prj. Press OK to add this Event layer to the map.

Turn this Event layer into a Shapefile. Right-click on its name in the Table of Contents on the left menu / Data / Export / Choose "the data frame" as the coordinate system / choose place to save it (C:\RivEX\Shapefiles) / Add it to the map. This is your culvert shapefile for use in the following analysis. (2007 culvert data named DMSVTStructures2007.shp)

Open RivEx Tool.

This should be a button on the tool bar that opens a RivEx window.

RivEx interface Window should say:

VHDCartoRivex_Statewide FID FNODE TNODE Press BUILD!

Sites / Snap Sites

Specify your culvert layer in the pull down menu.

Search Distance = 100 m, check avoid node, press GO!

When finished, close RivEx Tool Window, because it needs to restart for next step.

If any sites did not snap to the network they must be removed for this analysis. Do this by opening attribute table of snapped points shapefile, Select By Attribute if "snapdist"= -1, using editor, you need to Start Editing, delete these non-snapped culverts, Save Edits, Stop Editing.

Sites / Between Barrier Analysis

This step will take a very long time with this large dataset. It is recommended that it is run over a weekend. When the database was run with approximately 3,200 culverts it only completed 35% of the processing overnight. Before leaving the office for the weekend start here. Upon finishing a window appears asking for permission to write the data to an Excel file.

To do this: Reopen the RivEx window and rebuild the network to place snapped points on network:

Choose: snapped culvert data layer- you just created this
ID = FID - (This is the number that will identify the results in the Excel output)
Upstream Lengths = US_accum
Catchment Id = CatchIDVT
Check computed segment IDS
Press GO!

A warning window may appear describing an error during indexing. This is ok, press continue. When the process is done a window will appear asking to write the results to an Excel file. Press ok.

An Excel file should open with the barrier data. Save this file somewhere. Copy the data tables in the newly created Excel sheet and paste them into the *BetweenBarrierAnalysis* worksheet in *VT AOP Connectivity Screen.xls*.

This step has provided the values for the upstream network. With identification of downstream culvert FID numbers in column 2 in the *AOP connectivity screen(meters)* Excel worksheet, the downstream network reconnected can be calculated. It is not practical to calculate the downstream network reconnected for all culverts, but can be calculated as needed. Because multiple catchments are included in this analysis, the culvert farthest downstream in a particular watershed will not be accurately calculated by this method.

In order to connect this dataset back to the larger database see instructions below in section Post Analysis Data Management.

Calculate potential habitat reconnection for Mainstem Habitat for the Statewide Database:

Setup Map

Open RivEx map *RivEX_Tool_VermontMainstem.mxd* in ArcMap 9.x

This map has been setup specifically for the whole statewide database to run on the mainstem network. The mainstem was identified by selecting all streams with order larger than 3 (Strahler, 1952) as calculate using RivEx. VHDCartoMainstem_Statewide.shp should be loaded already.

Modify Snapped Culvert Layer

Add snapped culvert layer created during whole network statewide analysis, described above, to the map.

We need to select only culverts located along the mainstems using:

ArcToolbox / Analysis Tools / Overlay / Intersect

Choose snapped culverts layer and VHDcartoMainstem_Statewide.shp

Save as Mainstem culverts layer and add to map.

Open RivEx Tool.

This should be a button on the tool bar that opens a RivEx window.

RivEx interface Window should say:

VHDCartoMainstem_Statewide FID FNODE TNODE Press BUILD!

Sites / Between Barrier Analysis

This step will take a very long time with this large dataset. It is recommended that it is run overnight (but may need to run during the weekend if too many points are added). It is possible to run both this analysis and the whole network analysis at the same time in two different ArcMap windows if computer processing speed and GIS licensing allow. Upon finishing a window appears asking for permission to write the data to an Excel file.

Choose: snapped culvert data shapefile- you just created this

ID = FID_*** - this is the third column in the table and refers back to the FID found in the shapefile with all snapped culverts. If some culverts were not located on the mainstem, they were removed from this shapefile during the Intersect and the FID in the Mainstem culverts shapefile will not match the FID in the Snapped culverts shapefile.

Upstream Lengths = US_accum

Catchment Id = CatchIDVT

Check computed segment IDS

Press GO!

A warning window may appear describing an error during indexing. This is ok, press continue. When the process is done a window will appear asking to write the results to an Excel file. Press ok.

A new Excel file should open with the barrier data. I would save this file somewhere. Take the data tables in the newly created Excel sheet and paste them into the *MainstemBarrierAnalysis* worksheet in *VT AOP Connectivity Screen.xls*.

This will have calculated the upstream Mainstem reconnection distances. If the downstream culvert was identified in the Excel sheet for the downstream network analysis, the downstream Mainstem reconnection distances are automatically calculated.

In order to connect this dataset back to the larger database see instructions below in section Post Analysis Data Management.

SMALL AREA CALCULATIONS – SUBWATERSHED LEVEL

Calculate Upstream Reconnection Distance at Subwatershed Level

Setup Map

Open RivEx map in ArcMap 9.x

Save this map with another project name to ensure you do not overwrite the RivEx program. Set map frame projection to NAD83 Vermont meters.

Create Clip boundary for analysis area. It is recommended to use a subwatershed of the size HUC-12, but other basin sizes can be used as well. Load the watershed boundary shapefile: C:\RivEX\Shapefiles\WBD12VT_POLY.shp. Select the watershed of interest and export this as a new shapefile: Right Click on the shapefile in the Table of Contents/ Data / Export / Selected Features / check Use same coordinate system as: the data frame / save shapefile / add to map. This is your clip boundary.

Add stream layer C:\Rivex \ VHDCartoRivex_ToClip.shp. Clip this layer to area being analyzed using Toolbox / Analysis / Extract / Clip. Clip with the subbasin watershed shapefile of your analysis area. This isolates the stream network of interest in a new shapefile, removing areas outside of the watershed.

Create the culvert shapefile

The culvert database must be prepared before input to GIS for analysis. An Excel or text file must be created with columns for at least Latitude, Longitude, and an identification number for linking the culverts to the larger dataset after analysis. All culverts in list must have location information. Delete all culverts from spreadsheet that do not have latitude and longitude information before adding this data to GIS. It is convenient to have additional data in this table for viewing results in GIS in map form, such as culvert characteristics and results of other screening tools. You may want to modify the DMS culvert database to just remove culverts without location information, leaving all available culvert information in the table.

In GIS Tools Menu / Add X Y Data / Browse to Excel/text File containing culvert data / Specify LAT and LONG / SELECT… Select a Predefined Coordinate System – Geographic Coordinate Systems – World – WGS 1984.prj. Press OK to add this Event layer to the map.

Turn this Event layer into a Shapefile: Right-click on its name in the Table of Contents on the left menu / Data / Export / Choose “the data frame” as the coordinate system / choose place to

save it (C:\RivEX\Shapefiles) / Add it to the map. This is your culvert shapefile for use in the following analysis.
You may want to clip this culvert layer to the area being analyzed, if culverts are outside the analysis area.

Build Network
Click RivEx button on toolbar.
Select: polylines layer = VHDCartoRivex_ToClip.shp - clipped to area being analyzed
ID polyline = FID
From node = ***?***
To node = ***?*** press <u>BUILD!</u>
Warning window will appear – assumes we want to create node fields, press OK
Generate Node Data
Check Update Attribute Table - press <u>GO!</u>
Window will appear advising to update data
Rebuild Network with new Fnode and Tnode
RivEx interface Window should now say:
Clipped VHD FID FNODE TNODE press <u>BUILD!</u>
Run Quality Controls of your Network
This should not be necessary if starting with provided stream layer file - VHDCartoRivex_ToClip.shp. If needed, instructions for this process can be found in RivEx documentation.
Calculate Attributes
Check:
Strahler – Only calculate if you are not using the VHDCartoRivex.shp layer provided
Upstream Length
CatchID – Only calculate if you are not using the VHDCartoRivex.shp layer provided.
Press <u>Go!</u>
Analyze / Analyze Network
Check Segment Identifier Press GO! and then choose “identify all upstream polylines for all polylines”. For Catchment ID field choose: CatchIDVT (To simplify analysis, only one catchment is used for the entire state). This will create a database.
Sites / Snap Sites
Search Distance = 100 m, check avoid node, press <u>GO!</u>
This creates a new shapefile named *culvertfilename*_Snapped.shp, saved in the C:\Rivex\Output folder.
Sites / Between Barrier Analysis
If any sites did not snap to the network they must be removed for this analysis. Do this by opening attribute table of snapped points, select by attribute if “snapdist”= -1, using editor, delete these non-snapped culverts.

You need to exit and reopen the RivEx window and rebuild the network to place snapped points on network.

Choose: snapped culvert data layer
ID = FID
Upstream Lengths = US_accum (this was created in previous step)
Catchment Id = CatchIDVT
Check computed segment IDS
Press GO!

A warning window may appear describing an error during indexing. This is ok, press continue. An Excel file should open with the barrier data. Take the data tables in the newly created Excel sheet and paste them into the *VT AOP Connectivity Screen.xls* Excel document for the project in the *BetweenBarrierAnalysis* Worksheet.

BarriersProcessed Tab = total distance upstream of culvert
2nd *Tab* = Distance up to next barrier or stream source

This has provided the values for the upstream network. With identification of downstream culvert FID numbers in column 2 in the *AOP connectivity screen(meters)* Excel worksheet, the downstream network reconnected can be calculated.

In order to accurately calculate culverts near the mouth of the network's downstream distances, you must sum the network length in GIS. Open the Attribute table for the Stream shapefile that was clipped to the analysis area. Right click on the stream SHAPE_leng column heading (this is the length of the stream segment in meters). Choose Statistics. Record the sum in Excel sheet *AOP Connectivity Screen(meters)* at the top of the page.

In order to connect this dataset back to the larger database see instructions below in section Post Analysis Data Management.

Calculate potential habitat reconnection for Mainstem Habitat:

Setup for Mainstem Calculation

Create Mainstem Stream Shapefile or Clip provided Shapefile: VHDcartoMainstem_ToClip.shp

To Create a new Mainstem Stream Shapefile: Selection / Select by Attributes in clipped stream layer used in previous analysis

Select: "Strahler">=3
This should select higher order streams- check in map window.

Right click on stream layer / Data / Export Data / Selected Features
Save as Mainstem Stream Layer and Add to map
Create Mainstem Culvert Layer:
ArcToolbox / Analysis Tools / Overlay / Intersect
Choose snapped culverts and newly created Mainstem stream layer
Save as Mainstem culverts layer and add to map.

Build Network

Open RivEx window choose the following:

Mainstem Stream Layer FID ***?*** ***?*** press BUILD

Do not choose the Fnode and Tnode – these were created for the whole network and are not valid for this smaller dataset. We need to use RivEx to calculate these for the Mainstem network.

Generate Node Data

Check update attribute table, press GO!

Warning Window may appear – must rebuild data dictionaries

Rebuild Network with new attributes and nodes

Now window should say:

Mainstem Stream Layer FID Fnode1 Tnode1 press BUILD

Calculate Attributes

Calculate: Upstream Length - Need to select alternative names for fields because this was previously calculated for the network. Easy to use default of US_Accum2.

Analyze / Analyze Network

Check Segment Identifier, select identify all upstream polylines for all polylines

Sites / Between Barrier Analysis

Select: Mainstem Culverts Snapped

ID = FID_*** - the third column in the table, refers back to the FID in the shapefile with all snapped culverts. If some culverts were not located on the mainstem, they were removed from this shapefile by the Intersect and the FID in the Mainstem culverts .shp will not match the FID in the Network culverts .shp.

Upstream Lengths = US_Accum2 – these were created in previous step

Catchment Id = CatchIDVT

Check computed segment IDS

Press GO!

An Excel Spreadsheet will appear – paste the two new data tables into *VT AOP Connectivity Screen.xls* Excel document for the project on *MainstemBarrierAnalysis* worksheet.

This will have calculated the upstream Mainstem reconnection distances. If the downstream culvert was identified in the Excel sheet for the downstream network analysis, the downstream Mainstem reconnections distances are automatically calculated.

In order to accurately calculate culverts near the mouth of the network's downstream distances, you must sum the network length in GIS. Open the Attribute table for the Mainstem Stream shapefile that was clipped to the analysis area. Right click on the stream SHAPE_leng column heading (this is the length of the stream segment in meters). Choose Statistics. Record the sum in Excel sheet *AOP Connectivity Screen(meters)* at the top of the page.

In order to connect this dataset back to the larger database see instructions below in section Post Analysis Data Management.

POST ANALYSIS DATA MANAGEMENT

In *VT AOP Connectivity Screen.xls* in Excel:

Copy data for export to GIS into the *Export* tab. The table of results in Export(miles) is an easy source of this Export data. This table will be imported to GIS and joined with the culverts analyzed.

In GIS:

Add Data: Browse to the *VT AOP Connectivity Screen.xls* and choose the *Export$* table. This will load your new data into GIS as a table.

Join this data table with the Snapped Culverts shapefile to rejoin connectivity data to the culvert information. To do this:

In the Table of Contents, choose the Source Tab at the bottom of the page. You will now see the Export table we added in the step above. Right Click on this table. Join… Join attributes from a table:

1. GIS FID
2. Culverts_Snapped shapefile
3. FID

Click OK.

Now if you open the Export Table. It should be appended with all original culvert information columns, including any ID numbers and values imported in the original culvert file. Remember that some culverts were removed from the originally imported shapefile if they did not snap. So this table does not include all culverts in the larger dataset, only ones qualified for the analysis.

Appendix G – Guide to the Worksheets in VT AOP Connectivity Screen.xls

AOP connectivity screen(meters) - A summary of the AOP habitat connectivity potential screen results. The spreadsheet calculates habitat connectivity upstream of each culvert, including branches and mainstem only. With user input of downstream culvert id number, the downstream distances for both network and mainstem are calculated.

Results (miles) - A summary linked to the interactive *AOP connectivity screen(meters)* sheet that converts results to miles.

Results (miles to GIS) - A location to paste all information wanted for uploading to GIS. This convenient location can serve as a source of data to input to GIS. You may need to save this worksheet as a text file to be able to join this table with the culvert layer attribute table.

BetweenBarrierAnalysis - Enter the resulting tables from RivEx output into this worksheet to have an archive of the results and provide the results shown on the *AOP connectivity screen(meters)* sheet.

MainstemBetweenBarrierAnalysis - Enter the resulting tables from RivEx output for the mainstem analysis to have an archive of the results and provide the results shown on the *AOP connectivity screen(meters)*.

Export - A location to paste all information wanted for uploading to GIS (typically from the *Results(miles)* worksheet). This convenient location can serve as a source of data to input to GIS. You may need to save this worksheet as a text file to be able to join this table with the culvert layer attribute table.