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Analysis of an Efficient Fish Barrier Assessment Protocol for Highway Culverts

Prepared by: Kenneth F. Karle, P.E.
Hydraulic Mapping & Modeling
P.O. Box 181
Denali Park, Alaksa 99755

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

ANALYSIS OF AN EFFICIENT FISH BARRIER ASSESSMENT PROTOCOL FOR HIGHWAY CULVERTS

FINAL REPORT

Prepared for
Alaska Department of Transportation & Public Facilities

Hydraulic Mapping and Modeling
Denali Park, Alaska
April 2005

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Abstract

This report documents and presents the results of a study to validate the existing culvert assessment protocol with supporting hydraulic analysis and data, and recommend changes as necessary to assist state hydraulic engineers and habitat biologists in implementing a streamlined culvert assessment protocol. The primary validation effort consists of a comparison and analysis of modeled predictions from the FishXing program to actual flow and stage data from several different culvert types. Additional topics were researched for this report; topics included the Level 1 coarse criteria and fish passage assessment process, the concept of 'Occupied Zones' for fish passage in lower velocity areas, the use of appropriate and up-to-date flood regression methods and equations, and methods to prioritize culvert replacement/rehabilitation for fish passage restoration. The findings of the study suggest that several criteria from the Level 1 and Level 2 methods are conservative, and may cause a cascading effect toward an inaccurate determination of fish barrier status. Recommendations are made to improve the criteria, streamline the protocol, and create a prioritization methodology.

Summary of Findings

The main objectives of this study were to validate the existing culvert assessment protocol in Alaska with supporting hydraulic analysis and data, and recommend changes as necessary to assist state hydraulic engineers and habitat biologists in implementing a streamlined culvert assessment protocol. The existing culvert assessment protocol evaluates fish passage using a two-tiered analysis approach. The findings of this study suggest that a number of criteria from the Level 1 and Level 2 methods are conservative, and may cause a cascading effect toward an inaccurate determination of fish barrier status.

Level 1 Criteria

The Level 1 matrix has several deficiencies that should be corrected to improve the accuracy and relevance of the criteria. The use of upstream channel widths that are within the influence of the culvert restriction to determine the constriction ratio is not appropriate, as it likely leads to overestimations of the stream constriction ratio. Additionally, the current assessment protocol uses a flow independent definition of perch height, which results in the maximum perch height possible. This provides an unrealistic overestimate of perch height, and prevents comparisons of results from Alaska to those of other agencies.

Level 2 Criteria

A key requirement of the protocol's hydraulic analysis routine is the estimation of the fish passage design flow, designated as the Q_2-2 day duration flow, using U.S. Geological Survey (USGS) regression equations. The error statistics of the Q_2 regression equations from the Jones and Fahl (1994) report show a large range of standard error of predictions in both directions, though the range of error is greater for overestimation than underestimation. Improper methods for flood estimations using USGS regression equations were noted at several study sites. Additionally, alternative physical methods used to estimate the Q_2 flow tend to overpredict discharge values.

The Level 2 methodology relies on the use of the hydraulic analysis program FishXing to evaluate fish passage. A hydraulic validation study shows that the FishXing program consistently overpredicts water velocities within a culvert for various culvert types at low flows. The reasons for the program's tendency to overpredict velocities include: 1) FishXing's assumption of a zero approach velocity at the culvert inlet that increases the headwater depth, 2) the use of suggested coefficients from the pull-down menus without calibration, and 3) the non-use of velocity reduction factors to reflect lower velocities in culverts due to boundary friction effects.

In addition to providing separate tendencies toward a conservative outcome, the assumptions and methods used for the Level 2 analysis compound a conservative bias, and tend to provide an overestimation of culvert velocities, which can lead to an inaccurate determination of fish barrier status.

Prioritization Methodology

Limited resources for annual culvert retrofits and replacements necessitate the economical and accurate assignment of priorities for culvert replacement. The use of quantitatively ranked criteria is critical for developing a prioritized inventory for culvert repair and replacement. This report suggests an approach to a prioritization methodology for Alaska that places importance on biological criteria, including quantity/quality of habitat.

Recommendations

- Level 1 criteria should be modified to improve the accuracy of estimations of stream constriction ratios and perch height. Stream widths should be measured downstream of the culvert. Perch height should be determined using the 'flow-dependent' measurement. If a culvert is backwatered, then gradient, constriction and perch height should not be considered relevant for the assessment of passage.
- The updated USGS methods for estimating peak flow discharges and mean flow-duration statistics for Alaska should be used in lieu of older reports. Before attempting to employ advanced techniques for flood estimations, users should receive training to gain an understanding of the methods and limitations inherent in both the statistical methods and field techniques.
- All systematic users of the FishXing software for culvert replacement prioritization programs should be trained and supervised by a hydraulic engineer with expertise in classic open-channel hydraulic theory and numerical hydraulic modeling techniques.
- Calibration and validation with discharge-velocity data sets should occur with every culvert modeling effort using the FishXing program. Without successful calibration, the FishXing program should not be used to determine passage status.
- Efforts should be made to improve the computational abilities of culvert hydraulic programs such as FishXing and HY-8 by including approach velocity in the solution of the gradually varied flow equation.
- A prioritization method should be developed as part of the culvert fish passage assessment protocol, and include the following ranked criteria: 1) length/area of habitat recovered, 2) quality of upstream or downstream habitat recovered, 3) downstream barriers to fish passage, 4) species importance, 5) condition of culvert, 6) level of barrierity, and 7) replacement/retrofit costs.

CHAPTER 1 - INTRODUCTION AND RESEARCH APPROACH

Problem Statement

The Alaska Department of Transportation and Public Facilities (AKDOT&PF) is responsible for designing, installing, and maintaining culverts for stream crossings throughout Alaska. Culverts have both a hydraulic and structural function. In addition to conveying surface water across the highway right-of-way, culverts must also carry construction and highway traffic and earth loads. Design requirements for culverts have traditionally been driven by the need for managing and reducing risks to traffic, property damage, and flood failure. Guidelines for culvert hydraulic designs, such as the FHWA HEC-5, are well-understood and commonly utilized by highway engineers. However, the continued reliance on these methods is often at odds with natural resource agencies in Alaska and other states, who are increasingly concerned that many culverts are acting as barriers for fish to upstream habitat.

Efforts are being conducted nationally to develop a 'fish friendly' design for future stream crossings and for the thousands of retrofits expected to be completed in coming years. In Alaska, numerous projects have focused on developing techniques and guidelines which would allow engineers and biologists to design, construct, and maintain an acceptable structure with fish passage capabilities. A collaborative effort between AKDOT&PF hydraulic engineers and Alaska Department of Fish and Game (AKDF&G) habitat biologists resulted in a preliminary tentative culvert assessment protocol to identify existing culverts that pose potential barriers to fish and prioritize mitigation. An initial assessment of culverts on Alaska's Kenai Peninsula using this protocol took over a year, and resulted in a draft AKDF&G report which classified 78 percent of the studied culverts as fish barriers (Rich, 2003).

The effort and funding required to replace and modify such a large percentage of existing culverts to meet fish passage goals is prohibitively enormous. The goal of this collaborative project was to develop an assessment protocol for efficiently and rapidly prioritizing and programming fish barrier mitigation; however, these initial results indicate that additional research is needed to achieve this goal. Specifically, validation of the hydraulic methods used is required to modify and streamline the protocol's application for prioritizing mitigation of culverts that pose as barriers to fish in Alaska.

Research Objectives and Scope of Study

The objectives of this study are to:

1. validate the existing Level 1 and Level 2 culvert assessment protocol with supporting hydraulic analysis and data.
2. recommend changes as necessary to streamline the culvert assessment protocol.
3. assist state hydraulic engineers and habitat biologists in implementing a streamlined culvert assessment protocol.

4. provide Alaskan agencies with the information necessary to develop and use the revised protocols with confidence, while serving the Public's interest.

The FishXing computer program was developed to evaluate and design culverts for fish passage (USFS, n.d.), and provides the main analysis tool for the Level 2 passage assessment protocol. The primary validation effort consists of a comparison and analysis of modeled predictions from the FishXing software to actual flow and stage data from several different culvert types. The analysis was conducted to identify discrepancies between modeled hydraulic output and field-measured values, and to describe how those discrepancies affect the identification of a modeled culvert as fish passable or impassable. The project also focused on identifying where the data analysis tools were used appropriately in the draft protocol. This work was developed to identify the minimum data and analysis needs required for a functional streamlined fish passage assessment protocol for use in Alaska.

Research Approach

A critical analysis of the FishXing software program was conducted to review the underlying hydraulic theory, model construction, and mathematical equations used in the software code. Specific goals for the FishXing analysis focused on the following:

- How well does this method emulate real culvert conditions?
- How is the tail water elevation calculated? How does it affect the results of a culvert modeling analysis?
- How are inlet losses calculated in the program? How well does that method emulate real culvert conditions, and how does it affect the results of a culvert modeling analysis?
- In general, how does the FishXing program compare with other hydraulic culvert analysis programs that use backwater calculations?

An assessment of the hydraulic modeling performance of the FishXing software was accomplished by conducting model runs of culvert sites, and comparing modeled output results to field-measured data. Site surveys were conducted in the Kenai Peninsula to collect specific hydrologic and hydraulic data necessary to conduct the comparison. Many of the culverts were also part of the Kenai culvert inventory developed for the draft AKDF&G report, and were resurveyed for this study. Several new culverts were added for this study.

Conditions documented during the site visits included: pool surface elevation, outlet-pool bottom elevation, pool cross-section, culvert shape, span rise, length, inlet and outlet bottom elevations, channel slope, length of project, type of construction, condition of structure, and inlet and outlet appurtenances. A discharge measurement was made, and inlet and outlet velocities and water surface elevations were measured. The measured discharge and wetted perimeter measurements were used to estimate actual average velocity. All field data are found in Appendix D.

The field data were used, following the protocol, to model the culverts and produce estimations of average velocities and water surface elevations. These model-developed estimates were compared to field measurements of water velocities and surface elevations made at the time of data collection. An analysis was conducted to identify discrepancies between modeled hydraulic output and field-measured values, and describe how those discrepancies affect the identification of a modeled culvert as fish passable or impassable.

The Kenai Peninsula field trip also focused on the identification of the specific minimum number and types of field measurements needed to accurately model culvert conditions with the FishXing program. The effort also identified field data that are not required to run the FishXing program.

Additional topics were researched for this report through a variety of means, including literature reviews and interviews. They include:

- The Level 1 coarse criteria and fish passage assessment process (Rich, 2003).
- The concept of 'Occupied Zones' for fish passage in lower velocity areas, and findings from recent research.
- Use of appropriate and up-to-date flood regression methods and equations.
- Methods to prioritize culvert replacement/rehabilitation for fish passage restoration.
- Suggestions for improving the efficiency of the culvert analysis protocol.

CHAPTER 2 FINDINGS

Level 1 Coarse Filter

In the AKDF&G draft report (Rich, 2003), culverts were initially evaluated using the Level 1 fish passage evaluation criteria (Appendix A). This methodology is designed to act as a coarse-filter approach for inferring juvenile salmonid passage. The criteria are described in the report as conservative. Originally developed by an interdisciplinary working group consisting of U.S. Forest Service, and Alaska Departments of Fish and Game and Transportation and Public Facilities personnel, similar criteria are used in other programs, such as the State of Washington (WDFW, 2000). Individual agencies have adapted the criteria slightly for their own use, depending on agency preferences and local resource concerns.

The following parameters are used to construct the Level 1 filter:

- culvert or crossing structure type
- culvert gradient
- stream constriction ratio (width of culvert/width of upstream channel)
- outfall height or perch (elevation at bottom of culvert outlet – elevation of first downstream hydraulic control; flow independent).

These parameters are combined into a matrix to create a decision guide for the determination of fish passage adequacy.

The stratification and thresholds for the Level 1 criteria were developed in part by using hydraulic modeling runs to analyze constriction ratios and slope-velocity relationships (Robert Gubernick, USFS, personal communication, 2005). The results of that analysis were combined with the best estimates of the professional working group to develop the break off values for the criteria. Three of the four parameters used to create the passage matrix are essentially quick methods to assess whether velocities within the culvert are too great for fish passage. The fourth parameter is a direct measurement of the perch height, and relates directly to the ability of a fish to jump.

The Level 1 coarse filter criteria are used to classify culverts into three fish passage categories: green (adequate for fish passage), gray (requires additional hydraulic analysis), and red (not adequate for fish passage). Assessing the validity of the numerical values of the parameters, and the selection and relationships of these parameters to each other and ultimately to fish passage capability, is extremely difficult without the references, original data sets used to construct the matrix, or new quantitative information. Reports have noted the need for additional work to validate the Level 1 criteria matrix (USDA, 2002).

Additional discussion of each of the parameters follows:

Culvert Type

Eight separate culvert types are used in the filter matrix. Culvert types range in passage ability from mostly adequate (bottomless or counter sunk pipe arch) to mostly inadequate (concrete box). The 'green' passage status attributed to bottomless or counter sunk pipe arch culverts is supported by the current interest in Alaska and elsewhere to encourage the use of the stream simulation design method; this method generally attempts to replicate natural stream channel conditions within a culvert, by incorporating a large culvert width/streambed width ratio (equal to or greater than 0.9) and utilizing natural substrate material within the culvert.

Other culvert characteristics help determine fish passage status, including roughness and corrugation sizes. Circular CMPs with 2 inch by 6 inch corrugations are shown to provide better passage capability; this is most likely due to the boundary zone velocities in these rougher culverts, which can range between 10 and 40% of the average water velocity. In contrast, boundary zone velocities in culverts with shallower corrugations (3 inch by 1 inch) are reduced only about 20% over average water velocity (ADF&G/ADOT&PF, 2001). Concrete box culverts are presented in the matrix as the least likely culvert type to allow fish passage, presumably due to the low roughness coefficient of the culvert surface.

Culvert Gradient

A small range of culvert gradients, in conjunction with culvert types, provides for the determination of passage ability within the matrix. Within the matrix, the slope is used as a step parameter, with passage determination cutoffs at 0.5, 1, 2, 3, and 4 percent slopes (depending on other characteristics).

Empirical evidence indicates that the culvert gradient values used in the Level 1 matrix are conservative for low to moderate flows. For example, in the Level 1 filter, large diameter circular CMP culverts at grade are rated 'green' only if the slope is less than 0.5% (and no perch, and span/bedwidth ratio greater than 75%). However, Kane observed substantial juvenile coho passage through the Beaver Creek culvert at a discharge of 13.4 cfs; the culvert has a 1% slope through most of the culvert, and a 10% slope for a short distance in the upstream end (Kane et al., 2000). Investigators at the Skookumchuk culvert test facility report juvenile coho passage through a 6 ft round culvert, 40 ft long, 1.14% slope, bottom bare, with spiraled corrugations 1 inch by 3 inch (Pearson et al., 2003).

Culvert Corrugation

Corrugation sizes are used in the Level 1 filter to determine fish passage capability. Substantial evidence exists that large corrugations provide additional surface roughness in the culvert, resulting in boundary zone velocities that can range between 10 - 40% of the average water velocity (Kane et al., 2000; Kane and Wellen, 1985; Powers et al., 1997; and others). Large corrugations also provide resting places for juvenile salmon passing upstream through the culvert (Kane et al., 2000).

Stream Constriction Ratio

The stream constriction ratio reflects the relationship between upstream channel widths to culvert widths. A ratio of 0.75 or larger is used as delineation, along with other parameters, for indicating fish passage. A ratio of 0.5 to 0.75 is similarly used to recommend additional analysis, and sites with a ratio of 0.5 are classified as passage barriers. Backwater effects at the culvert are not considered for this parameter.

Stream constriction ratios are used in other fish passage assessment programs. In the Alaska protocol, the ordinary high water stream channel width is measured upstream of the culvert at three locations, which are labeled 5 ft, 50 ft, and 100 ft. Though not explicitly stated in the AKDF&G draft report, it is assumed that the width value is an average of the three measurements.

In the associated project database, the measured distances to those measured widths are recorded. Very few measurements were made at the 5, 50, and 100 foot distances, and many were made at significantly different distances. No explanation is given as to why the distances varied from the labeled distances and varied from each other from site to site.

Outfall Height or Perch

In the Rich report, the outfall height is defined as the distance from the invert at the downstream end of the culvert to the elevation of the first downstream control; this measurement is independent of flow. Culverts with an outfall height greater than 4 inches were assigned a ‘red’ rating (not passable).

Other publications and agency documents reviewed for this study reported outfall or perch height as the distance from the water surface at the downstream end of the culvert to the water surface of the plunge pool determined at the time of measurement, including the FishXing program help files. Many agencies use the 4 inch criteria, though at least one agency defines the non-passable perch as 6 inches or greater (Mirati, 1999).

Using the information available in the AKDF&G draft report associated database, Table 1 reports the number of culverts classified in the Level 1 filter as having an excessive outfall height of 4 inches, using the flow independent condition and the flow dependent condition. Additionally, it lists the excessive outfall height of culverts assessed using both methods and a 6 inch criteria.

The FishXing software help documentation defines tailwater as the water depth immediately downstream of the culvert outlet measured from the culvert outlet invert. Depths are positive when the tailwater elevation is greater than the outlet bottom elevation. No leap is required for the fish to enter the culvert when the tailwater depth is positive.

Table 1. Number of culverts in the AKDF&G draft report with an excessive outfall height, using four definitions.

Assessment Method	[1]F.I. -4 inch perch height	[2]F.D.-4 inch perch height	F.I.-6 inch perch height	F.D.-6 inch perch height
Number of culverts classified as excessive outfall	31	20	27	17

[1]Flow independent
[2]Flow dependent

Field investigations focused on the validity of the flow independent perch height definition. At one study site, a culvert designed specifically for fish passage had been installed at Beaver Creek on the Kenai Spur Highway in 2002 as a replacement for a culvert rated 'gray' in the Level 1 and 'red' in the Level 2 analyses. The replacement culvert design process was guided by the fish passage MOA (ADF&G/ADOT&PF, 2001). Fish passage design features of the structural plate pipe arch culvert included:

- an outlet plunge pool
- shallow slope
- channel constriction ratio near 1
- culvert bedload collector to retain a naturally appearing channel bottom
- no perch

The Beaver Creek culvert was constructed with a shallow slope and large constriction ratio. An untrained eye, observing the vertical difference of 0.94 feet between the culvert outlet invert and the invert of the plunge pool tailcrest, would likely assign a 'red' rating to the culvert using the definitions provided in the Level 1 matrix.

The apparent tailcrest at this culvert is located at the downstream edge of the plunge pool, a horizontal distance of approximately 70 feet. However, the culvert outlet transitions to the large plunge pool with a 1:2 slope of class II riprap (Figure 1). This wide transition acts as the outlet control and appears to provide a means of access to the culvert with no abrupt leap requirements, at least at the flows observed. A 9 inch difference was surveyed between the tailwater water surface elevation and the water surface elevation 3 feet inside the culvert outlet. The difference between the water surface elevation near the upstream end of the plunge pool, and the water surface at the lip of the culvert was estimated at 4 to 5 inches.

Regression Equations

A key requirement of the protocol's hydraulic analysis routine is the estimation of the fish passage design flow. The fish passage design flow is described in a Memorandum of Agreement (MPA) between AKDOT&PF and AKDF&G as the Q_2-2 day duration flow

Figure 1. Beaver Creek culvert outlet.

(ADF&G/ADOT&PF, 2001). Because only peak flow estimates are generally available rather than duration flow estimates, the Q_2-2 day duration flow was estimated as 40 percent of the instantaneous Q_2 discharge for the Kenai Peninsula study. This was based upon examination of limited gaged watershed hydrology records in southeastern Alaska, and has not been verified for watersheds on the Kenai Peninsula (ADF&G/ADOT&PF, 2001; Rich, 2003).

The Q_2 flow rates were estimated for each of the study watersheds through the use of a USGS report that describes methods for evaluating the magnitude and frequency of floods at sites on streams with natural flow (Jones and Fahl, 1994). The report provides procedures for estimating flood magnitude and frequency at ungaged sites in Alaska and conterminous basins of Alaska, and is based on flood data from stations that have been operated for at least 8 years.

The use of such regression equations in the design of culverts, bridges, and other hydraulic structures is a commonly accepted practice in Alaska, which suffers from a severe lack of gaging station data and analysis statewide. However, the use of these techniques requires an understanding of the statistical methods used to develop the regression equations, and a strict adherence to the limitations inherent in those methods.

In the Jones and Fahl report, the State of Alaska and conterminous basins of Canada were divided into five flood-frequency areas having similar flood characteristics on the basis of statistical cluster analyses and regional regression analyses. The study sites selected for the Rich report fell into two flood-frequency areas: Area 1 and Area 2. Six sites in Area 1, and 43 sites in Area 2, were analyzed using the Jones and Fahl equations.

The USGS report notes that the flood prediction equations are valid only at sites where the basin characteristics are within the range of variables used to develop the equations. However, several of the watersheds analyzed were outside of the reported range of basin areas for the two flood-frequency areas. Table 2 lists the valid basin size range for the two flood-frequency areas, and the corresponding basin size ranges for the 49 sites that were analyzed for the Rich report.

Table 2. Statistics of basin drainage areas used in USGS regression equations, and basin characteristics of Kenai culvert inventory.

Statistics of basin drainage areas used in USGS regression analysis				Statistics of study site basin characteristics analyzed			
Flood-Frequency Area	Maximum (mi^2)	Minimum (mi^2)	Mean (mi^2)	Maximum (mi^2)	Minimum (mi^2)	Mean (mi^2)	# of sites outside of valid range
1	571	1.35	37.0	52.63	0.26	10.49	2
2	19,400	1.28	1,030	69.98	0.43	11.03	10

In fact, two of the smallest watersheds, Stations 21 (0.49 mi^2) and 99 (0.45 mi^2) were listed as 'red' because of high modeled velocities at high flow. Incorrectly estimated design flows that are too large may be responsible for the modeled high velocities. Because the basin characteristics of the 12 sites are not within the valid range of the underlying statistics, these watersheds should not have been analyzed using the USGS regression equations. Two alternative methods that may have been more appropriate for use for these small watersheds include: 1) correlation to a similar watershed with gage data, or 2) a watershed simulation model.

It is also important to note the accuracy and limitations of the regression equations, even as they apply to watersheds that fall within the valid basin characteristics range. The accuracy of the estimating equations is expressed in the Jones and Fahl report as the average standard error of prediction, the range of standard error of prediction, and the average equivalent years of record. The USGS notes that the average standard error of prediction differs from the standard error of the regression because it indicates the error in the regression equation *as well as* the sampling error (Table 3).

Table 3. Error statistics of the Q_2 regression equations for Flood-frequency Areas 1 and 2 (from Jones and Fahl, 1994).

Flood-frequency area	Average standard error of prediction (percent)	Range of standard error of prediction (percent)		Average equivalent years of record
1	34	+39	-28	1
2	40	+47	-32	1

The average equivalent years of record value is an overall measure of predictive ability; it relates the predictive ability of the regression equations to that obtained by flood-frequency analysis of number of years of peak-discharge data collected at the site. In the case of the Q_2 regression equations, the average equivalent years of record is one year. As a comparison, the USGS generally requires a period of 10 years of record or more before using peak-discharge data to conduct a flood-frequency analysis (Curran et al., 2003).

The USGS, in cooperation with the AKDOT&PF, recently completed a project to update the peak-streamflow frequency statistics for streamflow-gaging stations in Alaska, and to update the regression equations for estimation of peak-streamflow frequency at ungaged sites (Curran et al., 2003). This new report supersedes previous reports describing peak-flow frequency statistics; it is recommended that any future estimations of peak-streamflow discharge for the fish passage study be conducted with this report.

The new USGS report incorporates several new changes. Where the Jones and Fahl report used relaxed criteria for minimum years of record (8), the new report utilized new data acquired at existing stations to increase the record-length to 10 years. On average, flood statistics dropped less than one percent, though differences ranged from about -50% to +50% (Janet Curran, USGS, personal communication, 2004). Several other changes in the new report are found in Appendix B.

FishXing Hydraulic Theory

The Level 2 component of the fish passage protocol utilizes the hydraulic analysis program FishXing Version 2 to evaluate passage for culverts rated as 'gray' in the Level 1 analysis. FishXing is an interactive analysis tool that calculates velocities and depths throughout the culvert pipe for a range of expected discharges, and compares these values to default or user-specified swimming capabilities and depth requirements for the fish species of interest.

Water surface profiles are calculated for a variety of culvert shapes using the gradually varied flow equation. The FishXing program then compares the flows, velocities and leap conditions with the swimming abilities of the fish species of interest. The output from the model includes tables and graphs summarizing the water velocities, water depths, and outlet conditions. The program lists the limiting flows and fish passage factors for the modeled culvert.

The program is user-friendly, and help documentation is readily available. However, explanations of the underlying hydraulic theories and techniques used to construct the program are cursory, both in the software documentation and at the FishXing website. A tutorial on the FishXing CD offers biologists a quick and superficial lesson in hydraulic theory, including flow profiles, the Froude number, Manning's equation, and other topics. The tutorial also offers engineers a similar look at fish biology and behavior patterns.

Though a comprehensive description of the underlying hydraulic theories and techniques used in the FishXing program are not available to the user through the software documentation, such information is available from standard open-channel engineering and hydraulics textbooks and references. A summary of how those theories, techniques, and calculations are compiled within the FishXing program is found in Appendix C. The information included in that summary was provided by members of the FishXing team to this author; citable references are not yet available to the public. This information will be readily available to users of an upcoming release of FishXing (Version 3). A description of some of the modifications to Version 3 is also found in Appendix C.

Comparison of FishXing to Other Gradually Varied Flow Hydraulic Models

A number of software programs are available for the design and analysis of culverts. The FHWA HY-8, used by AKDOT&PF and many other users to design and size culverts to the hydraulic design flow, automate the design methods described in FHWA publications HDS-5, "Hydraulic Design of Highway Culverts," HEC-14, "Hydraulic Design of Energy Dissipators for Culverts and Channels," and HEC-19, "Hydrology." Commercial vendors offer programs such as CulvertMaster that are also based on the procedures in HDS-5. The program BCAP (Broken-back Culvert Analysis Program) provides hydraulic analysis for steep culverts having one (Single Broken-back) or two (Double Broken-back) breaks in the vertical profile. BCAP uses the same routines as the FHWA HY-8 culvert program to determine headwater depth at the culvert entrance. BCAP then calculates the water surface profile through the entire culvert, using Gradually Varied Flow equations and boundary conditions at each vertical break (NDOR, n.d.).

The HEC-RAS hydraulic modeling system (USACE, 1998), which is a water-surface profile computational model for one-dimensional, gradually varied flow, may also be used to analyze culvert hydraulics. The culvert routines in HEC-RAS were adapted from the FHWA HDS No. 5 (FHWA, 2001). The basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses are evaluated in three parts: 1) downstream from the culvert (expansion loss), 2) flow into, through, and out of the culvert barrel (friction loss), and 3) flow into the culvert from the reach above (contraction loss). The momentum equation is utilized in situations where the water surface profile is rapidly varied.

HEC-RAS can perform culvert calculations for single culverts (up to 25 at a single crossing), multiple identical culverts, and multiple non-identical culverts (up to 10 at a single crossing). Culvert types include the following shapes: box, circular pipe, semi-circle, arch, pipe arch, vertical ellipse, horizontal ellipse, low profile arch, and high profile arch.

Four cross-sections are required to construct a numerical culvert model in HEC-RAS. Required cross-section locations include downstream (below culvert influence), at downstream end of culvert, at upstream end of culvert, and upstream. Separate culvert data is used to create cross-sections inside of the culvert. Additional cross-sections are recommended upstream and downstream when computing water surface profiles, to prevent boundary conditions from affecting the culvert hydraulic results (USACE, 1998). This feature offers a significant accuracy improvement when compared to FishXing and HY-8; those programs use a zero-approach velocity at the culvert inlet for all calculations, resulting in overestimates of the headwater and a steepened drawdown at the inlet.

In some comparison tests, FishXing has produced hydraulic results similar to results from other software programs such as HEC-RAS and CulvertMaster at a number of sites (Michael Furniss, USFS, personal communication, 2004). None of these programs offer a fish performance module to directly analyze and predict fish passage.

Occupied Zone

FishXing provides an option for the use of velocity reduction factors to account for reduced water velocities due to the boundary frictional effects of the culvert corrugations. Velocity reduction factors may be selected separately for the inlet and outlet zones and the culvert barrel. The AKDF&G draft report, noting that only limited research had been conducted on the use by fish of these reduced velocity (occupied) zones within culverts, conducted a limited analysis using velocity reduction factors of 0.4 (for 2 x 6 inch corrugations) and 0.8 (for 1 x 3 inch corrugations). The report notes that results showed that in all cases, application of velocity reduction factors did not alter whether FishXing identified a barrier for juvenile fish; all reported results were derived without the use of velocity reduction factors. The conclusion is somewhat contradictory with the use of the Level 1 criteria in this report, which acknowledges that culvert corrugations do improve fish passage by creating low boundary zone velocities.

A recent review found additional information on the occupied zone and reduced velocity zones available in the literature. For example, the authors of a study that analyzed hydraulic conditions and fish passage note that fish seek the path of least resistance (lower velocities) when traveling in streams and culverts, and developed an equation to predict the occupied velocity in a culvert, based on the average velocity and a roughness coefficient (Kane and Wellen, 1985). Kane and Wellen (1985) recommend that the concept of the velocity in the occupied zone be considered as the culvert design velocity.

Behlke et al. (1991) observed that fish tended to occupy and utilize a wedge-shaped zone of lower velocity water within the culvert to transit upstream; velocities in this occupied zone ranged from 0.1 to 0.8 of the average cross-section velocity. Other notes and recommendations from this study are noted below:

- a factor of 0.4 is a conservative value to use for adjusting barrel velocities in circular and circular depressed-invert structural steel plate culverts
- pipe arch culverts do not exhibit similar velocity reductions in ‘wedge-shaped’ locations near the culvert edge due to corrugation roughness
- culverts horizontally skewed from the stream by angles of 30° to 45° may exhibit reduced water velocities of up to one tenth that of the average velocity, for 8 to 10 diameters downstream
- in outlet zones with rapidly accelerating flows (where outlet depth is close to critical depth), the ratio of the velocity in the occupied zone to the average velocity is 0.6 to 0.8; a conservative value is 0.8 from the outlet to one foot upstream from the outlet
- in inlet contraction zones with rapidly varying flows, 0.8 is a conservative velocity reduction value (Behlke et al., 1991).

The utilization of slower water velocities near the culvert edge by fish moving upstream was confirmed by a study that focused on the behavior of juvenile coho salmon (Kane et al., 2000). Juvenile coho ranging in size from 40 to 100 mm were trapped, stained, and released for observation downstream of the outlet at four culverts in the Kenai Peninsula and Prince of Wales Island. An attractive food source was placed upstream to motivate the fish upstream. The juveniles were observed resting within large corrugations (2 x 6 inches) during the upstream transits of culverts with high water velocities. Observers noted the juvenile fish were attempting to minimize power output and energy expenditure by swimming close to the culvert wall and near the surface along the sidewall where velocities are reduced (Kane et al., 2000).

In one culvert (Beaver Creek), juveniles proceeded upstream by swimming for 2 or 3 corrugations lengths then resting for a minute or two; many fish were able to successfully transit the length of the culvert, which included a hydraulic jump and supercritical flow for the upper twelve feet of the culvert (Kane et al., 2000). Smaller juveniles were not as successful in traversing a culvert on Pass Creek Tributary with high velocities and smaller corrugation dimensions (1 x 3 inches). Observers noted that in areas of steep velocity gradients along the wall, where the areal extent of low velocities is limited, fish have difficulty maintaining their position and preferred orientation (Kane et al., 2000).

Powers et al. (1997) found that when water velocity increased above 0.4 feet per second (fps), juvenile salmon switched to a low velocity zone next to the culvert wall and just below the water surface. The maximum velocity in this zone that permitted successful juvenile fish passage was at or below 2 feet per second. Increased turbulence limited the maximum velocity at which juvenile fish can pass the culvert. Powers et al. (1997) surmised that the rough culvert walls reduced the velocity barrier but replaced it with a turbulence barrier to small fish. Also, fish size influenced behavioral response to turbulence and to culvert structures.

Ongoing studies at a research culvert facility in the State of Washington are focused on evaluating the success of juvenile fish passage upstream in a culvert test bed in relation to the velocity and turbulence conditions within the culvert for various discharges, slopes, and bottom types. In a 40-foot long, 6-foot round culvert with spiral corrugations, researchers noted an area of reduced velocity on the right side of the culvert (Figure 2); velocities in the reduced velocity zone (RVZ) were approximately 36% of the average velocity (Pearson et al., 2003). In biological tests using juvenile coho salmon, the researchers found that successful passage from the RVZ was three times higher than from the left side of the culvert and two times higher than from the center portion of the barrel.

Analysis of this limited data set suggests that the relatively low velocity and turbulence intensity in the RVZ may be an important factor determining success of upstream movement. The exception to this relationship occurred at the culvert inlet contraction zone, where fish were generally observed to dart out of the bottom center of the culvert. From testing a range of flows, researchers developed the following equation to predict velocity in the RVZ for the test culvert described above (Pearson et al., 2003):

$$V_{RVZ} = 0.48\ Vave^{0.83}$$

Hydraulic data analysis also showed that the velocity and turbulence intensity are reduced on the right side of the culvert as seen looking upstream due to the orientation of the 5°-pitch spiraled culvert corrugations. This information could be useful for design of culvert retrofits to investigate which commonly manufactured combinations of spiral angle, amplitude, and length maximize the cross-sectional area of the RVZ (Pearson et al., 2003).

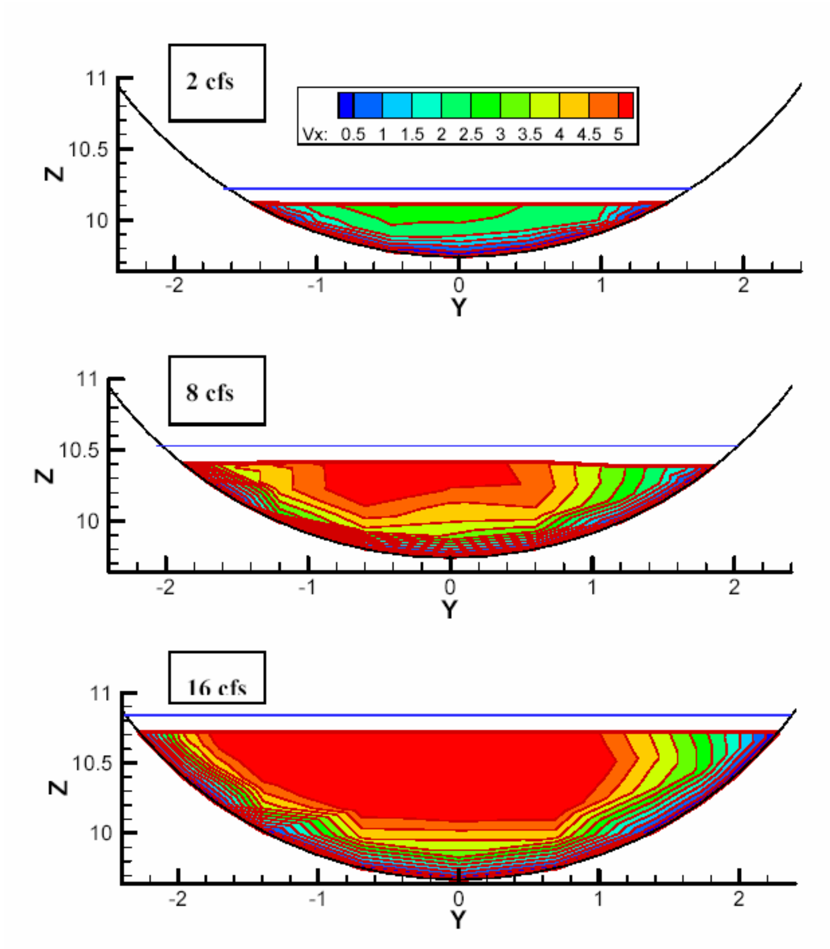

Figure 2. Reduced velocity zones skewed to the left as a result of spiral corrugations, measured at the Skoochumchuck culvert test facility (from Pearson et al., 2003).

The report notes the implication that average or maximum velocities across the culvert are not particularly useful design parameters, based on the observed preference for juvenile coho salmon to use the RVZ to pass upstream in the culvert, at least under the baseline conditions tested (Pearson et al., 2003).

FishXing Hydraulic Validation

Comparison of Modeled Results to Field Measurements

The FishXing hydraulic validation effort compared modeled results of velocity to field measurements in the following manner. After the data required to run the FishXing program were entered, the culverts were modeled using parameters and variables selected or suggested by the FishXing pull-down menus. Manning's *n* coefficients were selected according to the culvert type; *n* coefficients for the natural channel bottom roughness were selected based on a short description of the channel bed. Surveyed tailwater cross-sections were input and used to define the tailwater conditions and tailwater rating curve. The inlet head loss coefficients were selected from the pull-down menu to match the culvert inlet types observed in the field.

Culvert types included box culverts (Dave Creek), pipe arch (Beaver Creek, Bishop Creek), open bottom arch (Slikok Creek), circular CMP (Jean Creek, Corea Creek), and multiple pipe arch (Moose Creek). The recently completed Beaver Creek culvert is a large pipe arch culvert, but was constructed with a bedload collector to retain cobbles and boulders along the length of the bed. The pipe arch dimensions were too large for the FishXing Version 2 software. To accurately represent this culvert in FishXing, it was modeled as an open bottom arch, embedded one foot, using the measured dimensions. This selection results in a culvert with natural substrate along the bottom, which increases the bed roughness resulting in lower water velocities.

With all stream and culvert data loaded, model runs were conducted at the field-measured discharge value. The model output estimations of average velocities and water surface elevations were then compared to the field measurements of water velocities and surface elevations made at the time of data collection. Results are found in Table 4.

Table 4. Modeled and measured velocities at culvert inlets and outlets, this study.

Culvert	Culvert Type	Discharge (cfs)	Average Water Velocity (feet per second)			
			Inlet		Outlet	
			Modeled	Measured	Modeled	Measured
Beaver Creek	pipe arch	34.01	2.46	1.94	2.97	1.71
Bishop Creek	pipe arch	40.00	2.89	2.06	2.13	1.51
Corea Creek	cir-CMP	7.50	na-bb	2.29	na-bb	0.78
Dave Creek left	box	8.40	na-as	1.17	na-as	1.41
Dave Creek right	box	21.20	4.59	1.81	3.75	2.01
Jean Creek	cir-CMP	5.63	na	0.86	na	1.70
Moose Creek left	pipe arch	7.34	2.73	0.90	2.40	0.99
Moose Creek right	pipe arch	6.23	2.19	0.72	2.44	0.75
Slikok Creek	open bttm	20.16	1.37	0.92	0.62	0.63

na-bb. Culvert has broken back, cannot be modeled in FishXing
na-as. Culvert slope is negative, cannot be modeled in FishXing

At 11 sites, the FishXing model overestimated the actual average velocity by an average of 113 percent. At one location, the model underestimated the velocity by 2 percent.

The Rich report and associated database did not provide sufficient information to allow a similar comparison of modeled versus measured velocities for the culverts included in the ADF&G study.

The Use of Calibration to Improve Modeling Results

Calibration is a commonly used technique to improve the performance of numerical models that attempt to simulate natural system responses. Users of programs such as HEC-RAS and others are familiar with the process of tuning model coefficients so that modeled results will more closely match observed results. Calibration methods are not described in the FishXing documentation; however, several of the user-selected input parameters may be used to calibrate a modeled culvert before simulation runs are made. Adjustable parameters include the following: 1) Manning's *n* coefficient for the culvert and natural bed, 2) inlet head loss coefficient, and 3) tailwater Manning's *n* and slope.

For calibration of a FishXing model, calibration data requirements include a measured discharge value and the coincident water surface elevation at the tailwater cross-section. To calculate the observed average velocities, the wetted perimeter cross-sectional areas of the culvert inlet and outlet zones are also needed. By dividing the discharge by the cross-sectional areas, the average velocities within the culvert may be calculated. Once the observed average velocities in the culvert and water surface elevation at the tailwater are known, adjustments to the coefficients can made until the modeled parameters in the culvert match or approach measured parameters.

To illustrate this process, the culverts that were modeled for the hydraulic validation effort described above were subsequently calibrated. If the Cross-Section Method was used to develop the tailwater rating curve for a culvert, the rating curve was calibrated by adjusting two parameters such that the known discharge-elevation data pair matched the modeled results. In addition to the Manning's *n* coefficient, the slope of the tailwater section was adjusted from the initial value of the measured average slope through the tailwater control. Following the correction of the rating curve, calibration was conducted by adjusting the Manning's *n* coefficients and the inlet head loss coefficient for each model. The results of the calibration effort, including the changes in the coefficients from the original (model-suggested values) to calibrated, are found in Table 5.

Conservative Bias in Methodology

Three analyses were conducted to determine the direction and extent of the bias in the draft Level 2 methodology using FishXing. The first analysis was conducted using three of the study sites from this report. Culvert velocities were calculated using FishXing, following methods used in the AKDF&G draft report. This includes estimation of the Q_2 with the Jones and Fahl (1994) report, no calibration with field data, and no use of the velocity reduction factors. Then the same sites were re-analyzed using the updated USGS flood estimation regression equations (Curran et. al, 2003), calibration of coefficients, and conservative application of velocity reduction factors (0.8 for inlet and outlet, 0.4 for barrel; Behlke et al., 1991). No changes were made to the fish swim speeds or time to exhaustion. Table 6 notes the changes in calculated velocities at the culvert inlets, outlets, and mid-barrel, and changes to the calculated barrier status.

Table 5. Culvert calibration using adjustments to roughness *n* coefficients, inlet head loss coefficients, and tailwater slope.

Culvert	Coefficients *__before calibration__* *after calibration*					Modeled average velocities (ft/sec)		TW elevation from rating curve at measured discharge (ft)
	Manning's *n*			Inlet head loss	TW slope (ft/ft)	Inlet	Outlet	
	culvert	channel bed	TW xsec					
Beaver Creek	<u>0.028</u> 0.060	<u>0.040</u> 0.060	<u>0.040</u> 0.065	<u>0.5</u> 0.5	<u>0.015</u> 0.002	<u>2.46</u> 1.89	<u>2.97</u> 2.29	<u>95.55</u> 96.22
Bishop Creek	<u>0.028</u> 0.040	na na	<u>0.035</u> 0.057	<u>0.5</u> 0.2	<u>0.002</u> 0.0015	<u>2.89</u> 2.01	<u>2.13</u> 1.62	<u>94.75</u> 95.40
Dave Creek right	<u>0.013</u> 0.085	na na	<u>0.035</u> 0.030	<u>0.5</u> 0.1	<u>0.034</u> 0.010	<u>4.59</u> 1.80	<u>3.75</u> 2.82	<u>na</u>
Moose Creek left	<u>0.028</u> 0.10	na na	<u>0.030</u> 0.020	<u>0.9</u> 0.01	<u>0.0003</u> 0.0003	<u>2.73</u> 0.89	<u>2.40</u> 1.50	<u>na</u>
Moose Creek right	<u>0.028</u> 0.10	na na	<u>0.030</u> 0.020	<u>0.9</u> 0.01	<u>0.0003</u> 0.0003	<u>2.19</u> 0.74	<u>2.40</u> 1.40	<u>na</u>
Slikok Creek	<u>0.028</u> 0.028	<u>0.030</u> 0.10	<u>0.035</u> 0.033	<u>0.5</u> 0.01	<u>0.0014</u> 0.0014	<u>1.37</u> 1.01	<u>0.62</u> 0.63	<u>95.25</u> 95.21

A second analysis was conducted to determine what the minimum discharge was that triggered the fish barrier notice in a FishXing application, and how often that minimum flow occurs during the summer in an example watershed. The new Beaver Creek culvert was chosen for this analysis for two reasons: 1) this culvert was specifically designed and constructed for fish passage, and presents the most favorable configuration for fish passage in this culvert study group, and 2) there are 11 years of USGS gaging data from the culvert site.

Table 6. Correction to modeling bias using calibration.

Method of Calculation	**Site**		
	Beaver Creek	**Bishop Creek**	**Slikok Creek**
Q_2 -2 day (Jones and Fahl) (cfs)	130	67	72
Inlet/midbarrel/outlet average velocities, no calibration, no velocity reduction (ft/sec)	4.28/3.79/4.89	2.80/2.76/2.64	2.27/1.60/1.38
Barriers	V (juvenile)	EB (juvenile)	EB (juvenile)
Q_2 -2 day (Curran et. al, 2003) (cfs)	69†	53	58
Inlet-midbarrel-outlet velocities in the RVZ after calibration, velocity reduction factors (ft/sec)	2.05/0.92/2.47	2.24/1.02/2.04	0.81/0.32/0.50
Barriers	EB (juvenile)	EB (juvenile)	None

EB-Fish exhausted at burst speed
V-Strict velocity barrier
†log-Pearson Type III frequency distribution analysis

Both the uncalibrated and calibrated models of the Beaver Creek culvert were run repeatedly in the FishXing program with increasing discharge values until the thresholds for triggering fish passage barrier notices were achieved. For the uncalibrated model, the threshold was 4 cfs (fish exhausted at burst speed). For the calibrated model, the threshold was 45 cfs (fish exhausted at burst speed).

To get an idea of what the relationship would be between the passage barrier threshold discharge values and typical summer flows for the Beaver Creek watershed, daily streamflow records from the USGS gaging station at Beaver Creek (Station number 15266500) were retrieved for the summer flow months of May 1 to September 30 for the years 1968 through 1978 (Figure 3).

Based on results from the uncalibrated FishXing model, the new Beaver Creek culvert would have acted as a fish barrier for juvenile coho every day between May 01, 1968 and September 30, 1978. For the calibrated model, the Beaver Creek culvert would have acted as a fish barrier for juvenile coho for 173 days of the 1510 days between May 1 and September 30 for the years 1968 to 1978.

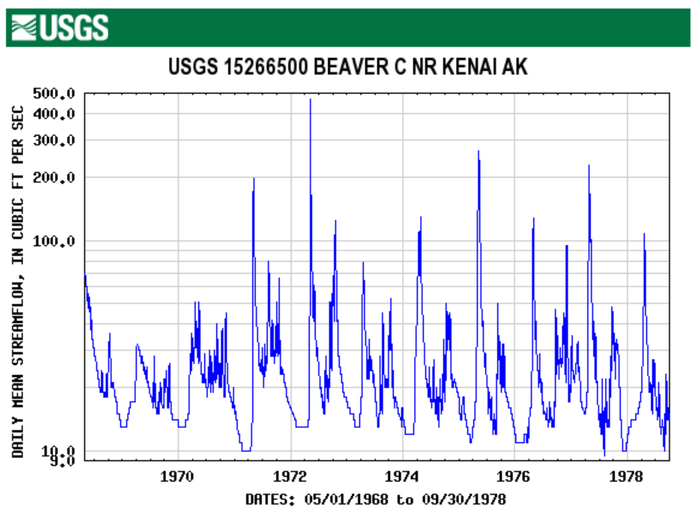

Figure 3. Beaver Creek hydrograph, 1968 through 1978.

A third analysis was conducted to determine the relative bias in FishXing compared to the Level 1 criteria. In the AKDF&G draft report, nine of the 97 culverts inventoried and assessed were assumed adequate for fish passage. The nine were rated ‘green’ using the Level 1 coarse filter (all culverts assessed using the FishXing program were rated ‘red’). The intent of the analysis was to test the Level 1 ‘green’ culverts with the FishXing program by the methods used in the Level 2 protocol.

Of the nine culverts, three were rated ‘green’ because they were located in palustrine channels where the outlet pool water elevations were higher than the elevation of the culvert inlets (culverts fully backwatered). Two of the nine culverts could not be analyzed with FishXing, as the database reported a negative or adverse slope for one (47), and one culvert had an elliptical shape (89). Three of the creeks (49, 13, 35) had insufficient information to develop an estimate of the Q_2, but were analyzed to determine the discharge required to make the culvert a barrier.

Four creeks with estimates of the Q_2-2 day discharge (Alder Creek, Slate Creek, Ohmer Creek, Grouse Creek) were analyzed with FishXing, using data from the AKDF&G Access database. If not included in the database, tailwater cross-sections were synthesized using downstream water surface elevations, channel widths, thalweg elevations, discharge measurement cross-section profiles, and photographs. The Q_2-2 day discharge was obtained from the AKDF&G draft report for Slate Creek, Grouse Creek and Alder Creek; it was estimated for Ohmer Creek using the Jones and Fahl (1994) regression equations and watershed characteristics obtained with standard methods. Slate Creek has two culverts; flow was proportioned and the two culverts were analyzed separately.

All four sites were calculated as 'red' or fish barrier culverts by the FishXing analysis. Ohmer Creek and Alder Creek were strict velocity barriers for juvenile coho, and the Slate Creek and Grouse Creek culverts exhausted juveniles at burst speed (EB) within a few feet of the culvert outlet.

Of the three sites without a known Q_2, two were in palustrine channels and were modeled using the Constant Tailwater Method. The minimum discharge values that triggered the resultant barrier conditions in the model were: 1.9 cfs for left and right culverts (tributary of Kenai River-EB); 1.0 cfs (tributary of Dave's Creek-EB); and 3.2 cfs (tributary of Kenai River-Fish exhausted at prolonged speed).

Culvert Prioritization Methodology

The AKDOT&PF appropriates competing and limited resources for annual culvert retrofits and replacements; this necessitates economical and accurate assignment of priorities for culvert retrofits or replacements in order to mitigate the most egregious problems first. Though initial work has been conducted by some AKDF&G personnel to develop such a prioritization method, the current protocol includes no such provisions. The following is a discussion of the criteria required for a prioritization method, and a brief review of three existing methods from other agencies.

The key element of a successful prioritization method is the development of a ranking system to determine whether a project is high or low priority within a study area. Some of the criteria are weighted more heavily than others. Criteria range in scope from biological considerations to amount and quality of habitat to cost effectiveness and maintenance needs. Some criteria will generally be weighted more heavily than others, depending on the relative value of the criterion to the agency personnel and concerned citizenry involved in the process. With relevant criteria defined and a ranking system developed, the prioritization method provides a quantitative, science-based, decision-making tool to help determine a culvert replacement prioritization list for fish passage.

Ranking Criteria

The following is a brief discussion of typical ranking criteria that are found in several prioritization methods from the Pacific Northwest region. Additional criteria may be required by special conditions, biological environments, or budgetary concerns; however, the use of supplementary criteria will likely create additional data needs, research efforts, and result in a burdensome process for prioritizing culvert inventories for replacement or rehabilitation. These criteria are provided here as examples from other programs, and not as specific recommendations for adoption in Alaska.

Quality of upstream or downstream habitat recovered-Perhaps the most important criterion to be ranked is the habitat along a stream that would be made available by culvert replacement. The quality of that habitat is used as the ranking value; that value is determined by organizing the habitat quality into several classifications. For example, habitat may be classified as highly degraded (no riparian vegetation, high sedimentation, invasive species), degraded (sparse riparian corridor, non-native species, little shading), average to good (mature trees, some shading, no development within a defined buffer), high quality (strong riparian corridor, no development within a defined larger buffer), and very high quality (undisturbed, no invasive species, mature trees and shrubs) (CCSRT, 2004).

Length/area of habitat recovered-In addition to the quality, the lineal or areal amount of aquatic habitat that is being restricted by the culvert needs to be considered and weighted appropriately. Streams with larger amounts of available habitat will be weighted heavier than streams with less upstream length.

In addition to the length of habitat, the ranking scheme should consider the direction of the available habitat, either upstream or downstream of the culvert. For streams with anadromous salmonids, habitat is always assessed upstream of the culvert. However, for streams with resident salmonid populations, upstream and downstream habitat areas both need to be assessed and measured; for determining the value of the added habitat, the benefit to the resident salmonid population is represented by the habitat segment between the barrier culvert and the closest natural barrier, either upstream or downstream.

Downstream barriers to fish passage-Two types of downstream barriers may limit fish mobility: natural (waterfalls, steep creek gradients, geological changes) and artificial (culverts, dams, flood control structures). Streams with no downstream barriers should receive the heaviest rank weighting. Streams with artificial barriers that can be removed should receive a middle weighting. Natural barriers should generally not be removed; these streams receive a zero ranking for this criterion.

Proportion of passage improvement-This criterion provides a greater weight for projects that will result in a greater margin of improvement of fish passage. The expected increase of the fish run to new access and habitat is determined by subtracting the passability of the project before the improvement from the expected passability after the improvement.

Species Importance-This criterion is ranked according to the status of the fish species that will benefit from the barrier removal. For example, prioritization programs in the Pacific Northwest give the heaviest ranking to species listed on the Federal or State Endangered Species Act, or described as less healthy in state stock inventory reports. Though Alaska currently has no salmonid fish species listed as threatened or endangered, heaviest ranking may be assigned to fish species that AKDF&G biologists determine to be of concern.

Condition of Culvert-The existing condition of a culvert, and the expected level of maintenance required to retain the hydraulic function of a culvert, may be used as a weighted criterion for a prioritization scheme. A culvert in serious disrepair may present a threat to the integrity of a roadbed; the need for repair or replacement can increase the ranking level of a lower priority barrier culvert, as repair or maintenance activities will be required for the structure. For this situation, it is generally cost-effective and efficient to address fish passage issues at the time of maintenance activities.

Several methods may be used to develop ranking divisions and scores for culvert condition. For example, the Federal Highway Administration developed a numerical rating system for summarizing the condition of culvert components, using clear definitions and specific numerical values to insure accurate and consistent results (FHWA, 1986). The rating system provides a numerical scale that is related to the urgency of maintenance action required; an increase in urgency in the FHWA rating system would increase the ranking weight for a culvert rated as a fish passage barrier. The FHWA ranking is described briefly in Table 7; note that the numerical scale would be reversed to show an increase in rank weighting when maintenance problems increase.

Table 7. FHWA maintenance rating scale (FHWA, 1986).

Maintenance urgency index	Maintenance immediacy of action
9	No repairs needed
8	No repairs needed. List specific items for special inspection during next regular inspection.
7	No immediate plans for repair. Examine possibility of increased level of inspection.
6	By end of next season, add to scheduled work.
5	Place in current schedule, current season.
4	Priority-current season-review work plan for relative priority-adjust schedule if possible.
3	High priority-current season as soon as can be scheduled.
2	Highest priority-discontinue other work if required-emergency basis or emergency subsidiary actions if needed.
1	Emergency actions required-reroute traffic and close.

Replacement/rehabilitation costs-The cost of a culvert replacement or rehabilitation project is another major criterion when developing a prioritization system. Many factors need to be considered when estimating the cost of a culvert replacement, including type of culvert, open cut versus trenchless excavation methods, fill volume, and design costs. A significant portion of the total cost may be incurred by traffic management, and detour and temporary bridge construction. Additional culvert costs include items such as riprap, gravel, erosion control geotextile, headwall construction, and inlet and outlet aprons. Experienced engineers may be able to provide quick 'off the cuff' estimates, based on the expected length and diameter of the culvert.

Another factor that affects construction costs is whether or not a culvert is located on a roadway listed in a periodic construction maintenance or rehabilitation schedule, such as the Alaska Statewide Transportation Improvements Program (STIP). As part of a larger construction project, replacement or rehabilitation costs may be somewhat lower. Mobilization costs can be an issue for smaller standalone projects versus larger construction projects. For a prioritization scheme, a range of project costs, based on historical values for typical culvert construction projects, is often sufficient to determine how much a project might cost. Projects that can be completed for less money are weighted more heavily than expensive projects.

Finally, another factor to consider is the potential for the target culvert to be retrofitted for fish passage, rather than replaced. Retrofitting may prove to be a cost-effective alternative to total replacement, assuming fish passage goals can be achieved. Accurate determination of the existing problem is essential for assessing the probability of a successful retrofit. For example, perching problems may be solved by modifying a downstream control structure to increase backwatering effects; high velocities and small culvert corrugations may be improved by installing a culvert bedload collector. However, options may be limited, and the designer must be able to recognize the false economy of unsuccessful retrofits. Additional discussion and some design techniques are found in Behlke et al. (1991).

Level of Barrierity-Many of the culverts identified in the 'red' and 'gray' categories are capable of passing fish in some or all life stages at some or most of the year. Indeed, fish are located upstream of many of the culverts. Studies have noted the upstream passage of juvenile fish through culverts in Alaska that were rated as barriers by the existing protocol (Kane et al., 2000). Culverts with characteristics such as large outfall heights (greater than 2 feet) or slopes steeper than 5% may act as total blockages for all life stages at all flows. Conversely, culverts with 4" outfall heights or small slopes may only act to block fish passage during either extremely low flows, or during the high passage design flow.

Concern has focused on providing passage for all life stages at all flows up to the fish passage design flow. However, it can be argued that, given two culverts with a similar quantity and quality of upstream habitat, more will be gained by replacing a culvert that is a total barrier than replacing a culvert that currently allows some passage upstream for some period of time, though it blocks one life stage of fish for another period of time.

For example, barrierity may be used to describe the length of delay a culvert may present to a fish traveling upstream, and the relative significance of that delay for the species and age class of concern. Culvert conditions that result in a several-day delay for upstream passage may have much more serious consequences for the success of spawning fish, as opposed to possible adverse effects on juveniles.

The level of a culvert's capacity to allow upstream passage may be determined either through professional judgment or through hydraulic analysis. A culvert's barrierity may be expressed as a percentage of total passage inability. For example, culverts may earn a ranking of some level between zero and 1. A culvert that acts as a total blockage would be rated as a 1; culverts that pass fish 50% of the time would be rated as a 0.5. In this manner, a factor is applied to quantify the level of the culvert's fish blockage characteristics.

Examples of three culvert priority methodologies are discussed in Appendix E. The programs are from the Oregon Department of Fish and Wildlife (ODFW), Washington Department of Fish and Wildlife (WDFW), and Clackamas County, Oregon; together, they display a wide range of methodology and information requirements. The ODFW methodology is the easiest of the three to use; data requirements for just six criteria are required, all of which relate to biological considerations. Criteria requiring estimations with low confidence levels, including engineering, passage values, and increases in production were left out of the methodology. The result is a simplified process, and results in calculated priority levels of high, medium, and low. This allows for flexibility and subsequent adjustment in the priority determinations, based on incidental knowledge, and can be viewed either as an advantage or disadvantage to the user.

The WDFW methodology presents a cumbersome process to understand and use when compared to the other two methods described above. The Priority Index calculation appears to be unnecessarily complicated, requiring the calculation of a fourth root. The value of determining the geometric mean from that calculation of the four criteria is also unclear.

The Clackamas County methodology presents a straightforward and easy-to-understand process for determining the priority of a culvert replacement inventory. Criteria include both biological and engineering costs.

CHAPTER 3 - INTERPRETATION, APPRAISAL, AND APPLICATIONS

Level 1 Criteria

Stream Constriction Ratio

The use of upstream channel width values to determine the constriction ratio may be incorrectly formulated for most culvert analyses. The use of upstream widths that are within the influence of the culvert restriction to determine the constriction ratio is not appropriate. Rather than estimating the upstream limit of that influence, alternative measures should be used.

Culverts in outlet control are in a downstream control regime; velocities and depths within the culvert are determined by conditions downstream. The control section for outlet control flow in a culvert is located at the barrel exit or further downstream (FHWA, 2001). For culverts under outlet control flow, a better representation of the ratio of the culvert span to channel bed width may be calculated by obtaining the channel bed width downstream of the culvert. For example, the State of Washington measures the streambed width at the second riffle downstream from the culvert (WDFW, 2000).

Investigators have noted that some stream types with naturally large width-to-depth ratios may be incorrectly placed in a no-passage category based on a large constriction ratio. For example, if a stream is unconfined, wide and shallow, the bankfull width can give a false indication of quantity of water in the stream when compared to the culvert span (as an indicator of the capacity of the culvert) (BLM, 2001). If this is the only evaluation criterion that results in a 'red' finding, it may be more appropriate to place the culvert into the 'gray' category until further evaluation is conducted to determine if the culvert is causing a flow constriction.

The Level 1 constriction ratio criteria should be adjusted to take into account backwater conditions at a culvert. Backwatering at the outlet zone generally results in increased depth of flow and reduced velocities. The draft protocol notes that culverts in palustrine channels are automatically rated 'green' due to the fully backwatered condition. Similarly, width ratios should be disregarded when rating backwatered culverts. In fact, gradient and perch height also should not be considered relevant for the assessment of passage of a fully backwatered culvert.

Outfall Height or Perch

The justification for using the flow-independent definition of perch is that, for a coarse filter analysis, water surface measurements at varying flows are not needed; the perch height can be determined with one measurement. However, some reports have noted that the flow independent assessment of culvert perch provides the maximum perch height possible, and as such provides an unrealistic over-estimate of perch height (USDA, 2002).

In fact, thirteen culverts in the study group classified as having an excessive perch were in a flow regime at the time of field measurement where the pool or tailwater water surface elevation exceeded the culvert outlet invert. For example, at Site 15, the downstream pool water surface elevation was 1.09 feet higher than the culvert invert at the time of measurement. At Site 66, the downstream pool water surface elevation was 2.56 feet higher than the culvert invert at the time of measurement. Without a hydraulic analysis, it is difficult to predict how low the flow would have to be to achieve the 4 inch perch condition at those culverts. It is apparent, however, that the independent flow definition can confidently define the true physical perch in only one hydraulic condition; that of zero flow.

The new Beaver Creek culvert illustrates an example where the transition geometry at the culvert outlet can eliminate a physical outlet drop and the necessity for a fish to jump, even as the flow-independent assessment reports a perch of almost one foot.

Some reports note that, because the flow-independent assessment is a conservative method to determine perch height, a preferable method would be to evaluate various discharges up to the high-flow design discharge if time considerations allow (Clifford and Kellet, 2004). An alternative to making multiple measurements would be to develop a rating curve for culverts which are categorized as 'red' by a single perch measurement. A graph would be developed showing perch height versus discharge. Such rating curves may show that, for many culverts, the limiting condition of the flow-dependent assessment occurs at the low-flow end of the discharge spectrum, where the actual perch is likely to be greatest to due low water surface elevations in the pool. Given this condition, culverts would be placed into the 'gray' category, and would be subjected to subsequent Level 2 analysis. If validated, this technique would lend confidence to the use of the flow-dependent assessment, and improve the ability to assess fish passability related to outfall height.

Regression Equations

The State of Alaska Fish Passage Memorandum of Agreement (ADF&G/ADOT&PF, 2001) notes that the use of regional regression equations and Manning's equation can produce higher discharge estimates relative to stream gaging and unit discharge/area estimates, and that such variability has the potential to incorrectly identify culverts as problems that actually do pass fish at design flows. An example of such an erroneous estimation is illustrated in the draft AKDF&G report. Peak streamflow data were available at two of the study sites (Beaver Creek and Fritz Creek). Using a Log-Pearson Type III frequency distribution analysis with the Beaver Creek 11-year data record, the USGS estimated the Q_2 at 172 cfs; however, the culvert analysis was conducted using the Jones and Fahl (1994) regression equation, which provided an estimate of 324 cfs, an 88% increase.

The peak discharge values estimated from the long-term Beaver Creek gaging station data were significantly smaller than those estimated from the regional equations. This disparity is likely explained by examining the individual watershed. Numerous beaver dams are found upstream of the gaging station in the Beaver Creek watershed; such dams likely affect the watershed hydrology by attenuating flood peaks. The attenuation is reflected in the long-term gaging data as lower instantaneous flood peaks when compared to area-adjusted regionwide hydrographs. As such, the use of the Q_2 estimate from the flood-frequency analysis of peak-discharge data would have been more appropriate than the use of the regression equation estimation (Tim Brabets, USGS, personal communication, 2004). Though the Rich report notes that estimations of flood magnitude are more accurately estimated when using streamflow data rather than regional regressions, the regression equation estimations were apparently favored for use at both sites mentioned above.

Another feature of the new USGS report is a downloadable computer program that allows for an easy application of the prediction regression equations. However, it cannot be overemphasized that the user of these techniques should have a basic understanding of the statistical methods used to develop the regression equations. When using the methods and equations presented in the report, the user must adhere to the limitations inherent in those methods. This includes an understanding of the accuracy of the estimating equations. The user should evaluate the adequacy of a prediction for all ungaged sites by calculating the site-specific standard error of prediction, and the equivalent years of record. A third measure to evaluate the adequacy of a prediction has been added to the new report; the user can generate the 5-percent and 95-percent confidence limits for each individual prediction. These calculations are included in the downloadable computer program.

It is crucial for the user to understand the ranges of basin characteristics used for equation development, and to develop predictions only for watersheds within those ranges. The minimum basin areas for several of the flood-frequency areas have been reduced. However, many streams that are small enough to accommodate culverts may still have watershed basins too small for the equation ranges; those streams should be evaluated by other measures until an alternative method for determining the Q_2 is developed.

The MOA notes that additional hydraulic and biological studies are needed to improve the fish passage design discharge for juvenile salmon (ADF&G/ADOT&PF, 2001). The Q_2 design flood flow is used to approximate the mean-annual spring-runoff flood, and is truncated for a two-day duration. This value appears to have been originally developed for grayling migrations, which occur during the mean-annual spring runoff flood (Behlke et al., 1991). The MOA notes that future estimates for fish passage design discharge will account for the specified time of year that the design fish is migrating upstream (ADF&G/ADOT&PF, 2001). In addition to considerations of different spawning timing windows, more information is needed on the consequences of upstream delays for species other than grayling, and different age classes (juvenile versus adult).

In addition to biological criteria, concern should be noted about the unverified method of estimating the Q_2-2 day discharge value as 40 percent of the instantaneous Q_2 discharge. Long-term hydrologic records from southcentral Alaska are readily available, and should be used to estimate the 2-day exceedance value for the Q_2 flood. Improvements to the estimations of the biological implications of migration delay, and the subsequent methods to determine the design flow exceedance values, are necessary to strengthen the validity of the fish passage protocol.

A companion study to the new USGS peak flow frequency analysis resulted in development of methods to estimate the daily mean flow-duration statistics for seven regions in Alaska and low-flow frequencies for southeastern Alaska. This report presents (1) computed annual high-flow and monthly and seasonal low-flow statistics for selected months and seasons for gaged rivers, and (2) equations for estimating high-flow and low-flow statistics at ungaged sites (Wiley and Curran, 2003). Such methods could prove especially useful for fish passage design if biologists can develop guidelines of acceptable fish migration delay for an entire month or migration season.

Other Methods for the Estimation of Design Flows

In the AKDF&G draft report (Rich, 2003), a brief discussion lists, in order of decreasing accuracy, five methods to derive estimates of watershed hydrology: 1) streamflow gaging data, 2) correlation to a similar watershed with gage data, 3) local regression model, 4) simulation model (i.e. HSPF), and 5) regional regression model. However, a sixth method was apparently used to estimate the Q_2 for an unknown number of streams. The Q_2 was estimated based upon the discharge calculated to occur at bankfull flow at the outlet pool tailcrest cross section using Manning's equation; this method relied upon the analysis of morphological indicators of the bankfull channel, such as a flat depositional area located above the ordinary high water mark (Rich, 2003).

The use of this method for determining the Q_2 discharge value is subject to substantial error, and should be attempted only by experienced geomorphologists. Two steps are required in this method; designating bankfull discharge in the field, and using Manning's equation to estimate the discharge value of the surveyed bankfull cross-section.

The determination of bankfull discharge is a multi-step process when performed correctly. The field effort should utilize a reach of length equal to about 20 widths; this reach should be 'representative' of the stream. Multiple bankfull indicators are then identified, marked, surveyed, and analyzed. Indicators include changes in vegetation types, topographic breaks, changes in the size distribution of surface materials, and changes in deposited debris (Leopold, 1994). The identification of bankfull indicators at a single cross-section immediately downstream from a hydraulic structure may produce widely inconsistent results, and is not recommended.

Using the Manning's equation with questionable field data compounds the problems with this method. Manning's equation is commonly used in natural channels for conditions that are not consistent with its underlying assumptions, including: non-uniform reaches, unsteady flow, irregular shaped channels, turbulence, steep channels, etc. Additionally, an accurate estimation of the flow roughness coefficient is crucial for predicting water surface elevations and water velocities; studies in Alaska have noted that field estimates by experienced hydrologists often underpredict Manning's *n* (Janet Curran, USGS, personal communication, 2005). The selection of underpredicted Manning's *n* coefficients will result in overestimations of discharge.

Without a substantial validation endeavor, this method should not be used for the determination of the Q_2 discharge. Future efforts should be directed toward using one or more of the five methods described in the report, with the focus on developing the data needed for the most accurate methods.

FishXing Modeling-Hydraulic Analysis

The results from the hydraulic validation are shown in Table 4. Based on modeling runs for 6 culverts, the FishXing program shows a consistent tendency to overpredict water velocities within a culvert for various culvert types at low flows, when using suggested coefficients. This tendency to overpredict velocities has a direct effect on the ultimate determination of fish passage; if not corrected, the modeling results cannot be represented as an accurate portrayal of actual hydraulic conditions within a culvert.

FishXing shares many of the same computational methods found in other numerical hydraulic codes such as HEC-RAS; however, the assumption in FishXing of quiescent conditions and no flow velocity at the culvert headwater likely leads to an overestimation of water velocity within the culvert barrel. Efforts should be made to improve the computational abilities of culvert hydraulic programs such as FishXing and HY-8 by including approach velocity in the solution of the gradually varied flow equation.

In addition to the computational framework in FishXing, user-selected variables within the software may be misapplied and result in erroneous output. User-selected variables are described below.

Manning's n

In Manning's equation, the mean estimated velocity is highly dependent on the roughness coefficient, as it varies inversely to the roughness coefficient. Within the FishXing program, the Manning's *n* roughness coefficient may be adjusted for three separate calculations during a typical culvert simulation, including culvert materials, natural channel beds, and the tailwater bed. The help files within FishXing note that values for different culvert materials are widely published and given as default values, and that roughness coefficients for natural channels and culverts containing natural channel substrate differ widely and need to be measured or estimated from experience. However, pull-down menus are limited and still suggest which values to use based on short descriptions of the channel materials.

Though Manning's equation was developed for uniform flow conditions, it is commonly used in natural channels where non-uniform conditions exist. This includes irregularly shaped natural channels where the water surface slope, friction slope, and energy gradient are not parallel to the streambed. The selection of a single value of the *n* coefficient results in problems, as the *n* value changes as the depth of flow, slope, discharge, and cross-sectional shape change.

Flow roughness generally cannot be measured directly. Though an accurate estimation of the flow roughness coefficient is crucial for predicting water surface elevations and water velocities, studies in Alaska have noted that field estimates even by experienced hydrologists underpredict Manning's *n* for streams in the state with steep gradients and coarse bed material. In such streams, ongoing studies are investigating the correlation of the reach-average Manning's *n* to slope; initial finding suggest that slope may provide a means for estimating flow roughness coefficients (Janet Curran, USGS, personal communication, 2005).

The selection of Manning's *n* coefficients that are smaller in value than those represented by the real-world conditions being modeled will result in overestimations of velocities in the culvert and natural channel bed. Suggested values in the coefficient pull-down menus commonly underestimated *n* coefficients for the sites analyzed in this study.

Inlet Head Loss Coefficient

The inlet head loss coefficient is a constant in the head-loss term of the energy equation for open-channel flow. This coefficient is a measure of the efficiency of the inlet to smoothly transition flow from the upstream channel into the culvert. The FishXing software provides a pull-down menu with 5 types of culvert inlet configurations, with coefficient values ranging from 0.2 to 0.9.

As the FishXing help files explain, the inlet head-loss coefficient is a function of the flow, and most published coefficients are for relative depths (headwater depth/culvert rise) of about 1.2. These published inlet loss coefficients assume quiescent conditions at the inlet that occur during high flows where significant ponding occurs. Such flows and relative depths are well above fish passage flows.

The selection of inlet head loss coefficients that are larger in value than those represented by the real-world conditions being modeled will result in overestimations of velocities in the culvert inlet. Suggested values in the head loss coefficient pull-down menu commonly overestimated the coefficients for the sites analyzed in this study.

Research is currently in progress to help determine appropriate entrance loss coefficients for buried inlet fish passage in Alaska (TRB, n.d.). The object of this National Cooperative Highway Research Program (NCHRP) project is to allow designers to use inlet loss coefficients for a range of pipe types, slopes and flows that more accurately reflect conditions at low-to-medium flow fish passage discharges, rather than resorting to using published "unburied," high flow inlet loss coefficients. Results from this research effort should improve computational simulations using FishXing. In the meantime, inlet loss coefficients can and should be adjusted during the calibration process to improve the model's ability to estimate entrance zone water velocities.

Tailwater Elevations

For outlet controlled culverts, the backwater calculation begins at the tailwater elevation or at critical depth, whichever is higher. If specified by the user, FishXing creates a tailwater elevation-discharge rating curve using a simplified routine based on Manning's equation by estimating tailwater elevations at different discharges. Based on the modeled discharge, the rating curve provides the downstream boundary condition to conduct the subsequent upstream elevation calculations.

To develop a rating curve for estimating tailwater elevations, the FishXing program requires a cross-section, roughness coefficient, and a slope of the channel bed downstream from the culvert outlet. The software's embedded help file (V2.2) states that the slope should be measured through the surveyed cross-section; in the standalone help document for Version 2.1, the recommendations include surveying either the slope of the downstream channel bed or water surface, beginning at the tailwater control and ending at the next significant break in slope. However, channel beds can exhibit substantial natural variability slope in a short reach relative to a longer section, especially in pool-riffle sequences.

Small variations in the selection of channel bed survey points during the field survey can result in significantly different slope calculations. Variations in the selected slope and roughness coefficient values will have a corresponding effect on the FishXing-constructed tailwater rating curve that establishes the downstream boundary control for initiating velocity and water surface elevation calculations upstream through the culvert. Similarly, the location of the surveyed tailwater cross-section is critical to the analysis, and should be selected after thorough consideration of the hydraulic conditions at the site.

Of the culverts analyzed for the FishXing analysis, three were modeled using the Channel Cross-Section Method to develop a tailwater rating curve. Using suggested *n* values from the pull-down menu in the tailwater component and field measurements of slope, the program underestimated the tailwater elevation and overestimated the downstream boundary condition velocity at one point on the rating curve for two sites. For the third site, the program estimation of tailwater elevation matched the field-measured elevation.

Model Calibration

Calibration can be defined as 'the first stage testing or tuning of a model to a set of field data, preferably a set of field data not used in the original model construction; such tuning to include a consistent and rational set of theoretically defensible parameters and inputs' (Thomann and Mueller, 1987). The purpose of model calibration is to obtain an accurate mathematical representation of reality, not a forced fit of a poorly constructed model (NHI, 2002). The process of calibration involves making several runs with the computer model while adjusting a chosen set of input parameters from a known field situation to match the observed output parameters. An exact match of several points is desirable; however, this is often impossible to achieve, and the modeler must either accept a solution with as small an error as possible, or choose not to use the model.

Just as important as the calibration process is the validation or verification of the model. By testing the calibrated model with a second independent data set, the modeler can increase confidence in the range of validity of the calibrated model. In the case of numerical hydraulic models, the goal is to obtain a discharge measurement near the upper end of the range of prediction for the project; in this case, the second discharge measurement should be taken at a flow close to the Q_2-2 day flow. Coincident measurements to obtain average velocity are also made at this time.

Fish Swim Speeds

The scope of this project did not include researching current literature on fish swimming performance. However, the accuracy of the performance values selected for use in the FishXing program is as important to the analysis as the accuracy of the hydraulic calculations.

The determination of fish passage capability using FishXing is extremely sensitive to fish performance values, especially short-duration burst swim speeds. However, the database for these performance data is very limited. Selecting the performance values to use for a particular analysis requires the use of best professional judgment.

Cumulative Effects of Conservative Methodology

As noted earlier in the report, the existing draft culvert assessment protocol may be characterized as a conservative methodology; that is, the criteria used in both the Level 1 coarse filter and the FishXing hydraulic software will tend to provide an overreaching level of questionable or non-passage status for culverts. The Level 1 criteria matrix was designed such that all culverts that are identified as ‘green’ are most likely able to pass fish at all life stages up to the fish passage design discharge for that culvert. However, not all culverts that are identified as ‘red’, either through the Level 1 or Level 2 filter, will act as fish barriers, even at the fish passage design discharge.

Individual criteria have been identified as conservative throughout this report; these criteria act in some way to increase the estimated velocities within a culvert, which act as a deterrent to fish passage. They include the following factors:

- Level 1 criteria-The criteria have been identified by the authors and users as ‘conservative.’ The use of the flow-independent perch definition and upstream width measurements increases the level of conservativeness.
- Determination of the Q_2-2 day duration flow-error statistics of the Q_2 regression equations from the Jones and Fahl (1994) report show a range of standard error of predictions in both directions, though the range of error is greater for overestimation than underestimation. Additionally, alternative methods using physical methods and roughness equations to estimate the discharge tend to overpredict discharge values.

- FishXing assumes a zero approach velocity at the culvert inlet that increases the headwater depth, and results in faster velocities in the culvert inlet zone.
- Velocity calculations in FishXing-The use of suggested coefficients from the pull-down menus without calibration tend to increase estimations of culvert water velocities in tests comparing modeled results to field data.
- Non-use of velocity reduction factors-Lack of baseline information and a lack of effect in modeling efforts as a result of overestimated velocities led to the rejection of the use of velocity reduction factors in the AKDF&G Kenai Peninsula study.

In addition to providing separate tendencies toward a conservative outcome, the criteria may cause a cascading effect toward an inaccurate determination of fish barrier status. Beginning with an overestimation of the fish passage design discharge, calculations involving velocity (either directly or indirectly) proceed in a succession of stages so that each stage derives from the product of the preceding. The cascade is initiated with an overpredicted discharge that will tend to inflate subsequent velocity estimations. Without calibration, the FishXing program will overestimate velocities already inflated by the overpredicted discharge value. The overestimated velocities overwhelm the velocity reduction factors. Finally, conservative values of swim time to exhaustion, when applied to overpredicted culvert velocities, result in a non-passage classification of culvert status.

The Level 1 criteria matrix appears to provide extremely conservative results when used to assess fish passage. The criteria matrix was devised such that culverts that pass the matrix successfully (green) are highly unlikely to be fish barriers. Along with the hydraulic evaluation discussed earlier, the fact that the ‘green’ culverts from the Level 1 assessment were subsequently determined to be fish barriers in the Level 2 assessment indicates the bias in FishXing toward consistently overestimating velocities. It is recommended that the FishXing program should not be used for fish passage assessment without first undergoing a model calibration and validation effort.

Field Data Needs and Methods

To support the development of the Level 2 protocol, data collection efforts for the Kenai Peninsula inventory project were extensive. Several of the data parameters were ultimately not included in the draft methodology; these measurements included 5 or more point velocity measurements upstream, in, and downstream of the culvert, ‘chip tests’ that involve timing the passage of a floating object 3 times through a culvert, ordinary high water widths and elevations at 5 or 6 locations, surveyed elevations of the culvert tops, and others.

Techniques are needed to improve the efficiency and time required to analyze culverts for fish passage. Three important goals in the effort to improve field techniques are to:

1. reduce the number of trips required to each site to one or two,
2. reduce the field measurements to a basic level, and
3. insure the accuracy and precision needed for a hydraulic survey.

The first goal is achieved by initially collecting only the data needed for the Level 1 assessment, then analyzing the data on-site to determine whether or not additional field data are needed. The level and complexity of data needed for the Level 1 matrix is low, and includes the following:

- culvert metrics (width, height, length, type, corrugation size, substrate depth and coverage)
- culvert invert elevations at both ends
- representative width of the channel, usually at the second riffle downstream from the culvert
- water surface elevation at the following: culvert outlet, outlet pool, tailcrest.

With this information, a competent crew should be able to quickly calculate the culvert slope, bedwidth ratio, and outfall height in the field. While still at the site, the crew should also be capable of quickly applying these data and calculations to the modified Level 1 criteria matrix to determine the classification of the culvert (green, gray, red). Culverts classified as 'red' or 'green' are completed, except for required biological surveys. Culverts classified as 'gray' will trigger the collection of additional field data during the site visit.

The additional procedures for culverts classified 'gray' will provide the data required to model the culvert in the FishXing program, and to calibrate and validate the model. The additional data requirements are:

- tailwater pool depth
- tailwater control cross-section that extends to the bank on either side
- tailwater substrate type
- discharge measurement coincident with the water surface elevation surveys
- area of the wetted perimeter cross-sections in the culvert inlet and outlet
- horizontal distance between the tailwater cross-section and the second riffle downstream
- culvert inlet type.

While conducting the fieldwork, efficiency is increased by conducting the discharge measurement at the same location as the tailwater cross-section. The incremental width-depth data from the discharge measurement is easily converted to station-elevation pairs for the wetted perimeter section of the cross-section. A level survey along the stretched tag line completes the cross-section from the edge of water up to the top of the bank for both sides, and provides the datum to convert the depth data to elevations.

Pins used to stretch a tag line at the tailwater cross-section should be noted on a site map and left in place; they will be used to relocate the cross-section during the follow-up fieldwork discharge measurement required for model validation.

The slope downstream of the tailwater cross-section is used to help develop the rating curve in the FishXing program. The slope should be measured by surveying the elevation difference of the water surface elevations at the tailwater cross-section and the second riffle downstream from the culvert. A measuring tape should be used to determine the channel distance between the two points.

Calibration of the FishXing program requires the adjustment of the slope and roughness coefficient at the tailwater control such that the measured discharge agrees with the surveyed stage elevation in the calculated rating curve. The calibration also requires the agreement of average velocities in the culvert inlet and outlet zones at the measured discharge value to modeled results.

Average velocity in the culvert inlet and outlet zones is determined by dividing the discharge by the measured area of the flow in the culvert at each end. In a rectangular section (box culvert), the area of flow is simply the width times the depth of water. For a circular culvert, the depth of water is measured and simple geometry is used to determine the wetted area. For an arch pipe, a top width and bottom width are measured, along with the water depth. For a culvert with a varying substrate, incremental depth and width measurements may have to be taken to determine incremental areas that are summed together for the total flow area (Figure 4).

Just as biological assessments should be conducted by biologists, hydraulic surveys should be conducted by hydrologists experienced with the techniques listed above. Personnel should understand the inherent lack of precision in river channel measurements; that understanding should be reflected in the number of significant digits that a measurement is recorded to.

Supplemental data are recorded at the field site to note the location of the culvert in several ways. To improve the flow and understanding of data between users, it is recommended that agencies agree upon a common datum to use for recording the latitude and longitude of the site. Additional items that would prove helpful to other users of the inventory data include the Highway Mile Point, and the Station (from the brass plate on the culvert marker).

Culvert Prioritization Methodology for Alaska

An accurate and practical prioritization methodology is an important and necessary element of a complete culvert assessment protocol. The use of ranked criteria to determine a quantitative value can be a straightforward and easy-to-understand process for developing a prioritized inventory for culvert repair and replacement. The key to developing the priority methodology is to decide which, and how many criteria, should be included in the prioritization decision matrix. Too many criteria will result in a process that is bulky and complicated, has extensive data requirements, and may significantly slow down or stop the prioritization process if the required data fields are difficult or impossible to fill. Too few criteria may result in a process that provides inaccurate or meaningless results, and can lead to a misdirection of funds and effort for a fish habitat enhancement program.

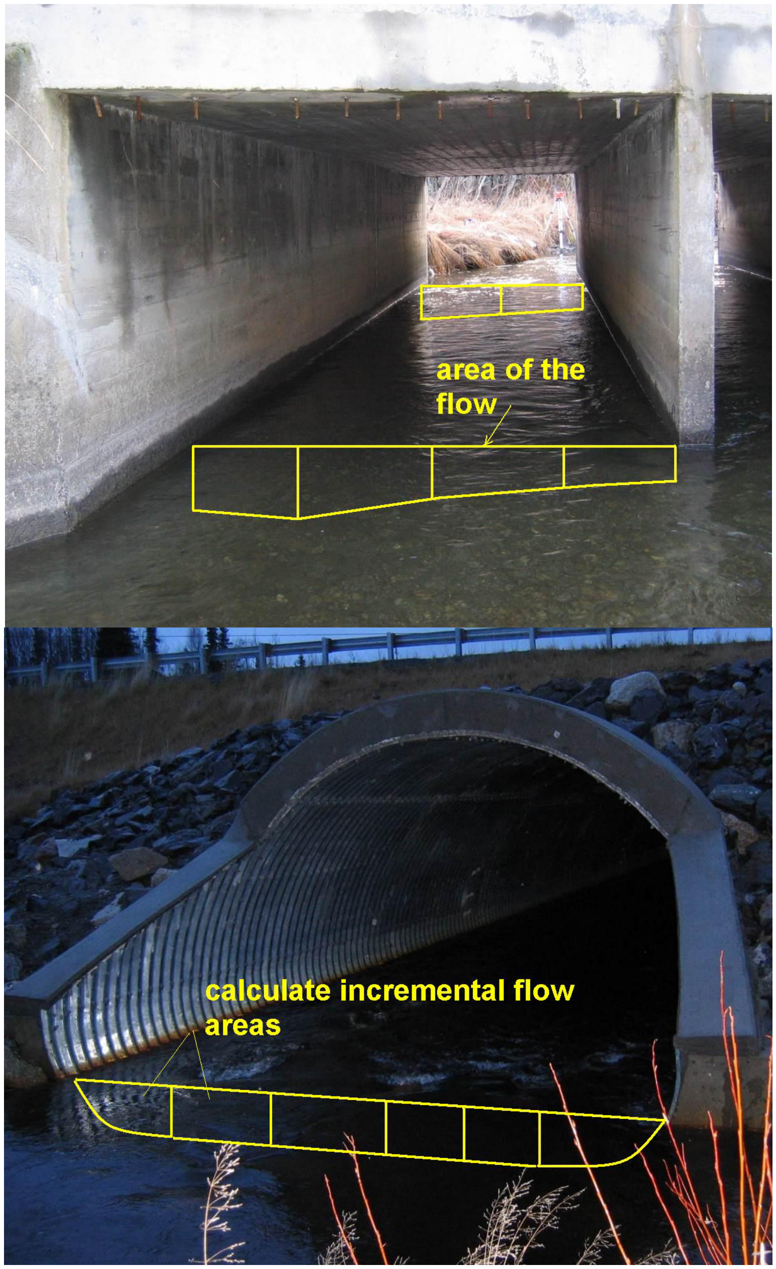

Figure 4. Measurements of flow area at culvert inlet and outlet.

The development of the criteria-ranking calculation requires the use of either an additive or multiplicative model. The additive model calculates the culvert replacement or retrofit (RR) priority as the sum of the individual criteria weights; the multiplicative model calculates the culvert RR model as the product of the weights. Both models are very straightforward and very easy to compute. They are equally accurate when all criteria weights have mid-level values. However, the additive model may overestimate priority under certain conditions. For example, the habitat quantity criteria would earn a ‘zero’ weighting if little or no upstream (or downstream) habitat were made available by culvert RR. With other criteria weights high, the culvert may earn a high priority rating with the additive model, even with no useful biological gain in habitat. The multiplicative model handles these extreme circumstances more accurately; as such, it is likely a better model.

The suggested approach to a prioritization methodology for Alaska places importance on several biological criteria, including quantity and quality of habitat. Assigning ranks to habitat criteria rely primarily on ground-based habitat surveys and assumptions about the value of measured habitat characteristics to both anadromous and resident fish. Conducting habitat surveys can be a tedious and labor-intensive effort. Though there may be an argument in Alaska for using quantity of habitat as a surrogate for quality, habitat surveys are essential for establishing and ranking the biological importance of a stream.

An effort has been underway for the past several years at the Tongass National Forest to develop a prioritization methodology based on biological significance. Biological significance indicators, based on upstream habitat surveys and other watershed parameters, are used to create a significance index. That index is combined with other criteria in a decision-making matrix to select culverts for replacement, retrofitting, or removal. The model is still in the development and testing phase (Robert Gubernick, USFS, personal communication, 2004). The techniques developed for this methodology may prove to be very appropriate for use in other agency programs throughout Alaska.

To streamline the prioritization process, the number of criteria should be kept to a minimum, at least for the initial development and testing. There may be a tendency to overload a methodology with many criteria, with the goal of recognizing all possible attributes and removing all human influence or advocacy from the process. However, a review of programs in other states that have larger culvert inventories and more urgent biological and regulatory problems, shows that a modest prioritization methodology can protect the resources while serving the Public’s need. If necessary, adjustments and fine-tuning can be applied to a methodology once it has been populated and tested with a large culvert inventory. The recommended criteria are listed here:

- Length/area of habitat recovered
- Quality of upstream or downstream habitat recovered
- Downstream barriers to fish passage
- Species Importance
- Condition of Culvert
- Level of Barrierity
- Replacement/retrofit costs

The replacement/retrofit cost may be used in one of two ways. As one of several criteria, the cost is used as another ranked attribute in either the additive or multiplicative model. Estimated projected costs may be used based on past projects. As a very rough guide, replacement costs may fall between $400 and $1,000 per lineal foot, depending on the diameter and fill required. Another method to rank replacement costs is to group them into a range of ranks, such as the following:

- $0 to $59,999-10 points
- $60,000 to $149,999-8 points
- $150,000 to $249,999-6 points
- $250,000 to $499,999-2 points
- $500,000+-1 point

A second way to utilize cost value in a prioritization scheme is to create a cost-benefit ratio for each culvert. The benefit is determined by using the model to calculate a value based on the first 4 criteria listed above. In typical economic evaluations, benefits are expressed directly in terms of money. Then, if the dollar value of the benefits exceed the estimated cost of the project, the project proceeds. In this case, the calculated value of the biological criteria would have no direct meaning; however, divided into the total cost, it provides a ratio to be compared to all other projects. Projects with the lowest cost per benefit ratio would receive a high priority ranking.

Application of Study Results

The review of the Level 1 and Level 2 criteria, and the analysis of hydraulic modeling results from study sites both old and new has provided important information about the draft fish passage protocols in Alaska. Combined with the review of existing literature, this analysis can be used to provide recommendations to AKDOT&PF and AKDF&G for the implementation of more accurate and streamlined procedures that will prioritize the mitigation of culverts that pose barriers to fish in Alaska. Recommendations are made for several specific areas of concern, and for four protocol topics: Level 1 criteria matrix, Level 2 methods (FishXing), field data needs and methods, and a prioritization methodology.

The Levels 1 and 2 'Red' rating achieved by using the draft protocol to analyze a newly installed 'fish-friendly' culvert on Beaver Creek indicates the need for revision of the protocol, and the need for additional data to validate the threshold values. Until such information is available, the overall structure of the protocol would be significantly improved by setting screening thresholds or criteria for absolute passage adequacy/failure and simplifying the Level 1 category composition.

One specific concern of note involves the terminology used in the classification of culverts. The assignment of 'Red' from either the Level 1 or Level 2 analysis is used to indicate conditions not adequate for fish passage (Rich, 2003). In fact, fish passage is indeed occurring at many of these culverts, at different life stages and at different flow conditions. Other researchers have noted similar concerns. In a Montana study of 48 culverts, researchers reported that the FishXing program indicated over 90 percent of those culverts impaired fish movement at some discharge (Burford and McMahon, 2004).

However, in studies using a subset of the culvert group, electrofishing results showed little difference in fish population characteristics above and below culverts, and direct passage studies showed that fish passage was occurring at a majority of the sites, for both juvenile and adult trout.

Culvert assessment validity and efficiency would be improved by creating a distinction between culverts that present a total barrier to all fish at all discharges, and those that present barriers to juveniles at some or all discharges. Such a distinction, incorporated into the Level 1 matrix as a preliminary threshold, would streamline the decision process. That threshold would include agreed-upon levels for outfall height and slope, which would be set at a level unattainable by the species of concern. For example, the Level 1 process would be initiated by answering the following screening questions:

Screening Question 1.

> Is outfall height greater than documented leaping ability, or culvert gradient greater than 4%? (or alternate validated value). Yes-culvert is Red (total barrier)-no need for additional analysis.
> No-proceed to Screening Question #2.

Screening Question 2:

> Is the culvert fully backwatered?
> Yes-culvert is Green (Adequate)-no need for additional analysis.
> No-proceed to Level 1 Matrix.

Culverts that proceed to the Level 1 matrix analysis are subsequently analyzed and labeled as *Adequate* (formerly Green), *Needs Additional Analysis* (formerly Gray), or *Partial Barrier* (formerly Red).

The efficiency of the assessment methodology would also be improved by stipulating that additional analysis is conducted only for those culverts that fall into the 'Gray/Needs Additional Analysis' category. Culverts rated in the matrix analysis as 'Red' or 'Partial Barriers' should not be subjected to additional (Level 2) analysis.

Additional improvements to the Level 1 analysis would be realized by combining culvert categories. Unless significantly undersized, large circular CMP culverts with 100 percent coverage will present essentially the same surface roughness to flow as will bottomless pipe arch culverts at flows up to the fish passage design flow. As a result, Structure Type 1 culverts should readily be combined with Type 2 culverts in a single threshold category. Similarly, culverts with less than 100% linear coverage, whether pipe arches or circular CMPs, should be combined into a single category.

Additional specific suggestions for improving both the Level 1 and Level 2 criteria and procedures are listed below.

Level 1 Criteria Matrix

- The use of upstream channel width values to determine the constriction ratio may be incorrectly formulated for most culvert analyses. The ratio of the culvert span to channel bed width should be calculated by obtaining the channel bed width downstream of the culvert. One representative width should be measured, usually at the second riffle downstream from the culvert. Channel width should be measured as the distance from the ordinary high water mark of one bank to the opposite OHW mark.

- The flow independent assessment of culvert perch provides the maximum perch height possible, and as such provides an unrealistic over-estimate of perch height. A flow dependent assessment of culvert perch will make results from Alaska comparable to those of other agencies. If not taken at multiple discharges, a single measurement should be taken at low flow. Conditions that alleviate or eliminate an actual physical outlet drop from the culvert lip should be documented and noted.
- Constriction ratio, gradient and perch height should not be considered relevant for the assessment of passage of a fully backwatered culvert.

- Additional data is needed to validate the Level 1 criteria matrix. Data should be obtained for the range of culvert types and slopes listed in the matrix. Fish passage and velocity data should be obtained at these sites during flows up to the Q_2-2 day discharge. Though fish information for species not found in Alaska is not valuable, velocity data from other regions is valuable, and should obtained from all sources possible.

Level 2 Methods-FishXing Analysis

- Without calibration and validation, the FishXing program should not be used for assessing fish passage for a culvert replacement prioritization program.

- Calibration with at least one set of discharge-velocity data sets should occur with every culvert modeling effort using the FishXing program. When used to assess a large culvert inventory for a regional assessment such as the Kenai Peninsula or other areas, validation of the model with a second set of discharge-velocity data, at a higher discharge, should occur for at least one culvert in each category of culvert type, and through a range of culvert gradients. FishXing should not be used where calibration attempts are not successful.

- The FishXing program is based on advanced hydraulic theory. At the very least, all systematic use of the FishXing software for culvert replacement prioritization programs should be reviewed by a hydraulic engineer well-trained in classic open-channel hydraulic theory, including derivation and solutions for the gradually varied flow equation. The cursory reviews of hydraulic theory included with the FishXing documentation do not provide an adequate background for understanding how the program works.

- The revised USGS methods (Curran et al., 2003; Wiley and Curran, 2003) should be used in lieu of older methods (Jones and Fahl, 1994) for calculating the 2-year discharge and other flow statistics on ungaged streams in Alaska. Before attempting to employ these advanced techniques, users should be required to attend a 1-day training course offered periodically by the USGS to gain understanding of the methods and limitations inherent in the statistical methods.

- The error metrics should be calculated for each site Q_2 estimation. The upper and lower range of discharge values from the standard error of prediction should be included in the numerical hydraulic modeling effort to determine the impact of flood estimation error on the assessment of fish passage.

- Skewed statistical distributions, such as the log-Pearson Type III distribution, should be used to develop estimations of the 2-year discharge when sufficient gage data is available from the stream in question. Such analysis should be performed in consultation with the USGS or another qualified hydrologist.

Field Data Needs and Methods

- The acquisition of field data for culvert assessment should be simplified and applied consistently to all sites. A field hydrologist with training and experience in physical stream surveys should lead the field crew. Crews should review the difference between precision and accuracy of hydraulic surveys, and the level of both necessary to conduct meaningful and efficient hydraulic surveys for culvert analyses.
- For a **Level 1** analysis, the data requirements include:
    1. culvert metrics (width, height, length, type, corrugation size, substrate depth and coverage),
    2. culvert invert elevations,
    3. width of the channel at the second riffle downstream from the culvert,
    4. water surface elevation of the culvert outlet, outlet pool, and tailcrest.

- The field crew should calculate the culvert slope, bedwidth ratio, and outfall height onsite and apply the data and calculations to the Level 1 criteria matrix to determine the classification of the culvert (green, gray, red). Culverts classified as ‘red’ or ‘green’ are completed, except for required biological surveys. Culverts classified as ‘gray’ will trigger additional field measurements immediately.

- For a **Level 2** analysis and calibration, data requirements include:
    1. pool depth,
    2. tailwater cross-section that extends to the bank on either side,
    3. tailwater substrate type,
    4. discharge measurement coincident with the water surface elevation surveys,
    5. area of the wetted perimeter cross-sections in the culvert inlet and outlet,

6. horizontal distance between the tailwater cross-section and the second riffle downstream,
7. culvert inlet type.

- For a **Level 2** model validation, the additional data requirements include:

8. area of the wetted perimeter cross-sections in the culvert inlet and outlet,
9. a second discharge measurement at a substantially higher (or lower) flow,
10. coincident water surface elevations at the tailwater cross-section and the second riffle downstream.

Prioritization Methodology

- The use of quantitatively ranked criteria is critical for developing a prioritized inventory for culvert repair and replacement. To streamline the process, the number of criteria should be kept to a minimum, at least for the initial development and testing.
- The suggested approach to a prioritization methodology for Alaska places importance on biological criteria, including quantity and quality of habitat. Much of this data may have already been acquired through habitat surveys; additional surveys may be required and should be conducted.

- The range of criteria and techniques used in other prioritization programs is extensive. Recommendations for a modest program include the following:

1. length/area of habitat recovered,
2. quality of upstream or downstream habitat recovered,
3. downstream barriers to fish passage,
4. species importance,
5. condition of culvert,
6. level of barrierity,
7. replacement/ rehabilitation costs.

CHAPTER 4 - CONCLUSIONS AND SUGGESTED RESEARCH

Determining the effect of culverts on fish migration is a difficult process due to the inherent nature of hydrology and natural variability. Actual fish passage is difficult to measure, and has resulted in the reliance on hydraulic assumptions, hydrologic estimations, and fish performance databases to predict whether individual culverts pass fish or act as barriers. Without an understanding of the validity and limitations of those assumptions and estimations, the predictions may be subject to bias and error.

The field of computational hydraulic modeling is extremely complex. Using the dimensions of simplified geometric elements and empirical hydraulic coefficients to represent known reality is complicated, and requires an extensive knowledge of physics. Using those same dimensions to then extrapolate conditions to some unknown state places a severe burden on the modeler. Until very recently, modeling of open channel and pipe hydraulics was conducted only by engineers performing tedious calculations on handheld calculators or early computers. The difficulty in performing the calculations acted as a filter for users with at least a rudimentary background in hydrologic and hydraulic engineering. The advent of Windows-based software, where interactive menus and radio buttons with pre-selected coefficients to choose from have made the underlying theory transparent, has resulted in a basic shift of the expertise of the user. As a result, such software is often misused, and confidence in the results is misplaced.

Several conclusions and recommendations concerning the draft culvert assessment protocol may be made based this study. The conclusions are based on reviews and comparisons to other projects, field investigations, a hydraulic analysis, and comparisons between modeled and measured values. Recommendations are made for the purpose of improving and streamlining the culvert assessment protocol.

The intent of a conservative bias is to provide protection to the resources at risk. However, the unintended consequences of an overreaching bias include harm to resources that require help and protection, as a 'red' inventory overloaded with failed culverts that do indeed pass fish dilutes the capability for agencies to focus on and correct the most egregious problems first.

The Level 1 and Level 2 criteria used in the culvert assessment protocol are conservative. The result of this bias is that all culverts that are identified as 'green' are most likely able to pass fish at all life stages up to the fish passage design discharge for that culvert. However, not all culverts that are identified as 'red', either through the Level 1 or Level 2 filter, will act as fish barriers, even at the fish passage design discharge.

Modifications to the operational criteria used in the Level 1 matrix and Level 2 procedures will improve the validity of the hydraulic assumptions, increase the ability to exchange data with other agencies by adopting similar definitions, and streamline the passage assessment protocols by reducing fieldwork. A slight reduction in the conservative bias of the Level 1 criteria will strengthen the confidence that the goal of the protocol is being met-that is, culverts that are identified as 'red', either through the Level

1 or Level 2 filter, are most likely acting as fish barriers at the fish passage design discharge.

Specific applications of the results from this study to improve the fish passage protocols are described at the end of Chapter 3. They include modifications to the criteria in the Level 1 matrix, calibration and validation procedures for the Level 2 FishXing analysis, recommendations for improvements in design flood discharge estimations, and recommendations to properly train and supervise workers involved in statistical analysis, field measurements, and numerical hydraulic computer modeling.

Additional recommendations are made for the economical and accurate assignment of priorities for culvert retrofits or replacements in order to mitigate the most egregious problems first. The use of quantitatively ranked criteria is critical for developing a prioritized inventory. The suggested approach to a prioritization methodology for Alaska places importance on biological criteria, including quantity and quality of habitat.

One possibility for improving the culvert assessment process is to contract such work out to a private firm. Contracting out work projects that involve specific and repetitive tasks can often shorten the project timelines and improve cost efficiency. Steps should be taken to insure that workers involved in the project would have or receive proper training for field techniques.

Suggested Research

Additional research is needed to continue the evaluation of fish movement and passage through culverts. Many of the documents reviewed for this study contain extensive recommendations for specific research topics. The work done so far has identified a need for more information in several areas. Research is currently being conducted by the Pacific Northwest National Laboratory using full-scale physical models of culvert systems deployed in an experimental test bed at the Skookumchuck Hatchery near Tenino, Washington. This research is providing unique information involving fish performance for culvert passage, and should continue to be supported. Addition research topics specific to the development of a fish passage assessment protocol in Alaska are outlined below.

- Validation of the Level 1 juvenile fish passage evaluation criteria matrix.
- Assessment of the ability of juvenile coho to pass through structures at different flows. Assessment of fish swimming performance values in natural field conditions to verify the assumptions used in the mathematical predictions.
- Improvement to the estimation of appropriate fish design flows is of pressing concern. Specifically,

information is needed to assess whether monthly or seasonal exceedance flows would better provide a biologically valid design discharge as compared to a flow derived from the Q_2 instantaneous discharge. More knowledge is needed on the biological implications of a delay in fish migration or upstream movement.

- Additional quantitative information on the stream flow characteristics in small watersheds in Alaska.

- Additional testing of the FishXing program, using multiple data sets that include high flow measurements for full calibration and validation. Improvements are needed in the FishXing code to correct the constraint of the zero approach velocity assumption.

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APPENDIX A- LEVEL 1 CRITERIA FOR KENAI CULVERT ASSESSMENT

Structure category	**Green** *Conditions assumed adequate to pass fish*	**Gray** *Conditions may not be adequate to pass fish, additional analysis required*	**Red** *Conditions assumed not adequate to pass fish, additional analysis required*
1. Bottomless pipe arch or countersunk pipe arch, substrate 100% linear coverage and substrate depth greater than or equal to 20% of culvert rise.	Installed at channel grade (+/- 1%), AND culvert span to bedwidth ratio of 0.75.	Substrate not at channel grade (+/- 1%), OR culvert span to bedwidth ratio less than 0.75.	None.
2. Circular CMPs with 2x6 corrugations (all spans), 100% substrate coverage and substrate depth greater than or equal to 20% of culvert rise.	Grade less than 2.0%, AND no perch, AND culvert span to bedwidth ratio greater than 0.75	Grade 2.0 to 4.0%, OR less than 4" perch, OR culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 4.0%, OR greater than 4 inch perch, OR culvert span to bedwidth ratio less than 0.5.
3. Circular CMPs (>48" span), with 1x3 or smaller corrugations, 100% substrate coverage, and substrate depth greater than or equal to 20% of culvert rise.	Grade less than 1%, AND no perch, AND culvert span to bedwidth ratio greater than 0.75	Grade 1.0 to 3.0%, OR perch less than 4 inches, OR culvert span to bedwidth ratio of 0.5 to 0.75.	Culvert gradient greater than 3.0%, OR perch greater than 4 inches, OR culvert span to bedwidth ratio less than 0.5.
4. Pipe arches (1x3 corrugation and larger). Substrate less than 100% linear coverage or substrate depth less than 20% of culvert rise.	Grade less than 0.5%, AND no perch, AND culvert span to bedwidth ratio greater than 0.75.	Grade between 0.5 to 2.0%, OR less than 4" perch, OR culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 2.0%, OR greater than 4" perch, OR culvert span to bedwidth ratio less than 0.5.
5. Circular CMPs (>48" span with corrugations 1x3 and larger, substrate less than 100% coverage or invert depth less than 20% culvert rise.	Grade less than 0.5%, AND no perch, AND culvert span to bedwidth ratio greater than 0.75.	Grade between 0.5 to 2.0%, OR less than 4" perch, OR culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 2.0%, OR greater than 4" perch, OR culvert span to bedwidth ratio less than 0.5.
6. Circular CMP 48 inch span and smaller, regardless of substrate coverage.	Culvert gradient less than 0.5%, AND no perch, AND culvert span to bedwidth ratio greater than 0.75.	Culvert gradient 0.5 to 1.0%, OR perch less than 4 inches, OR culvert span to bedwidth ratio of 0.5 to 0.75.	Culvert gradient greater than 1.0%, OR perch greater than 4 inches, OR span to bedwidth ratio less than 0.5.
7. Concrete Box Culvert, all sizes, no substrate coverage (if full substrate coverage then treat as item 1 above) .	Assumed "GRAY" pending outlet control determination.	Culvert gradient 1.0% or less, OR perch less than 4 inches, OR culvert span to bedwidth ratio of 0.5 to 0.75	Culvert gradient greater than 1.0%, OR perch greater than 4 inches, OR span to bedwidth ratio less than 0.5.
8. Baffled or multiple structure installations.		All.	

APPENDIX B-UPDATED USGS FLOOD FREQUENCY EQUATIONS

Changes to the revised USGS flood frequency equations (Curran et al., 2003) include the use of fewer variables in the equations. For example, Region 7 (Arctic) uses only drainage area as a variable. Two regions have been added, and region numbers have changed as a result. Regions used in the Kenai fish culvert study have changed from 1 to 3 (coastal southwest) and 2 to 4 (Southcentral).

Other changes are noted in Table 8. This includes changes in the 100-year flood estimate from the regression equations. For example, the biggest change is in the Arctic and northwest Alaska (Region 7), where 100-year flood estimates have increased by 7%. Additionally, increases were noted in Region 4, and decreases were noted in Region 5 (Yukon).

Also noted in Table 8 are changes in the generalized skew coefficients. Generalized skew coefficients are computed from long-term stations to improve the estimate of the skew coefficient for individual stations. The Jones and Fahl report computed generalized skew coefficients from gaging stations having 22 or more annual peaks; the new report used stations with at least 25 years of systematic peak-streamflow data to obtain the seven generalized skews.

Table 8. Changes to the 2003 100-yr flood equation estimates from the 1994 estimates.

	Change in 100-yr flood equation estimates (for selected stations)	Generalized Skew Coefficients	
Region	2003 relative to 1994	1994	2003
1 (SE)	Up 7%	0.31	0.16
2 (Upper Yukon)	Down 1%	0.39	0.31
3 (SW)	Up 7%	0.31	0.16
4 (SC)	Up 30%	0.55	0.60
5 (Yukon)	Down 20%	0.21	0.28
6 (Lower Yukon)	Down 3%	0.13	0.13
7 (Arctic)	Up 86 to 130%	0.13	-0.52

APPENDIX C- FISHXING HYDRAULIC THEORY

Reference: FishXing unreleased Version 3 Help files and documentation

FishXing determines the depth of flow in a modeled culvert by calculating a water surface profile within the culvert; the calculation boundaries are the upstream headwater and downstream tailwater water surface elevations. Once the water depth in the culvert is calculated, flow area, velocity and other hydraulic parameters are determined. The calculation procedure generally occurs in the following order:

1) Model hydraulic input, including design flow(s), culvert geometry, and tailwater condition
2) calculate hydraulic slope of the culvert at the design flows (mild, steep, adverse, horizontal)
3) determine the boundary condition at the outlet, based on tailwater elevation
4) perform gradually varied flow calculations to determine the water surface profile
    a. backwater calculations for non-steep slopes
    b. frontwater calculations for steep slopes
    c. frontwater, backwater and momentum calculations for hydraulic jumps on steep slopes
5) calculate headwater elevation based on energy losses within the culvert
6) calculate hydraulic geometry, and velocities within the culvert
7) calculate outlet plunge characteristics
8) perform fish leaping and swimming calculations

The hydraulic slope of the culvert is determined by assuming steady flow and calculating the Froude number. Once the hydraulic regime of the culvert is classified, various calculation methods are used to determine the water depth profile through the length of the culvert.

The methods used to determine the water profile are based on a determination of either gradually varied flow (GVF) or rapidly varied flow (RVF). The GVF equation is used for steady flow, non-uniform flow calculation. The solution to the GVF is commonly referred to as a backwater or step calculation; calculations of the flow profile start at a control or boundary condition, and proceed in the direction in which control is being exercised. The boundary condition controls the water depth that changes gradually through the culvert until it reaches normal depth.

For inlet controlled culverts, the calculations begin at the culvert inlet, where the water surface passes through the critical depth. For outlet controlled culverts, the backwater calculation begins at the tailwater elevation or at critical depth, whichever is higher. The tailwater elevation controls the backwater conditions at a culvert. Tailwater elevations may vary with discharge, or may be fixed in elevation, depending on the local discharge configuration. There are three different methods to define the tailwater elevation within the FishXing program:

1. Constant Tailwater Method
2. User Defined Rating Curve Method
3. Channel Cross-Section Method

The Constant Water Surface Method was developed for use at sites where the tailwater elevation does not change with changes in discharge. This method requires the least amount of site information and may be appropriate for preliminary culvert assessments. A single tailwater elevation is used as the downstream boundary condition for subsequent calculations; a pool bottom elevation is used to calculate the pool depth at the culvert outlet.

The Rating Curve Method allows the user to specify tailwater elevations corresponding to a range of discharges, forming a stage-discharge rating curve. The specified tailwater elevations act as the downstream boundary condition to conduct the subsequent upstream elevation calculations.

The Channel Cross-Section Method allows the user to specify the shape and roughness of the stream channel downstream of the culvert outlet. Using a simplified routine based on Manning's equation, FishXing then creates a tailwater elevation-discharge rating curve by estimating tailwater elevations at different discharges. Based on the modeled discharge, the rating curve provides the downstream boundary condition to conduct the subsequent upstream elevation calculations. This method requires a surveyed downstream channel cross-section, the downstream channel slope, and an estimate of the roughness coefficient of the downstream channel bottom.

The derivative of the energy equation is expressed as the general form of the gradually varied flow equation:

$$\frac{\partial x}{\partial y} = \frac{So - Sf}{(1 - Fr^2)}$$

where:
S_o = bottom slope, positive in the downward direction
S_f = friction slope, positive in the downward direction
y = water depth measured from channel bottom to water surface
x = distance along the channel bottom
Fr = Froude number

This differential equation is not explicitly soluble, but many numerical methods have been developed for its solution. The FishXing program utilizes a discrete analog routine, called the finite difference method, to solve for y as a function of x. Using iterative calculations, the water depth is determined at nodes, or steps, moving upstream (subcritical flow) or downstream (supercritical flow) through the culvert.

When flow profiles cross through critical depth, it signifies abrupt changes in depth and/or velocity; FishXing assumes that RVF is occurring. The occurrence of RVF is usually a local phenomenon; within culverts, it can occur at the inlet contraction, outlet plunge, or at hydraulic jumps.

Hydraulic jumps occur when the flow profile changes from supercritical to subcritical. The energy losses of a hydraulic jump cannot be calculated within the energy equation, and require the use of the momentum function to solve. In the FishXing software, a hydraulic jump can only occur during the following two conditions:
1. The culvert has a steep hydraulic slope
2. The tailwater depth is greater than critical depth

If either of these conditions exist, FishXing checks for the possibility of a jump occurring within the culvert. The location of a hydraulic jump depends on depths and velocities of flow that will satisfy the momentum principle.

FishXing solves the GVF equations in the downstream direction starting from critical depth at the inlet and upstream starting from the outlet boundary condition. At each node the momentum equation is solved for each profile. When the upstream momentum and downstream momentum values are equal, a hydraulic jump occurs. FishXing does not locate the exact location of the jump but determines the up and downstream nodes of the jump and connects sub and supercritical flow between these nodes. The momentum equation is solved at each node:

$$M = \frac{Q^2}{gA} + (y - \bar{y})A$$

where:
M = momentum
Q = flow rate
g =acceleration of gravity
A = cross-sectional area
y = water depth
$\bar{y}$ = the distance from the water surface to the centroid of the cross section

The steps followed to locate the jump are summarized here:
1. Compute the upstream supercritical water surface profile by solving the GVF equations from the inlet depth equal to critical depth.
2. Compute the downstream subcritical water surface profile by solving the GVF equations from the downstream boundary condition.
3. At each node, compute the momentum (specific force) for each profile.
4. When the momentum associated with the subcritical profile is less than the momentum associated with the supercritical profile the jump occurs between these two nodes.

Another area within a culvert where RVF is observed is the inlet zone. Two distinct sections exist within the inlet zone: a contraction zone and expansion zone. Head loss occurs as water passes through the inlet zone. The magnitude of the head-loss is dependent on the velocity within the culvert barrel and inlet geometry, which is represented by the selected head-loss coefficient. The head-loss coefficient is a function of transition efficiency as the water enters the culvert from the upstream channel. As the water enters the culvert, velocities increase until they reach the point of maximum contraction.

FishXing approximates the maximum contraction velocity by assuming the calculated head-loss through the inlet zone is converted entirely to kinetic energy; this gained kinetic energy is then lost in the expansion. Frictional losses, which would lower the water velocity, are neglected in these calculations.

FishXing uses the following equation to calculate the contraction velocity, and reports it as the inlet velocity in the Water Surface Profile output.

$$V_{cntr} = V_B \sqrt{1 + Ke}$$

where:
Vcntr = contraction velocity
Ke = inlet head loss coefficient
V_B = water velocity within the culvert barrel

In the FishXing calculations, the water velocity within the culvert barrel (V_B) is the average cross-sectional flow in the barrel approximately one culvert diameter downstream from the inlet and represents the area immediately downstream of the inlet contraction and expansion zone. For calculations, the length of the inlet zone is defined as 2 feet from the inlet for 9 ft diameter culverts or smaller, and 3 feet for culverts larger than 9 feet (Behlke, 1992). It is assumed that there is zero velocity in the headwater just upstream of the inlet.

Other zones used in the FishXing calculations include the outlet zone and the barrel zone. The outlet zone is defined as the distance from the outlet invert to a distance equal to 4Yc (critical depth), and is reported as the last two nodes of the culvert. The barrel zone is defined as all the nodes between the first two nodes and last two nodes in the culvert.

When the culvert becomes submerged (HW/D=1) flow becomes pressurized and calculations switch to full flow analysis.

Plunging Water-Water leaving a perched culvert has a velocity with both horizontal and vertical components. By neglecting all frictional losses, FishXing uses a simplified projectile equation to calculate the path of the falling water, from the culvert outlet to the outlet pool. It is assumed that this is the place where the fish will leap from.

The height the water plunges, *H*, and the horizontal distance, *L*, the water travels from the outlet is described by the following standard projectile equations:

$$H = V_{out}(\sin\theta)t - \frac{1}{2}gt^2$$

$$L = V_{out}(\cos\theta)t$$

where:
$Vout$ = the exiting water velocity at the culvert outlet,
g = gravitational acceleration,
t = the time for the exiting water to fall from the culvert outlet to the pool,
θ = the angle at which the water exits the culvert outlet

The exit angle is the angle that the water makes with horizontal between the last two nodes of the culvert that define the Outlet Zone. The depths of the water at the outlet and at the second to last node are determined by the hydraulic slope of the culvert and the boundary conditions used in the GVF calculations.

Since the depth of water at the culvert outlet and outlet pool are known, the plunge height is also known. The time, t, can then be solved for by substituting in the equation for outlet angle. When the time is known, the horizontal distance L can be calculated.

Entrance loss depends on the geometry of the inlet edge. This loss is expressed as the barrel velocity head reduced by a factor known as the inlet head loss coefficient, Ke.

$$H_L = K_e \frac{V^2}{2g}$$

where:
H_L = head loss (ft)
Ke = head loss coefficient
V = velocity in the barrel (ft/s)
g = acceleration due to gravity

The inlet head loss coefficient, Ke, is a constant in the head loss term of the energy equation for open-channel flow. The head loss coefficient is a measure of the efficiency of the inlet to smoothly transition flow from the upstream channel into the culvert.

The coefficient can range in value between 0 and 1. Larger head loss coefficients are associated with increased flow contraction in the inlet zone. Culverts having a width less than the upstream channel will constrict flow and can create a steep drop in the water surface profile at the inlet, often resulting in a velocity barrier for fish attempting to exit the culvert.

The inlet head loss coefficient is a function of the flow. Coefficients are often supplied by culvert manufacturers and are for relative depths (headwater depth/culvert rise) of about 1.2, well above fish passage flows.

The FishXing help file suggests that inlet coefficients should not exceed 0.7 for adult salmonid fish passage, 0.5 for sites with marginal passage conditions, and 0.2 for juvenile salmonid passage.

Version 3 Features

The FishXing software is currently being upgraded to provide several new features and expand the capabilities of the program. A Beta version of the revised software will be released to a limited test group in January or February 2005 for testing and review (Michael Furniss, USFS, personal communication., 2004). Full release of the revised software, designated Version 3, will occur after Beta testing is completed.

There are essentially no changes between Versions 2 and 3 in the basic underlying hydraulic theories and techniques used to construct the code. Similarly, the methods used to assess fish capabilities (prolonged speed, burst speed, leap speed), fish passage factors, and limiting flows have not changed between the two versions. Most changes are found in expanded options and capabilities.

One of the most anticipated features of the new version is the ability to model multiple culverts at one site. After data entry, the flow will be hydraulically proportioned for each of the culverts; the user will then evaluate one culvert at a time. At this time, Version 3 will analyze up to 5 culverts at one site. Another major improvement in the software will be the ability to work with S.I. units; this feature will be especially useful for Canadian users and various U.S. resource agencies.

Version 2 analyzed four different culvert types: circular, box, open-bottom arch, and pipe arch. Several culvert types have been added to the new version, including: single radius arch, low profile arch, high profile arch, horizontal ellipse, and metal box. Additionally, more choices are available for specifying the configuration and size of culvert types.

Version 2 offered suggested values for the Manning's n coefficient based on selected culvert and natural channel bottom types. This feature remains in Version 3, but is improved by a feature that provides for quick access to expanded information on n coefficients, with minimum, normal, and maximum values for a large number of culvert materials and natural stream types.

A new function in the Version 3 release allows the user to set regional hydraulic criteria, which will subsequently be used to determine fish passage. For example, if a state has set a maximum water velocity value as a passage criterion, the value can be entered into the program, and utilized as a decisive value. Additionally, supplemental fish speed information has been added to the fish information utility, and provides the user with a wider selection of swim speed values to select from.

Finally, the program's operational ability has been somewhat enhanced by the addition of a new Navigation Bar. The toolbar is designed to allow users easy access to various features of the software. The navigation feature is divided into four sections: Project Management, Tabular Output, Graphical Output, and Exit/Help options. Included on the navigation bar is a button titled 'Animated Profile.' Using the numerical results of the model FishXing provides an animated "dramatization" of the hydraulics and fish performance within the culvert.

APPENDIX D-FIELD STUDY SITES 2004

Site Name: Beaver Creek

Location-Lat: 60.56384d Long: 151.11798d

Culvert type:pipe-arch with bedload collector Width: 16.5 ft Height: 9.5 ft

Length: 190 ft Corrugation: 6” x 2” Inlet type: headwall

Discharge: 34.01 cfs

Cross-section	Notes	Area (ft^2)	Wetted Perimeter (ft)	Average Velocity (ft/sec)	WSEL (ft)	Invert (ft)
1	D.S. xsec	17.00	18.03	2.35	95.38	93.93
2	tailcrest	40.37	49.86	0.99	96.22	94.42
3	cul outlet	23.44	18.70	1.71	97.03	95.36
4	cul inlet	20.62	17.07	1.94	97.10	95.86

Figure 5. Beaver Creek inlet (top) and outlet plunge pool (bottom).

Site Name: Bishop Creek

Location-Lat: 60.77564d Long: 151.09644d

Culvert type: pipe-arch Width: 13.7 ft Height: 8.4 ft

Length: 114 ft Corrugation: 6"x 2" Inlet type: Mitered

Discharge: 40.00 cfs

Cross-section	Notes	Area	Wetted Perimeter	Average Velocity	WSEL	Invert
1	D.S. xsec	28.88	17.79	1.38	95.40	92.82
2	cul outlet	26.53	15.72	1.51	95.52	93.16
3	cul inlet	19.42	13.77	2.06	95.43	93.51
4	U.S. xsec	64.61	32.18	0.62	95.77	93.17

Figure 6. Bishop Creek culvert inlet.

Site Name: Corea Creek

Location-Lat: 60.17229d Long: 151.44377d

Culvert type: CMP-round (brokenbk) Width: 6 ft Height: 6ft

Length: 75 ft Corrugation: 6” x 2” Inlet type: Projecting

Discharge: 7.50 cfs

Cross-section	Notes	Area	Wetted Perimeter	Average Velocity	WSEL	Invert
1	D.S. xsec	3.61	6.91	2.08	91.50	90.60
2	tailcrest	4.96	11.75	1.51	92.63	91.88
3	cul outlet	9.65	8.98	0.78	92.67	91.03
4	cul inlet	3.28	5.15	2.29	94.48	93.44
5	U.S. xsec	4.27	5.97	1.32	94.58	93.50
6	U.S. xsec	7.20	10.27	0.78	94.97	93.97

Figure 7. Corea Creek culvert inlet (top) and outlet (bottom).

Site Name: Dave Creek

Location-Lat: 60d31'32.49"   Long:149d38'54.39"

Culvert type: box-double culvert   Width: 8 ft ea   Height: 7 ft ea

Length: 45.5 ft ea   Corrugation:na (concrete)   Inlet type: wingwall

Discharge: left-8.40 cfs right-21.20 cfs

Cross-section	Notes	Area	Wetted Perimeter	Average Velocity	WSEL	Invert
1	D.S. xsec	23.21	18.03	0.24	94.75	92.75
2	tailcrest	17.55	16.99	0.32	95.44	93.64
3	left cul outlet	5.94	9.33	1.41	95.41	94.45
	right cul outlet	10.53	10.64	2.01	95.42	93.88
4	left cul inlet	7.15	10.08	1.17	95.51	94.25
	right cul inlet	11.73	10.71	1.81	95.45	93.99

Figure 8. Dave Creek outlet (top) and inlet (bottom).

Site Name: Jean Creek

Location-Lat: 60.4842d Long: 150.11443d

Culvert type: CMP round Width: 5 ft Height: 5 ft

Length: 40 ft Corrugation: 1”x3” Inlet type: Projecting

Discharge: 5.63 cfs

Cross-section	Notes	Area	Wetted Perimeter	Average Velocity	WSEL	Invert
1	D.S. xsec	4.33	7.88	1.30	91.46	90.54
2	tailcrest	3.19	10.60	1.77	92.04	91.46
3	cul outlet	3.31	6.09	1.70	92.31	91.65
4	cul inlet	6.52	6.71	0.86	92.71	91.02
5	U.S. xsec	6.10	8.09	0.92	92.69	91.44
6	U.S. xsec	4.69	7.28	1.20	92.79	91.89

Figure 9. Jean Creek inlet (top) and outlet (bottom).

Site Name: Moose Creek

Location-Lat 60d30’8.31”   Long: 149d25’14.6”

Culvert type: double pipe arch   Width: 137 in   Height: 87 in

Length: 120 ft   Corrugation: 6” x 2”   Inlet type: mitered

Discharge: 7.34 cfs (left) 6.23 cfs (right)

Cross-section	Notes	Area	Wetted Perimeter	Average Velocity	WSEL	Invert
1	D.S. xsec	24.06	18.80	0.56	95.00	93.00
2	tailcrest				95.05	93.84
3r	cul outlet	8.33	10.87	0.75	95.46	94.77
3l	cul outlet	7.40	10.15	0.99	95.82	94.74
4r	cul inlet	8.63	11.38	0.72	96.00	95.01
4l	cul inlet	8.11	11.64	0.90	96.15	95.21
5	u.s. xsec	23.33	36.31	0.58	96.75	95.58
6	U.S. xsec	26.32	28.61	0.52	96.78	93.86

Figure 10. Moose Creek inlet (top) and left outlet (bottom).

Site Name: Slikok Creek

Location-Lat: 60.47384d Long: 151.13797d

Culvert type: open bottom arch Width:17.5 ft Height: 8 ft

Length: 96 ft Corrugation: 6” x 2” Inlet type:headwall

Discharge: 20.16 cfs

Cross-section	Notes	Area (ft^2)	Wetted Perimeter (ft)	Average Velocity (ft/sec)	WSEL (ft)	Invert (ft)
1	tailcrest	13.27	16.10	1.52	95.19	94.02
2	cul outlet	31.95	21.11	0.63	95.31	93.33
3	cul inlet	22.01	21.14	0.92	95.34	94.24
4	u.s. xsec	20.93	22.73	0.96	95.31	94.14
5	u.s. xsec	20.78	14.33	0.97	95.40	93.20

Figure 11. Slikok Creek outlet (top) and inlet (bottom).

APPENDIX E-CULVERT PRIORITIZATION PROGRAMS

Four prioritization methods are discussed in this section. The first three have been developed by resource agencies in the Pacific Northwest. The fourth method, only in development stages, is briefly discussed. The methods are listed in order of increasing complexity and difficulty of use.

Method 1

The Oregon Department of Fish and Wildlife (ODFW), in cooperation with the Oregon Department of Transportation (ODOT), began a program in 1996 to inventory, assess and prioritize for repair, all culverts associated with State- and county-owned roadways in all river basins in the State (Mirati, 1999). After classifying culverts as either passable or deficient, the culverts were assigned a priority for repair or replacement. Though several different approaches were researched, all but one was rejected because one or more criteria information elements were missing.

The Oregon system generates priority based on the following criteria:

- the number and status of species present;
- population size and condition; and
- the estimated quantity and quality of habitat blocked.

Using ranking values assigned to the criteria, culverts for each state district were rated by the district ODFW biologist most familiar with fish populations and habitat in each stream. In some cases involving small unnamed tributaries and headwater areas, the ratings were based on estimates and guesses (Mirati, 1999). The culverts were assigned a priority rating of HIGH, MEDIUM or LOW priority for repair. The Oregon culvert inventory is still updated using this procedure. Once assigned a rating by ODFW, the Oregon Department of Transportation selects culverts from the HIGH priority group for repair or replacement (Thomas Stahl, ODFW, personal communication, 2005). .

In addition to the criteria used, it is important to note the criteria rejected by ODFW for use in the prioritization process. These criteria included estimated cost of repair, proportion of passage improvement, and estimated increase in production. These criteria were eliminated, as it was felt there were too many unknowns associated with these elements (Mirati, 1999).

Method 2

The second system was developed by the Clackamas County Salmon Recovery Team, which is a collection of staff from various departments of the Clackamas County (CC) government agency in the State of Oregon (CCSRT, 2004). The Department of Water Environment Services leads the culvert prioritization and replacement program.

The prioritization methodology adopted by CC was developed in cooperation with the National Marine Fisheries Service and the ODFW. The CC methodology uses a ranking system to determine whether a culvert replacement project is high or low priority within a watershed. Eight criteria are used in an additive scheme to rank the inventoried culverts. The criteria and relative ranking weights are found in Table 9 (CCSRT, 2004).

Table 9. Prioritization criteria and relative ranking weights (CCSRT, 2004).

Criteria	weight
Upstream length recovered	**1**-0.0 to 0.49 miles **5**-1.0 to 2.49 miles **10**-5.0 + miles **2**-0.5 to 0.99 miles **8**-2.5 to 4.99 miles
Upstream habitat quality recovered	**0**- Highly degraded habitat, no riparian corridor, high sedimentation in creekbed, no gravel evident (90-10 relationship). Invasive species, if present, dominate streambank vegetation. dense development within ½ mile of each creekbank. **2**- Degraded habitat; sparse riparian corridor, non-native or invasive vegetation present (blackberry, teasel, Scots broom), very little shading of creek. Sedimentation evident in streambed, but gravel still evident (80-20 relationship) **6**- Average to good habitat; riparian corridor consists of some mature trees, some native, some non-native. Shading from trees partially keeps invasive vegetation out of riparian corridor. Sedimentation is evident, but about equals the clean gravel in streambed. Development outside of a 50 ft buffer of creekbanks. **8**- High quality habitat; strong riparian corridor consists of mostly mature trees and shrubs, with very little invasive species in corridor. Creek about 80% shaded by mature trees, very little sedimentation, many clean gravel. Development impacts outside of a 100 ft buffer. **10**- Very high quality habitat; basically undisturbed. Riparian corridor consists only of mature trees and shrubs, no invasive species present. No sedimentation evident in creekbed and creek is 90%+shaded. Development impacts outside of a 200 ft buffer.
Upstream Watershed Area	**0**-0 to 99 ac = 0 **6**-200-499 ac **10**-1000+ ac **2**-100 – 199 ac **8**-500-999 ac
Barriers to Fish Passage Downstream	**0**-Natural Downstream Barrier **5**-No Downstream Barrier **3**-Artificial Downstream Barrier
Species Known	**0**-None Known **7**-Coho Salmon **10**-Steelhead **3**-Cutthroat Trout **10**-Chinook Salmon
Maintenance Life Expectancy/Condition of Structure	**0**-FHWA rating 9 to 6 **10**-FHWA rating 4 **45**-FHWA rating 2 to 0 **5**-FHWA rating 5 **40**-FHWA rating 3
Cost	**10**-$0 to $59,999 **6**-$150,000 to $249,999 **0**-$500,000+ **8**-$60,000 to $149,999 **2**-$250,000 to $499,999

Method 3

The most complex prioritization methodology of the three reviewed for this report is the method developed by the State of Washington Department of Fish and Wildlife (WDFW). The Environmental Restoration Division of the WDFW has established a comprehensive program to provide guidance on how to identify and prioritize culverts, dams, and fishways that impede fish passage.

The WDFW prioritization protocol provides methods for assessing the value of a fish passage restoration project to fish production, and is focused on anadromous fish passage, though resident fish passage is also incorporated. The WDFW protocol uses information from a variety of ground surveys, in conjunction with assumptions about the value of measured habitat characteristics to anadromous fish, to determine habitat suitability.

Complete evaluations of culverts on streams with anadromous fish populations are conducted only when a significant quantity of resident salmonid habitat exists immediately downstream of the culvert. A significant reach is defined as at least 200 meters long, having a gradient of less than twenty percent, and having no natural point barriers. Sites not meeting these qualifications are removed from consideration for replacement or repair.

The WDFW inventory procedure develops a Priority Index (PI) value to rank and prioritize culverts for repair or replacement; the PI is used to assess production benefits to both anadromous and resident salmonid species. The PI is calculated as the fourth root (incorrectly identified as a quadratic root in the WDFW manual) of a multiplicative equation; the total PI is the sum of individual PI values, one of which is calculated for each species present in a stream:

$$PI = \sum_{all\ species} \sqrt[4]{(BPH)xMDC}$$

The WDFW manual reports that the 'quadratic' (fourth) root is used because it provides a more manageable number and represents a geometric mean of factors used. However, the importance of developing the geometric mean of four dissimilar factors is unclear. The criteria and ranking are found in Table 10.

Table 10. Criteria and ranking weights for WDFW prioritization methodology (WDFW, 2000).

Criteria	Rank
B (proportion of passage improvement)	1.0- zero percent passable 0.67- 33% passable 0.33- 67% passable
P (annual adult equivalent production potential per m^2)	0.016-chinook salmon 1.25-pink salmon 0.0007-bull trout/d. varden 1.25-chum salmon 3.00-sockeye salmon 0.037-searun cutthroat trout 0.05-coho salmon 0.0021-steelhead salmon 0.04-resident cutthroat trout 0.04-rainbow trout 0.04-brook trout 0.0019-brown trout
H (habitat gain)	measured or calculated value in m^2
M (mobility modifier)	2-highly mobile stock (anadromous species) 1-moderately mobile stock (resident species) 0-negative impacts from increased mobility (exotic salmonid species)
D (species condition modifier)	3-condition of species considered critical 2-condition of species considered depressed or stock of concern 1-species not meeting the conditions for 2 or 3
C (cost modifier)	3-incremental funds needed ≤ $100,000 2-incremental funds needed >$100,000 and ≤ $500,000 1-incremental funds needed > $500,000

Method 4

The USDA Forest Service, in consultation with professionals from other agencies, is in the process of developing a culvert prioritization methodology for use in the Tongass National Forest. The model uses a biological significance indicator that is based on an upstream habitat assessment and several other watershed parameters. The biological significance indicator is a biological ranking procedure; the results from that process are put into a decision making matrix. That matrix uses criteria such as costs, quantity of upstream habitat, choices for rehabilitation, replacement, or removal, and other factors to determine the priority of an individual culvert within a surveyed culvert inventory (personal communication, Robert Gubernick). Testing of the methodology will occur during 2005.

Discussion

An accurate and practical prioritization methodology is a key element of a complete culvert assessment protocol. The use of ranked criteria to determine a quantitative value can be a straightforward and easy-to-understand process for developing a prioritized inventory for culvert repair and replacement. The crucial aspect of developing a criteria list is deciding how many criteria should be included in the prioritization decision matrix. Too many criteria will result in a process that is bulky and complicated, has extensive data requirements, and may significantly slow down or stop the prioritization process if the required data fields are difficult or impossible to fill. Too few criteria may result in a process that provides inaccurate or meaningless results, and can lead to a misdirection of funds and effort for a fish habitat enhancement program.

The three program examples provided above display a wide range of methodology and information requirements. The ODFW methodology is the easiest of the three to use; data requirements for just six criteria are required, all of which relate to biological considerations. Criteria requiring estimations with low confidence levels, including engineering, passage values, and increases in production were left out of the methodology. The result is a simplified process, and results in calculated priority levels of high, medium, and low. This allows for flexibility and subsequent adjustment in the priority determinations, based on incidental knowledge, and can be viewed either as an advantage or disadvantage to the user.

The WDFW methodology presents a cumbersome process to understand and use when compared to the other two methods described above. The Priority Index calculation appears to be unnecessarily complicated, requiring the calculation of a fourth root. The value of determining the geometric mean from that calculation of the four criteria is also unclear.

The CC methodology presents a straightforward and easy-to-understand process for determining the priority of a culvert replacement inventory. Criteria include both biological and engineering costs.