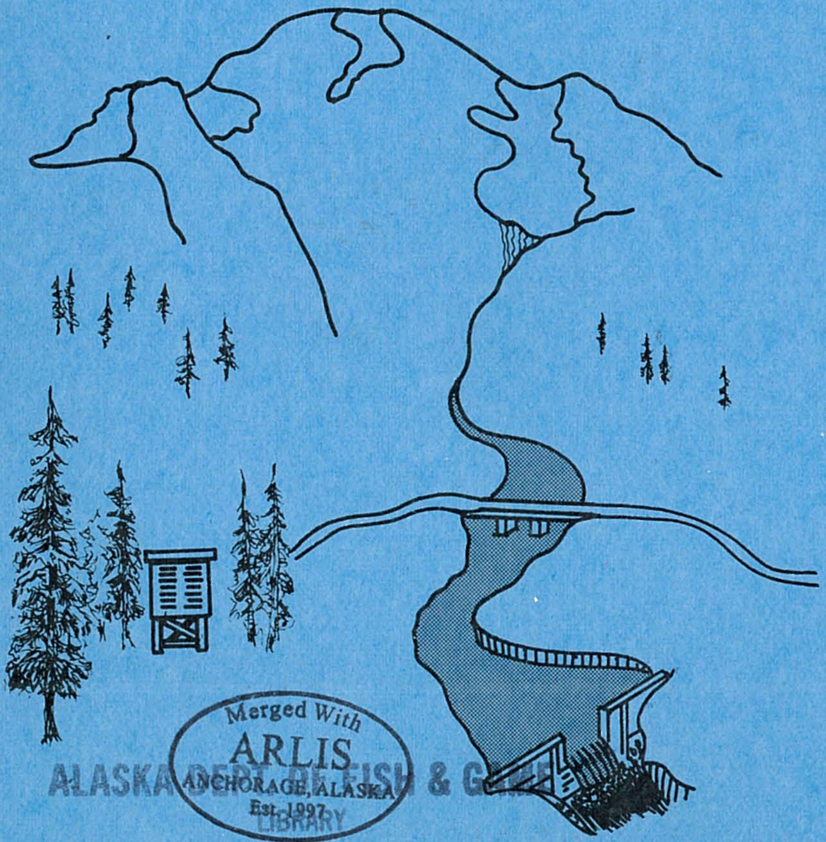
DISCHARGE VELOCITIES IN CULVERTS THAT ENSURE PASSAGE OF ARCTIC GRAYLING (*Thymallus arcticus*)



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DISCHARGE VELOCITIES IN CULVERTS THAT ENSURE PASSAGE OF ARCTIC GRAYLING (*Thymallus arcticus*)

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May 10, 1985

EXECUTIVE SUMMARY

An equation has been developed to predict the average velocity at which a specified percentage of a specified length class of Arctic grayling (Thymallus arcticus), in a culvert of specified length, can pass. The equation was developed using data collected by MacPhee and Watts (1976), and multiple linear regression techniques. The equation is:

$$V = 0.541 - 4.972\log(CL) + 5.757\log(FL) + 0.786\log(T) - 1.129\log(P+1)$$

where:

- V is the average water velocity in a culvert at which grayling can pass,
- CL is culvert length in feet,
- FL is fork length of grayling class in millimeters,
- T is water temperature in degrees Celsius (C), and
- P is percentage of grayling in a given length class (FL) required to pass the culvert, in percent.

When using the above equation to design culverts to pass adult grayling during spring high water, and when the data required to use the equation are unavailable for the particular stream of interest, the Alaska Department of Fish and Game (ADF&G) has suggested (Post, 1981) that:

(1) the water temperature (T) be assumed to be 37 degrees Fahrenheit (2.78 degrees C),
(2) the grayling fork length (FL) be assumed to be 9-1/2 inches (241mm),
(3) the percent passing be specified as 75 percent, and
(4) the velocity predicted with the above equation be taken as the allowable velocity during the instantaneous peak of the mean annual spring flood.

Using the values suggested above, the equation reduces to:

$$V = 12.483 - 4.972 \log (CL)$$

Based on the above equation, the allowable velocity for various culvert lengths, and the approximate 67 and 95 percent confidence limits are presented in Table I.

To design a culvert to ensure that the maximum allowable velocity for adult grayling is not exceeded during the mean annual spring flood, the following steps should be taken:

(1) determine the instantaneous discharge of the mean annual spring flood peak,
(2) determine the velocity in the culvert at the peak discharge,

(3) calculate the maximum allowable velocity using one of the above equations, and
(4) ensure that the velocity in the culvert will be less than or equal to the maximum allowable grayling passage velocity.

Since use of the above described design technique involves the use of a regression relationship and typical values of the input parameters, there will be circumstances where the predicted velocity will cause actual fish passage to be either more restrictive or less restrictive than desired. Although the number of cases of under- and over-design can be expected to be approximately equal, the impact on the fisheries population is not equal. For this reason a sensitivity analysis was performed to determine the impact due to under-design as a result of using the average regression relationship and the specified values of the parameters. The analysis suggests that there are seven possible sources of variability, and that six can be analyzed in a semiquantitative manner.

In analyzing the six sources of variability, it is shown that in all cases the average maximum delay (for 9-1/2 inch grayling and the range of culvert lengths analyzed) due to any single source of variability is less than 3.6 days, 90 percent of the time. It is noted that 50 percent of the time there is no delay (for 9-1/2 inch grayling) when considering any single source of variability.

The sensitivity analysis also notes that when the maximum allowable velocity is exceeded for a given period of time, only a portion of the spawning population will appear at the culvert during that time. An analysis of the MacPhee and Watts data (1976), suggests that an average of 16 percent of the spawners approached the culvert on the day of the migration peak. Of the spawners that do approach the culvert during the time when the allowable velocity is exceeded, the analysis showed that approximately 24 percent or more of the adult grayling will pass through unrestricted, 90 percent of the time.

Although it was beyond the scope of this project to quantify the delay associated with various combinations of errors, it is noted that such combinations will occur. For this reason, as well as for others, it is stated that the sensitivity analysis only provides an indication of the approximate magnitude of the impact that could occur.

Due to the economic and ecological ramifications of either over- or under- design, further studies are recommended. Specific recommendations are also made concerning additional design practices that might be used to ensure grayling passage. Finally, recommendations are made concerning the interpretation of the results obtained from the equations developed herein, during design review and culvert monitoring.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Problem

Culverts, which are otherwise properly designed, may create a combination of stream bed conditions and water velocities in excess of those negotiable by fish. Such a situation can seriously impact the fisheries resource of a stream.

One species of fish in particular, the Arctic grayling (Thymallus arcticus), migrates to its spawning beds during spring runoff. A temporary blockade, such as high water velocities in a culvert, may prevent the grayling from reaching suitable habitat before spawning. When forced to spawn in habitat that is less than suitable, egg survival is likely to be significantly reduced and the fisheries resource for the entire stream may be seriously impacted. Therefore, it is necessary to design culverts to ensure that an acceptable number of grayling are able to migrate upstream during peak flows.

The discharge velocities at which grayling can negotiate a culvert are not well understood. A study by MacPhee and Watts (1976) relates swimming ability to fork length and water temperature for 60-foot and 100-foot culverts. However, the study does not present the error associated with the relationship, nor does it suggest a means of determining an acceptable velocity for culverts of other lengths.

Objective

The objectives of this study are as follows.

1) Develop a relationship with a known error that relates the average water velocity at which grayling of various lengths can negotiate culverts, to parameters that appear to influence the performance of grayling.

2) Document a method of predicting the velocity at which adult grayling can pass a particular culvert during the mean annual spring flood.

3) Make recommendations for design, design review and culvert monitoring, and future studies of fish passage criteria.

METHOD OF ANALYSIS

To develop a relationship between the average water velocity at which grayling can negotiate a culvert and the parameters which appear to influence the ability of grayling to negotiate culverts, the BMDP Biomedical Computer Programs (UCLA, 1979) were used. In particular, a multiple linear stepwise regression program, BMDP-2R, was used to determine the relationship which best describes the velocity at which grayling can pass a culvert. The analysis was conducted using the data collected by MacPhee and Watts (1976).

MacPhee and Watts (1976) performed a total of 44 tests over a three-year period to determine the ability of grayling to ascend culverts under various conditions. In each test, the general procedure was:

(1) to block the upstream migration of grayling with a dam,
(2) capture the grayling in a riffle and pool area close to the dam,
(3) place the grayling in the tailbox below the culvert, and
(4) count the grayling that successfully ascended or failed to ascend the culvert in a 24-hour period.

The data were categorized according to fish length to produce 466 cases. The parameters measured during each of the tests and considered herein, included: average water velocity in the culvert, fish length, culvert length, percent of grayling passing the culvert, water temperature, and the headwater depth to culvert diameter ratio (HW/D). The range over which each of the variables was measured is as follows:

Velocity:	2.0-6.2 feet per second.
Culvert Length:	60 feet and 100 feet.
Fish Length:	96-360 millimeters.
Temperature:	2-14 degrees Celsius (C).
Headwater Depth/Diameter:	0.3-0.8 feet per foot.

In the regression analysis, velocity is designated as the dependent variable and fish length, percent passing, culvert length, water temperature, and HW/D are designated as the independent variables. Correlation coefficients are determined for each of the pairs of variables to ensure the independence of the independent variables. Each of the 466 cases is weighted according to the number of fish observed in each case.

The independent variables were entered (one each step) into the regression equation in a stepwise manner. At each step, the variable with the highest F ratio was added (Younger, 1979) and a new equation was formed. The equation which had the least error associated with the estimate (i.e., standard error of the estimate, SEE) was chosen. If a particular variable had a small range, it was removed from the equation, if its removal did not increase the SEE substantially.

It should be noted that percent passing might have been more properly (in a statistical sense) designated as the dependent variable. However, velocity was designated as the dependent variable for the following reasons.

(1) Designation of percent passing as the dependent variable does not present an equation which yeilds velocities at which grayling can pass culverts that are significantly different from those yielded from the above described analysis.

(2) The approach taken in this study enables a more straight forward analysis of the consequences resulting from the errors associated with use of an acceptable grayling passage velocity equation.

The approximate 67 percent confidence limits for the velocities predicted with the best-fit regression equation were calculated as follows. The upper limit was calculated by adding one standard error of the estimate (SEE) to the predicted velocity. The lower limit was calculated by subtracting one SEE from the predicted velocity. The approximate 95 percent confidence limits were calculated in a similar manner using two standard errors of the estimate. However, it should be noted that these confidence limits are only approximate, as the error will increase beyond that stated above as the conditions represented by the independent parameters deviate from the average condition.

In order to use the regression equation for culvert design, without obtaining site specific information, it is necessary to make some assumptions as to the typical value of each of the independent parameters. Typical values were provided by the Alaska Department of Fish and Game (Post, 1981).

In order to analyze the impact of using the regression equation and typical parameter values in culvert design, a sensitivity analysis was performed. To do this, the possible sources of error were identified and the possibility of quantifying the error determined.

For the quantifiable sources of error, an attempt is made to determine the impact of an error in terms of: (1) the time the design length class of grayling is delayed, (2) the percentage of a typical spawning population likely to pass at the peak discharge despite the error, and (3) the percentage of the spawning population affected by the adverse conditions. Adverse conditions are defined as those conditions which are more severe (in terms of velocity) than those considered acceptable for design purposes. The Poplar Grove Creek grayling population is assumed typical and the data available for it (MacPhee and Watts, 1976) are used in this portion of the analysis.

In order to determine the amount of time the design length class of grayling is delayed, the time necessary for the velocity in the culvert to drop to an acceptable velocity was determined. To do this, a median dimensionless flood hydrograph (Figure I) and a hydraulic elements chart (Figure II) were used. The median dimensionless flood hydrograph shown in Figure I was developed from 41 individual flood hydrographs on the following nine streams:

Atigun River Tributary,
Putuligayuk River,
Jim River,
Wiseman Creek,
Caribou Creek,
Poker Creek,
Boulder Creek,
Berry Creek, and
Dry Creek.

From Figure I, the flow in a stream on any given day prior to or following the peak can be predicted knowing only the magnitude of the instantaneous peak.

In cases where the actual velocity at which grayling can pass a culvert is less than that used to design the culvert, the following procedures were used to determine the delay time.

(1) The culvert is assumed to be half full at the fish passage design discharge. Thus, the ratio of the fish passage design discharge to the pipe full discharge is 0.5 (see Figure II).

(2) The velocity ratio (actual water velocity at which grayling can pass the culvert divided by the fish passage design velocity) is used in conjunction with Figure II to determine the discharge ratio (the discharge at which grayling could pass the culvert divided by the pipe full discharge).

(3) The difference between .5 and the discharge ratio determined in Step 2, divided by .5, yields the percentage by which the discharge must drop, in order for the velocity at which grayling can pass the culvert to equal the water velocity in the culvert.

(4) Finally, Figure I is used to determine the length of time necessary for the discharge to drop by a percentage equal to that determined in Step 4.

The potential error associated with an estimate of the fish passage design discharge is assumed to be similar in magnitude to that associated with the regional regression equations presented in "A Regional Flood Frequency Analysis for That Portion of the Proposed Alaska Natural Gas Transportation Service Company Route in Alaska" (Alaska State Pipeline Coordinator's Office, 1981). It is felt that the error associated with the Alaska State Pipeline Coordinator's Office (ASPCO) flood frequency method is of approximately the same magnitude as the error associated with most of the Alaskan flood estimation procedures developed from regional regression analyses.

In order to determine the percentage of the sexually mature grayling passing a given culvert at the peak discharge, it is necessary to adjust the size-frequency distribution of ripe grayling suggested by the MacPhee and Watts (1976) data for the Poplar Grove grayling population. The adjustment is necessary due to the fact that ripeness as defined by MacPhee and Watts (1976) does not include all grayling that will spawn in the year in which the ripeness determination is made. In other words, the fact that a particular grayling is not ripe at the time it is sampled does not mean it will not spawn that year.

Using the data on grayling ripeness presented by MacPhee and Watts (1976) and by accounting for the error in estimating the sexual maturity of males and females, an average size-frequency distribution (Figure III) for the sexually mature Poplar Grove Creek grayling was developed. The error in estimating the sexual maturity of males and females was partially accounted for by assuming that all grayling in the 10.6 inches (270 mm) or greater length classes were sexually mature. Additionally, the number of ripe males in all length classes less than 10.6 inches (270 mm) was increased by 12 percent (Chihuly, 1982), and the percentage of ripe females was assumed equal to the percentage of ripe males (Chihuly, 1982). The percentage of each length class (sexually mature grayling) passing a culvert for a given set of circumstances is determined using the equation to predict the average allowable velocity. By summing the percentage of sexually mature grayling in each length class that can pass the culvert, the total percentage of sexually mature grayling passing the culvert at the peak discharge is determined.

To determine the approximate percentage of the primary spawning size grayling affected by the adverse conditions, the Poplar Grove Creek data (MacPhee and Watts, 1976) on the number of 9-1/2 inch (241 mm) or larger grayling approaching the culvert each day of the run were utilized. The average percentage of grayling, in the 9-1/2 inch (241 mm) or larger size classes, approaching the culvert on each day of the run was determined from the three years of data presented by MacPhee and Watts (1976). It is assumed that the migration and discharge peaks coincide, and that the time period during which the adverse conditions prevailed is equal to the time the design length class of grayling (i.e. 9-1/2 inch grayling) would be delayed.

It should be noted that there is a difference in the size of grayling used to determine the percentage of sexually mature grayling able to pass the culvert during the adverse conditions and the percentage of fish approaching the culvert during the adverse conditions. Ideally, both of these analyses would have considered grayling down to 7.5 inches (190 mm) in size, as this is the minimum size of grayling thought to be capable of spawning (in this system). However, due to the manner in which the Poplar Grove Data were presented (MacPhee and Watts, 1976), this was not possible.

To estimate the percentage of sexually mature grayling unable to move through the culvert unrestricted, during adverse conditions, the percentage of sexually mature grayling not able to pass through the culvert during the peak flow is multiplied by the percentage of primary spawning size grayling approaching the culvert during the adverse conditions. Although this procedure will tend to mildly over-estimate the number of sexually mature grayling which are delayed, data needed to do a more precise estimate were not available from the MacPhee and Watts (1976) report.

Finally, to estimate the amount of time 9-1/2 inch (241 mm) grayling would be delayed during floods larger than the mean annual flood, the index method flood peak ratios developed by the Alaska State Pipeline Coordinator's Office (1981) were used. The ratios represent the relative magnitude of the flood of interest to the mean annual flood. Since different sets of ratios were developed to describe the streams that are located north and south of the Yukon River, along the proposed gas pipeline route, the ratios were averaged for this study. Using the average ratios and the median dimensionless hydrograph, the delay time for 9-1/2 inch (241 mm) grayling was computed.

RESULTS AND DISCUSSION

Equation For Average Water Velocities At Which Grayling Can Pass Culverts

To establish an acceptable relationship for predicting the velocity at which grayling can pass a specified length of culvert, three different regression equations were considered. Each equation and the reasons for selecting one equation as being better than the others is presented below.

The first equation is a linear function of the untransformed variables and is as follows.

EQUATION 1:

$$V = 5.04 - 0.024(CL) + 0.011(FL) + 0.025(T) - 0.023(P+1) - 1.60(HW/D)$$

where:

- V is water velocity in feet per second (fps),
- CL is culvert length in feet,
- FL is grayling fork length in millimeters,
- T is water temperature in degrees Celsius,
- P is percentage of fish ascending the culvert in percent, and
- HW/D is headwater depth to culvert diameter ratio.

The standard error of the estimate (SEE), the mean sample velocity (VEL), the correlation coefficient (R), and the coefficient of determination (R-square) are as follows:

SEE = 0.758 fps
VEL = 3.57 fps

R = 0.688
R-square = 0.473

From the coefficient of determination it can be seen that approximately 47 percent of the variation in the velocity at which grayling can pass a culvert is explained by this equation.

The second equation was developed by taking the logarithms of the independent variables. Thus, velocity is expressed as a linear function of the logarithms of the independent variables. The equation is as follows.

EQUATION 2:

$$V = -0.183-4.77\log(CL)+5.77\log(FL)+0.763\log(T)-1.21\log(P+1)-1.30\log(HW/D)$$

SEE = 0.698 fps
VEL = 3.57 fps
R = 0.744
R-square = 0.554

As can be seen from the coefficient of variation, the equation explains approximately 55 percent of the variability in the data. Since the SEE has been reduced, this equation is considered to be an improvement over Equation 1.

However, the HW/D variable in Equation 2 was measured over a relatively small range, only 0.3-0.8. Therefore, a third equation was developed using the form of Equation 2 but without the HW/D variable. The resulting equation is as follows.

EQUATION 3:

$$V = 0.541-4.97\log(CL)+5.7\log(FL)+0.786\log(T)-1.13\log(P+1)$$

SEE = 0.700 fps
VEL = 3.57 fps
R = 0.742
R-square = 0.550

The regression equation explains approximately 55 percent of the variability in the original data. Since the SEE in Equation 3 is essentially the same as the SEE in Equation 2, Equation 3 is considered to be the most practical equation (of those considered) for use in culvert design. However, it should be noted that the values of the standard error of the estimate and the coefficient of variation are not particularly good. Thus, although the equation provides a useful tool, it has considerably more variability associated with it than one would like. The order of importance of the independent variables in explaining the variability in the average velocity at which grayling can pass a culvert is as follows:

(1) percent of fork length class passing the culvert (P),

(2) average grayling fork length in class (FL),
(3) culvert length (CL), and
(4) water temperature (T).

Typical Conditions For Use In Design

In order to use the above equation to ensure that grayling will be capable of passing a culvert installation, during the design of the culvert, some additional information and guidance is necessary. Specifically, information is needed concerning the:

(1) critical grayling size,
(2) water temperature during the critical migration period,
(3) average percentage of the critical grayling size expected to pass the culvert unrestricted, and
(4) discharge during the critical migration period.

The Alaska Department of Fish and Game (Post, 1981) has determined that typically the most critical conditions occur during the spawning run, that the spawning run usually occurs during spring breakup, and that it is necessary to pass, on the average, 75 percent of the practical minimum size of spawning grayling without delay. Thus, ADF&G has suggested (Post, 1981) that the following typical values be used with Equation 3, where site specific information is unavailable.

Temperature	= 37 degrees Fahrenheit (2.78 degrees Celsius),
Fish Length	= 9-1/2 inches (241 mm)
Percentage Passing	= 75

Using these values, Equation 3 reduces to :

EQUATION 4:

$$V = 12.483 - 4.972 \log (CL)$$

Therefore, to design a culvert to ensure that the allowable velocity is not exceeded during the mean annual spring flood, the following steps must be taken during culvert design:

(1) determine the peak discharge of the mean annual spring flood,
(2) determine the velocity in the culvert at the discharge determined in Step 1,
(3) calculate the allowable velocity using Equation 3 (if site specific information is available) or using Equation 4 (if site specific information is unavailable), and
(4) ensure that the velocity in the culvert will be less than or equal to the allowable velocity.

In order to simplify the design effort when the typical conditions apply, Table 1 was prepared using Equation 4. In Table 1, the allowable velocity for various culvert lengths, and the approximate 67 and 95 percent confidence limits are presented.

Implications For A Typical Spawning Population

Equation 4 and Table I can also be used to consider the effect on the spawning population (as a whole) of designing for 75 percent passage of a practical minimum size of spawning grayling. To do this, two types of variation must be considered: unexplained variability in the regression equation (due to possibly swimming ability), and natural variation in the size of spawning grayling.

In order to consider the unexplained variation in the regression equation, it is necessary to consider the confidence limits associated with the regression equation. Thus, the approximate confidence limits are presented in Table I in order to emphasize that the regression relationship describes average conditions. To clarify the interpretation of the approximate confidence limits, the following example is presented.

In the case of a 90-foot culvert, Table I can be used to determine that, on the average, the velocity at which 75 percent of the 9-1/2 inch (241 mm) grayling in 37 degree F water can pass is 2.8 fps. However, approximately 16.5 percent of the 9-1/2 inch grayling would not pass a 90-foot culvert with a velocity of 2.1 fps, and 2.5 percent would not pass a 90-foot culvert with a velocity of 1.4 fps. On-the-other-hand, approximately 16.5 percent of the 9-1/2 inch (241 mm) grayling would pass a 90-foot culvert with a 3.5 fps velocity, and approximately 2.5 percent would pass a 90-foot culvert with a 4.2 fps velocity. Thus, the use of 2.8 fps for design involves the use of an average swimming ability at which the above criteria can be satisfied.

It is also important to note that 75 percent passage of the 9-1/2 inch grayling ensures a higher percent passage for the adult grayling population as a whole. As shown in Table II (Case No. 1), culverts designed to pass 75 percent of the 9-1/2 inch grayling at the mean annual peak discharge can pass, on the average, approximately 88 percent of the sexually mature grayling (given the range of culvert lengths analyzed).

However, not all of the primary spawning size grayling will approach the culvert at the peak discharge. The average percentage of primary spawning size grayling approaching the Poplar Grove Creek study area, each day of the migration period, is shown in Table III. From Table III it can be seen that on the average approximately 16 percent of the primary spawning size grayling moved on the day of the migration peak. Therefore, assuming that the migration peak and the discharge peak coincide, approximately 16 percent of the spawning population will approach the culvert on the day of the peak discharge. If 88 percent of the sexually mature grayling that approach the culvert during the flood peak can pass, then approximately 2 percent of the sexually mature grayling expected to move up the stream will be delayed.

Impact Of Actual Conditions Varying From The Assumed Conditions

The above discussion assumes that the actual spawning population and environmental conditions are as specified in the typical conditions. However, actual conditions may vary from the assumed conditions in a particular year and/or on a particular stream. Therefore, in using Equation 4 to design culverts to ensure a given level of grayling passage, there are seven possible sources of variability that should be considered:

(1) the assumption that Equation 4 applies to all grayling populations as well as it applies to the Poplar Grove Creek population,
(2) the assumption that the water temperature is 37 degrees F,
(3) the assumption that the practical minimum size of spawner is 9-1/2 inches (241 mm),
(4) the unexplained variability in Equation 4 (expressed as confidence limits),
(5) the ability to calculate the expected velocity in a culvert during design.
(6) the unexplained variability of the method used to predict the mean annual flood (usually expressed as confidence limits), and
(7) the variability in severity of flood that actually occurs from one year to the next (i.e. 1-, 2-, 5- year flood).

In each case there is an equal chance that the variation will enhance or hinder fish passage. To analyze the effect on the grayling population, of sizing culverts using the procedures suggested above, an attempt is made to quantify the possible variability. Only variations from the average that would hinder fish passage are considered in the analyses. However, it must be remembered that approximately 50 percent of the time the variation from assumed conditions will enhance fish passage.

It should be noted that the numbers presented for delay times and percentage of grayling affected are averages, based on the culvert lengths analyzed. The actual delay times and percentage of grayling affected at a particular culvert vary depending on the culvert length (all other parameters being as assumed in the analysis). To determine the effect of culvert length, Tables II, IV and V should be consulted.

Each of the above referenced sources of possible variation is discussed briefly below.

Case 1

The use of Equation 3 on streams other than Poplar Grove Creek assumes that the grayling populations of the other streams are similar to the Poplar Grove grayling population. However, the amount of variation from one population to another is unknown, since data from only one population were used in this study.

Therefore, when applying the regression equation to populations on streams other than Poplar Grove Creek, it should be remembered that there is no way of knowing whether the populations are similar. Since only one population was studied, the possible variability cannot be quantified.

Case 2

For design purposes, it has been suggested that the water temperature be assumed to be 37 degrees F. This represents the average water temperature, at the peak of the spring flood, on a number of streams for which data were available. However, in approximately 10 percent of the cases analyzed, the temperature was 33 degrees F or less at the peak discharge. Thus, if the water temperature is really 33 degrees F, the effect of designing a culvert assuming a water temperature of 37 degrees F is presented in Table II as Case No. 2.

As can be seen in Table II, the result of such an error is that approximately 25 percent of the primary spawning size grayling might be expected to approach the culvert during a period when conditions were more severe than anticipated. However, approximately 47 percent of the sexually mature grayling approaching the culvert at the instantaneous peak discharge will pass the culvert successfully.

Therefore, in 90% of the cases where an error occurs due to the water temperature being different than assumed, less than approximately 13 percent of the sexually mature grayling will be delayed. Furthermore, the average maximum delay time for 9-1/2 inch (241 mm) grayling will be less than approximately 1.5 days. In 50 percent of the cases where an error occurs due to the water temperature being different than assumed, less than approximately 2 percent of the sexually mature grayling will be delayed, and grayling 9-1/2 inches (241 mm) or larger will not be delayed.

Case 3

It has also been suggested that for design purposes the practical minimum length of spawner is typically 9-1/2 inches (241 mm), and that the design be based on this length class of grayling. However, it seems reasonable that the practical minimum length of spawner will vary from one stream to another. In discussions with the Alaska Department of Fish and Game (Chihuly, 1981), it was suggested (based on experience) that on approximately 10% of the streams along the Dalton, Richardson and Alaska highways the practical minimum length of spawner is probably equal to or less than 9 inches (229 mm).

Thus, if the practical minimum length of spawner in a particular stream is 9 inches (229 mm), the effect of designing a culvert assuming a practical minimum length of 9-1/2 inches (241 mm) is presented in Table II as Case No. 3. As can be seen in Table II, the percentage of primary spawning size grayling approaching a culvert during a period when a significant portion of 9-inch (229 mm) grayling could not pass through unrestricted, is approximately 12 percent. Although it was not possible (without assuming a new spawning size frequency distribution) to analyze the percentage of the population passing the culvert immediately, it is expected that it would be nearly as good as in Case No. 1, since the practical minimum size has been only slightly reduced.

Therefore, in 90 percent of the cases in which the practical minimum size of spawner is less than the assumed size, the number of sexually mature grayling actually delayed will probably be substantially less than 12 percent. The average maximum delay for 9-inch (229 mm) grayling is expected to be on the order of 0.33 days. In 50 percent of the cases, less than approximately 2 percent of the spawning population are likely to be delayed, and grayling 9-1/2 inches (241 mm) or larger will not be delayed.

Case 4

Another potential source of error is the unexplained variability in Equation 4. This variability is due to the fact that Equation 4 does not completely explain the average water velocity at which the Poplar Grove Creek grayling can pass a culvert.

For this reason, the unexplained variability in Equation 4 is analyzed to determine the effect of this variability on any given design. The situation analyzed is such that 90% of the time the effect due to unexplained variability in Equation 4 is less than that for the situation examined. The results of this analysis are presented in Table II as Case No. 4.

As can be seen in Table II, approximately 47 percent of the primary spawning size grayling are likely to approach the culvert when the conditions exceed those at which 75 percent of the 9-1/2 inch (241 mm) grayling can pass. Approximately 24 percent of the sexually mature grayling approaching the culvert at the instantaneous peak discharge will pass the culvert successfully.

Therefore, in 90 percent of the cases where an error occurs due to the unexplained variability in Equation 4, less than approximately 36 percent of the sexually mature grayling will be delayed. The average maximum delay for 9-1/2 inch (241 mm) grayling will probably be less than 3.6 days. In 50 percent of the cases where an error occurs due to the unexplained variability in Equation 4, less than approximately 2 percent of the spawning population will be delayed, and grayling 9-1/2 inches (241 mm) or larger will not be delayed.

Case 5

Another potential source of error is in estimating the water velocity in a culvert at the instantaneous peak of the mean annual spring flood. In order to quantify the effect of this potential source of error it was assumed (based on experience) that 90 percent of the time the error would be less than 20 percent. The results of this analysis are presented in Table IV.

As can be seen, approximately 25 percent of the primary spawning size grayling will approach the culvert when conditions exceed those at which 75 percent of the 9-1/2 inch (241 mm) grayling can pass. Approximately 39 percent of the sexually mature grayling approaching the culvert at the instantaneous peak discharge will pass the culvert unrestricted.

Therefore, in 90 percent of the cases where an error occurs due to incorrectly estimating the water velocity during the culvert design, less than approximately 15 percent of the sexually mature grayling will be delayed. Furthermore, the average maximum delay for 9-1/2 inch (241 mm) grayling will be less than approximately 1.3 days. In 50 percent of the cases, less than approximately 2 percent of the spawning population will be delayed, and grayling 9-1/2 inches or larger will not be delayed.

Case 6

Another potential source of error is in estimating the discharge at the instantaneous peak of the mean annual flood. From "A Regional Flood Frequency Analysis for That Portion of the Proposed Alaskan Gas Transportation System Route in Alaska" (Alaska State Pipeline Coordinator's Office, 1981) it can be seen that 90 percent of the time the actual mean annual spring flood peak discharge will have to drop 51 percent or less to equal the predicted discharge. Note that 50 percent of the time the predicted mean annual spring flood peak discharge will be greater than the actual mean annual peak discharge. The results of this analysis are presented in Table V.

As can be seen in Table V, approximately 27 percent of the primary spawning size grayling might be expected to approach the culvert when the conditions exceed those at which 75 percent of the 9-1/2 inch (241 mm) grayling can pass. Approximately 54 percent of the sexually mature grayling approaching the culvert at the instantaneous peak discharge will pass the culvert successfully.

Therefore, in 90 percent of the cases where the actual mean annual peak discharge is greater than the predicted mean annual peak discharge, less than approximately 12 percent of the sexually mature grayling will be delayed. The average maximum delay time for 9-1/2 inch (241 mm) grayling will be less than approximately 1.4 days. In 50 percent of the cases, 2 percent or less of the sexually mature grayling will be delayed, and grayling 9-1/2 inches or longer will not be delayed.

Case 7

There is one final type of variation that must be recognized in order to fully appreciate the proposed method of designing culverts to pass grayling during peak flows. The proposed design procedures specify that fish passage be provided during the mean annual spring flood. However, it should be noted that 50 percent of the time the spring flood will be larger than the mean annual spring flood, and 50 percent of the time it will be smaller. Using the relationships presented in "A Regional Flood Frequency Analysis for That Portion of the Proposed Alaska Natural Gas Transportation System Route in Alaska," the delay time associated with 9-1/2 inch (241 mm) grayling caught in a flood larger than the mean annual flood is presented in Table VI. Thus, on the average, once every 5 years we might expect the delay time for 9-1/2 inch (241 mm) grayling to be 0.6 days or longer and once every 10 years we might expect the delay to be 1.5 days or longer, all other things being as assumed in the design.

Some Final Thoughts

The above analyses have considered the effect of each potential source of error separately. However, in reality, there will be times when errors from different sources will combine: sometimes to negate each other, and sometimes to further hinder fish passage. When errors combine to further hinder fish passage, the delay times may be longer than those suggested by the above analyses.

It should also be noted that the number of assumptions necessary to perform the sensitivity analyses are almost overwhelming. Thus, the numbers are only representative of the order of magnitude of the effects discussed.

Furthermore, note should be made of the fact that the discharge and migration peaks were assumed to coincide. From the MacPhee and Watts (1976) data presented in Figures 2, 3 and 4 of that report, it can be seen that in two of the three years the grayling migration occurred primarily before or after the occurrence of the peak discharge. Thus, the delays predicted can be expected to happen less frequently than if the migration and discharge peaks actually coincided every year.

Finally, it should be noted that the error in the fish passage velocity relationship presents the potential for the single largest impact on fish passage, of the error sources studied. The sources of error (excluding Case Numbers 1 and 7) from largest to smallest in terms of magnitude of impact on fish passage are as follows:

(1) the fish passage velocity relationship,
(2) the estimation of the velocity in the culvert,
(3) the water temperature assumption,
(4) the estimation of the mean annual spring flood peak discharge, and
(5) the practical minimum spawner length assumption.

RECOMMENDATIONS

Design

The recommendations for design include two types of recommendations. The first type includes four possible alternative actions, when the intended culvert will not provide an acceptable velocity for grayling passage. The second type involves an action that should be taken during culvert design which is unrelated to the discharge velocity at which grayling can pass a culvert, but which significantly affects fish passage. Each recommendation is discussed below.

When the intended culvert cannot meet the velocity criteria, there will generally be four possible alternative approaches involving the use of culverts. If only circular culverts have been considered, the design should consider pipe-arch culverts and possibly open-arch culverts. Pipe-arches provide a larger proportion of cross-sectional area at lower flows and will help minimize the velocities during flows substantially less than the culvert design flow. This may provide some benefit at fish passage design flows (i.e. the mean annual flood) when the culvert has been designed for a 10- to 50-year flood. Open-arch culverts will generally provide a larger proportion of cross-sectional area at lower flows, than will either circular culverts or pipe-arches.

Secondly, if these approaches are infeasible and there is sufficient width between the banks, consideration should be given to the use of multiple culverts. The use of a number of slightly smaller culverts, rather than one large culvert, will sometimes provide lower velocities during critical fish passage periods while still accommodating culvert design flows.

Thirdly, consideration should be given to using a shorter culvert with headwalls and tailwalls. The allowable velocity becomes significantly larger as the length of culvert decreases. By using headwalls and tailwalls, the culvert will only need to be slightly longer than the width of the driving lanes and shoulder. In a high fill area, this could shorten the length of the culvert considerably.

Fourthly, where a culvert cannot meet the velocity criteria and all else fails, consideration should be given to the use of baffles. Baffles have not received much attention due to the potential ice and debris problems. However, they have proven effective in the Pacific Northwest region of the United States (McClellan, 1970) and thus, merit consideration where all other alternatives (short of a bridge) are unacceptable.

It is important to note that changing the culvert slope does not normally change the peak velocities, since the flow within a culvert during a flood the size of the mean annual flood (or larger) is not normally uniform. Although Manning's Equation is often used to show that changing the slope does change the velocity, Manning's Equation assumes uniform flow (i.e. the bed slope, water surface slope and energy slope are all parallel). When the flow is not uniform, it is the energy slope rather than the bed slope that must be considered in determining the velocity.

It is also important to note that changing the culvert diameter will not normally have a significant effect on the discharge velocity during the mean annual flood. The reason for this is that the culvert is being sized for a much larger flood. Therefore, the mean annual flood only occupies the lower portion of the culvert, and the area and depth of the flow do not change significantly with relatively small diameter changes.

Finally, it is extremely important to ensure that a scour hole does not form at the outlet end of the culvert, which in time will cause the culvert to become perched. A culvert which has acceptable velocities but is perched, is of little help in protecting the fishery upstream of the culvert. On a number of trips along the Dalton Highway in 1981, in which it was desired to find a culvert with unacceptable fish passage velocities and no other problems, it was impossible to find a suitable culvert without a perched outlet (Shideler, 1981). The search finally encompassed, to a much more limited degree, all the roads in the Interior. Even then, the investigators were unable to find a culvert with a grayling passage velocity problem that was not also perched at the outlet. Therefore, an attempt should be made during the design of a culvert (that must pass grayling) to ensure that the stream bed will be stable throughout the life of the culvert, and if necessary, to design an apron that will ensure stability. During the design and construction of the apron, it is important to ensure that flow will be over the top of the apron. Aprons designed and/or constructed such that the discharge at low flow passes entirely within the apron rock, will present a fish block. Setting the culvert invert below the stream bed will also prevent a perched culvert in some situations.

Design Review And Culvert Monitoring

In using the regression equation developed in this report to regulate the acceptable velocity in a culvert, a number of points should be considered. Each of these is presented below.

First, it should be noted that motivation is a large factor affecting the performance of grayling in negotiating a culvert. Not all of the grayling approaching the culvert in the MacPhee and Watts study (1976) were ripe. Thus, it seems likely that not all of the grayling were highly motivated to pass through the culvert. Since no distinction was made between motivated and unmotivated grayling in developing the regression equation, it is likely that the regression equation under-estimates the discharge velocity at which highly motivated grayling can pass a culvert. Therefore, culverts with velocities slightly in excess of those suggested by the equation may not seriously affect the number of ripe (and presumably highly motivated) grayling passing a culvert.

The amount of acceptable increase is probably less for the larger grayling than it is for the smaller grayling, as a higher percentage of the larger grayling were ripe. For 9-1/2 inch (241 mm) grayling a reasonable tolerance might be 0.5 fps. Note that the magnitude of this tolerance is based strictly on judgement. Nevertheless, it is recommended that the values computed using this equation be considered mildly conservative estimates of the velocity at which highly motivated grayling can pass culverts.

Finally, caution should be exercised in using the equation to extrapolate the discharge velocity negotiable by grayling in culverts with lengths less than 60 feet or greater than 100 feet. For culverts greater than 100 feet in length, the velocity calculated with the equation should be compared with the voluntary cruising speed for grayling (MacPhee and Watts, 1976). If the acceptable velocity predicted using the regression equation is less than the voluntary cruising speed for grayling, the voluntary cruising speed should probably be used.

Future Studies

Making recommendations for future studies is very difficult. Certainly the variability associated with the regression equation suggests that a lot more refinement is possible. However, due to the cost involved in many of the possible studies, substantial thought should be given to exactly what will be gained prior to an expenditure of time and money. The important question is likely to be similar to the following. Is the particular refinement being considered likely to change the discharge velocity at which grayling can pass a culvert by enough to justify the expense of the study? With this in mind the following is presented.

With regard to refining the regression equation, some thought should be given to a means of removing from the sample, those cases suffering from a lack of motivation. For instance, one means of estimating the velocity at which motivated grayling could pass culverts might be to repeat the analyses presented herein using only those data that showed an increase in the percent passing, as fish length increased (assuming all other parameters are equal).

As mentioned earlier, the present study does not consider variation in swimming ability from one stream to another. Therefore, some consideration should be given to duplicating the study as performed by MacPhee and Watts (1976), on another stream. The test should probably be performed with at least one culvert length being the same as that used in the MacPhee and Watts study. Consideration should also be given to performing the test on a stream with cooler water temperatures and for measuring additional parameters, such as turbulence and ripeness of each fish. Remember that only 55 percent of the variation was explained by the current parameters.

An investigation should also be made as to the possibility of using a prefabricated footing with open bottomed structural plate pipe arch culverts. In situations where the stream bed will remain stable during the life of the culvert, open bottomed structural plate pipe arch culverts might provide a suitable solution for fish passage problems. In the past, such culverts have often been rejected due to the need to provide a concrete footing. However, the U.S. Forest Service (McClellan, 1970) has used a prefabricated footing consisting of structural steel tee sections, with the tee stems punched to receive bolts. The arch plates are bolted to the structural steel tee sections, and the footing is backfilled with crushed rock and topped with larger rock.

Research should also be conducted to determine the amount of delay migrating grayling can withstand without detriment to the fishery. If for instance, such a study would suggest that it is possible to delay spawning grayling for three days during the mean annual flood (a criteria which is used in Canada), the magnitude of the discharge during which fish passage must be accommodated would be cut in half on some streams.

Finally, research should also be conducted on the use of baffles. Although debris and ice problems would certainly appear to be potential problems, baffles are used successfully in the Pacific Northwest. Given the lack of other alternatives for preventing fish passage problems, that involve such a low construction cost, it seems appropriate to study this alternative. The study should include a review of current practice in the Pacific Northwest, construction of a baffled culvert installation, and monitoring of the installation. Detailed monitoring should take place through the first breakup. Thereafter, the installation should be monitored in the spring to determine its ability to function when the upstream grayling migration arrives, and to determine the impact of debris and bedload on the baffles.

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ACKNOWLEDGEMENTS

This report presents work started by the Alaska State Pipeline Coordinator's Office (ASPCO). Although most of the calculations were finished, the report was not finalized prior to the closing of the office in 1982. The following individuals contributed substantially to the work done by the ASPCO: John Belcourt, Mike Chihuly, Roger Post, Dick Shideler, Carl Yanagawa, John Johansen, and Al Ott. Their conscientiousness and contributions are acknowledged here.

Acknowledgement is also given to Northwest Alaskan Pipeline Company for providing the funding for the work performed by the Alaska State Pipeline Coordinator's Office.

FIGURE I

MEDIAN DIMENSIONLESS HYDROGRAPH

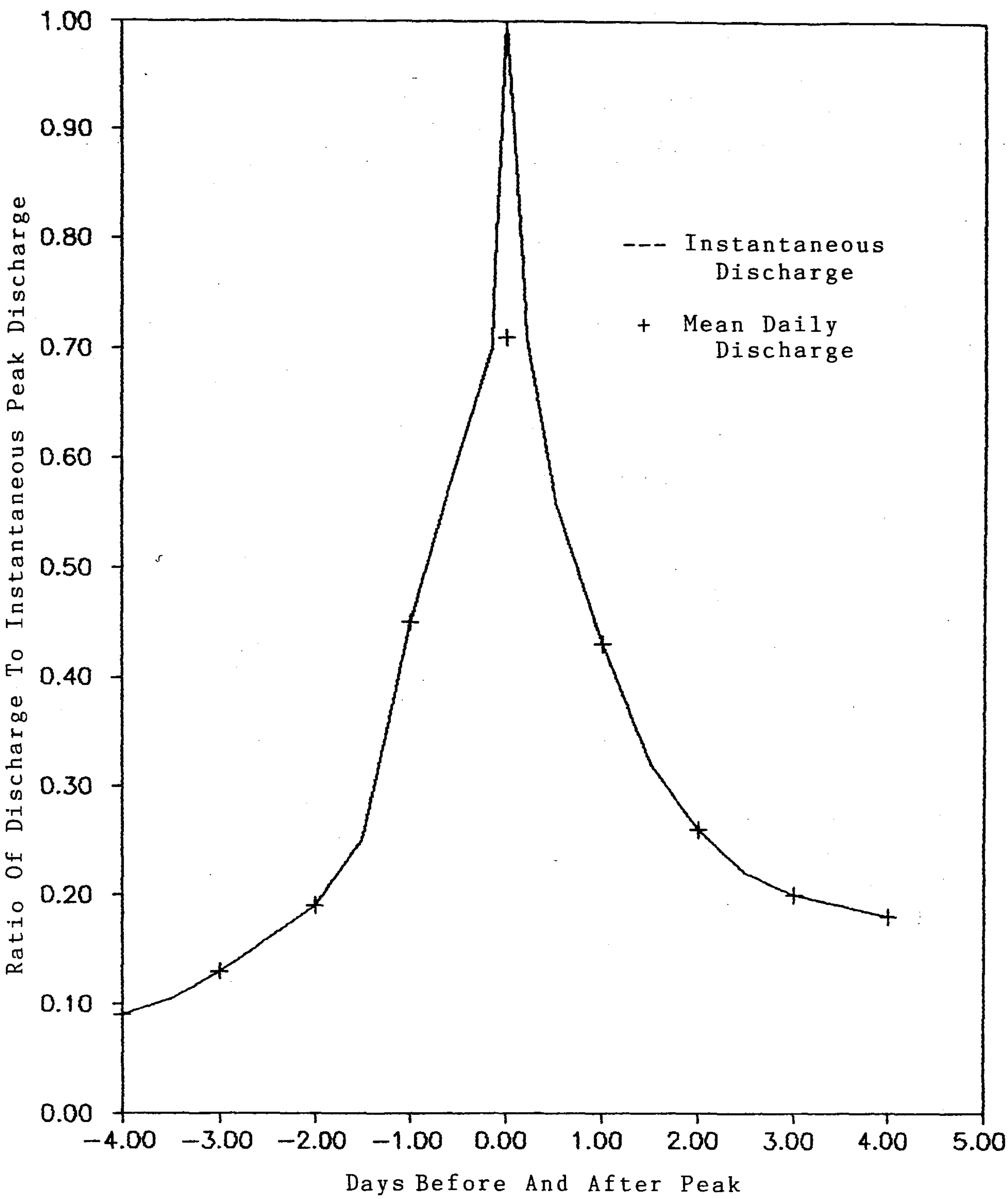
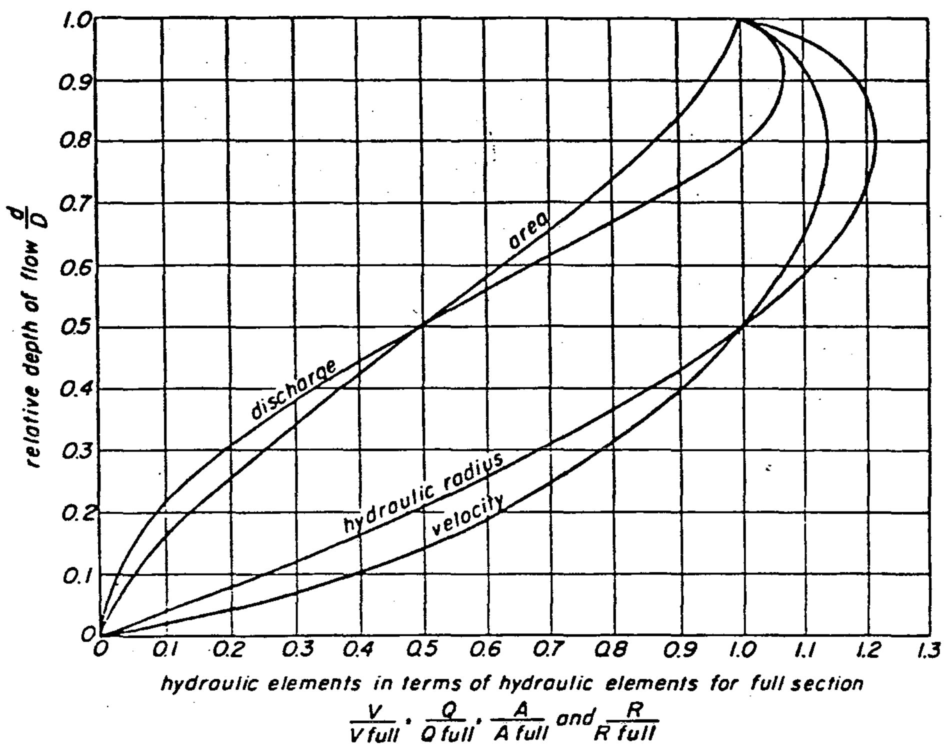


FIGURE II

RELATIVE FLOW PROPERTIES OF CIRCULAR CONDUITS (1)



(1) From Portland Cement Association. 1964. Handbook of Concrete Culvert Pipe Hydraulics.

FIGURE III

DISTRIBUTION OF TOTAL NUMBER OF SPAWNING SIZE GRAYLING SAMPLED IN 1973, 74 & 75 ON POPLAR GROVE CREEK

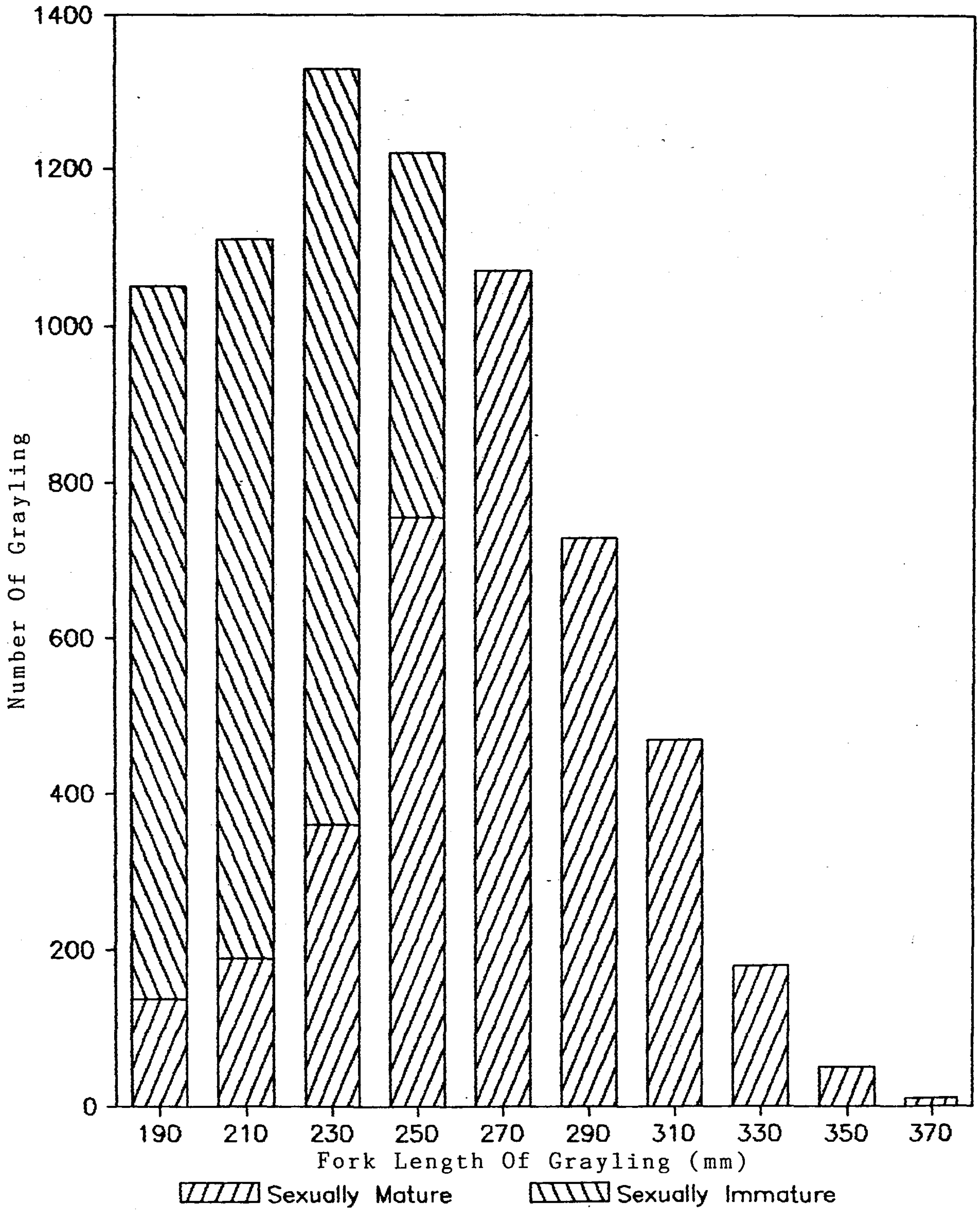


TABLE I

ACCEPTABLE DISCHARGE VELOCITIES FOR GRAYLING PASSAGE DURING TYPICAL DESIGN CONDITIONS (1,2)

CULVERT LENGTH (ft)	ACCEPTABLE VELOCITY (ft)	67% CONFIDENCE LIMITS	95% CONFIDENCE LIMITS
40	4.5	3.8 - 5.2	3.1 - 5.9
50	4.0	3.3 - 4.7	2.6 - 5.4
60	3.6	2.9 - 4.3	2.2 - 5.0
70	3.3	2.6 - 4.0	1.9 - 4.7
80	3.0	2.3 - 3.7	1.6 - 4.4
90	2.8	2.1 - 3.5	1.4 - 4.2
100	2.5	1.8 - 3.2	1.1 - 3.9
110	2.3	1.6 - 3.0	0.9 - 3.7
120	2.2	1.5 - 2.9	0.8 - 3.6

(1) Design conditions are:

- (1) 9-1/2 inch fish length
- (2) 37 degrees Fahrenheit water temperature
- (3) 75% passing

(2) Note that acceptable velocities for culvert lengths less than 60 feet or greater than 100 feet represent extrapolations beyond the range of the original data.

TABLE II

SENSITIVITY ANALYSIS FOR ERRORS IN ESTIMATING
VELOCITY AT WHICH GRAYLING CAN PASS VARIOUS LENGTH CULVERTS (1)

Culvert Length (ft)	Acceptable Velocity Assuming Design Conditions (fps)	Acceptable Velocity Considering Actual Conditions (fps)	Delay Time for 9-1/2 inch Grayling (days)	Percentage of the Sexually Mature Grayling Passing at the Peak (%)	Percentage of Spawning Size Grayling Reaching Culvert During Time Design Conditions are Exceeded (2) (%)
CASE NO. 1: CONDITIONS AT CULVERT EXACTLY AS ASSUMED IN DESIGN					
30	5.1	5.1	0	90	0
60	3.6	3.6	0	90	0
90	2.8	2.8	0	90	0
120	2.2	2.2	0	85	0
CASE NO. 2: WATER TEMPERATURE 33 DEGREES F INSTEAD OF 37 DEGREES F AS ASSUMED IN DESIGN					
30	5.1	4.6	0.6	51	16
60	3.6	3.1	0.9	51	16
90	2.8	2.2	2.0	44	27
120	2.2	1.6	2.6	43	38
CASE NO. 3: PRACTICAL MINIMUM SPAWNER 9" INSTEAD OF 9-1/2" AS ASSUMED IN DESIGN					
30	5.1	5.0	0.2 (3)	--	8
60	3.6	3.5	0.2 (3)	--	8
90	2.8	2.6	0.4 (3)	--	16
120	2.2	2.0	0.5 (3)	--	16
CASE NO. 4: ERROR IN FISH PASSAGE VELOCITY REGRESSION EQUATION					
30	5.1	4.2	1.2	26	27
60	3.6	2.7	2.4	26	38
90	2.8	1.9	3.8	22	48
120	2.2	1.3	7.1	21	73

(1) Analysis such that 90% of the time the effect will be less than that shown here.

(2) Based on the total number of 9-1/2 inch and larger grayling.

(3) Delay for 9 inch grayling.

TABLE III

PERCENTAGE OF 9-1/2 INCH AND LARGER GRAYLING MOVING EACH DAY OF THE SPAWNING MIGRATION ON POPULAR GROVE CREEK

	DAYS	1973	1974	1975	3-YEAR AVERAGE
	5	0%	1%	0%	0%
	4	0%	8%	0%	3%
BEFORE PEAK	3	0%	6%	0%	2%
	2	0%	8%	0%	3%
	1	12%	11%	0%	8%
PEAK	0	17%	15%	15%	16%
	1	8%	14%	13%	11%
	2	12%	11%	10%	11%
	3	13%	5%	10%	10%
AFTER PEAK	4	8%	8%	11%	9%
	5	7%	5%	10%	7%
	6	7%	1%	4%	4%
	7	7%	3%	4%	5%
	8	5%	2%	4%	4%
	9	2%	1%	4%	2%
	10	1%	1%	4%	2%
	11	1%		3%	1%
	12			2%	1%
	13			2%	1%
	14			1%	0%
	15			1%	0%
	16			1%	0%
	17			1%	0%
	18			1%	0%

TABLE IV

SENSITIVITY ANALYSIS FOR ERROR IN PREDICTING VELOCITY IN CULVERT (1)

Culvert Length (ft)	Predicted Culvert Velocity (fps)	Actual Culvert Velocity (fps)	Delay Time for 9-1/2 inch Grayling (days)	Percentage of the Sexually Mature Grayling Passing at the Peak (%)	Percentage of Spawning Size Grayling Reaching Culvert During Time Design Conditions are Exceeded (2) (%)
30	5.1	6.1	1.3	21	24
60	3.6	4.3	1.3	39	24
90	2.8	3.4	1.4	40	27
120	2.2	2.6	1.3	55	24

(1) Analysis is such that 90% of the time the effect on the spawning population would be less than shown here.

(2) Based on the total number of 9-1/2 inch and larger grayling.

TABLE V

SENSITIVITY ANALYSIS FOR ERROR IN PREDICTING MEAN ANNUAL DISCHARGE (1)

Culvert Length (ft)	Predicted Culvert Velocity (fps)	Actual Culvert Velocity (fps)	Delay Time for 9-1/2 inch Grayling (days)	Percentage of the Sexually Mature Grayling Passing at the Peak (fps)	Percentage of Spawning Size Grayling Reaching Culvert During Time Design Conditions are Exceeded (2) (%)
30	5.1	5.8	1.4	38	27
60	3.6	4.1	1.4	55	27
90	2.8	3.2	1.4	57	27
120	2.2	2.5	1.4	64	27

(1) Analysis is such that 90% of the time the effect on the spawning population would be less than shown here.

(2) Based on the total number of 9-1/2 inch and larger grayling.

TABLE VI

THE DELAY LIKELY TO BE INCURRED BY 9-1/2 INCH GRAYLING EXPECTED TO PASS WITH NO DELAY AT THE MEAN ANNUAL FLOOD BUT ENCOUNTERING A LARGER FLOOD

FLOOD RETURN PERIOD YEARS	PROBABLITY OF OCCURRENCE	SOUTH RATIO (1)	NORTH RATIO (2)	AVERAGE RATIO	DELAY TIME (DAYS)
2	.5	1.0	1.0	1.0	0
5	.2	1.66	1.37	1.52	0.6
10	.1	2.45	1.76	2.10	1.5
25	.04	3.97	2.35	3.16	2.6
50	.02	5.69	2.89	4.29	4.1
100	.01	8.21	3.66	5.93	6.7

(1) Index ratios developed by the Alaska State Pipeline Coordinator's Office (1981) for areas along the proposed natural gas pipeline, south of the Yukon River.

(2) Index ratios developed by the Alaska State Pipeline Coordinator's Office (1981) for areas along the proposed natural gas pipeline, north of the Yukon River.